Dark Matter Model Building

Guest Lecture

MIT Graduate Course

8.811: Particle Physics II

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Outline

1. Evidence for DM
2. Theories for DM
3. Dark Portals
4. Model Independent Approaches

① Evidence for dark matter

1.1 - First observation in galaxies

- first suggested to explain discrepancies in expected total density near the Sun / in Milky Way.

- By 1931, Hubble + Humason published results on redshifts of galaxies.

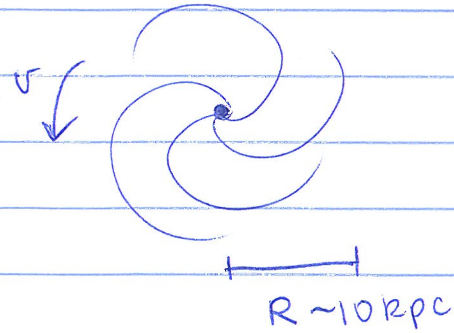
- Zwicky noticed strange behavior in Coma Cluster.

$$v^2 \sim \frac{GM}{r}$$

$\boxed{\text{"dunkle kalte materie"}}$

- related kinetic energy to gravitational potential
- amount of matter needed ≠ observed motion!

1.2 Galactic Rotation Curves



Find rotational velocity:

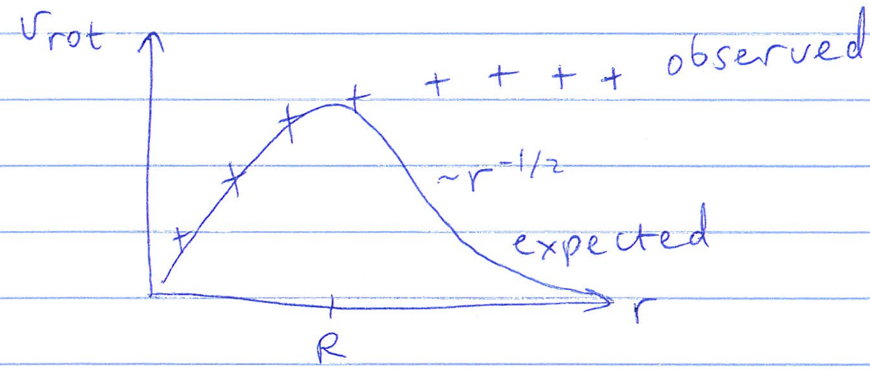
$$F = ma,$$

$$\frac{GMm}{r^2} = \frac{m v_{rot}^2}{r}$$

$$\therefore \quad v_{rot} = \sqrt{\frac{GM(r)}{r}}$$

For $r > R$, $M(r) \approx M(R)$, expect

$$v_{rot}(r) = \sqrt{\frac{GM(R)}{r}} \approx r^{-1/2}$$



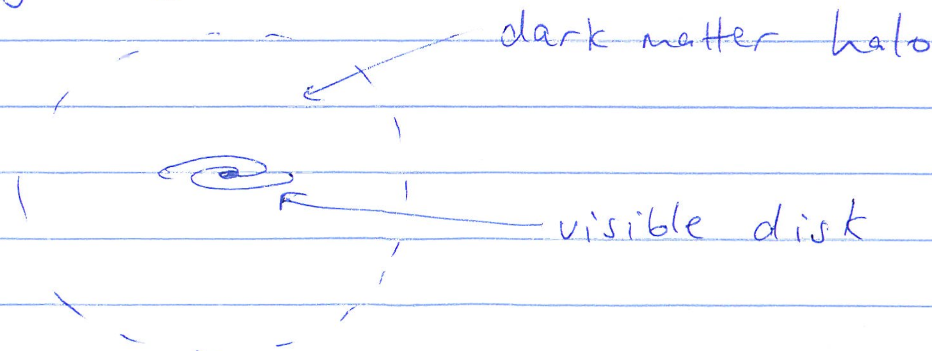
Observe v_{rot} constant for $r > R$!

$$\Rightarrow \quad M(r) \propto r$$

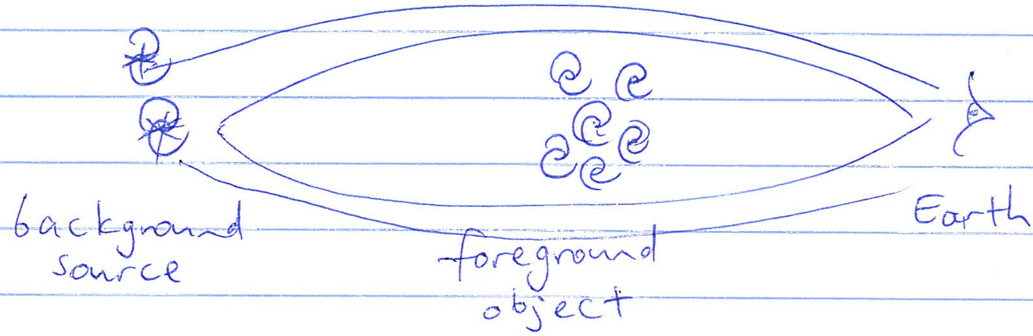
Now $M(r) = 4\pi \int r^2 \rho(r)\, dr$

$$\Rightarrow \quad \rho(r) \propto \frac{1}{r^2}$$

Behavior explained by dark halo extending further than visible component of galaxy.

