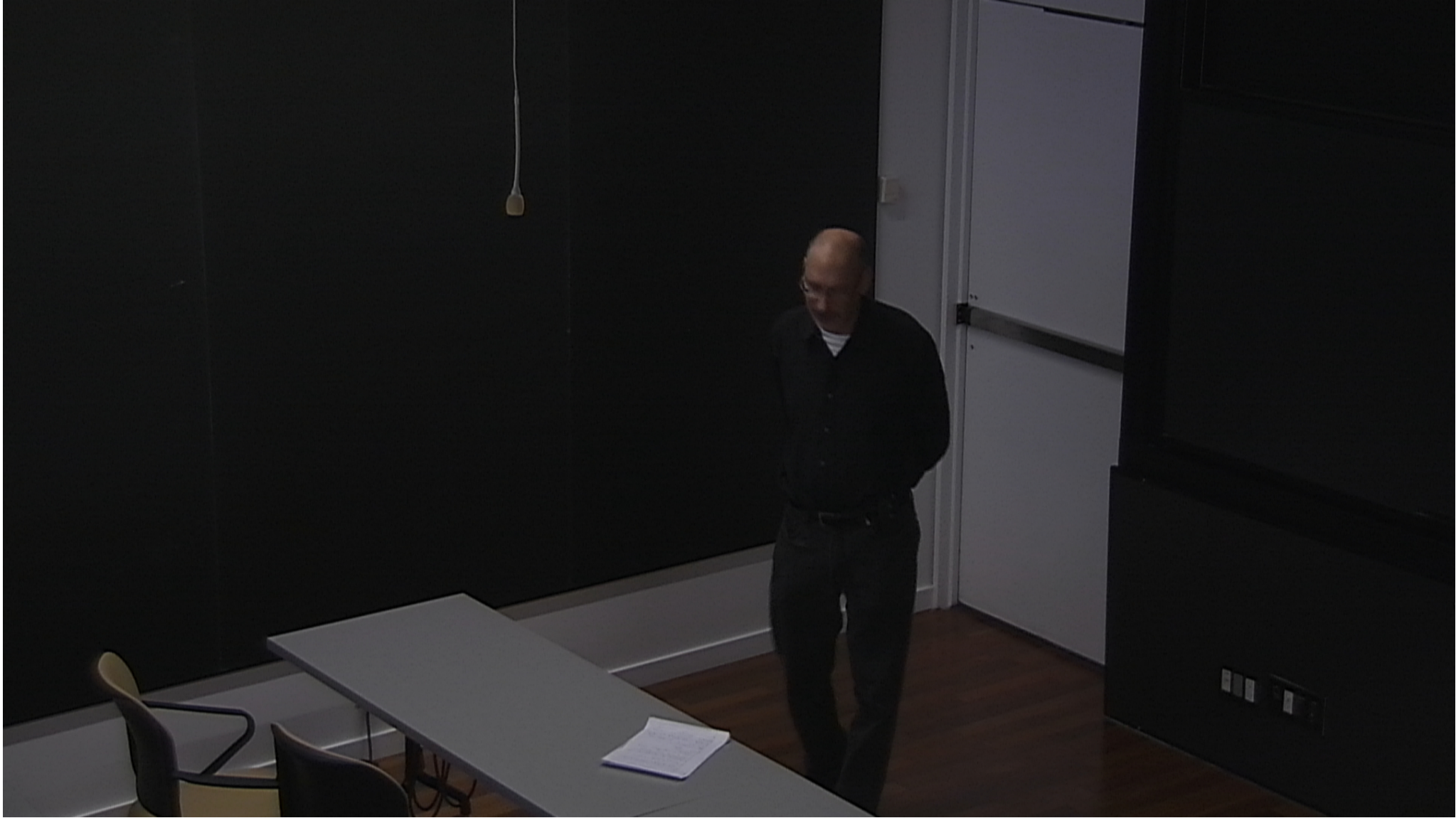


Title: Asymmetric Dark Matter Bound States

Date: Sep 02, 2014 01:00 PM

URL: <http://pirsa.org/14090068>

Abstract: One of the simplest low energy effective theories with Asymmetric Dark Matter contains a gauge singlet Dirac Fermion for the dark matter and a gauge singlet scalar as the mediator that the dark matter decays into. In this model I discuss the spectrum of bound states (two body and multi-body) and the cosmological production/dissociation of dark matter two body bound states.



