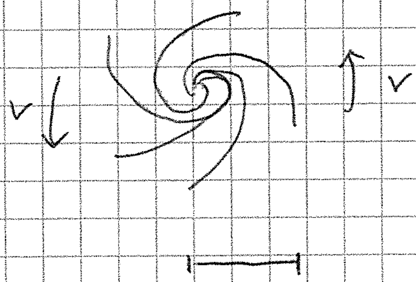
1. Evidence for Dark Matter

1.1 Galactic rotation curves

A typical spiral galaxy:



$R \sim 10\,\mathrm{kpc}$ ($\approx 3 \cdot 10^4$ ly)

Expected rotational velocity:

$$F_r = m \cdot a \Rightarrow \frac{G \cdot M(r)}{r} = \frac{v^2}{r}$$

where $M(r) = 4\pi \int r^2 \rho(r)\, dr$
(total mass within radius r)

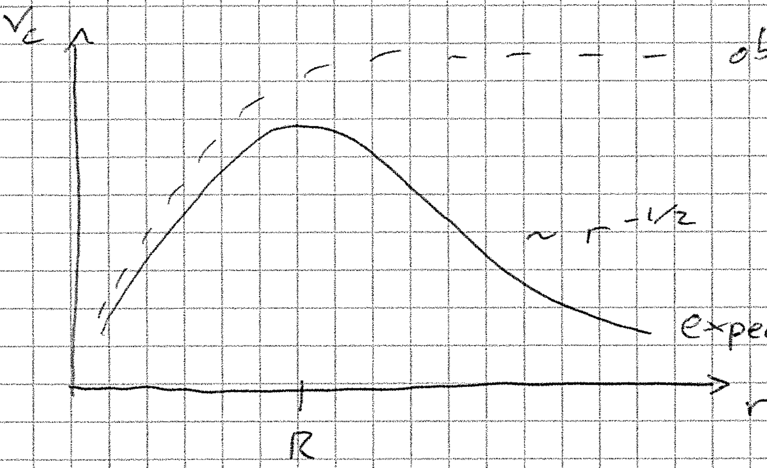
$$\Rightarrow v_c(r) = \sqrt{\frac{G\, M(r)}{r}}$$

Can be measured using Doppler shift of star light.

Idea: Extend measurements beyond visible disk using neutral hydrogen gas (21 cm line)

Expectation: For $r > R$ $M(r) \approx M(R)$

$$\Rightarrow v_c(r) = \sqrt{\frac{G \cdot M(R)}{r}} \sim r^{-1/2}$$



slide

Observation: $v_c(r) \to$ const for $r > R$

$\Rightarrow M(r) \sim r$

$\Rightarrow \rho(r) \sim \frac{1}{r^2}$ (isothermal sphere)

Explanation: Visible disk embedded in 3D halo of dark matter

1.2 Can we trust Newton's law?

Assume that for very weak acceleration ($a \ll a_0$)

$$F_N = m \cdot \frac{a^2}{a_0}$$ (modified Newtonian dynamics)

$$\Rightarrow \quad \frac{G \cdot M}{r^2} = \frac{\left(\frac{v^2}{r}\right)^2}{a_0}$$

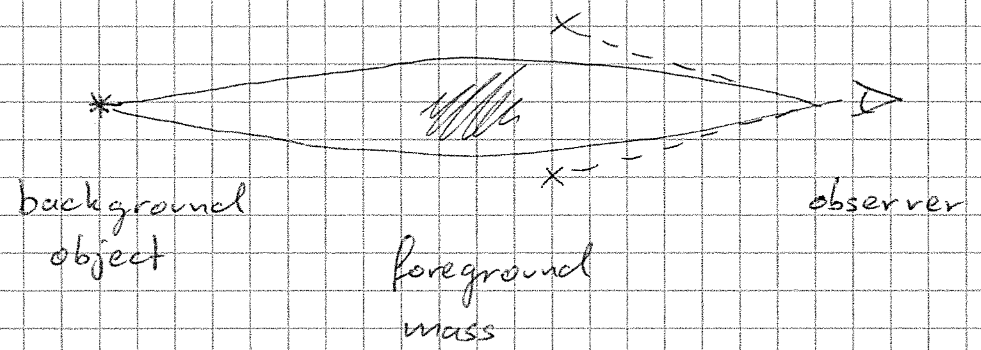
$$\Rightarrow \quad v_c(r) = (a_0 \; G \cdot M)^{1/4} \rightarrow \text{const}$$

Explains galactic rotation curves!