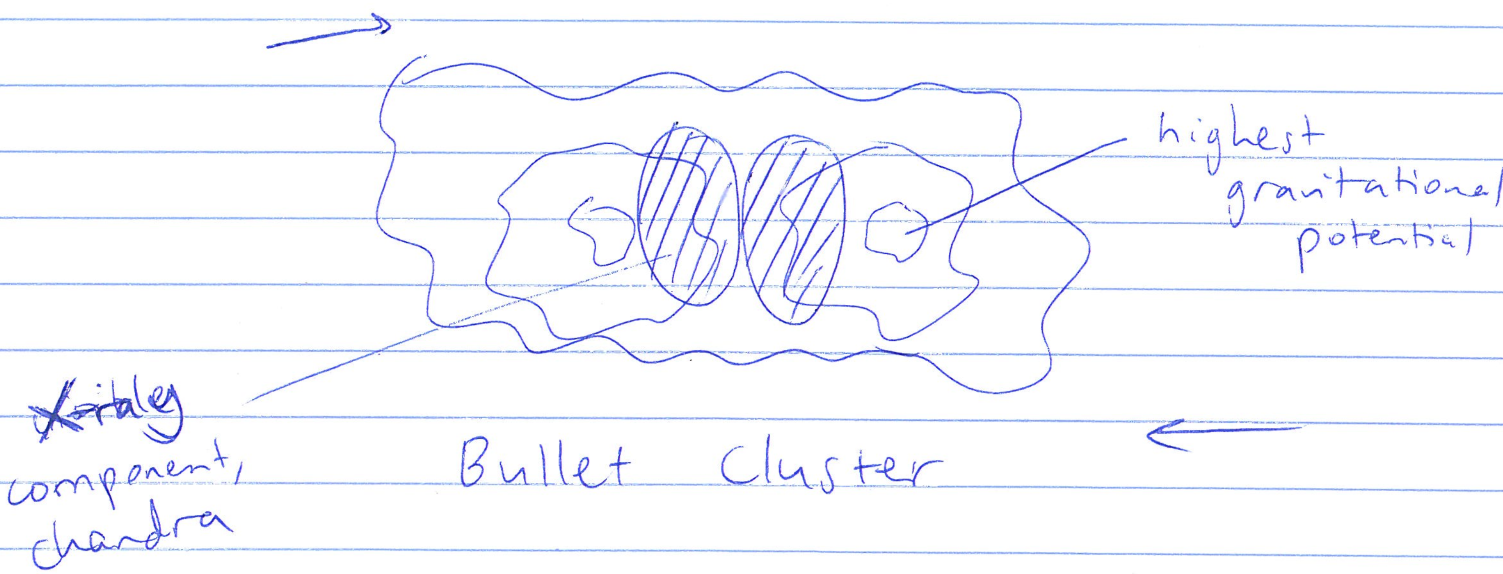


1.3 Gravitational Lensing



- light from background source bent by foreground object

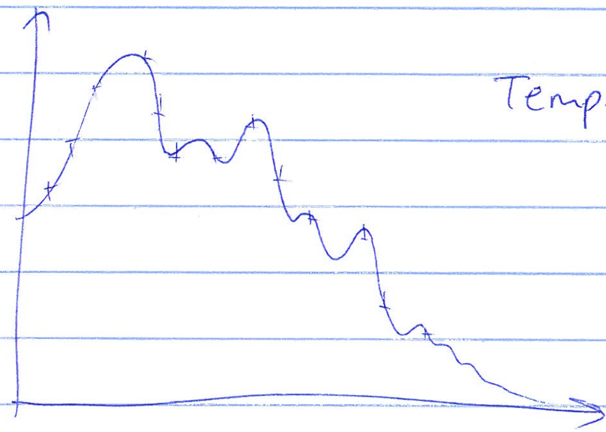
- degree of distortion can be used to determine mass of foreground object.



Bullet Cluster

Gravitational potential displaced from bulk of the luminous matter!

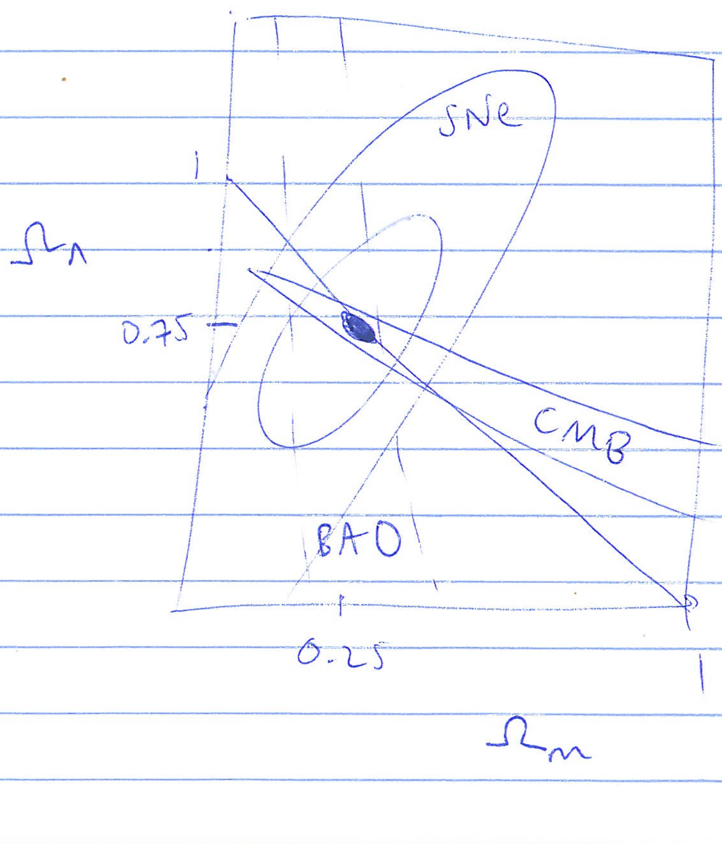
1.4 - CMB



Temperature power spectrum

$\Omega_b h^2 \simeq 0.02$

$\Omega_\chi h^2 \simeq 0.12$



② Theories for dark matter

2.1 – Requirements

- About five times more abundant than baryonic matter (BBN, CMB, large scale structure)

