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DARK MATTER & NEW PARTICLES

INTRODUCTIONS (1/2)

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INTRODUCTIONS (2/2)

RESEARCH INTERESTS:

- DARK MATTER
  - MODEL BUILDING
  - INDIRECT DETECTION (γ's, ANTIMATTER, ...)
  - ASTRO BACKGROUNDS
- BARYOGENESIS
  - ESP. @ EW SCALE
  - EDM, COLLIDERS, DM, ...

WHAT DO WE KNOW RE: DARK MATTER?

1. ABUNDANCE

$$\bar{\rho}_{DM} \simeq \underbrace{\rho_{crit}}_{\frac{3H_0^2}{8\pi G_N}} \sim \begin{cases} 3\times 10^{10} \frac{M_\odot}{Mpc^3} & \left(\text{CLUSTERS: } \sim 10^5 \text{ OVERD.}\right) \\ 10^{-6} \frac{GeV}{cm^3} & \left(@ \text{ SUN: } 0.3 \frac{GeV}{cm^3}\right) \end{cases}$$

2. "WEAKLY" INTERACTING

... HAVEN'T DETECTED IT YET!

MUSTN'T TALK TO BARYONS TOO STRONGLY (STRUCTURE FORMATIONS)

... RULES OUT MANY SM PARTICLES:

q's, $\ell^{\pm}$'s, g, γ, ...

3. COLD (OR WARM AT BEST)

TOP-DOWN (HOT DM) VS BOTTOM-UP (COLD DM)

→ MUST BE ~NON-RELATIVISTIC @ DECOUPLING

(SEE ALSO J. PRIMACK'S LECTURES)

... RULES OUT ν's

4. LONG-LIVED ENOUGH!

... WE OBSERVE IT TODAY, SO LIFETIME MUST

$$\tau \gg \tau_{\text{UNIVERSE}}$$

$$\tau_{\text{UNIVERSE}} \sim 10\ \text{Gyr} \sim 10 \times 10^9 \times (\pi \times 10^7)\ \text{s}$$

$$\sim \pi \times 10^{17}\ \text{s}$$

- ABSOLUTELY STABLE (e.g. THANKS TO A SYMMETRY IN THEORY, e.g. SUSY, UED, ...)
- VERY LONG LIVED (e.g. M_P-SUPPRESSION ...)
  $\tau_{\tilde{g}} \sim M_P^2 / m_{\tilde{g}}^3$

... FOR PARTICLE PHYSICISTS, DM IS A CLEAR HINT TO **BEYOND-SM PHYSICS!**

NO CANDIDATE PARTICLES IN SM!

⟶ WHICH **GUIDELINES** ON MODEL BUILDING CAN WE EXTRACT FROM WHAT WE KNOW ABOUT DM?

USE 1, 2, 3 TO EYEBALL DM **PARTICLE PROPERTIES** ⟶ **DETECTION STRATEGIES!**

ONE POSSIBLE SCHEME: USE IDEA OF

THERMAL DECOUPLING

... A SUCCESSFUL PARADIGM IN COSMOLOGY:

- RECOMBINATION ($H \leftrightarrow e^- + p$)
- BBN (e.g. $e^+ n \leftrightarrow p + \bar{\nu}$)
- NEUTRINO DECOUPLING

IN SHORT: INTERACTION RATE $\Gamma \lesssim H$

SIGNALS DECOUPLING FROM TH. BATH

AFTER DECOUPLING: SIMPLE RED-SHIFTING OF MOMENTA / DENSITIES.