Minimality
Simplicity

Minimality

Simplicity

SM + Dark Sector

ϕ a complex scalar
no SM gauge coupling.

Simplicity

SM + Dark Sector

ϕ a complex Scalar
no SM gauge coupling.

ADM

Ψ Dirac Fermion SM singlet
 ϕ real scalar

Ψ Dirac Fermion SM singlet

ϕ real scalar

$$\mathcal{L}_{SM} + \Delta \mathcal{L}$$

Ψ Dirac Fermion SM singlet

ϕ real scalar

$$\mathcal{L}_{SM} + \Delta \mathcal{L}$$

$$\begin{aligned} \Delta \mathcal{L} = & i \bar{\chi} \not{\partial} \chi - m_\chi \bar{\chi} \chi - \bar{\chi} (g_V + i g_5 \gamma_5) \chi \phi \\ & + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{1}{4} \phi^4 - \frac{1}{6} \lambda_\phi \phi^3 \\ & - \frac{1}{2} m_\phi^2 \phi^2 - \mu_{\phi h} \phi (H^\dagger H - v^2) - \frac{1}{2} \lambda_{\phi h} \phi^2 (H^\dagger H) \end{aligned}$$

Ψ Dirac Fermion SM singlet

ϕ real scalar

$$\mathcal{L}_{SM} + \Delta \mathcal{L}$$

$$\begin{aligned} \Delta \mathcal{L} = & i \bar{\chi} \not{\partial} \chi - m_\chi \bar{\chi} \chi - \bar{\chi} (g_V + i g_5 \gamma_5) \chi \phi \\ & + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{1}{24} \lambda_4 \phi^4 - \frac{1}{6} \lambda_3 \phi^3 \\ & - \frac{1}{2} m_\phi^2 \phi^2 - \mu_{\phi h} \phi \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{2} \lambda_{\phi h} \phi^2 \left(H^\dagger H - \frac{v^2}{2} \right) \end{aligned}$$

Ψ Dirac Fermion SM singlet

ϕ real scalar

$$\mathcal{L}_{SM} + \Delta \mathcal{L}$$

$$\begin{aligned} \Delta \mathcal{L} = & i \bar{\chi} \not{\partial} \chi - m_\chi \bar{\chi} \chi - \bar{\chi} (g_V + i g_5 \gamma_5) \chi \phi \\ & + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{1}{24} \lambda_4 \phi^4 - \frac{1}{6} \lambda_3 \phi^3 \\ & - \frac{1}{2} m_\phi^2 \phi^2 - \mu_{\phi h} \phi \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{2} \lambda_{\phi h} \phi^2 \left(H^\dagger H - \frac{v^2}{2} \right) \end{aligned}$$

ϕ a complex scalar
no SM gauge coupling.

ADM

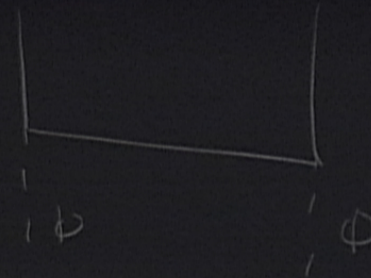
$$\chi \rightarrow e^{i\alpha} \chi$$

$$\tilde{m}_\chi \chi \chi$$

$$\mathcal{L}_{SM} + \Delta \mathcal{L}$$

$$\begin{aligned} \Delta \mathcal{L} = & i \bar{\chi} \not{\partial} \chi - m_\chi \bar{\chi} \chi - \\ & + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{24} \Lambda^4 \phi^4 \\ & - \frac{1}{2} m_\phi^2 \phi^2 - \mu \phi h \phi \left(\frac{1}{f} H^\dagger H - \frac{v^2}{2} \right) - \end{aligned}$$

$$\begin{aligned}
 & -\frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{24} \lambda_4 \phi^4 - \frac{1}{6} \lambda_3 \phi^3 \\
 & -\frac{1}{2} m_\phi^2 \phi^2 - \mu_{\phi h} \phi \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{2} \lambda_{\phi h} \phi^2 \left(H^\dagger H - \frac{v^2}{2} \right)
 \end{aligned}$$



Complex Scalar
in gauge coupling.