- Stable, or have lifetime greater than age of the universe

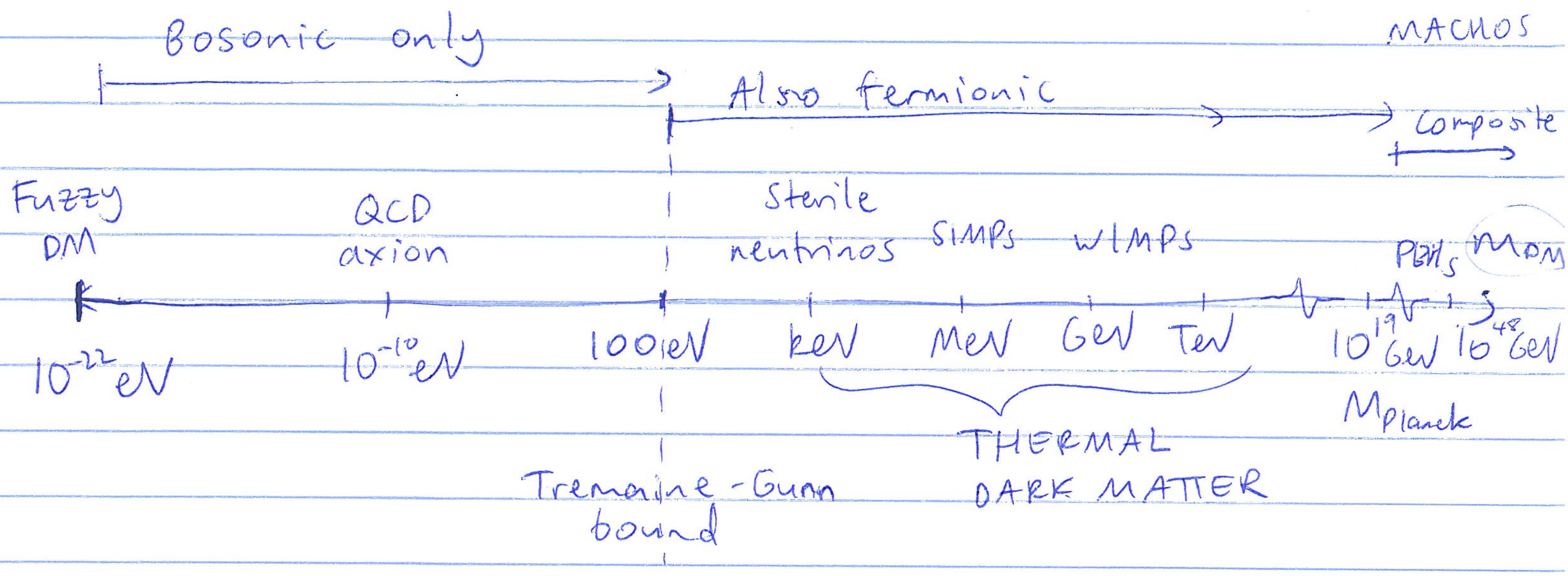
- Neutral, or very small EM charge

- Cold (non-relativistic) or warm (semi-relativistic). Cannot be hot, tension with small scale structure.

- Can be self interacting or non-self interacting, bound is from Bullet Cluster:

$$\frac{\sigma_{DM-DM}}{m_{DM}} \lesssim 1.8 \text{ barn/GeV}$$

$\Rightarrow$ can be used to solve galactic structure problems.



Plethora of BSM models, many with their own distinct DM candidates.

Motivations behind models greatly varied; ie:

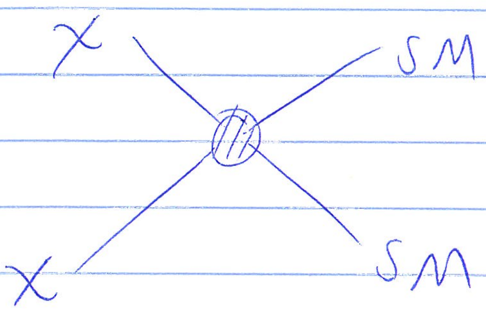
+ linking origin of baryonic asymmetry in visible sector with asymmetry in dark sector (asymmetric DM)

+ solving strong CP problem (QCD axion)

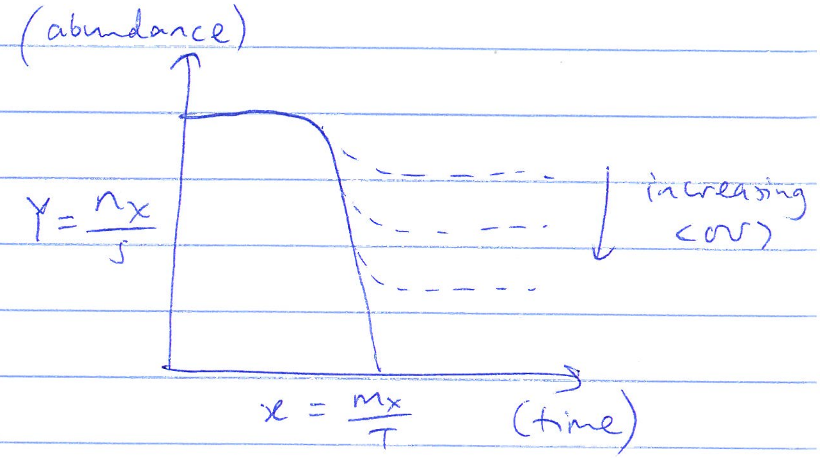
~~Many~~ BSM theories aim to solve missing observational predictions of SM, many provide DM candidate as byproduct, that just happen to emerge at the weak scale.

