Problems

CMB + BBN

Baryogenisis : $\eta \equiv \dfrac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$ ... Why not zero?

Initial conditions? No, inflation + reheating

1) Inflation dilutes initial excess
2) Reheating produces γ + particles

Inflation:

* CMB is uniform T, even patches that would otherwise have been out of causal contact

Friedman $\dfrac{\ddot{a}}{a} = H^2 (1 - 3w)$, $w = \dfrac{P}{\rho}$: E.of.State

$H = \dfrac{\dot{a}}{a}$, a: scale parameter

Inflaton:

$$\mathcal{L} = \frac{1}{2} \dot{\phi}^2 - V(\phi)$$

$$\rho = \frac{1}{2}\dot{\phi}^2 - V(\phi) , \quad P = \frac{1}{2}\dot{\phi}^2 + V(\phi) , \quad w = \frac{P}{\rho}$$

'Exponential' expansion: $\ddot{a} > 0 \Rightarrow w < -1/3 \Rightarrow \dot{\phi}^2 \ll V$

Ends when $\dot{\phi} \sim V$ ($V \sim \phi^2$, ϕ driven towards minimum

Then: oscillates around minimum.

Coupling to SM: decays $\rightarrow$ reheating $\rightarrow$ hot Big bang!

Baryogenisis require:

1) B Violation:

$$\underbrace{X}_{B} \rightarrow \underbrace{Y + Z}_{B' > B}$$

Is allowed in SM! (anomalous)
Not observed.

2) C and CP Violation:

$$\bar{X} \rightarrow \bar{Y} + \bar{Z}$$

Require $R(X \to YZ) \neq R(\bar{X} \to \bar{Y}\bar{Z})$

3) Departure from thermal equillibrium:

$$R(X \to YZ) \neq R(YZ \to X) \quad (+\ X \leftrightarrow \bar{X})$$

In equillibrium:
$$\frac{n_X}{n_{\bar{X}}} \sim \exp\left(-\frac{E_X - E_{\bar{X}}}{T}\right) \cong 1$$

Require: $R(YZ \to X) < H$

decay $X \to YZ$ still occurs

All allowed in SM, but CP violation too small

$\Rightarrow$ New sources of CP violation

Dark Matter

~85% of matter

- BBN: - ratios of light elements very sensitive to baryon density.

  (efficiancy of $p \xrightarrow{D_\gamma} {}^3He \to 4He \to {}^7Be \to {}^7Li$ etc.)

  - gives η

- CMB: Distribution (Power spectrum) of anisotropies very sensitive to Ω_m / Ω_b

  Ω_b: ~~reionis~~ recombination $\Rightarrow$ intensity

  Ω_m: gravity : clumps

  $\Rightarrow \Omega_m = \Omega_b + \Omega_c$

- Large-scale structure : Clumpyness
- Rotation curves

$\Rightarrow$ New particles

$m_\chi \gtrsim 10^{-21}$ eV : $\lambda_B < L_{galaxy}$

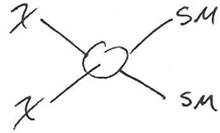
$m_\chi \lesssim 10^{28}$ eV : Planck mass

$\Rightarrow$ 50 o.o.f

WIMP miracle

1) Initially in thermal equill:

$$Y \sim e^{-m/T}$$
for $T < m$



2) Expansion shuts off ~~[illegible]~~ anhialation } Freeze out
(T < m prevents creation)

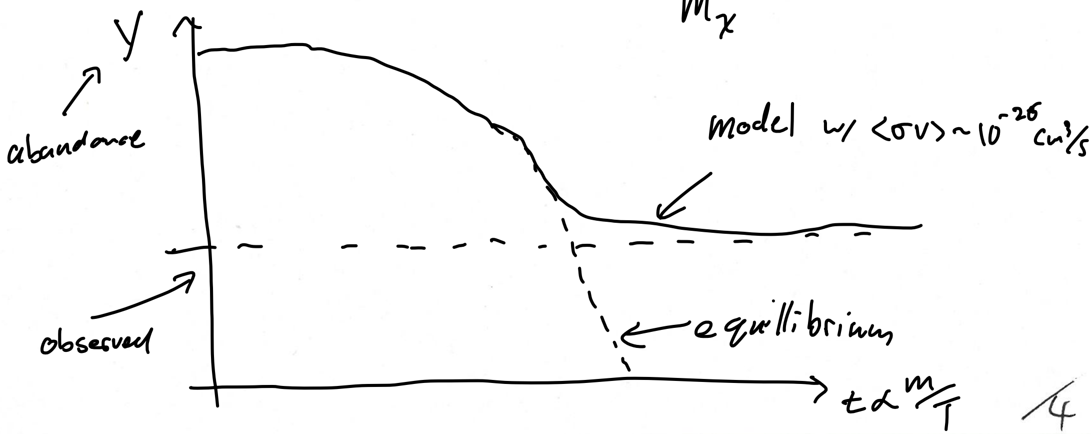
$$T \lesssim H \quad \Rightarrow \quad \Omega_\chi h^2 \sim 0.1 \; \frac{3\times10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma v\rangle}$$