We need more evidence for dark matter

1.3 Gravitational lensing

Basic idea: Gravity bends light (like a lense)



$\Rightarrow$ Look for distortion of background objects to measure gravitational potential (e.g. of galaxy clusters)

Observation: Potential deeper than expected from stars and gas.

In some systems the region of highest luminosity is different from the region of highest density! (slide)

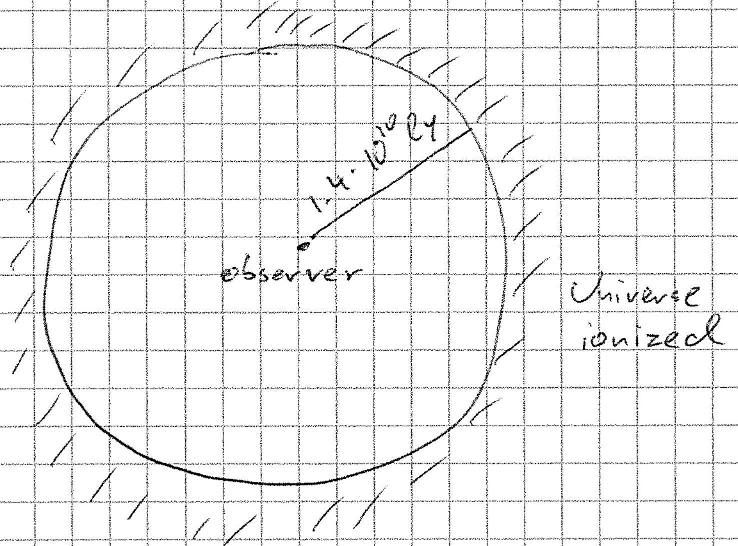
1.4 How much dark matter is there?

Need observations of the early Universe
→ Cosmic Microwave Background (CMB)

Basic idea: – At temperatures $T > 1\,\mathrm{eV}$ the early Universe is ionized

→ intransparent to radiation

– Once neutral atoms form (recombination), photons propagate freely



The CMB is almost exactly a black-body spectrum with $T \approx 2.7\,\mathrm{K}$.

Tiny fluctuations across the sky:

$$\delta T / T \sim 10^{-5}$$ slide

Write $$\frac{\delta T}{T}(\vartheta, \phi) = \sum_{\ell} \sum_{m} a_{\ell m} Y_{\ell m}(\vartheta, \phi)$$

spherical harmonics

and define

$$C_\ell = \frac{1}{2\ell+1} \sum_m |a_{\ell m}|^2$$

(temperature correlation) slide

Observation: Peak at $\ell \sim 250$ $(\vartheta \sim 1^\circ)$

Reason: Oscillations in the plasma from competition between gravitational attraction and photon pressure

Both dark matter (DM) and ordinary matter (baryons) contribute to gravitational potential.

Only ordinary matter feels photon pressure.

$$\Omega_M = \Omega_{DM} + \Omega_B$$

$$\Omega_{DM} / \Omega_M \approx 0.85$$

$$\Omega_{DM} / \Omega_B \approx 5.5$$

2. Explanations for Dark Matter

2.1 Properties of Dark Matter (DM)

By definition: - DM is <u>stable</u>
($\tau_{DM} \gg t_{universe}$)

- DM is <u>electrically neutral</u>
($q_{DM} \ll e$)

- From CMB: $\Omega_B \ll \Omega_M$

Same conclusion obtained from Big Bang Nucleosynthesis (abundance of elements)

$\Rightarrow$ DM is <u>non-baryonic</u>

- From galactic rotation curves:
DM does not collapse into a disk. Halos are 3D.

$\Rightarrow$ DM does not dissipate energy
(it is <u>collisionless</u>)

– From structure formation:

DM moves sufficiently slowly that it can become gravitationally bound.

$\Rightarrow$ DM is <u>cold</u>

2.2 Conventional explanations

- Could DM just be ordinary matter that doesn't emit light?

  - Diffuse neutral gas
  - Planets
  - Faint stars

  No, because DM must be non-baryonic

- Could DM just be ordinary neutrinos?