$\Rightarrow$ appealing WIMP DM candidate from both particle & astro/cosmology perspective.

Thermal Freezeout



annihilation $\xrightarrow{}$
$\langle \sigma v \rangle$



DM contribution to critical density ρ_c is

$$\Omega_\chi = \frac{m_\chi s_0 Y_0}{\rho_c} \qquad \left(= \frac{\rho_\chi}{\rho_c} \right)$$

$$\Rightarrow \quad \Omega_\chi h^2 \approx 0.1 \left(\frac{0.01}{\alpha} \right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}} \right)^2$$

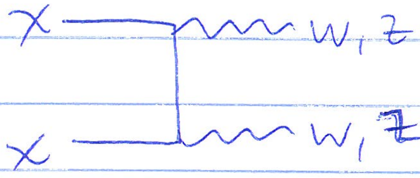
Planck and WMAP measure $\Omega_\chi h^2 \approx 0.12$,

$\Rightarrow$ assuming WIMP DM with $\alpha \sim 0.01$, $m_\chi \sim 100$ GeV, produces correct relic abundance of DM.

+ this is right at the electroweak scale, "WIMP miracle".

$$\begin{pmatrix} \text{WIMPs} \quad m_\chi \sim \alpha_{ann} (T_{eq} M_{pl})^{1/2} \sim \mathrm{TeV} \\ \text{SIMPs} \quad m_\chi \sim \alpha_{eff} (T_{eq} M_{pl})^{1/3} \\ \sim 100\ \mathrm{MeV} \end{pmatrix}$$

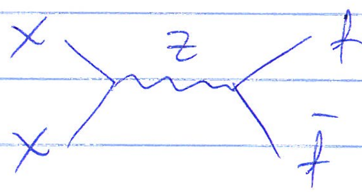
$m_\chi > m_{W,Z}$:



$$\langle \sigma v \rangle \approx \frac{\alpha_W^2}{m_\chi^2}$$

$$= 1\,\text{pb} \left(\frac{\alpha_W}{1/30}\right)^2 \left(\frac{\text{TeV}}{m_\chi}\right)^2$$

$m_\chi < m_Z$:



$$\langle \sigma v \rangle \sim 1\,\text{pb} \left(\frac{m_\chi}{5\,\text{GeV}}\right)^2$$

$G_F (\bar{\chi}\Gamma\chi)(\bar{f}\Gamma f)$

$\frac{G_F^2}{\pi} m_\chi^2$.

m_χ L ~~not thermal,~~ ~~DM~~ overproduce DM

Lee-Weinberg bound, $m_\chi \gtrsim 2$ GeV for WIMPs.

$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{m_W^2}$

Experimentally, very ruled out. Need to move beyond.

What are our options?

③ Dark Portals

$$\text{Dark Sector} \xleftrightarrow{\text{Portals}} \text{SM}$$

- new particles
- new forces

$SU(3) \otimes SU(2) \otimes U(1)$

Relevant portal depends on mediator spin and parity. Can have:

scalar ϕ, pseudoscalar a, fermion N, vector Z'.

Symmetries of SM restrict how these mediators interact with the SM.

$-\frac{\epsilon}{2} B_{\mu\nu} Z'^{\mu\nu}$ Hypercharge portal

$-\lambda_{HS} (\phi^\dagger \phi)(H^\dagger H)$ Higgs portal

$y_n LHN$ Neutrino portal

$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$ Axion portal

3.1 - Hypercharge portal

Extend SM by new $U(1)_X$, model gauge group is $SU(3) \otimes SU(2) \otimes U(1) \otimes U(1)_X$.

$\Rightarrow$ Covariant derivative is

$$D_\mu = D_\mu^{SM} + i q_X g_X Z'_\mu$$

where
q_X is the dark $U(1)_X$ charge
g_X is the $U(1)_X$ gauge coupling
Z' is the $U(1)_X$ gauge boson.

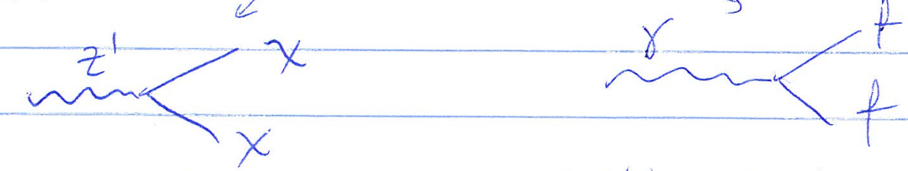
Z' also called "dark photon", "hidden photon".

$U(1)_X$ is spontaneously broken, Z' has mass.

Introduce dark matter candidate, χ.