$$\mathcal{L}_{SM} + \Delta \mathcal{L}$$

$$\begin{aligned} \Delta \mathcal{L} = & i \bar{\chi} \not{\partial} \chi - m_\chi \bar{\chi} \chi - \bar{\chi} (g_V + i g_5 \gamma_5) \chi \\ & + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{1}{24} \lambda_4 \phi^4 - \frac{1}{6} \lambda_3 \phi^3 \\ & - \frac{1}{2} m_\phi^2 \phi^2 - \mu_\phi h \phi \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{2} \lambda_{\phi h} \phi^2 \left(H^\dagger H - \frac{v^2}{2} \right) \end{aligned}$$

$$\alpha_\chi = \frac{g_\chi^2}{4\pi}, \quad \alpha_\Gamma = \frac{g_\Gamma^2}{4\pi}$$

propagator
gauge coupling.

$$\Delta \mathcal{L} = i \bar{\chi} \not{\partial} \chi - m_\chi \bar{\chi} \chi - \bar{\chi} (g_V \not{\partial} + i g_5 \gamma_5) \chi$$

$$+ \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{1}{24} \lambda_4 \phi^4 - \frac{1}{6} \lambda_3 \phi^3$$

$$- \frac{1}{2} m_\phi^2 \phi^2 - \mu_\phi h \phi \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{2} \lambda_{\phi h} \phi^2 \left(H^\dagger H - \frac{v^2}{2} \right)$$

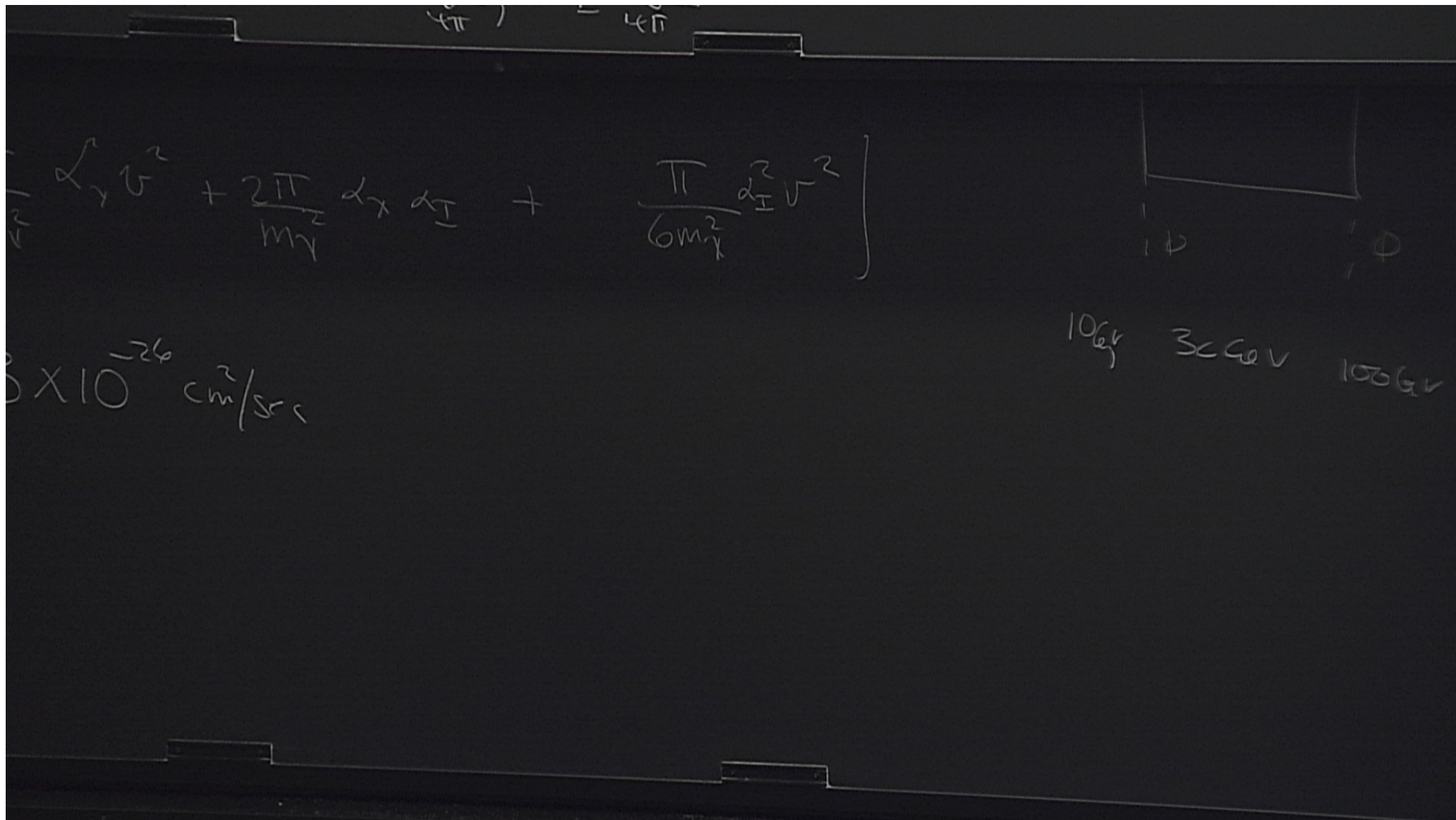
$$\alpha_\chi = \frac{g_\chi^2}{4\pi}, \quad \alpha_\pi = \frac{g_\pi^2}{4\pi}$$