  No, because $m_\nu \lesssim 0.2$ eV, so would be relativistic during recombination (hot DM)

Moreover, Pauli exclusion means that there would be an upper bound on halo masses:

$$M_{halo} = m_\nu \int \underbrace{f(\vec{x}, \vec{p})}_{\leq 1} \, d^3x \; d^3p$$

$$\leq m_\nu \, R_{halo}^3 \, (m_\nu v_{DM})^3$$

with $v_{DM} \sim \sqrt{\frac{G \cdot M_{halo}}{R_{halo}}}$

$$\Rightarrow m_\nu \gtrsim (G^3 \cdot M_{halo} \cdot R_{halo}^3)^{-1/8}$$

For $M_{halo} \sim 10^{12} M_\odot$
$R_{halo} \sim 10$ kpc

$$\Rightarrow m_\nu \gtrsim 10 \text{ eV} \quad ⚡$$

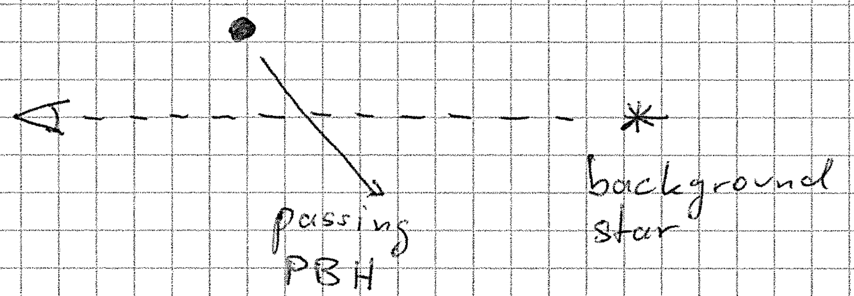
(Stronger bound from dwarf galaxies: $m_\nu \gtrsim 0.7$ keV)

- Could DM be black holes ?

CMB: Black holes must have formed (long) before recombination:

Primordial Black Holes (PBH)

Can look for them via gravitational lensing:



Microlensing causes variation in brightness.

Absence of such variations:

PBH cannot be all of DM for

$$10^{-9}\, M_0 \lessapprox M_{PBH} \lessapprox 10\, M_0$$

Larger masses may be viable (gravitational wave signals ?)

9 - Most exciting possibility:
New, yet undiscovered particle !

2.3 Structure formation with particle dark matter (N-body simulations)

- Assume simple initial conditions
- Evolve under influence of gravity
- Determine size, shape and number of dark matter halos

- Challenge: Simulate star formation, supernova explosions, ...

slide

Output (example):

$n(M_h)$: Number of DM halos with mass $M > M_h$

$\rightarrow$ Compare to observations

slide

$\Rightarrow$ Upper bound on the mass of warm dark matter

Note: Individual particles macroscopic ($M_{part} \gg M_{sun}$)

↳ Particle physics captured by initial conditions

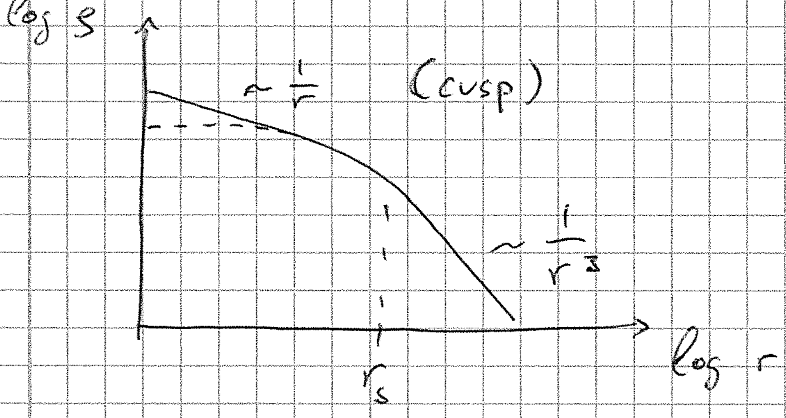
N-body simulations make new predictions

E.g. profile of DM halos is not

$$\rho(r) \sim \frac{1}{r^2}$$

but

$$\rho(r) \sim \frac{1}{r\,(r_s + r)^2} \qquad r_s: \text{ scale radius}$$



Compare to observations:

- Good fit for large r
- In central region possible discrepancy:

$v_c(r)$ smaller than predicted

$\Rightarrow \rho(r) \rightarrow$ const ?

Cusp - core problem!

↳ Baryonic effects not included ?

↳ Dark matter self - interactions ?

