SUSY 2013 SCHOOL

LECTURE #1

WELCOME !

- HOW IS THE SCHOOL GOING SO FAR?
- EXCUSE ME FOR BEING SLOWER THAN USUAL TODAY
BLAME IT ON RED EYE FLIGHT!

INTRODUCTIONS : S. PROFUMO

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INTERESTS: DM PHENO
BARYOGENESIS (ESP. @ WEAK SCALE)
ASK ME!

ORDINARY WOULD ASK YOU TO INTRODUCE YOURSELVES
... NOT MUCH TIME THOUGH — PLS COME SEE ME @
COFFE BREAKS ETC.

NETWORKING KEY IMPORTANCE IN SCIENCE (AS IN ANYTHING ELSE!)

TAKE ADVANTAGE OF LECTURERS / CONF. ATTENDEES ETC!

HOW MANY { PURE-BREED THEORY
PHENO
EXPERIMENTALISTS

MY LECTURES: GOOD FOR ALL, BUT FOCUS ON:

PHENO / MODEL BUILDING GUIDELINES
[DM EXCITING AS IT IS A FIELD IN ITS INFANCY / CHAPTER YET TO BE WRITTEN]

... GET STARTED: GLOBAL PROPERTIES OF DM

TO KEEP IN MIND

(KEY E.G. TO EYEBALL DETECTION STRATEGIES / OR WHETHER YOUR FAVORITE MODEL IS RULED OUT OR NOT!)

1. ABUNDANCE

$$\overline{\rho_{DM}} \simeq 0.23 \underbrace{\rho_{CRIT}}_{\frac{3H_0^2}{8\pi G_N}} \sim \begin{cases} 3\times 10^{10} \frac{M_\odot}{Mpc^3} & \left(\begin{matrix}\text{CLUSTERS}\\ \sim 10^5\\ \text{OVERDENSE}\end{matrix}\right) \\ 10^{-6} \frac{GeV}{cm^3} & \left(\begin{matrix}@\text{ SUN:}\\ 0.3 \frac{GeV}{cm^3}\end{matrix}\right) \end{cases}$$

H_0 → FROM ELEM. SCHOOL: $\sim 70 \frac{km}{s} \frac{1}{Mpc}$
PRESENT-DAY HUBBLE EXP. RATE

G_N → FROM KINDERGARTEN

2. "WEAKLY" INTERACTING

... HAVEN'T DETECTED IT YET!
MUSTN'T TALK TO BARYONS TOO STRONGLY
(STRUCTURE FORMATION)

3. COLD (OR WARM AT BEST) — TOP-DOWN VS BOTTOM UP
(NON-REL @ DECOUPLING)

WILL USE 1 (AND ALSO 2, 3) TO EYEBALL PARTICLE PROPERTIES OF DARK MATTER

DECOUPLING : KEY CONCEPT IN COSMOLOGY

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

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

SIGNALS DECOUPLING FROM THE BATH

AFTER WHICH : SIMPLE REDSHIFTING OF MOMENTA / DENSITIES (MORE QUANTITATIVE TOMORROW)

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

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

$n \downarrow$ STAT MECH.

NOW, RIGHT HAND SIDE: $H \sim \dfrac{T^2}{M_P}$

[FROM FRIEDMANN EQ: $H^2 = \frac{8\pi G_N}{3}\rho$; $M_P = \frac{1}{\sqrt{8\pi G_N}}$

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

EXAMPLE: A SM WI(M)P : LIGHT NEUTRINO DECOUPLING T_ν

$$\Gamma \sim G_F^2 T^2$$

ON DIMENSIONAL GROUNDS, IF $T \gg m_\nu$ (WILL CHECK THIS!)

$G_F \sim \frac{1}{m_W^2}$

$\Gamma \sim H$ FOR $\underbrace{T_\nu^3}_{n} G_F^2 T_\nu^2 = \frac{T_\nu^3}{M_P}$

$\rightarrow n \cdot \sigma$

(AGAIN: VALID IF $T \gg m_\nu$)

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

$T_\nu \gg m_\nu$ OK! SO: HOT RELIC (FREEZE-OUT WHEN RELATIVISTIC)

NOW: LET'S CALCULATE RELIC DENSITY!