Interactions are described by the Lagrangian:

$$\mathcal{L} \supset i\bar{\chi}(\partial_\mu + \underbrace{i g_X q_X Z'_\mu}) \gamma^\mu \chi - m_\chi \bar{\chi}\chi$$
$$\underbrace{\boxed{- \frac{\epsilon}{2} Z'^{\mu\nu} F_{\mu\nu}}}_{\text{portal}} + \sum_f q_f \underbrace{e \bar{f} \gamma^\mu f A_\mu} + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu$$

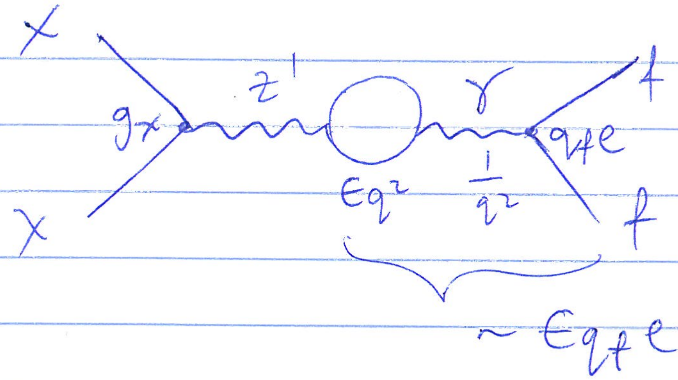


dark sector

visible sector

New parameters to test:

m_χ,	$m_{Z'}$,	g_χ,	ϵ
DM mass	Z' mass	Z'-dark interactions	Z'-visible interactions



For small ϵ, diagonalize,

$$A_\mu \longrightarrow A_\mu - \epsilon Z'_\mu, \qquad Z'_\mu \longrightarrow Z'_\mu .$$

shows vertex $\longrightarrow \epsilon e q_f Z'_\mu \bar{f} \gamma^\mu f$.

3.2 - Higgs Portal

Extend SM by new scalar ϕ.

Simplest scenario: take ϕ to be DM.

Interactions:

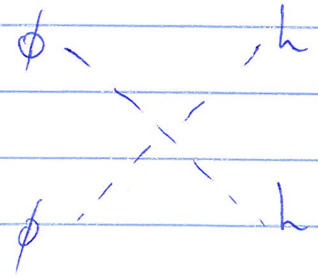
$$\mathcal{L} \supset \lambda_{h\phi}(\phi^\dagger \phi)(H^\dagger H)$$

After EW symmetry breaking,

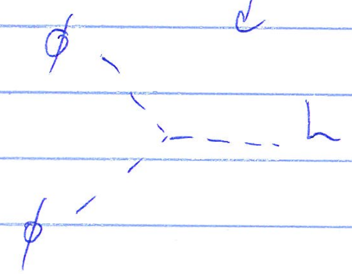
$$H \rightarrow \frac{1}{\sqrt{2}}(h + v)$$

$$\Rightarrow \mathcal{L} \supset \lambda_{h\phi}(\phi^\dagger \phi)\left(\frac{1}{\sqrt{2}}(h+v) \cdot \frac{1}{\sqrt{2}}(h+v)\right)$$

$$= \frac{1}{2}\lambda_{h\phi}\,\phi^2 h^2 + \lambda_{h\phi}\,\phi^2 h v + \frac{1}{2}\lambda_{h\phi}\,\phi^2 v^2$$



quartic term

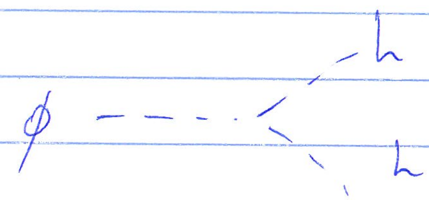


trilinear term

$m_\phi = \sqrt{\lambda_{h\phi} v^2}$

mass term!

Note as ϕ is DM, cannot have



Need stability!

New parameters to test:

m_ϕ, $\lambda_{h\phi}$

DM mass — DM-Higgs interactions

Problem: very experimentally constrained!

Make ϕ only mediator, not DM:
Can have:

$$\mathcal{L} \supset -y_\chi \bar{\chi}_R \chi_L \Phi + h.c.$$

$$+ D^\mu \Phi D_\mu \Phi - \mu_\phi \Phi^\dagger \Phi - \lambda_\phi (\Phi^\dagger \Phi)^2 - \lambda_{h\phi} (\Phi^\dagger \Phi)(H^\dagger H)$$

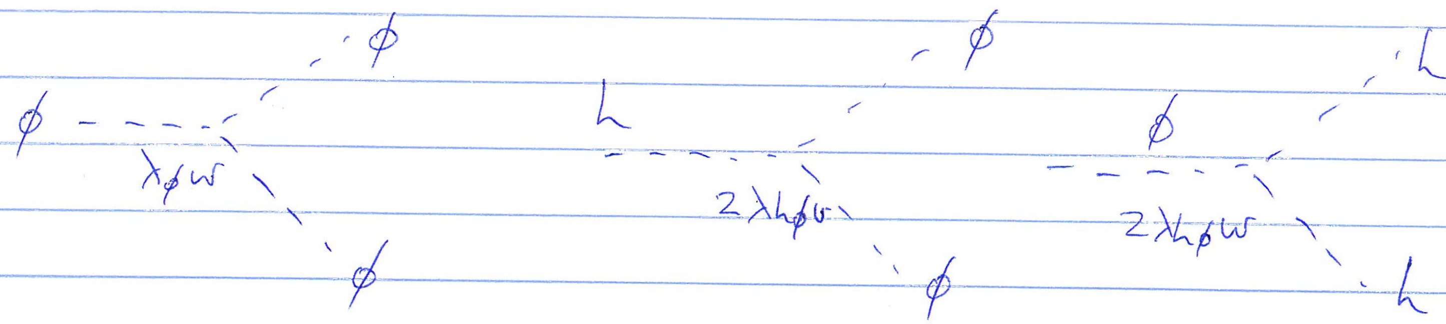
Both Φ and H can obtain vevs:

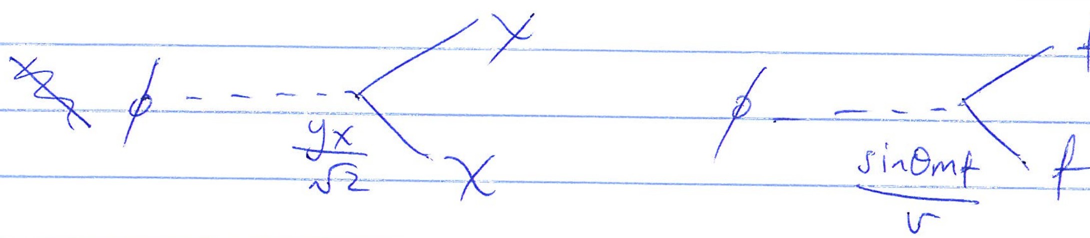
$$\Phi \to \frac{1}{\sqrt{2}}(w + \phi), \quad H \to \frac{1}{\sqrt{2}}(h + v)$$

(Goldstones omitted)

After EW & dark symmetry breaking,

$$\mathcal{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - m_\chi \bar{\chi}\chi$$
$$- \lambda_\phi w \phi^3 - 2\lambda_{h\phi} h\phi(v\phi + wh)$$
$$- \frac{y_\chi}{\sqrt{2}} \phi \bar{\chi}\chi - \sin\theta \frac{m_f}{v} \phi \bar{f} f$$





Mass mixing

$$V = V_H + V_\Phi + V_{\Phi H}$$

where $V_H = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$

$V_\Phi \ni \frac{\mu_\Phi^2}{2} \Phi^2$

$$V_{\Phi H} = \left(A_{\Phi H} \Phi + \lambda_{\Phi H} \Phi^2\right) H^\dagger H$$

After EWSB, Φ, H mix, mass matrix

$$M^2 = \begin{pmatrix} 2\lambda_H v^2 & A_{\Phi H} v \\ A_{\Phi H} v & \mu_\Phi^2 \end{pmatrix}$$

diagonalized by

$$\begin{pmatrix} H \\ \Phi \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

with h SM Higgs, ϕ dark mediator,

$$\tan 2\theta = \frac{2A_{\Phi H} v}{\mu_\Phi^2 - 2\lambda_H v^2}, \qquad H = h\cos\theta + \phi\sin\theta, \quad \Phi = -h\sin\theta + \phi\cos\theta$$

and mass eigenvalues

$$m_{h,\phi}^2 = \frac{1}{2}\left(\mu_\Phi^2 + 2\lambda_H v^2 \pm \sqrt{\mu_\Phi^4 + 4A_{H\Phi}^2 v^2 + 4v^4\lambda_H^2 - 4\lambda_H m_\Phi^2 v^2}\right)$$

3.3 - Neutrino portal

Extend SM by new fermion N (Dirac & sterile ν), DM candidate χ (Dirac), & complex scalar ϕ.

Interactions contained within Lagrangian:

$$-\mathcal{L} \supset m_\phi^2 \phi^2 + m_\chi \bar{\chi}\chi + m_N \bar{N} N$$

$$+ \underbrace{\lambda_\ell \overline{L_\ell} \hat{H} N_R}_{\text{portal}} + \phi \bar{\chi}(y_L N_L + y_R N_R) + h.c.$$

where

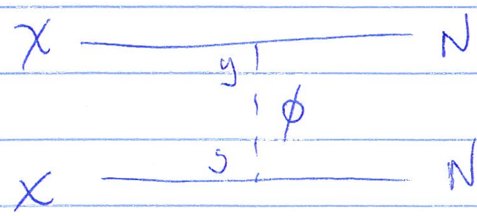
$$\hat{H} = i\tau_2 H^*$$

$$L_\ell = (\nu_{\ell L}, \ell_L)^T$$

λ_ℓ neutrino Yukawa couplings, $y_{L,R}$ N couplings to dark sector.

$m_\chi < m_\phi$, & charged under Z_2 symmetry for stability.

Relic density from $\chi\chi \to NN$,



Test

m_ϕ, m_χ, m_N, λ_ℓ, $y_{L,R}$

④ Model Independent Approaches

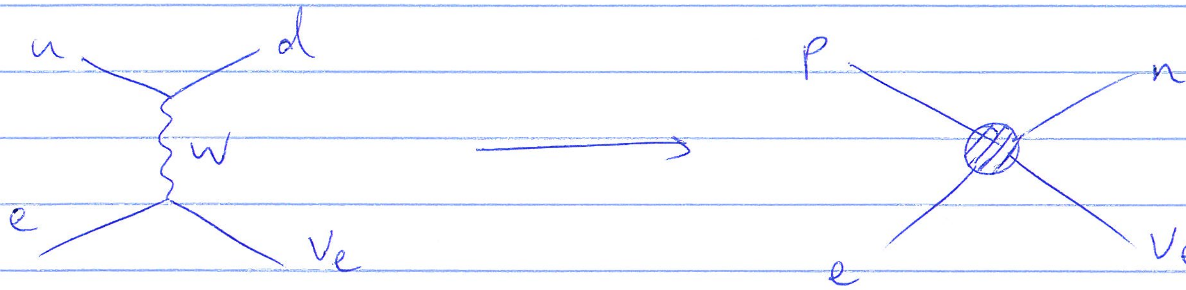
4.1 - Effective field theories (EFTs)

Many theories & DM candidates, model independent interpretation of experimental results is desirable.

EFTs: low-energy approximation to complete high-energy theory.