$$= \int \frac{3\pi}{2m_V^2} \alpha^2$$

$$(\sigma V)_{\text{annihil}} = \left[\frac{3\pi}{2m_\nu^2} \alpha_\gamma^2 v^2 + \frac{2\pi}{m_\gamma^2} \alpha_\gamma \alpha_I + \frac{\pi}{6m_\gamma^2} \alpha_I^2 v^2 \right]$$

$$(\sigma_V)_{\text{annihil}} = \left[\frac{3\pi}{2m_\nu^2} \alpha_\gamma^2 v^2 + \frac{2\pi}{m_\gamma^2} \alpha_\gamma \alpha_I + \frac{\pi}{6m_\gamma^2} \alpha_I^2 v^2 \right]$$

$$\sigma_V \left(T \approx \frac{m_\nu}{30} \right) > 3 \times 10^{-26} \text{ cm}^2/\text{s}$$

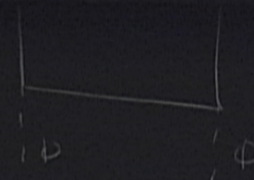


$$\tilde{m}_{\chi\chi}$$

$$-\frac{1}{2}m_\phi^2\phi^2 - \mu\phi h\phi\left(H^\dagger H - \frac{v^2}{2}\right) - \frac{1}{2}\lambda\phi h\phi^2\left(H^\dagger H - \frac{v^2}{2}\right)$$

$$\alpha_\gamma = \frac{g_\gamma^2}{4\pi}, \alpha_\pm = \frac{g_\pm^2}{4\pi}$$

$$(\sigma v)_{\text{annihil}} = \left[\frac{3\pi}{2m_\chi^2} \alpha_\gamma v^2 + \frac{2\pi}{m_\chi^2} \alpha_\gamma \alpha_\pm + \frac{\pi}{6m_\chi^2} \alpha_\pm^2 v^2 \right]$$



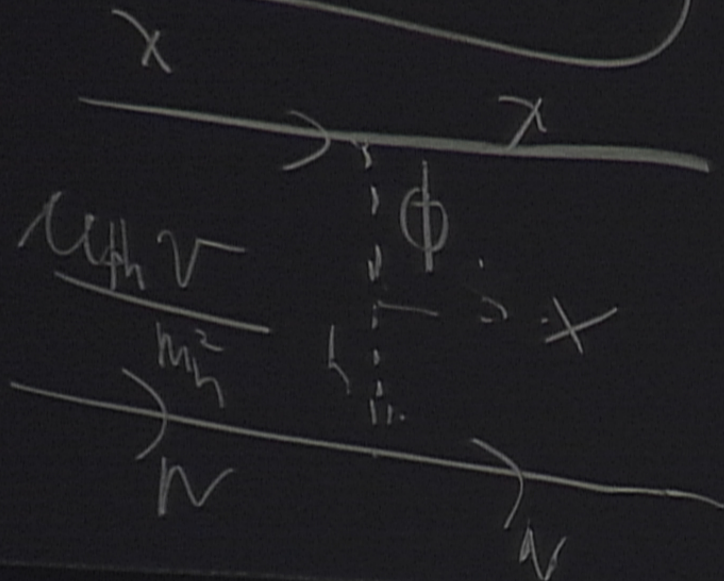
$$\sigma v \left(T \approx \frac{m_\chi}{30} \right) > 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