IN NATURAL UNITS: $\Gamma \sim \underbrace{n}_{\text{\# DENSITY}} \cdot \underbrace{\sigma}_{\text{CROSS SECTION}}$

$$\underbrace{n \sim}_{\text{STAT MECH}} \begin{cases} \cdot\ T^3 & \text{FOR } m \ll T \text{ (REL. LIMIT)} \\ \cdot\ (mT)^{3/2} \exp\left(-\frac{m}{T}\right) & m \gg T \text{ (NR LIMIT)} \end{cases}$$

RIGHT-HAND SIDE $$H \sim \frac{T^2}{M_p}$$

(FROM FRIEDMANN EQ: $H^2 = \frac{8\pi G_N}{3}\rho$, $\rho \sim T^4$)

$$M_p = \frac{1}{\sqrt{8\pi G_N}}$$

EXAMPLE: A SM WIMP: NEUTRINO DECOUPLING

$$\sigma \sim G_F^2 T^2$$

T^2 → ON DIMENSIONAL GROUNDS, FOR $T \gg m_\nu$

G_F^2 → $G_F \sim \frac{1}{m_W^2}$

$\boxed{\Gamma \sim H}$ FOR $T_\nu^3 \, G_F^2 T_\nu^2 = \frac{T_\nu^2}{M_P}$

T_ν^3 ~ n, IF $T_\nu \gg m_\nu$; $G_F^2 T_\nu^2$ ~ σ; $\frac{T_\nu^2}{M_P}$ ~ H

SO $T_\nu = \left(G_F^2 M_P\right)^{-1/3} = \left(10^{-10} \cdot 10^{18}\right)^{-1/3} \text{GeV} \sim \underline{\underline{1\,\text{MeV}}}$

$T_\nu \gg m_\nu$ SO OK, AND HOT RELIC

... NOW, LET'S CALCULATE **RELIC DENSITY**

CONVENTION: DEFINE $Y \equiv \frac{n}{s}$ NUMBER / ENTROPY DENSITY

... IN ISO-ENTROPIC UNIVERSE $s \cdot a^3 = \text{CONST}$, SO

$Y \sim n a^3$ IS A "COMOVING" # DENSITY

IF NO ENTROPY IS PRODUCED, $\boxed{Y_{\text{TODAY}} = Y_{\text{FREEZE OUT}}}$

AND

$$\rho_{\text{HOT RELIC}} = m_{\text{HOT RELIC}} \cdot s_{\text{TODAY}} \cdot Y_{\text{F.O.}}$$

FOR HOT RELICS, $Y_{EQ}(T) \simeq 0.3 \cdot \dfrac{g_{\text{eff}}}{g_{*s}(T)}$

$g_{\text{eff}} \rightarrow \begin{cases} g, & \text{BOSONS} \\ \frac{3}{4} g, & \text{FERMIONS} \end{cases}$

$g_{*s}(T) \rightarrow$ 107 FOR HIGH-T SM

10.7 ~1 MeV

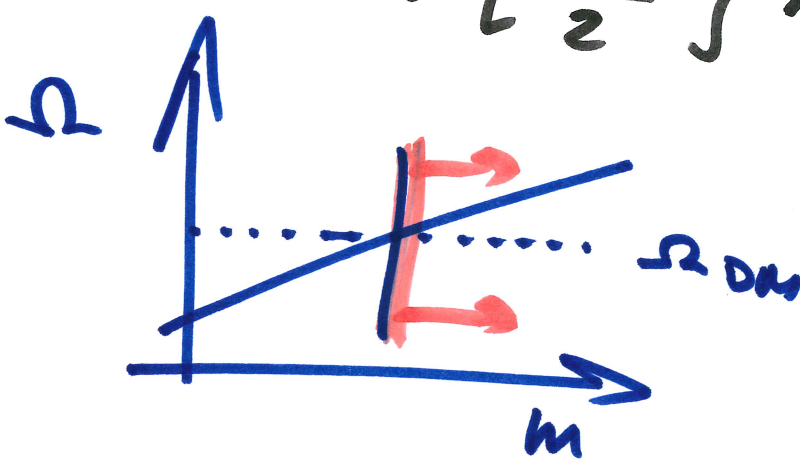
So $\Omega_{\text{HOT RELIC}} h^2 = \frac{\rho_{\text{HOT RELIC}}}{\rho_{\text{CRIT}}} h^2 = 0.08 \frac{g_{\text{eff}}}{g_{*S}(T_{f.o.})} \cdot \left(\frac{m}{eV}\right)$