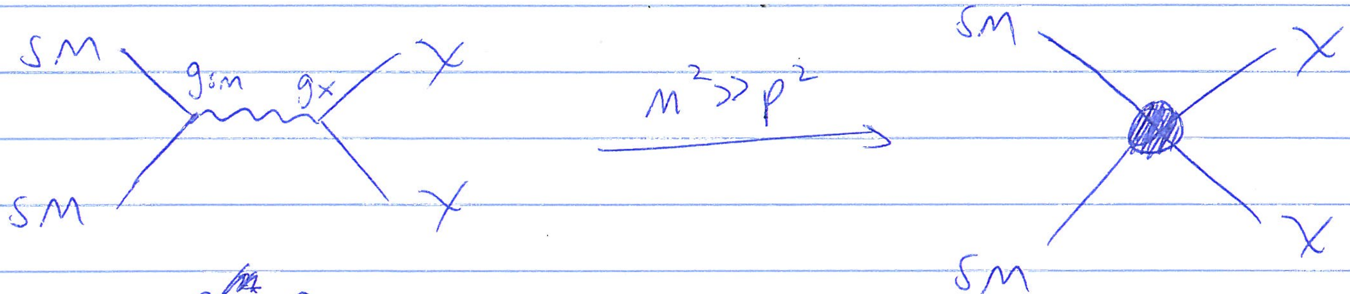
$\Rightarrow$ model specific details not important.

Weak interactions were first cast this way,



$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2}$$

Borrow idea for DM:



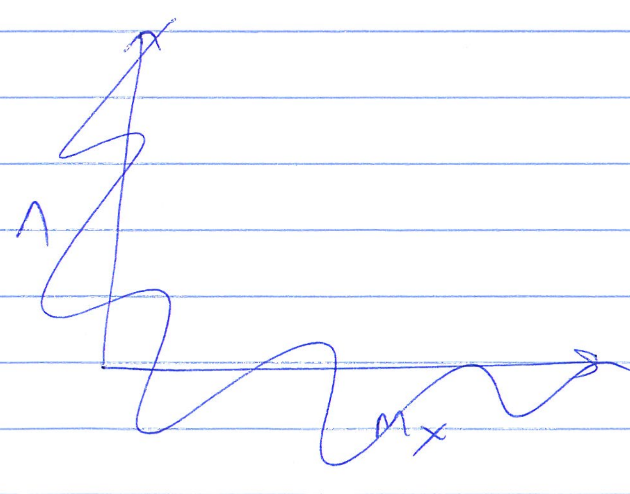
$$\frac{g_{SM}\, g_\chi}{p^2 - M^2}$$

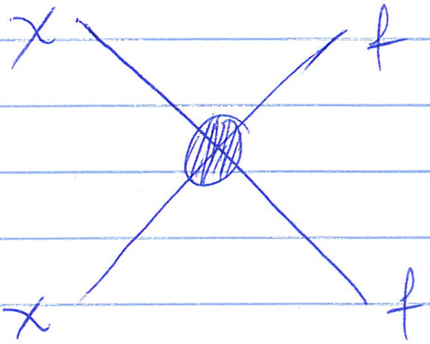
$$\frac{g_{SM}\, g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

Write interaction as i.e. $\frac{1}{\Lambda^2}(\bar{\chi}\Gamma_\chi \chi)(\bar{f}\Gamma_f f)$.

Call Λ the "cut off scale".

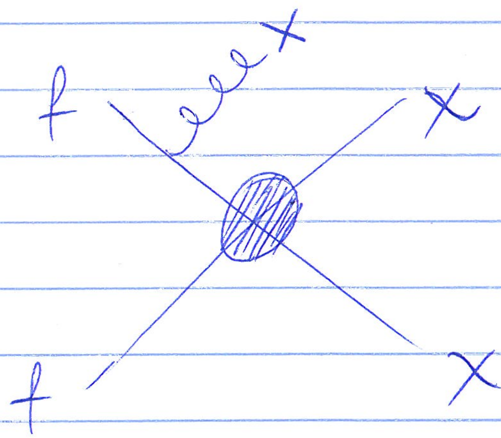
Powerful framework because higher dimensional theory is reduced to two dimensional parameter space, same across all processes & experiments.





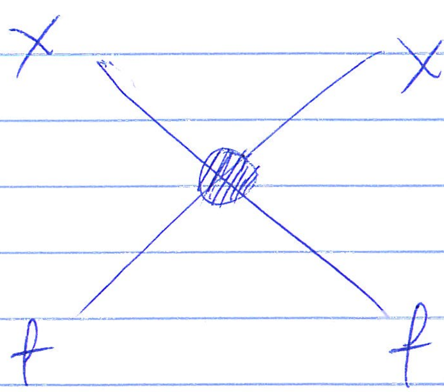
DM annihilation

- Relic abundance
- Indirect detection signals (telescopes)



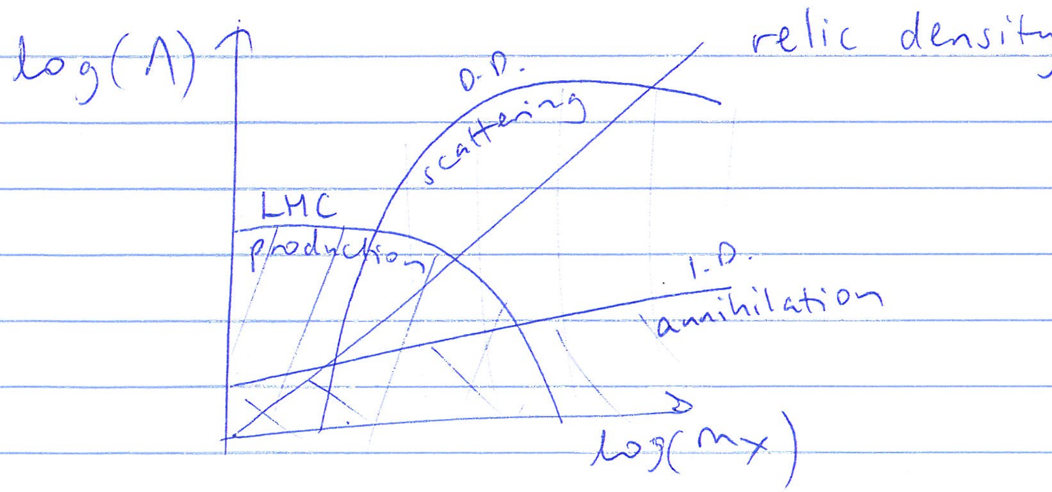
DM production

- colliders (mono-x)



DM scattering

- Direct detection



Problem: not always valid!