CONVENIENT TO DEFINE $Y = \frac{n}{s}$ — n: # DENSITY, s: ENTROPY DENSITY

IN ISO-ENTROPIC UNIVERSE $s \cdot \underbrace{a}_{\text{SCALE FACTOR}}{}^3 \simeq$ CONSTANT

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

IF NO ENTROPY IS PRODUCED, $Y_{TODAY} = Y_{F.O.}$

$= \frac{n \cdot m}{=}$

AND $\rho_{\substack{HOT\\RELIC}} = m_{\substack{HOT\\RELIC}} \cdot S_{TODAY} \cdot Y_{F.O.}$

FOR HOT RELICS $Y_{EQ}(T) \simeq 0.3 \cdot \frac{g_{eff}}{\underbrace{g_{*S}(T)}_{\text{K-T NOTATION}}}$

$g_{eff} \longrightarrow \begin{cases} g & \text{(BOSONS)} \\ \frac{3}{4} g & \text{(FERMIONS)} \end{cases}$

$g_{*S}(T) \longrightarrow$ 107 FOR HIGH-T S.M.; 10.7 FOR ~ 1 MeV

H_0 IN UNITS OF $100 \frac{km}{s\,Mpc}$

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

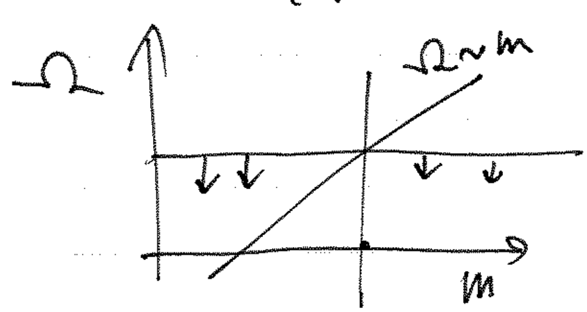
FOR ν'S $\xrightarrow[\Omega h^2 \lesssim 0.1]{}$ $m \lesssim$ ~~[illegible]~~ $10\,eV \left[\frac{g_{*S}(T_{F.O.})}{g_{eff}}\right]$

$T_{F.O.} \sim 1$ MeV $\longrightarrow m \lesssim 10\,eV \left[\frac{10}{2 \times \frac{3}{4}}\right] \sim 70\,eV$

$T_{F.O.} \gtrsim 100$ GeV $\longrightarrow m \lesssim 10\,eV \left[\frac{100}{2}\right] \sim 0.5\,keV$

EXAMPLE PERTINENT TO SUSY (e.g. GRAVITINOS)

GENERAL TREND, FOR GIVEN T : $\Omega_{HOT} \sim m$



COSMIK-MC-CLELLAND LIMIT

OTHER EXAMPLE, MATTER-ANTIMATTER ANNIHILATION

$$p\bar{p} \to \pi\text{'s} \ldots$$

HERE $\sigma \sim \frac{1}{m_\pi^2}$ IS THIS A HOT RELIC PROBLEM?

TRY $\Gamma \sim H$ WITH $n \sim T^3$

$$T^3 \frac{1}{m_\pi^2} = \frac{T^2}{M_p} \qquad T_{f.o.(?)} \sim \frac{m_\pi^2}{M_p} \sim \frac{10^{-2}}{10^{18}}\,\text{GeV} \sim 10^{-20}\,\text{GeV}$$

NOPE! $m_p \sim 1\,\text{GeV}$

HW: (i) CALCULATE $T_{f.o.}$; (ii) ESTIMATE RELIC $p\bar{p}$ DENSITY; (iii) COMPARE WITH OBSERVATION.

... WE'LL NEED TO UNDERSTAND: (ALSO FOR # 3)

COLD RELICS: $T_{f.o.}$ IN NON-REL. REGIME

(e.g.: "HEAVY" NEUTRINO $m_\nu \gtrsim 1\,\text{MeV}$) CALL THEM χ

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

AGAIN, FREEZE-OUT CONDITION: $n \cdot \sigma \sim H \Rightarrow n_{f.o.} \sim \frac{T_{f.o.}^2}{M_p \cdot \sigma}$

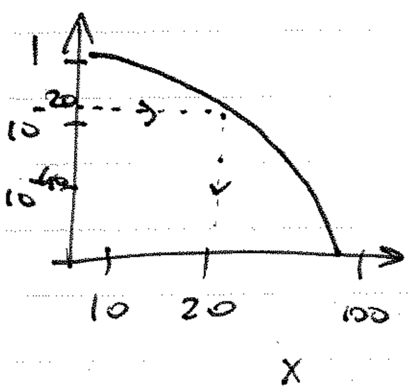
CALL $\frac{m_\chi}{T} \equiv x$, $T = \frac{m}{x}$ (COLD RELIC REGIME: $x \gg 1$)

