Title: Explorations in Particle Theory-5

Date: Apr 10, 2015 09:00 AM

URL: http://pirsa.org/15040010

Abstract:

Tutorial today

on estimating rates & abundances (2-3:30 pm)

Problem Set #1 due next Friday

Boltzmann eq.

$\chi\bar{\chi} \to f\bar{f} \qquad \Gamma = n\langle\sigma v\rangle$

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

$$\frac{dY_\chi}{dx} = \frac{-x\,s(x)}{H(x=1)}\langle\sigma v\rangle\left[Y_\chi^2 - (Y_\chi^{eq})^2\right]$$

where $Y_\chi = \frac{n_\chi}{s}$, $x = \frac{M_\chi}{T}$

Using $\langle\sigma v\rangle = \sigma_n x^{-n}$

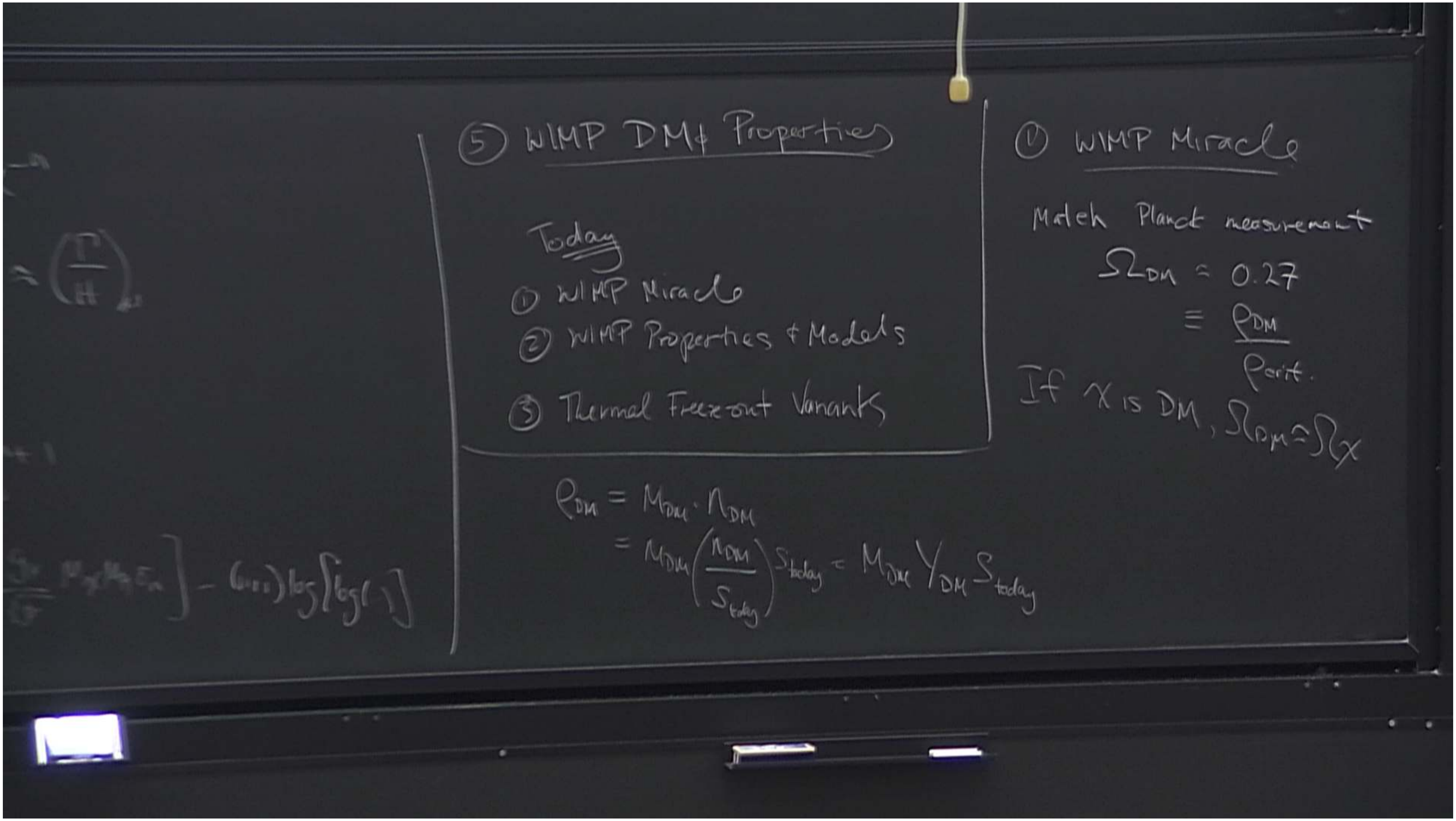
$$\lambda \equiv \left[\frac{s\langle\sigma v\rangle}{H(x)}\right]_{x=1} \approx \left(\frac{\Gamma}{H}\right)_{x=1}$$

we found

$$Y_\chi^\infty = \frac{n+1}{\lambda} x_{fo}^{n+1}$$

$$x_{fo} = \log\left[k\sqrt{\frac{90}{8\pi^3}}\frac{g_\chi}{\sqrt{g_*}} M_\chi M_{Pl}\sigma_n\right]$$

