1.7

CH6 DARK MATTER

→ Many evidences from ≠ astrophysic scales:
radial $\vec{v}$ of galaxies, CMB, structure formations, bullet cluster, ...

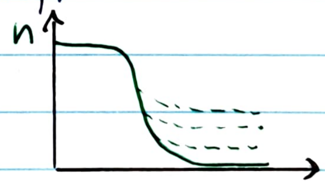
→ What we know:
- → neutral
- → not baryonic } particle properties
- → not short-lived
- → not hot } cosmology
- → gravitationaly coupled

→ What we don't:
- → if it's a particle, its property: mass, spin, CP, ...
- → its other coupling: Higgs, quark, leptons, ...
- → if it's a thermal relic, if there is an asymmetry, ...

⊙ Thermal dark matter production:

→ We assume thermal DM production: $\chi\chi \leftrightarrow f\bar{f}$
As the $T\downarrow$, $\chi\chi \to f\bar{f}$: DM Boltzman suppressed untill freeze-out

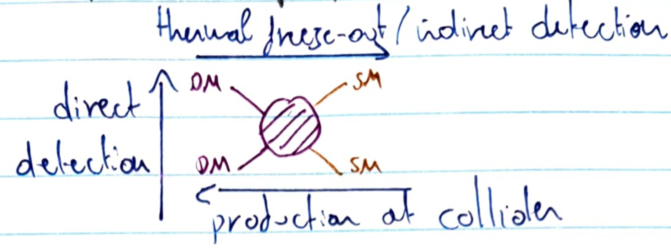
→ Evolution given by: $\dfrac{dn}{dt} = -3Hn - \langle \sigma_{annihi}\, v\rangle (n^2 - n_{eq}^2)$
(Boltzmann)



→ The WIMP miracle: assuming on top a coupling similar to the weak interaction, $\langle \sigma v\rangle \sim 10^{-26}\ cm^3 s^{-1}$ and $m \sim 100$ GeV.

6.1 Searches for dark matter

→ Pictorially;



1) Direct detection:

→ Searches for elastic collisions of DM on nuclei
→ Typically: < 100 keV
→ No sensitivity at low mass
→ Assumption: { DM static and we're travelling through it
{ density
→ Problem of the ν coherent scattering, can be solved if we know the direction of the incoming particles.

2) Indirect detection:

→ Annihilation in region of high DM density: galaxy center, ...
→ Annihilation into γ-rays (good messenger)
↳ monochromatic line? (⇐ Cold DM)
→ Annihilation into $\tau^+\tau^-$, $b\bar{b}$, WW, ZZ, $t\bar{t}$ ...
↳ give neutrinos (⇝ IceCube, Super-K)

3) Collider searches:

→ Conditions: kinematic, coupling, ...
→ Direct production. Look for M_{ET}, recoil.
↳ Results very sensitive to the model

CH7 NEUTRINOS

7.1 Neutrino mass

⊙ $\mathcal{L}_m$ for neutrinos :

→ No Dirac mass : $\mathcal{L} \not\ni m_D \bar{\nu}\nu = m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$
↳ No mass term for neutrinos in the SM

⊙ Neutrinos mass limits :

→ From tritium β- decay end point measurement
$m(\nu_e) < 0,8\ eV$ from KATRIN exp.
→ From : $\pi \to \mu$, $\tau \to \dots$: $m(\nu_\mu) < 180\ keV$, $m(\nu_\tau) < 18,2\ MeV$
→ From cosmology : $\sum_i m(\nu_i) < 0,3\ eV$
→ From supernovae : $m(\nu_e) < 5,7\ eV$

7.2 Neutrino oscillations

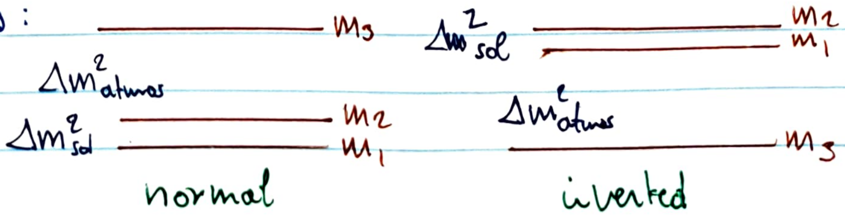
→ First proof in 2001 at SNO exp.

DEF | The flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ are related to mass eigenstates (ν_1, ν_2, ν_3) through the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

→ The PMNS is very non diagonal. Can be described by :

$$\begin{cases} \theta_{12} \sim 33° \text{ the solar angle} \to \Delta m^2_{21} \sim 10^{-4}\ eV^2 \\ \theta_{23} \sim 50° \text{ the atmospheric angle} \to \Delta m^2_{31} \sim \Delta m^2_{32} \sim 10^{-3}\ eV^2 \\ \theta_{13} \sim 8° \\ \delta_{CP} \sim 194° \end{cases}$$

→ 2 hierarchies :



7.3 Theory of m_ν

→ For a Majorana fermion: part = CPT (part) = antipart

→ See-saw mechanism: add a sterile neutrino:

$$-\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R\end{pmatrix}\begin{pmatrix}\cancel{m_{M,L}} & m_D \\ m_D & m_{M,R}\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix} \rightsquigarrow M = \begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}$$

with m_D a Dirac mass, and M_R arbitrary.

↳ Diagonalizing, the eigenvalues are M_R and $-m_D^2/M_R$

We expect $M_R \sim \frac{m_{top}^2}{\sqrt{\Delta m^2_{atmo}}} \sim 10^{15}$ GeV ~ GUT

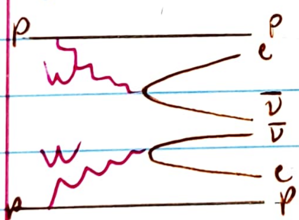
↳ We need:

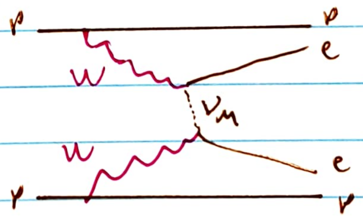
1) ν = Majorana part.
2) $\exists\, \nu_R$, heavy

} gives a tiny mass to ν_L

⊙ Observing Majorana neutrinos:

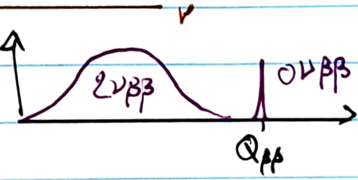
→ If ν = Majorana, then neutrinoless double β-decay is possible:





→ lepton number: $\Delta L = 2$

→ Expected distribution:



→ If we can observe such a decay, we have

$$\Gamma \sim |\Sigma\, m_i U_{ei}^2|^2 \rightarrow \text{the neutrino mass scale}$$

↑ PMNS

↳ Also gives the hierarchy

→ Other possibility: double-μ decay

→ In accelerators

→ VBF production