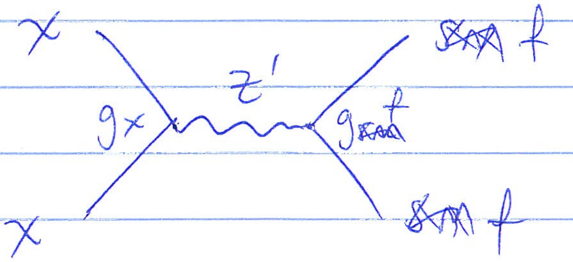
At LHC, $p \sim$ TeV, while for WIMP type theories, not true that $M \gg$ TeV!

Violation of unitarity! Not good!

4.2 - Simplified Models

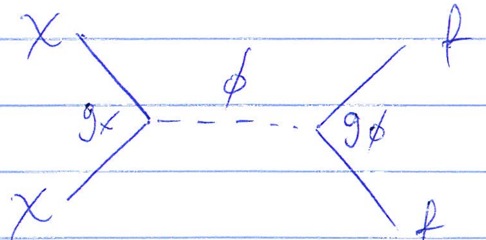
- include one mediator, set limits on

$$m_{med}, \quad g_\chi, \quad g_f, \quad m_\chi, \quad \Gamma_{med}.$$



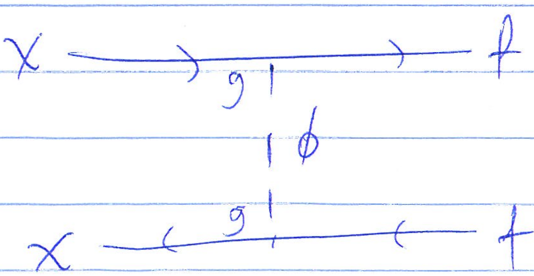
$$\mathcal{L}^V_{int} \supset g_f Z'_\mu \bar{f}\gamma^\mu f + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

(also $\mathcal{L}^A_{int}$).



$$\mathcal{L}^\phi_{int} \supset g_\chi \phi \bar{\chi}\chi + \frac{\cancel{y}}{\sqrt{2}} g_f \bar{f} f \phi$$

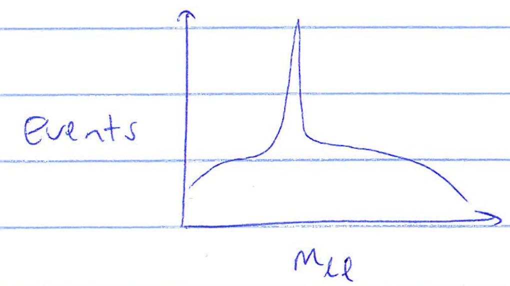
(also $\mathcal{L}^a_{int}$)



$$\mathcal{L}_{int} \supset g \sum_{i=1,2} \left(\phi_{i,L}\bar{Q}_{i,L} + \phi_{i,R}\bar{f}_R + \dots\right)\chi$$

Bonus features:

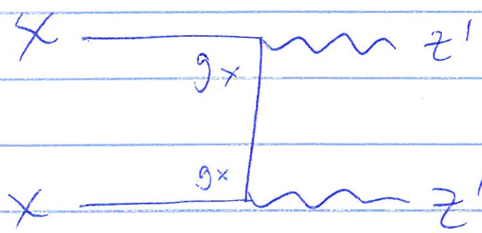
+ searches for mediators themselves



· resonant production

· extra phenomenology

+ includes hidden sectors



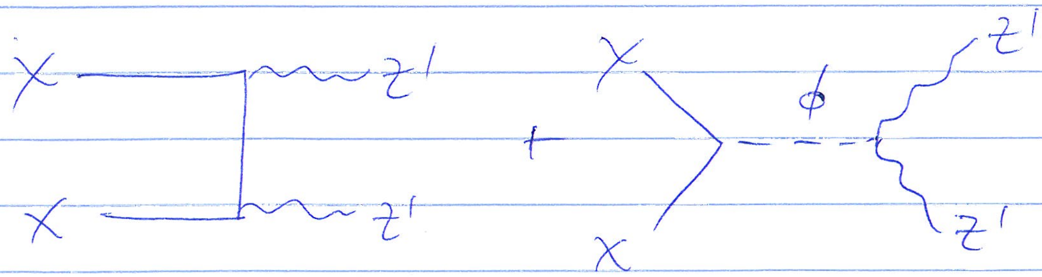
· relic abundance can be set by dark sector,

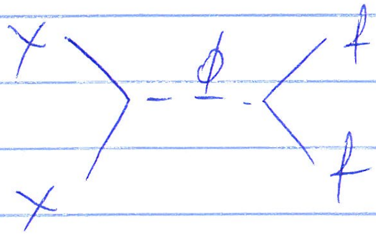
$\langle \sigma v \rangle \sim \frac{g_\chi^4}{M_\chi^2}$ (no g_f!)

Drawbacks:

- can't capture everything (that's ok...)

- gauge invariance issues for both s-channel mediators!





LH f SU(2) doublet,
DM & RH f are singlets.

⇒ Two Higgs doublet model.

⇒ two-mediator simplified models can be helpful. At least need to be aware of regions of validity.