$\approx 20-30$



5 WIMP DM Properties
Today
1 WIMP Miracle
2 WIMP Properties & Models
3 Thermal Freeze-out Variants
$\rho_{DM} = M_{DM} \cdot n_{DM}$
$= M_{DM} \left(\frac{n_{DM}}{S_{today}} \right) S_{today} = M_{DM} Y_{DM} S_{today}$
1 WIMP Miracle
Match Planck measurement
$\Omega_{DM} \simeq 0.27$
$\equiv \frac{\rho_{DM}}{\rho_{crit.}}$
If χ is DM, $\Omega_{DM} \simeq \Omega_\chi$

$$Y_\chi^\infty = \frac{n+1}{\lambda}\, x_f^{n+1}$$

$$\lambda = \left.\frac{x\, s(x) \langle \sigma v \rangle}{H(x)}\right|_{x=1}$$

$$s(T) = \frac{2\pi^2}{45} g_{*s} T^3$$

$$\xrightarrow{x=1} \frac{2\pi^2}{45} g_{*s} M_\chi^3$$

$$H(T) = 1.66\sqrt{g_*}\,\frac{T^2}{M_{Pl}}$$

$$\rightarrow 1.66\sqrt{g_*}\,\frac{M_\chi^2}{M_{Pl}}$$

$$\lambda = \text{coeff} \cdot \frac{M_\chi^3}{M_\chi^2/M_{Pl}}\, \sigma_n$$

$$= \text{coeff}\; M_{Pl} M_\chi \sigma_n$$

$$\boxed{Y_\chi^\infty \sim \frac{(n+1)\, x_f^{n+1}}{M_\chi M_{Pl} \sigma_n}}$$

$$\rho_\chi = M_\chi Y_\chi^\infty s_0 \leftarrow 2000/\text{cm}^3$$

$$\boxed{\rho_\chi = \frac{x_f^{n+1} s_0}{\sigma_n M_{Pl}}}$$

$$\boxed{\rho_\chi \sim \frac{1}{\langle \sigma v \rangle}}$$

direct link b/w particle physics & cosmology.

$$\Omega_{DM} = \frac{\rho_\chi + \rho_{\bar\chi}}{\rho_{crit}} = \frac{2\rho_\chi}{\rho_{crit}}$$

- s-wave annihilation
  $(n=0)$.

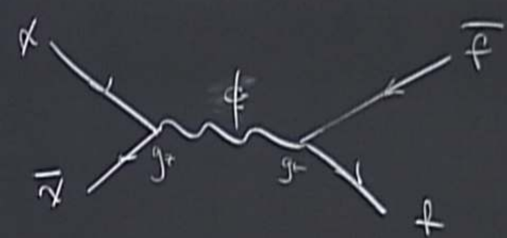
$$\langle \sigma v \rangle = a + \cancel{b x^{-2} + \dots} \xrightarrow{\text{Planck}} \boxed{\begin{aligned} \langle \sigma v \rangle &\approx 4.4 \times 10^{-9}\,\mathrm{GeV}^{-2} \\ &\simeq 6 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \end{aligned}}$$

- $g_* \approx 100$
- $x_{fo} \approx 30$

$$\Omega_{DM} = \frac{1.09 \times 10^{-9}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

↳ "Dirac" DM $\chi \neq \bar{\chi}$

→ "Majorana"; $\chi = \bar{\chi} \longrightarrow \langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$



$m_Z, m_f \ll T \ll M_\chi$

$$\boxed{\langle \sigma v \rangle \simeq \frac{1}{8\pi} \frac{g_Z^4}{M_\chi^2} = \left(4.4\times 10^{-9}\,\mathrm{GeV}^{-2}\right)\left(\frac{g_\phi}{0.6}\right)^4 \left(\frac{700\ \mathrm{GeV}}{m_\chi}\right)^2}$$

WIMP Miracle $\rightarrow$ "weakly interacting massive particle"

(perturbative)
Unitarity bound

$\uparrow m_\chi , \ \uparrow g(m_\chi)$

$g \lesssim 4\pi$

$M_\chi \lesssim O(100)\,\mathrm{TeV}$

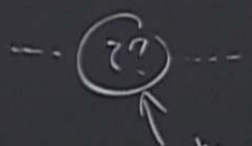
$\overset{h}{\text{- - -}} \circlearrowleft_{t} \overset{h}{\text{- - -}} \rightarrow \Delta m_h^2 \sim m_t^2$

$\text{- - -}\,(??)\,\text{- - -} \rightarrow \Delta m_h^2 \sim -m_t^2$

$m \sim$ weak scale.