$\Rightarrow$ For ν's $\xrightarrow[\Omega h^2 \lesssim 0.1]{}$ $m \lesssim 10\,eV \left[\frac{g_{*S}}{g_{\text{eff}}}\right]$

- $T_{f.o.} \sim 1\,MeV$: $m \lesssim 10\,eV \cdot \left[\frac{10}{2 \times \frac{3}{4}}\right] \sim 70\,eV$
- $T_{f.o.} \gtrsim 100\,GeV$: $m \lesssim 10\,eV \left[\frac{100}{2}\right] \sim 0.5\,keV$

GENERAL TREND:

$\Omega_{\text{HOT}} \sim m$



"COSWIK-MC-CLELLAND LIMIT"

... OTHER EXAMPLE: **BARYON-ANTIBARYON ANNIHILATION**

IS IT A HOT RELIC PROBLEM ?!

HERE, $\sigma \sim \frac{1}{m_\pi^2}$, TRY $n \sim T^3$

$$T^3 \cdot \frac{1}{m_\pi^2} = \frac{T^2}{M_P} \Rightarrow T \sim \frac{m_\pi^2}{M_P} \sim 10^{-20}\,\text{GeV}$$

... SO THIS IS NOT A HOT RELIC PROBLEM

$\Rightarrow$ NEED TO DEAL WITH COLD RELICS!

[HW: FIND RELIC $\bar{p}$ ABUNDANCE!]

COLD RELICS: $n \sim (m_\chi T)^{3/2} \exp\left(-\frac{m_\chi}{T}\right)$

... AGAIN, FREEZE-OUT: $n \cdot \sigma \sim H$

$$\downarrow$$

$$n_{f.o.} \sim \frac{T_{f.o.}^2}{M_p \cdot \sigma}$$

CALL $\frac{m_\chi}{T} \equiv x \longrightarrow T = \frac{m_\chi}{x}$ (COLD: $x \gg 1$)

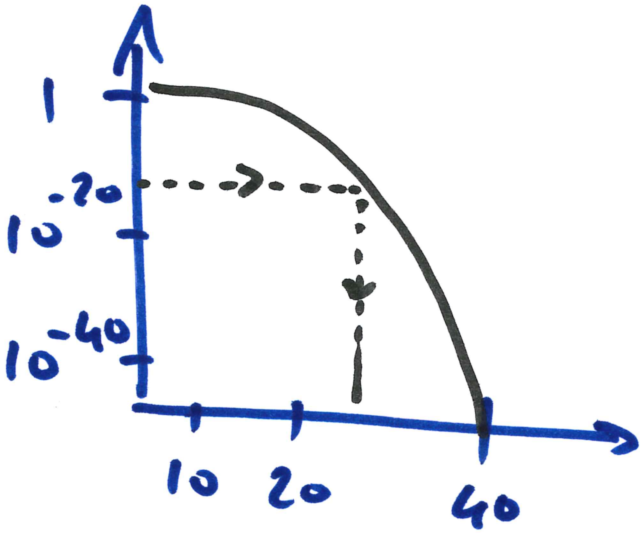
$$\underbrace{\frac{m_\chi^3}{x^{3/2}} e^{-x}}_{n} = \frac{m_\chi^2}{x^2 M_p \sigma}$$

... NEED TO SOLVE: $\sqrt{x}\, e^{-x} = \frac{1}{m_\chi M_p \sigma}$

$$\frac{1}{m_\chi M_p \sigma} \sim \frac{1}{10^2 \cdot 10^{18} \cdot 10^{-6}} \sim 10^{-14}$$