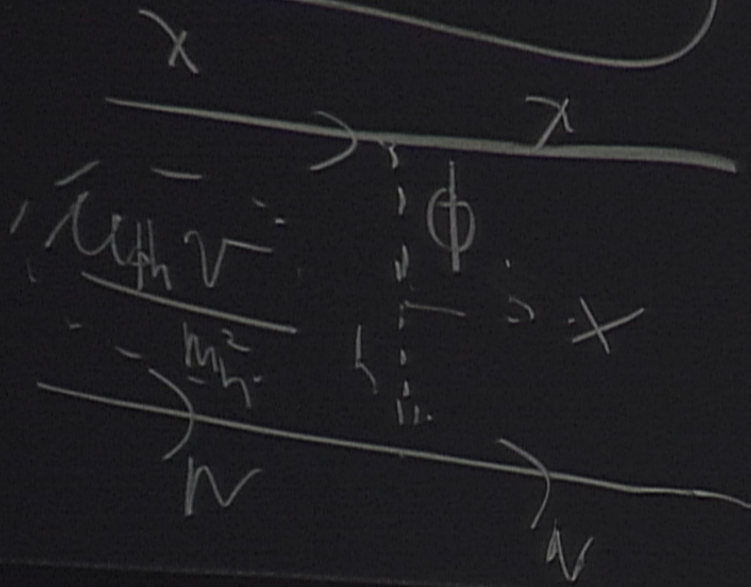
Direct

$$g_5 = g_\lambda \quad m_\chi = 100 \text{ GeV}$$

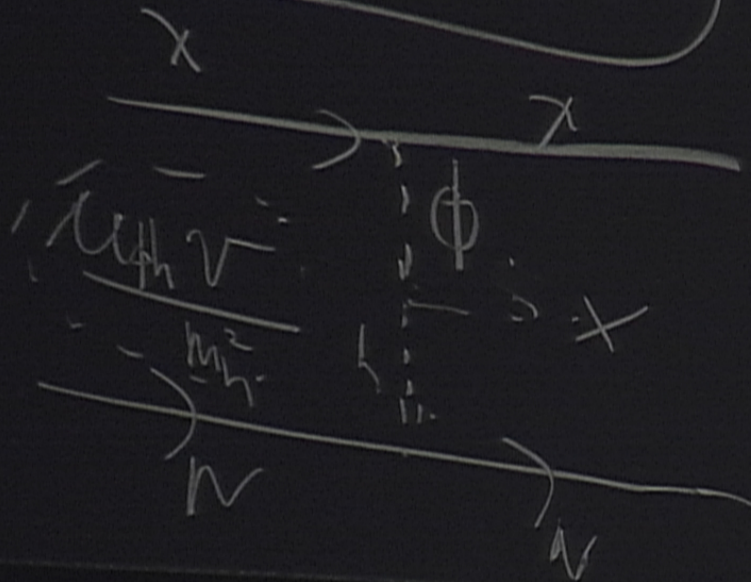
$$\alpha_\gamma \gtrsim 5 \times 10^{-3}$$

$$10_{\text{GeV}} \quad 3 < 40 \text{ V} \quad 100 \text{ GeV}$$





Direct



$$m_\phi = 500 \text{ MeV}$$

$$\alpha_\gamma = 0.1$$

$$10^{-6} - 10^{-7}$$

$$\alpha \chi \gtrsim 5 \times 10^{-3}$$

ϕ decay before BBN

$$\alpha \chi \gtrsim 5 \times 10^{-3}$$

ϕ decay before BBN

→ conflict unless $m_\phi > 250 \text{ MeV}$ (2 MeV)

$$\Gamma_{\phi} \leq 10^{-2} \left(\frac{1 \text{ GeV}}{m_{\phi}} \right) \text{ sec}$$

$$\frac{M_{\phi h} v}{m_h^2} = 10^{-7}$$

$$H = -\frac{\nabla_{cm}^2}{4m_\gamma} - \frac{\nabla^2}{m_\gamma} - \frac{\alpha_\gamma}{r} e^{-m_\pi r} + H_{int}$$

$\hookrightarrow$ int with
on shell $d's$

$$H = -\frac{\nabla_{cm}^2}{4m\chi} - \frac{\nabla^2}{m\chi} - \frac{\alpha_Z}{r} e^{-m_\pi r} + H_{int} \rightarrow \text{int with on shell } d's$$

$$a_0 = \frac{2}{2\chi m\chi}$$

$$\frac{1}{a_0 m_\pi} > 0.8399$$

$$H = -\frac{\nabla_{cm}^2}{4m_\chi} - \frac{\nabla^2}{m_\chi} - \frac{\alpha_\chi}{r} e^{-m_\phi r} + H_{int} \quad \begin{array}{l} \text{int with} \\ \text{on shell } \phi's \end{array}$$