- WIMPs have "large" $\langle \sigma v \rangle$ at $E \sim \mathrm{TeV}$
  → look for WIMPs in experiments.
- very predictive.

$\rightarrow \Delta m_h^2 \sim m_t^2$



$\rightarrow \Delta m_h^2 \sim -m_t^2$

$m \sim$ weak scale.

- WIMPS have "large" $\langle \sigma v \rangle$ at $E \sim$ TeV
  - $\longrightarrow$ look for WIMPs in experiments.
- very predictive.

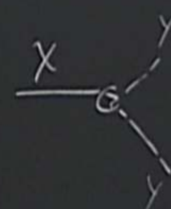
② WIMP Properties + Models

1) $\Omega_\chi = \Omega_{DM}$.

$$\langle \sigma v \rangle = 6 \times 10^{-26}\ cm^3/s.$$

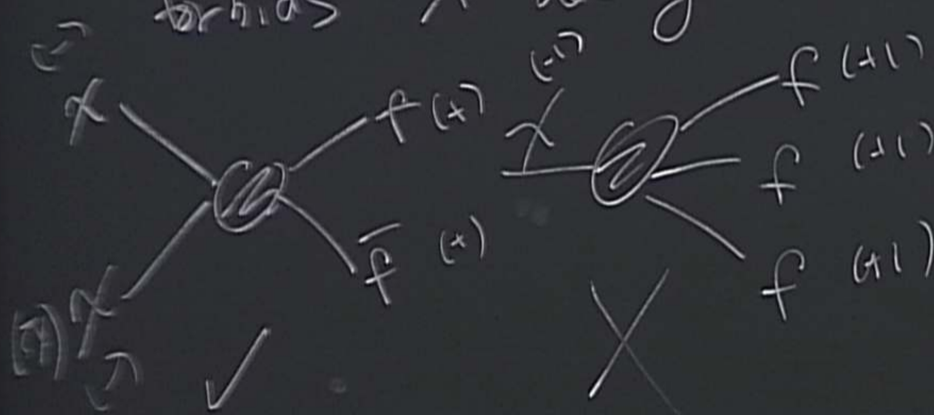
2) Forbidden χ decays.

$\tau_{univ} \sim 14$ Gyr., $\Gamma_\chi \lesssim 10^{-40}$ GeV



$$\Gamma_\chi \simeq \frac{g_{decay}^2}{8\pi} \underbrace{M_\chi}_{TeV}, \quad g_{dec} \lesssim 10^{-21}$$

Adding a symmetry that forbids χ decay



· any interaction requires 2χ

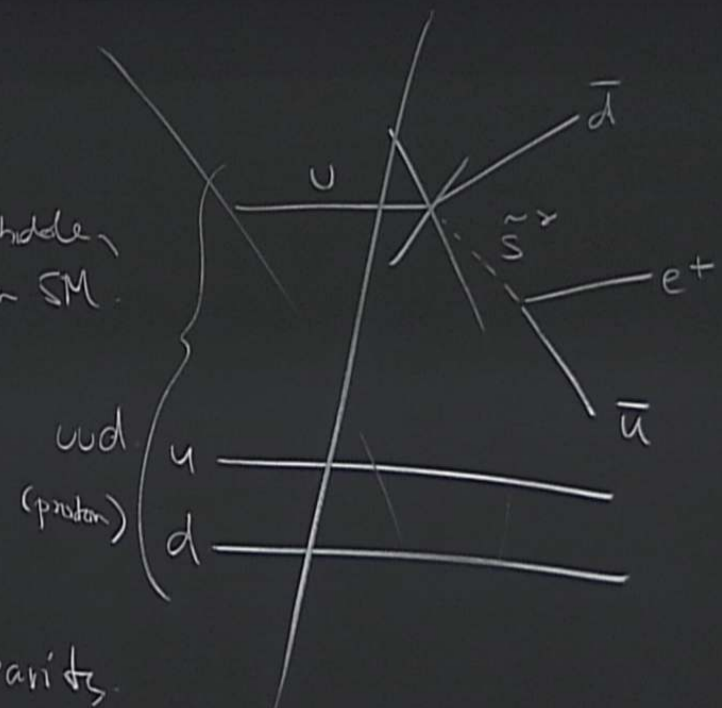
$\mathbb{Z}_2$ symmetry (parity)