Weak scale! ($G_F \sim 10^{-5}\,\mathrm{GeV}^{-2}$, $m \sim 100$ GeV)

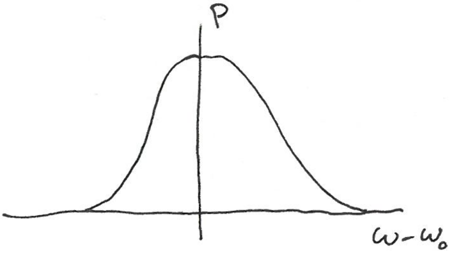
Gives correct abundance!

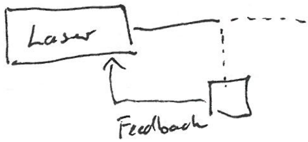
Observed (Planck): $\Omega_\chi h^2 = 0.120 \pm 0.001$
(~25% of energy
or ~ 85% of matter)

Weak scale: $\langle \sigma v\rangle \sim \dfrac{g_\chi^4}{m_\chi^2} \sim 3\times10^{-26}\,\mathrm{cm}^3/\mathrm{s}$

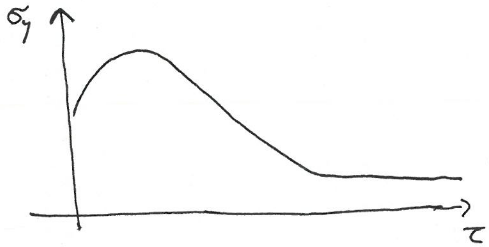


Atomic Clocks





$$\sigma(\tau) \sim \frac{\Delta\omega}{\omega} \frac{1}{\sqrt{N}} \sqrt{\frac{T_m}{\tau_{avg}}}$$



$\sim 10^{-18}$ or better!

$1s / T_{universe}$!

→ Gravitational redshift : $\frac{\Delta f}{f} \approx \frac{\Delta U}{c^2} \sim 10^{-16} \frac{\Delta r}{1m}$

→ Absolute frequencis to 18 digits!

→ Cannot calculate .... require differential observations

→ Precise atomic theory still required

↳ $\sim 1 - 0.1\%$ (not 10^{-18}..)

Nuclear Clock

Atomic $\Delta E \sim eV$

Nuclear $\sim$ 100 keV or MeV $\leftarrow$ hopeless (laser)

Insane coincidence: ^{229}Th has nuclear level $\sim$ 8.4eV

$\rightarrow$ Meased last year by Ekhardt Peik @ PTB

100 keV $\rightarrow$ eV : 4-7 orders of magnitude small

$\Rightarrow$ cancellations between EM, Strong parts

$\Rightarrow$ Very sensitive to new physics in EM or QCD sectors.

New Physics in heavy Atoms

1) New particles: new forces

e-N : - S/V (P even) energy shifts, isotope shifts
- PS/PV (P-odd) PNC, EDM

2) Variation of constants

→ dark energy (long)
→ ultralight dark matter

e.g. $\phi F^{\mu\nu} F_{\mu\nu} \to \delta\alpha$

$\frac{\delta \nu}{\nu} \sim K \frac{\delta\alpha}{\alpha} \propto \phi$

3) Direct detection of DM

→ ultralight ↗

→ Scattering / absorbtion

→ axion

4) Lorentz / CPT / EEP tests

→ Position / orientation dependant shifts

→ Gallileo satillite

→ Add random disallowed terms to SM $\mathcal{L}$

Parity Violation

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left(c_1 \, \bar{N}\gamma_\mu N \, \bar{e}\gamma^\mu\gamma^5 e + c_2 \, \bar{N}\gamma_\mu\gamma^5 N \, \bar{e}\gamma^\mu e \right)$$