FOR EW SCALE DM

$\sigma \sim G_F^2 m_\chi^2 \sim 10^{-10} (10^2)^2$



$$X_{f.o.} \sim 20 \div 50$$

10^{-10} : $x \sim 26.6$

10^{-15} : $x \sim 36.3$

10^{-20} : $x \sim 48$

NOW, $\Omega_\chi = \frac{m_\chi \cdot n_\chi}{\rho_c} \cdot \frac{T_0^3}{T_0^3}$

$T_0 \simeq 2.75K \sim 10^{-4} eV$

BUT $\frac{n_0}{T_0^3} \simeq \frac{n_{f.o.}}{T_{f.o.}^3}$

SO:

$$\Omega_x = \frac{m_x}{\rho_c} \cdot T_0^{\,3} \cdot \frac{n_{f.o.}}{T_{f.o.}^{\,3}} = \frac{T_0^{\,3}}{\rho_c} \cdot x_{f.o.} \cdot \underbrace{\left(\frac{n_{f.o.}}{T_{f.o.}^{\,2}}\right)}$$

THIS IS $\frac{1}{M_p \cdot \sigma}$!!

SO FINALLY:

$$\Omega_x = \underbrace{\left(\frac{T_0^{\,3}}{\rho_c M_p}\right)}_{\text{SOME CONSTANT}} \cdot \frac{x_{f.o.}}{\sigma}$$

OR:

$$\left(\frac{\Omega_x}{0.2}\right) \approx \left(\frac{x_{f.o.}}{20}\right)\left(\frac{10^{-8}\,\text{GeV}^{-2}}{\sigma}\right)$$

... OFTEN QUOTED: $\langle \sigma v \rangle$, $\langle\ \rangle$: TH. AVERAGE

v : Møller VELOCITY

$\frac{1}{2} m v^2 \sim \frac{3}{2} T$, $v \sim \sqrt{3\frac{T}{m}}\, c$

$\sim 0.3\, c$

SO $\langle \sigma v \rangle \sim 10^{-8}\, \mathrm{GeV}^{-2} \left(3 \times 10^{-28}\, \mathrm{GeV}^2\, \mathrm{cm}^2\right) \cdot 10^{10}\, \frac{\mathrm{cm}}{\mathrm{s}}$

$$\langle \sigma v \rangle \sim 3 \times 10^{-26}\, \frac{\mathrm{cm}^3}{\mathrm{s}}$$

KEY QUANTITY FOR DM SEARCHES (ESP. INDIRECT!)

(SEE J.S-G's LECTURES)

IS $3\times10^{-26}\ \frac{cm^3}{s}$ UNIQUE TO THE WEAK SCALE?

NO

WHAT DID WE ACTUALLY USE?

(i) $\frac{1}{m_\chi \sigma M_p} \ll 1$ (COLD RELIC)

(ii) $\sigma \sim 10^{-8}\ GeV^{-2}$

... SUPPOSE $\sigma \sim \frac{g^4}{m_\chi^2}$: WHEN DO I GET GOOD RELIC DENSITY?

ENOUGH TO REQUIRE $g^4 \sim \frac{m_\chi^2}{10^8 GeV^2}$ OR $g^2 \sim \frac{m_\chi}{10\,TeV}$

NOW, FROM (i) $M_p \gg \frac{1}{m_\chi \sigma} = \frac{m_\chi^2}{m_\chi (g^2)^2} = \frac{m_\chi^2 10^8 \text{GeV}^2}{m_\chi^3}$

SO $m_\chi \gg \frac{10^8 \text{GeV}^2}{10^{18} \text{GeV}} = 0.1 \text{ eV}$

TO BE COLD + THERMAL: NEED $m_\chi \gtrsim 0.1 \text{ eV}$

(TELL B. SADOULET HOW LIGHT COLD WIMPS CAN BE!)

... STILL AMAZING THAT $\sigma_{EW} \sim G_F^2 T_{f.o.}^2 \sim 10^{-8} \text{GeV}^{-2}$

$T_{f.o.} \sim \frac{E_{EW}}{20} \sim 10 \text{ GeV}$

"WIMP MIRACLE"

WHAT DO WE LEARN ABOUT DM MASS RANGE IN THE PARADIGM OF THERMAL DECOUPLING?