$$a_0 = \frac{2}{\alpha_\chi m_\chi}$$

$$\frac{1}{a_0 m_\phi} > 0.8399$$

$$\begin{aligned} H_{int} &= g_\chi \left[\phi(\vec{x}_1) + \phi(\vec{x}_2) \right] \\ &= g_\chi \left(\phi\left(\vec{x}_{cm} + \frac{\vec{r}}{2}\right) + \phi\left(\vec{x}_{cm} + \frac{\vec{r}}{2}\right) \right) \end{aligned}$$

$$H = -\frac{\nabla_{cm}^2}{4m\gamma} - \frac{\nabla^2}{m\gamma} - \frac{\alpha_\gamma}{r} e^{-m_\gamma r} + H_{int} \quad \begin{matrix} \text{int with} \\ \text{on shell } \phi's \end{matrix}$$

$$a_0 = \frac{2}{\alpha_\gamma m_\gamma}$$

$$\frac{1}{a_0 m_\phi} > 0.8399$$

$$\frac{1}{m} (\vec{p} - e\vec{A})^2 \Rightarrow H_{int} = \frac{e}{m} \left[\vec{A}(\vec{r}_1) \vec{p}_1 + \vec{A}(\vec{r}_2) \vec{p}_2 \right]$$

$$H_{int} = g_\phi \left[\phi(\vec{x}_1) + \phi(\vec{x}_2) \right] \\ = g_\phi \left[\phi\left(\vec{x}_{cm} + \frac{\vec{r}}{2}\right) + \phi\left(\vec{x}_{cm} + \frac{\vec{r}}{2}\right) \right]$$

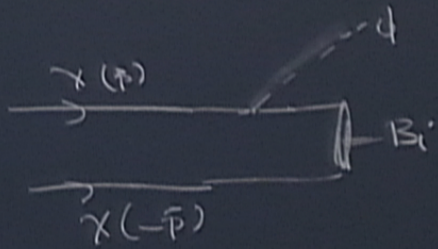
$$H = -\frac{\nabla_{cm}^2}{4m\gamma} - \frac{\nabla^2}{m\gamma} - \frac{\alpha_\gamma}{r} e^{-m_\pi r} + H_{int} \quad \rightarrow \text{int with } \phi \text{'s on shell } \phi \text{'s}$$

$$a_0 = \frac{2}{\alpha_\gamma m_\gamma}$$

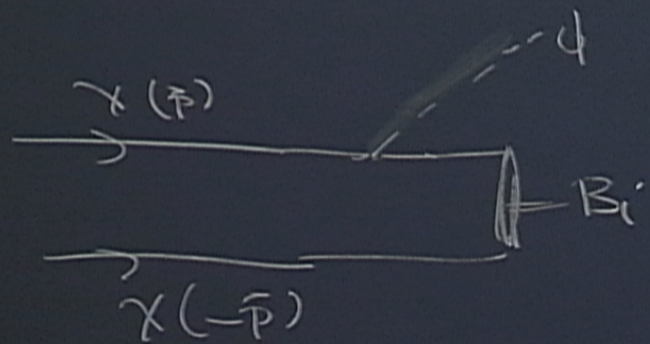
$$\frac{1}{a_0 m_\phi} > 0.8399$$

$$\frac{1}{2m} (\vec{p} - e\vec{A})^2 \Rightarrow H_{int} = \frac{e}{m} [\vec{A}(\vec{r}_1) \vec{p}_1 + \vec{A}(\vec{r}_2) \vec{p}_2]$$

$$H_{int} = g_\chi \left[\phi(\vec{x}_1) + \phi(\vec{x}_2) \right] \\ = g_\chi \left(\phi\left(\vec{x}_{cm} + \frac{\vec{r}}{2}\right) + \phi\left(\vec{x}_{cm} + \frac{\vec{r}}{2}\right) \right)$$



$$x(p) + x(-p) \rightarrow B_i + \phi(p)$$



$$\chi(\vec{p}) + \chi(-\vec{p}) \rightarrow B_i + \phi(t)$$

$$F_i(\vec{p}, t) = \int d^3\vec{r} \psi_i^*(\vec{r}) ($$

$$\alpha_Y = \frac{g_Y^2}{4\pi}, \quad \alpha_Z = \frac{g_Z^2}{4\pi}$$

$$-\frac{1}{2} \lambda \phi_h \phi^2 \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{2} \lambda \phi_h \phi^2 \left(H^\dagger H - \frac{v^2}{2} \right)$$