$\chi, \bar{\chi}$ charge -1

SM charge $+1$

neutron = udd

$\underbrace{\varepsilon_{ijk}\, u^i d^j d^k}_{\text{colour-invariant}}$ ← forbidden in SM



$\mathcal{L} = \varepsilon_{ijk}\, u^i d^j \tilde{d}^k$

Introduce $\mathbb{Z}_2$ called R-parity

ψ_{SM} (+1)

$\tilde{\psi}$ (−1)

$\underbrace{u\bar{d}}_{\pi^+}\ \underbrace{\bar{u}d}_{\pi^-}\ e^+$

$m_\pi \sim 130$ MeV

$m_e \sim 0.5$ MeV

$p \to \pi^+ \pi^- e^+$

↑ $\gtrsim 10^{34}$ s

$\mathbb{Z}_2$-even

t

h

$\vdots$

e

$\mathbb{Z}_2$-odd

$\tilde{q}$

$\vdots$

$\tilde{H}, \tilde{B}, \tilde{W}$

lightest SUSY particle (LSP).

$$\underbrace{\tilde{H}_u, \tilde{H}_d, \tilde{W}, \tilde{B}}_{\text{mix}}$$

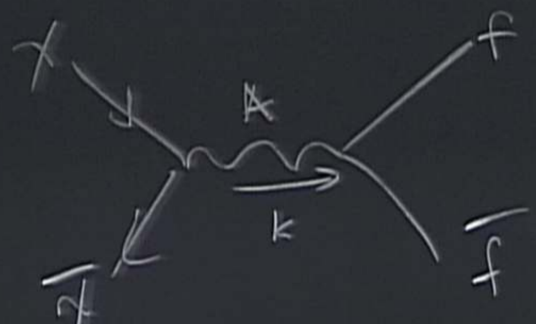
$\boxed{\text{MSSM} \sim 105 \text{ parameters.}}$

③ Variants on Freeze-out

Potentially Lots of new particles in the spectrum

↳ change the predictions of freeze-out.

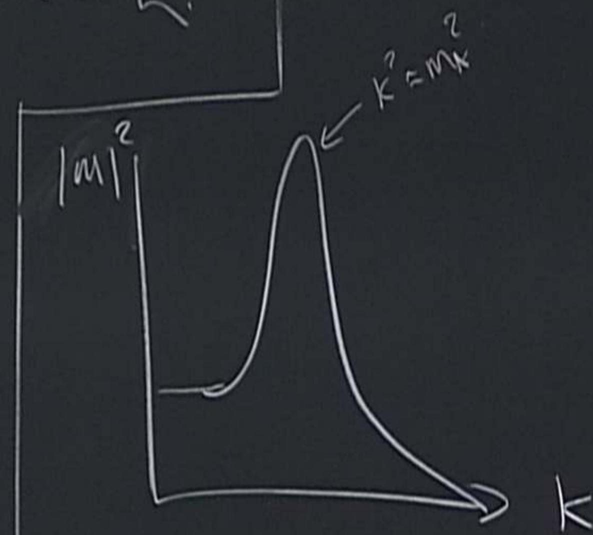
a) Resonant DM annihilation



$m_\chi \gg m_A$

$$M \sim \frac{1}{k^2 - m_A^2} \sim \frac{1}{m_\chi^2}$$

$\sigma \sim |M|^2 \leftarrow$ pole in σ as well



real pr

Im(

real prop $\dfrac{i}{k^2 - m_A^2 + i m_A \Gamma_A}$

$\mathrm{Im}\Big($  $\Big)$

$$\sigma \sim \frac{1}{8\pi}\frac{g^4}{m_\chi^2} \longrightarrow \frac{1}{8\pi}\frac{g^4}{m_A \Gamma_A}.$$

Γ

$\bar d$

e^+

$\bar u$

$\underbrace{u\bar d}_{\pi^+}\ \underbrace{\bar u d}_{\pi^-}\ e^+$

$m_\pi \sim 130\ \mathrm{MeV}$

$m_e \sim 0.5\ \mathrm{MeV}$

$p \longrightarrow \pi^+ \pi^- e^+$

$\tau \gtrsim 10^{34}\ s$

$\Gamma_A \sim \frac{g^2}{8\pi} M_A .$

σ is enhanced by $\frac{m_\chi^2}{M_A^2 g^2}$

If g is too small to give the naive thermal abundance,

or if $m_\chi^2 = \frac{1}{4} M_A^2$.