3. Dark matter in the early Universe

3.1 A brief introduction to cosmology

General relativity:

Geometry of Universe depends on the matter and energy content.

The geometry is characterised by a metric, which defines distance between points in spacetime.

Homogeneous + isotropic Universe:

$$ds^2 = -dt^2 + a(t)^2 \left[dx^2 + dy^2 + dz^2\right]$$

scale factor: → describes how space expands (or shrinks)

$a(t)$ captures evolution of Universe.

Hubble expansion rate:

$$H(t) = \frac{1}{a} \frac{da}{dt}$$

From Einstein equation derive relation between H and ρ (energy density):

$$H^2 = \frac{8\pi G \rho}{3} = \frac{8\pi}{3 M_p^2}\rho$$

(Friedmann equation) $\quad M_p \sim 1.2 \cdot 10^{19}\,\text{GeV}$

What is ρ?

1) Universe filled with non-rel. particles:

$$\rho_{nr}(t) = m \cdot n_{nr}(t) = \frac{m \cdot N}{V(t)} \sim a(t)^{-3}$$

2) Universe filled with rel. particles (or radiation)

$$\rho_r(t) = E_r(t) \cdot n_r(t) \sim a(t)^{-4}$$

redshift: $E_r(t) \sim a(t)^{-1}$

Case 1) $\frac{\dot{a}^2}{a^2} \sim a^{-3}$

$$\Rightarrow \dot{a} \sim a^{-1/2}$$

$$\Rightarrow a^{3/2} \sim t$$

$$\Rightarrow a(t) \sim t^{2/3}$$

Case 2) $\frac{\dot{a}^2}{a^2} \sim a^{-4} \Rightarrow a(t) \sim t^{1/2}$

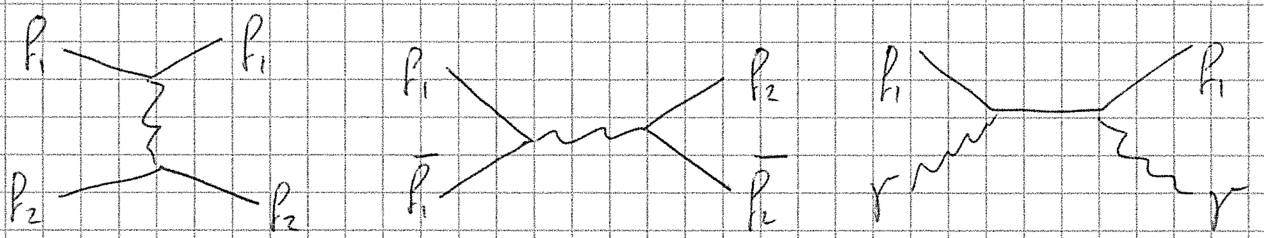
Let's focus on case 2:

$$H = \frac{1}{a}\frac{da}{dt} \sim t^{-1/2} \cdot t^{-1/2} \sim t^{-1}$$

Time not a convenient variable.

More useful: temperature T

Assume the relativistic particles interact



$\Rightarrow$ Thermal distribution

$$f(E) \sim e^{-E/T} \qquad (k_B = 1)$$

Stefan-Boltzmann law: $\rho_r \sim T^4$

$$\rho = \frac{\pi^2}{30} g_*(T)\, T^4$$

degrees of freedom

$$\Rightarrow \quad T \sim a(t)^{-1} \sim t^{-1/2}$$

(Universe cools down)

$$\Rightarrow \quad H = 1.66 \sqrt{g_*}\, T^2 / M_P$$

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As T decreases:

- Relativistic particles lose energy
- Particles become non-relativistic
- Matter-radiation equality
  ↳ Transition to case I

Some useful notation:

Rather than n_f, one often quotes

$$\Omega_f = \frac{m_f \cdot n_f}{\rho_c}$$

where

$$\rho_c = 3 H^2 M_p^2 / (8\pi)$$

For a flat Universe

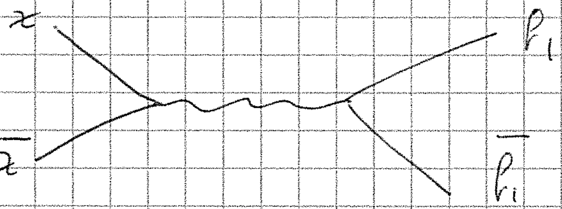
$$\sum_f \Omega_f = 1$$

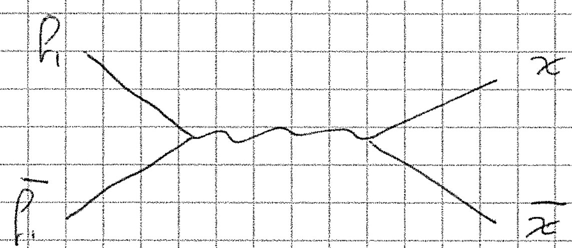
One also finds

$$\Omega_f h^2 = \Omega_f \underbrace{\left(\frac{H(\text{today})}{100 \text{ km s}^{-1}} \right)^2}_{\approx 0.7}$$