$$H = -\frac{\nabla_{cm}^2}{4m_Y} - \frac{\nabla^2}{m_Y} - \frac{\alpha_Y}{r} e^{-m_Y r} + H_{int}$$

int with
on shell d's

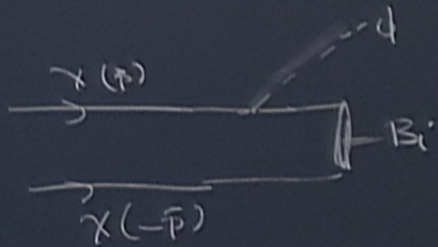
$$a_0 = \frac{2}{\alpha_Y m_Y}$$

$$\frac{1}{a_0 m_Y} > 0.8399$$

$$\frac{1}{2m} (\vec{p} - e\vec{A})^2 \Rightarrow H_{int} = \frac{e}{m} \left[\vec{A}(\vec{r}_1) \vec{p}_1 + \vec{A}(\vec{r}_2) \vec{p}_2 \right]$$

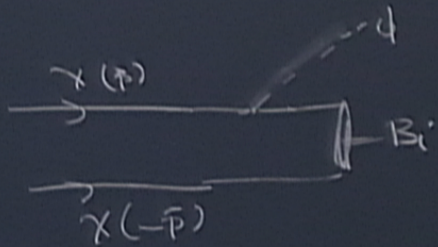
$$H_{int} = g_Y \left[\phi(\vec{x}_1) + \phi(\vec{x}_2) \right]$$

$$= g_Y \left[\phi\left(\vec{x}_{cm} + \frac{\vec{r}}{2}\right) + \phi\left(\vec{x}_{cm} - \frac{\vec{r}}{2}\right) \right]$$



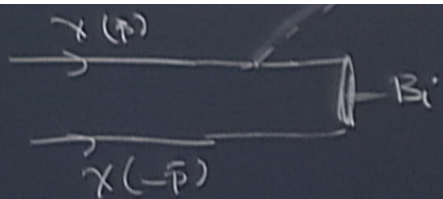
$$\chi(\vec{p}) + \chi(-\vec{p}) \rightarrow B_i + \phi(\vec{p})$$

$$F_i(\vec{p}, t) = \int d^3\vec{r} \psi_i^*(\vec{r}) \left(e^{i\vec{t} \cdot \vec{r}/2} + e^{-i\vec{t} \cdot \vec{r}/2} \right)$$



$$\chi(\vec{r}) + \chi(-\vec{r}) \rightarrow B_i + \phi(\vec{r})$$

$$\psi(\vec{p}, t) = \int d^3\vec{r} \psi_i^*(\vec{r}) \left(e^{i\vec{t} \cdot \vec{r}/2} + e^{-i\vec{t} \cdot \vec{r}/2} \right) \psi_{sc}(\vec{p}, \vec{r})$$



$$\chi(\vec{p}) + \chi(\vec{r}) \rightarrow B_i + \phi(\vec{r})$$

$$F_i(\vec{p}, t) = \int d^3\vec{r} \psi_i^*(\vec{r}) \left(e^{i\vec{t} \cdot \vec{r}/2} + e^{-i\vec{t} \cdot \vec{r}/2} \right) \psi_{sc}(\vec{p}, \vec{r})$$

$$H\psi(\vec{r}) = E\psi(\vec{r})$$

$$\psi_i, E_i, \psi_p, E = \frac{\vec{p}^2}{m_x}$$

$$H(\vec{r}, \vec{p}) = \dots$$

$$H\psi(\vec{r}) = E\psi(\vec{r})$$

$$\psi_i, E_i, \psi_p, E = \frac{\vec{p}^2}{m_p}$$

$$|F_{eff}(\vec{r}, k)|^2 = \left(\frac{128\pi^2}{e^4 p} \right) \left[\frac{\alpha_V^2}{m_V^2} - \frac{2k^2}{3} \frac{a_0^3}{m_p} + \frac{7}{15} k^4 a_0^5 \right]$$