- $m_\chi \gtrsim 0.1$ eV
- UPPER LIMIT TO MASS: $\sigma \lesssim \frac{4\pi}{m_\chi^2}$ (UNITARITY)

$$\longrightarrow \quad \frac{\Omega_\chi}{0.2} \simeq \frac{10^{-8}\ \text{GeV}^{-2}}{\left(\frac{4\pi}{m_\chi^2}\right)}$$

SO $\Omega_\chi \lesssim 0.2 \longrightarrow \left(\frac{m_\chi}{120\ \text{TeV}}\right)^2 \lesssim 1$

OR $m_\chi \lesssim 120$ TeV

NOW, FOCUS ON WIMPS : IS THERE A LOWER LIMIT?

$\sigma \sim G_F^2 m_\chi^2$

$$\Omega_\chi h^2 \sim 0.1 \frac{10^{-8} \text{GeV}^{-2}}{G_F^2 m_\chi^2} \sim 0.1 \left(\frac{10 \text{ GeV}}{m_\chi}\right)^2$$

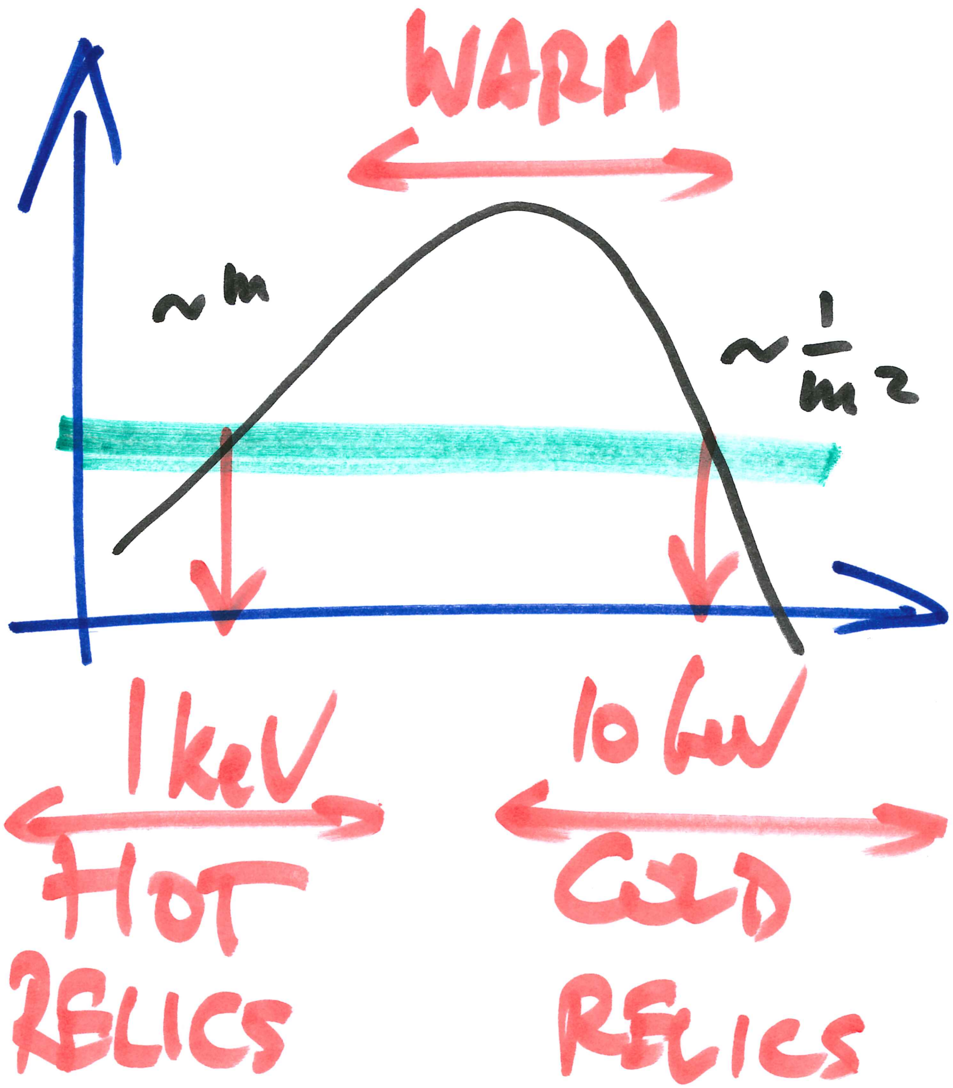
SO: **FOR WIMPS, $m_\chi \gtrsim 10$ GeV**