3.2 Thermal freeze-out

Consider a Universe filled with relativistic particles f with temperature T. Consider a heavy DM species χ with $m_\chi \gg T$.

Annihilation process: 

Production process: 

Rate: $\Gamma_{ann} = \langle \sigma_{ann} v \rangle n_\chi$

$\Gamma_{prod} = \langle \sigma_{prod} v \rangle n_f$

$\langle \rangle$: Thermal average

In thermal equilibrium

$$\Gamma_{ann} = \Gamma_{prod}$$

Since $m_f \ll T \ll m_\chi$, annihilation is always possible.

But production is only possible if $E_f \sim m_\chi$

$\Rightarrow \quad \langle \sigma_{prod} v \rangle \sim e^{-m_\chi/T}$

$\Rightarrow \quad n_\chi$ must be exponentially suppressed:

$$n_\chi \sim e^{-m_\chi/T} \qquad (*)$$

If thermal equilibrium continues

$$n_\chi \to 0 \quad \text{as} \quad T \to 0$$

To obtain sizeable abundance of DM, it must decouple from T.E.

This happens if

$$\underbrace{\Gamma_{ann}}_{\substack{\text{interaction rate} \\ \sim e^{-m_\chi/T}}} \lesssim \underbrace{H}_{\substack{\text{expansion rate} \\ \sim T^2}}$$

(*) The exact expression is

$$n_\chi = g_\chi \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$$

The temperature for which

$$\Gamma_{ann} = H$$

is called freeze-out temperature T_f:

$$\langle \sigma v \rangle \, g_x \left(\frac{m_x T_f}{2\pi} \right)^{3/2} e^{-m_x/T_f} \approx 1.66 \sqrt{g_*} \, \frac{T_f^2}{M_p}$$

Define $x_f = m_x / T_f$, drop constants:

$$\langle \sigma v \rangle \, m_x^3 \, x_f^{-3/2} \, e^{-x_f} \sim \frac{m_x^2}{x_f^2 \, M_p}$$

$$\Rightarrow \langle \sigma v \rangle \, m_x \, M_p \sqrt{x_f} \sim e^{x_f}$$

$$\Rightarrow \frac{1}{2} \log x_f + \log \left(\langle \sigma v \rangle m_x M_p \right) + \text{const} = x_f$$

Typically $\langle \sigma v \rangle \sim \frac{1}{m_x^2}$ and $m_x \ll M_p$

$$\Rightarrow \log \left(\langle \sigma v \rangle m_x M_p \right) \gg \frac{1}{2} \log x_f + \text{const}$$

$$\Rightarrow x_f \approx \log \langle \sigma v \rangle m_x M_p$$

$$T_f = \frac{m_x}{\log \left(\langle \sigma v \rangle m_x M_p \right)} \ll m_x$$

Estimate: $\langle \sigma v \rangle m_x M_p \sim \frac{M_p}{m_x} \sim \frac{10^{19} \text{ GeV}}{10^3 \text{ GeV}}$

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$$\Rightarrow x_f = \log 10^{16} \approx 30$$

We conclude

$$n_\chi(T_f) \sim \frac{T_f^2}{\langle \sigma v \rangle \, M_p}$$

After freeze-out, DM particles stop interacting

$$\Rightarrow \quad n_\chi(T) \sim a(T)^{-3} \sim T^3$$

$$\Rightarrow \quad n_\chi(\text{today}) = \left(\frac{T_{\text{today}}}{T_f} \right)^3 n_\chi(T_f)$$

$$\sim \frac{1}{\langle \sigma v \rangle \, M_p \, T_f}$$

$$\Omega_\chi = \frac{m_\chi \, n_\chi(\text{today})}{\rho_c(\text{today})} \sim \frac{x_f}{\langle \sigma v \rangle \, M_p}$$