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

NEED TO SOLVE $\sqrt{x}\, e^{-x} = \frac{1}{\underbrace{m_\chi M_p \sigma}} \sim \frac{1}{10^2 \cdot 10^{18} \cdot 10^{-6}} \sim 10^{-14}$

e.g. FOR EW DM

$\sigma \sim G_F^2 m_\chi^2 \sim 10^{-10} \cdot (10^2)^2 \sim 10^{-6}$



$$x_{f.o.} \sim 20 \div 50 \quad \begin{cases} 10^{-10} : & x \sim 24.6 \\ 10^{-15} : & x \sim 36.3 \\ 10^{-20} : & x \sim 48.0 \end{cases}$$

RELEVANT FOR $p\bar{p}$

Now, $\Omega_\chi = \frac{m_\chi \cdot n_\chi (T = T_0)}{\rho_c} \cdot \frac{T_0^3}{T_0^3}$

T_0: $2.75\,k \sim 10^{-4}\, eV$

BUT $\frac{n_0}{T_0^3} \simeq \frac{n_{f.o.}}{T_{f.o.}^3}$ (SINCE $a \cdot T \sim$ CONST AS $S \sim T^3$)

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

SO $\Omega_\chi = \frac{m_\chi}{\rho_c} T_0^3 \cdot \frac{n_{f.o.}}{T_{f.o.}^3} = \frac{T_0^3}{\rho_0} \cdot x_{f.o.} \overbrace{\left(\frac{n_{f.o.}}{T_{f.o.}^2} \right)}$

SO $\Omega_\chi = \underbrace{\left(\frac{T_0^3}{\rho_c \cdot M_P}\right)}_{\text{SOME CONSTANT}} x_{f.o} \cdot \frac{1}{\sigma}$

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

$\boxed{\begin{array}{l} \frac{1}{2} m v^2 \sim \frac{3}{2} T \\ v \sim \sqrt{3 \cdot \frac{T}{m}}\, c \end{array}}$

OFTEN QUOTED (WE'LL SEE WHY): $\langle \sigma v \rangle$ $\quad v \sim \frac{c}{3}$ FOR $x \sim 20$

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

$= 3 \times 10^{-26}\,\frac{\text{cm}^3}{\text{s}}$ MAGIC NUMBER!

IS THIS UNIQUE TO EW-SCALE? NO!

WHAT DID WE USE?

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

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

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

FROM (ii): $g^4 \sim \frac{m_\chi^2}{10^8\,\text{GeV}^2} \Longrightarrow g^2 \sim \frac{m_\chi}{10\,\text{TeV}}$

(i). $M_p \gg \frac{1}{m_\chi \sigma} = \frac{m_\chi^2}{m_\chi (g^2)^2} = \frac{m_\chi^2 \cdot 10^8 GeV^2}{m_\chi^3}$

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

i.e: TO BE COLD, NEEDS TO BE AT LEAST 0.1 eV
- NO MATTER HOW TINY g IS!

BUT IT'S AMAZING THAT $\sigma_{EW} \sim G_F T_{f.o.}^2 \sim 10^{-8} GeV^{-2}$

$\downarrow$

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

• IS THERE AN UPPER LIMIT TO m_χ? YES!
"g" CANNOT BE ARBITRARILY LARGE!

ROUGHLY, $\sigma \lesssim \frac{4\pi}{m_\chi^2}$ (MORE ACCURATE LIMIT VIA UNITARITY IN PARTIAL WAVE EXPANSION)

$\downarrow$

$\frac{\Omega_\chi}{0.2} \simeq \frac{10^{-8} GeV^{-2}}{\left(\frac{4\pi}{m_\chi^2}\right)}$ SO $\Omega_\chi < 0.2$ IMPLIES:

$\left(\frac{m_\chi}{120 \text{ TeV}}\right)^2 \lesssim 1$, OR $m_\chi \lesssim 120 \text{ TeV}$

NOW, FOCUS ON <u>WIMPS</u>

- IS THERE A <u>LOWER LIMIT</u> TO <u>WEAKLY INT.</u> MASSES ?

$$\sigma \sim G_F^2 m_\chi^2 \quad \text{FOR WIMP}$$

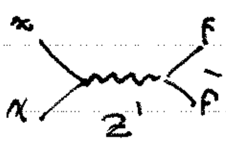
$$\Omega_\chi h^2 \sim 0.1 \cdot \frac{10^{-8}\,\text{GeV}^{-2}}{G_F^2 m_\chi^2} \sim 0.1 \left(\frac{10\,\text{GeV}}{m_\chi}\right)^2$$