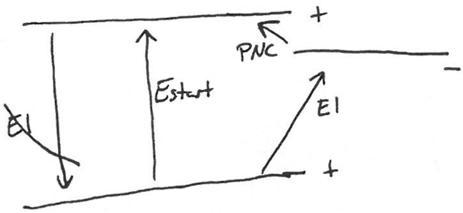
$$h_{eff} \approx \frac{-G_F}{2\sqrt{2}}\left(\gamma^5 Q_w\right)\rho(r)$$

$+$ Nuclear anapole moment $\sim \vec{\alpha}\cdot\vec{I}\,\rho(r)$

Mixes parity:

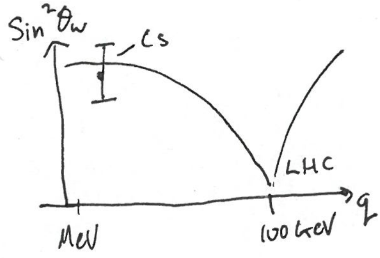
$$|\psi^+\rangle \to |\psi^+\rangle + \overset{\sim 10^{-11}}{\eta}\,|\psi^-\rangle$$

$$\frac{G_F Q_w \, |n\rangle\langle n|\gamma^5\rho|\psi\rangle}{\varepsilon - \varepsilon_n}$$



$$R \sim |A_{stark} + A_{PNC}|^2$$

$$\sim A_s^2 + \underbrace{A_s \cdot A_{PNC}\,\vec{\varepsilon}\cdot\vec{E}}$$



$$A_{PNC} = Q_w \, k_{PNC}$$

A_{PNC}: measure to 0.3%

k_{PNC}: Calc to 0.5%

Plan: both to 0.1%

$$\Delta Q_w \sim 0.4(2N+Z)\left(\frac{M_W}{M_{Z'}}\right)^2$$

$$\Rightarrow M_{Z'} \gtrsim 0.7 \text{ TeV}$$

Bismuth: First observation 1978

0.1% $\rightsquigarrow$ 3 TeV

How to Calculate

$$|\psi\rangle = |\psi_c\rangle \times |\psi_v\rangle$$

① Average core (HF)

$$H = \sum_i^N h_0(r_i) + \sum_{\{ij\}}^N \frac{1}{|\vec{r}_i - \vec{r}_j|}$$

$$\approx \sum_i^{N_v} \left(h_0(r_i) + V^{HF}(r_i)\right) + \sum_{\{ij\}}^{N_v} \frac{1}{|\vec{r}_i - \vec{r}_j|}$$

HF :

$\hookrightarrow$

Σ_2 : Core not independent: Correlations

Screening:

$$Q + (-i)\, Q\Pi Q + (-i)^2\, Q\Pi Q \Pi Q + \dots$$

$$\tilde{Q} = Q[1 + i\Pi Q]^{-1}$$

all orders!

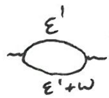
Feynman approach

$$(H_0 + V_d + \cancel{V_x} - \varepsilon)\,\phi = 0 - V_x\phi$$

$$(H + V_d - \varepsilon)\,\chi = 0$$

Feynman propagator

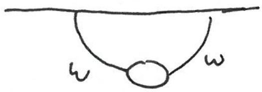
$$G_0(\chi)\,,\qquad G = G_0 + G_0 V_x G$$
$$= G_0\left[1 - V_x G_0\right]^{-1}$$

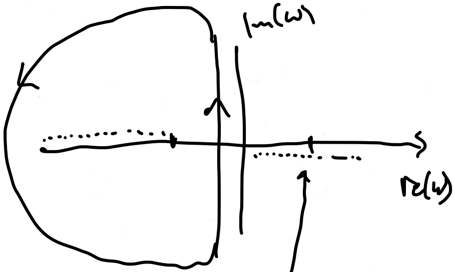


$$\Pi(\omega) = \int \frac{d\varepsilon}{2\pi}\, G_{12}(\varepsilon')\, G_{12}(\omega + \varepsilon')$$

analyticly

Σ_D :





$$= \int \frac{d\omega}{2\pi}\, G_{12}(\underline{\varepsilon+\omega})\, Q_{1i}\, \Pi_{ij}(\underline{\omega})\, Q_{j2}$$

Poles along real axis

none between $(-|\Delta E|, 0)$

core energy gap!

$$Q \to \tilde{Q}(\omega) \quad \text{for all orders}$$

"Typical" approach

$|\Psi_0\rangle$ reference

$$|\Psi\rangle = \left(1 + \rho^{1} a_i^{\dagger} a_j + \rho^{(2)} a_i^{\dagger} a_j^{\dagger} a_k a_l + \dots\right)|\Psi_0\rangle$$

Solve for $\rho, \rho \dots$