Z_2 - even

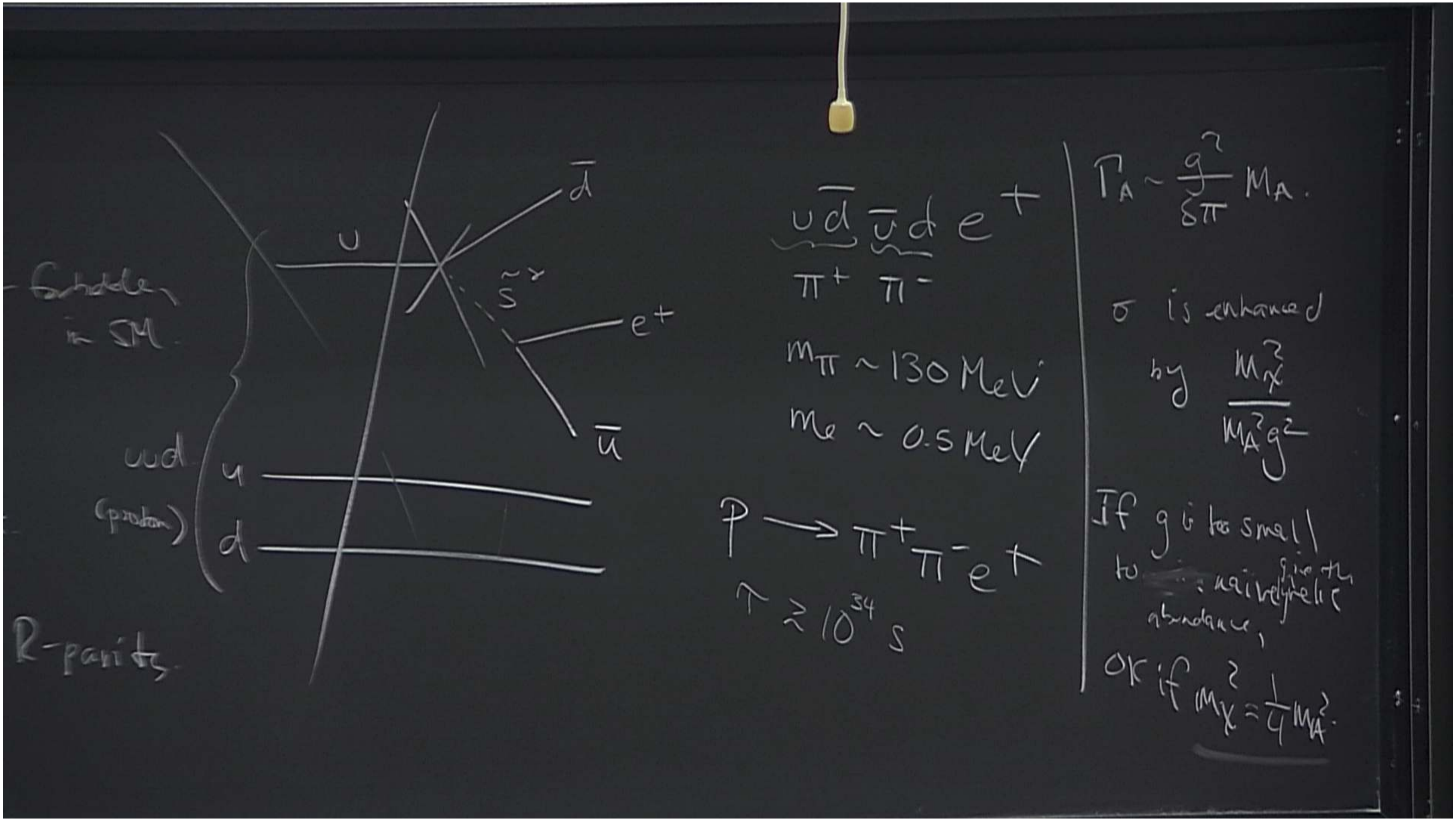
t

h

$\vdots$

e

$\tilde H_u$


forbidden in SM.
uud (proton)
u
d
R-parity
u
$\bar{d}$
$\tilde{s}^*$
e^+
$\bar{u}$
$u\bar{d}\ \bar{u}d\ e^+$
$\pi^+\ \ \pi^-$
$m_\pi \sim 130$ MeV
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$\tau \gtrsim 10^{34}$ s
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σ is enhanced by $\frac{m_\chi^2}{m_A^2 g^2}$
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