SO $m_\chi \gtrsim 10$ GeV FOR WIMPS (<u>LEE-WEINBERG</u> LIMIT)

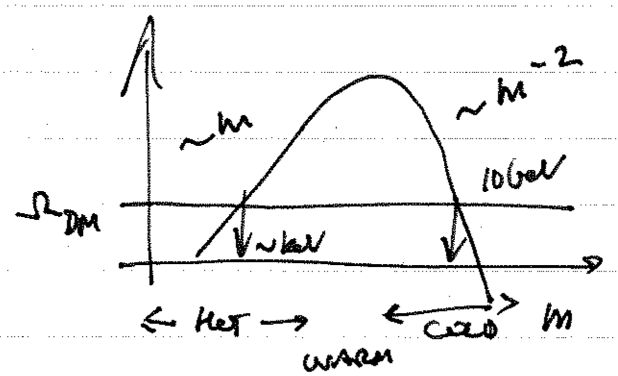
CASE FOR 10 GeV WIMP – PROBLEMATIC?

<u>NOTICE</u> THE $\Omega \sim \frac{1}{m_\chi^2}$ DEPENDENCE

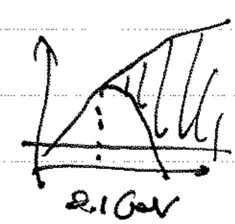
FOR A GIVEN (WIMP) σ,



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



SUSY: BIG SPREAD : σ NOT UNIQUELY FIXED



(THE LIGHTEST LIGHTEST NEUTRINO)

A FEW CAVEATS TO KEEP IN MIND

(i) NON-THERMAL PRODUCTION ((ii) OR FROM ASYMMETRY)

(iii) POST FREEZE-OUT ENTROPY INJECTION

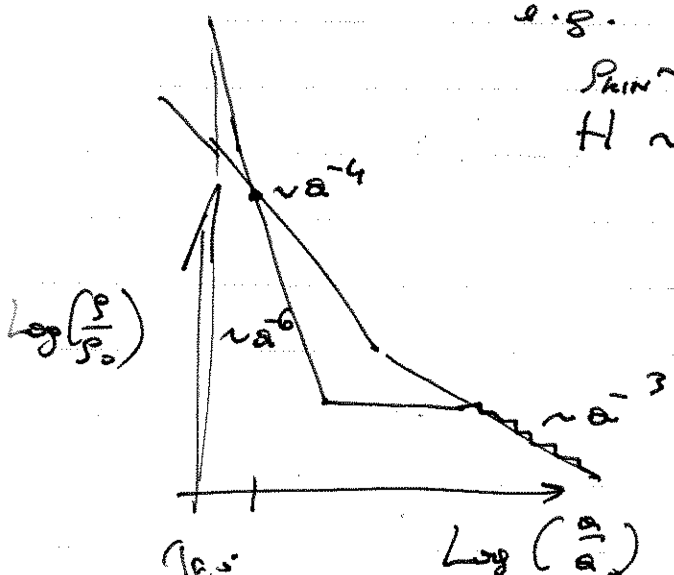
(iv) MULTI-COMPONENT DM

(v) MODIFIED EXP. RATE

e.g. WITH KINATION (QUINTESSENCE)

$\rho_{kin} \sim T^6$

$H \sim T^3$, DECOUPLING OCCURS EARLIER → ENHANCE RELIC DENSITY



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

$$n_{f.o.}\langle\sigma v\rangle = \frac{T^2}{M_p}\left(\frac{T}{T_{KRE}}\right)$$

$$\frac{n_{f.o.}}{T_{f.o.}^2} \sim \frac{1}{M_p\langle\sigma v\rangle}\,\frac{T_{f.o.}}{T_{KRE}}$$

AT MOST: $\frac{m_\chi}{20}\cdot\frac{1}{T_{BBN}} \sim \left(\frac{m_\chi}{100\,\text{GeV}}\right)\cdot 10^4$

SUSY 2015

Lecture 1

(Intro / Importance of Naturalness in Science

(MS, science) ... ? take advantage of observed / consistency

- theory : use

Global Properties of SM (and relevance to above [illegible])

? to Optimal Research Strategy ?

• New Physics
• Cold Dark
• Heavy m

R Symmetry, Hot Relic, PP, [illegible]

Lecture 2 : [illegible]

• [illegible]
• Direct Detection
• Indirect Detection
• LHC → [illegible] → [illegible] → [illegible]

Lecture 3 :

Lecture 4 : [illegible] :

• Cosmic [illegible]
• Neutrinos
• [illegible]