$$\alpha_Y = 0.1$$

energy before BBN
→ conflict w/ m_{ν} small

$$\tau_p \leq 10^{-2} \left(\frac{16 \text{ eV}}{\text{}} \right) \text{ sec}$$

$$V = \frac{4\pi}{3} R^3$$

$$N = 2V \int \frac{d^3p}{(2\pi)^3} \text{PF}$$

Dirac Fermion SM singlet
Majorana Fermion
Scalar
Vector
Tensor
Graviton



$$\alpha_Y = 0.1$$

→ conflict with m > 200 GeV

$$\tau_p \leq 10^{-2} \left(\frac{1 \text{ GeV}}{\dots} \right) \text{ sec}$$

$$V = \frac{4\pi}{3} R^3$$

$$N = 2V \int_{\text{PF}} \frac{d^3p}{(2\pi)^3}$$

$$KE = 2V \int_{\text{PF}} \frac{d^3p}{(2\pi)^3} \frac{p^2}{2m_\chi}$$

CPE

$$V = \frac{4\pi}{3} R^3$$

$$N = 2V \int_{\text{PF}} \frac{d^3p}{(2\pi)^3}$$

$$KE = 2V \int_{\text{PF}} \frac{d^3p}{(2\pi)^3} \frac{p^2}{2m_\chi}$$

$$dPE = N \left(\frac{r}{R} \right)^3 4\pi r^2 dr \left(\frac{N}{\frac{4\pi}{3} R^3} \right) \left(\frac{dr}{r} \right)$$

$$V = \frac{4\pi}{3} R^3$$

$$N = 2V \int \frac{d^3p}{(2\pi)^3} \text{PF}$$

$$KE = 2V \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{2m_x}$$

$$dPE = N \left(\frac{r}{R} \right)^3 4\pi r^2 dr \left(\frac{N}{\frac{4\pi}{3} R^3} \right) \left(\frac{dr}{r} \right)$$

$$E = KE + PE \rightarrow E(N, R) = \text{singlet}$$

$$V = \frac{4\pi}{3} R^3$$

$$N = 2V \int_{PF} \frac{d^3p}{(2\pi)^3}$$

$$KE = 2V \int_{PF} \frac{d^3p}{(2\pi)^3} \frac{p^2}{2m_x}$$

$$dPE = N \left(\frac{r}{R} \right)^3 4\pi r^2 dr \left(\frac{N}{\frac{4\pi}{3} R^3} \right) \left(\frac{dr}{r} \right)$$

$$E = KE + PE \rightarrow E(N, R) = \text{inlet}$$

$$KE \sim \frac{N^{5/3}}{R^2 m_x}$$

$$PE \sim - \frac{N^2 \alpha_x}{R}$$

$$\frac{\partial E}{\partial R} = 0$$

$$\frac{x}{\lambda} \rightarrow \frac{x}{\lambda}$$

$$\alpha_Y = 0.1$$

energy before BBN
 $\leftrightarrow$ conflict with m_{ν} small

$$\tau_{\phi} \leq 10^{-2} \left(\frac{1 \text{ GeV}}{\dots} \right) \text{ sec}$$

$$V = \frac{4\pi}{3} R^3$$

$$N = 2V \int \frac{d^3p}{(2\pi)^3} \text{PF}$$

$$KE = 2V \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{2m_Y}$$

$$dPE = \ln \left(\frac{N}{R^3} \right) \left(\frac{dY}{dN} \right)$$

$$E = KE + PE \Rightarrow E(N, R) \text{ - invariant}$$

$$KE \sim \frac{N^{5/3}}{R^3 m_Y}$$

$$PE \sim - \frac{N^2 \alpha_Y}{R}$$

$$\frac{\partial E}{\partial R} = 0$$

$$R = \left(\frac{9\pi}{4} \right)^{1/3} \frac{a_0}{2} \frac{1}{N^{1/3}}$$

$$BE \simeq 0.1 \alpha_Y^2 m_Y^{-1} N^{7/6}$$

$$\frac{PF}{m_{\pi}} \ll 1$$

$$N \ll 3 \left(\frac{1}{d_x} \right)^{2/3} + H_{int}$$

on small

$$\Delta P \Delta x \gg 1$$

$$\frac{P_F}{m_\pi} \ll 1$$

$$N \ll 3 \left(\frac{1}{d_x} \right)^{2/3} + H_{\text{eff}}$$

on shell

$$\Delta P \Delta x \gg 1, \quad P_F R \gg 1$$

$$H_{\text{eff}} = 0$$

$$= 0$$

$$\frac{P_F}{m_\chi} \ll 1$$

$$N \ll 3 \left(\frac{1}{d_\chi} \right)^{2/3} + H_{\text{inf}}$$

on shell

$$\Delta P \Delta x \gg 1, \quad P_F R \gg 1$$

$$N \gg 1$$