(A.K.A. LEE-WEINBERG LIMIT)

→ BIG BIAS FOR DIRECT / INDIRECT SEARCH STRATEGIES!!

FOR A GIVEN WIMP σ, e.g.:

$m_{Z'} \gg m_\chi$



... A FEW CAVEATS!

(i) NON-THERMAL PRODUCTION

(ii) PRODUCTION FROM ASYMMETRY

(iii) POST FREEZE-OUT ENTROPY INJECTION

(iv) MULTI-COMPONENT DM

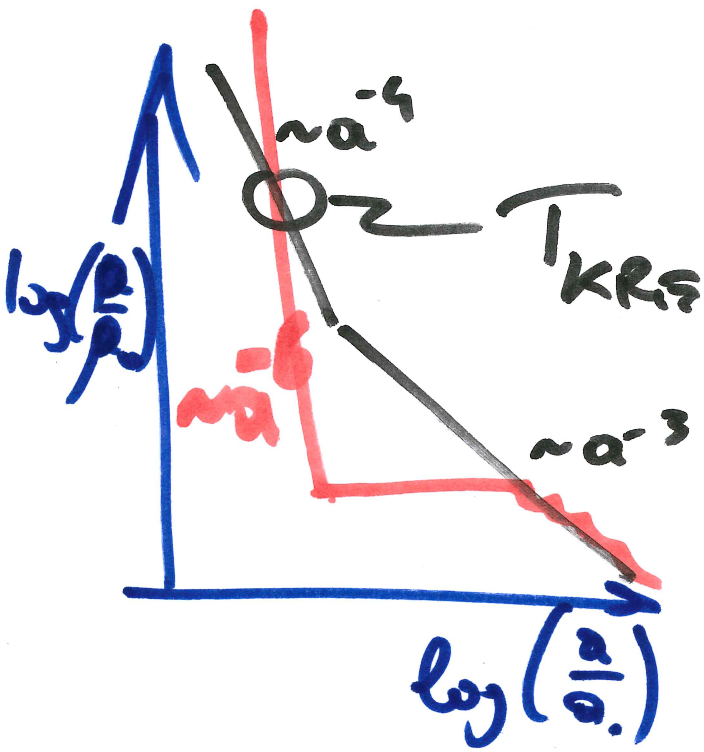
(v) MODIFIED EXPANSION RATE

LIFE IS NEVER EASY!

(v): MY FIRST GRAD-SCHOOL PAPER...

SUPPOSE $\exists$ DYNAMICAL DARK ENERGY

e.g. QUINTESSENCE w/ KINATION



KINATION, $\rho_{KIN} \sim T^6$

$$H \sim T^3$$

$$H = \frac{T^2}{M_P}\left(\frac{T}{T_{KRE}}\right)$$

$$\frac{n_{f.o}}{T_{f.o}^2} \sim \frac{1}{M_P \langle f.o \rangle} \cdot \left(\frac{T_{f.o.}}{T_{KRE}}\right)$$

$$\lesssim \frac{m_\chi}{20} \cdot \frac{1}{T_{BBN}} \sim 10^4$$