Restoring missing factors:

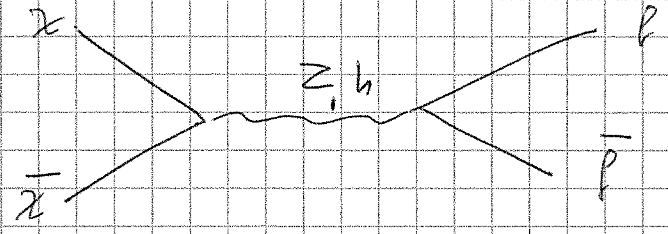
$$\Omega_\chi h^2 \approx \frac{10^9 \, \text{GeV}^{-1} \cdot x_f}{\sqrt{g_*} \, M_p \, \langle \sigma v \rangle}$$

Typically $g_* \approx 80$ and $x_f \approx 30$

$$\Rightarrow \quad \Omega_\chi h^2 \approx \frac{3 \cdot 10^{-27} \, \text{cm}^3 \, \text{s}^{-1}}{\langle \sigma v \rangle}$$

The WIMP miracle

Typical annihilation process:



For $m_\chi \gg m_Z, m_f$ dimensional analysis gives

$$\langle \sigma v \rangle \sim \frac{1}{m_\chi^2}$$

Constant of proportionality depends on coupling strength.

For weak interactions

$$\langle \sigma v \rangle \sim \frac{\alpha_w^2}{m_\chi^2} \qquad (\alpha_w \sim 10^{-2})$$

Assume m_χ is close to electroweak scale: $m_\chi \sim v \sim 250\,\mathrm{GeV}$

$$\Rightarrow \langle \sigma v \rangle \approx 10^{-26}\ \mathrm{cm^3/s}$$

$$\Rightarrow \Omega_\chi h^2 \sim 0.1$$

Observed value: $\Omega_\chi h^2 = 0.1199$

Remarkable coincidence!

Why is it interesting to consider

$m_\chi \sim 250$ GeV ?

May play a role in electroweak symmetry breaking!

Hierarchy problem:

Why is $m_h \ll M_P$?

New symmetry?

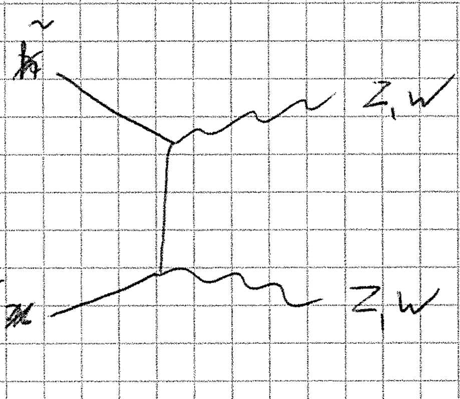
$\Rightarrow$ Expect new states at the electroweak scale!

Lightest new state can be stable!

Prominent example:

Supersymmetric neutralino

E.g. higgsino $\tilde{h}$



$$\Omega_{\tilde{h}} h^2 \approx 0.1 \left(\frac{m_{\tilde{h}}}{1\,\mathrm{TeV}} \right)^2$$

3.3 Misalignment mechanism

Consider scalar field $\phi(x,t)$ with potential $V(\phi) = \frac{1}{2} m^2 \phi^2$

$$\mathcal{L} = T - V$$

$$= \frac{1}{2} \dot{\phi}^2 - \frac{1}{2} m^2 \phi^2$$

Assume ϕ is the same everywhere

$$\phi(x, t_0) = \phi_0$$

Equation of motion in static universe:

$$\ddot{\phi} = - \frac{\partial V}{\partial \phi} = - m^2 \phi$$

$$\Rightarrow \phi(x,t) = \phi_0 \cos(mt)$$

↳ oscillation between large T and large V

In expanding universe, kinetic energy is dissipated (redshifted):

$$\ddot{\phi} = - \frac{\partial V}{\partial \phi} - 3 H \dot{\phi} \quad \text{(Hubble friction)}$$

↑ Hubble constant

$\Rightarrow$ Damped harmonic oscillator

For $3H > m$: Overdamped

$$\Rightarrow \quad \dot{\phi} \approx 0 \qquad \Rightarrow \quad \phi \approx \phi_0$$

For $3H < m$: Oscillations possible

$$\phi(t,x) = \phi_0(t) \cos(mt)$$

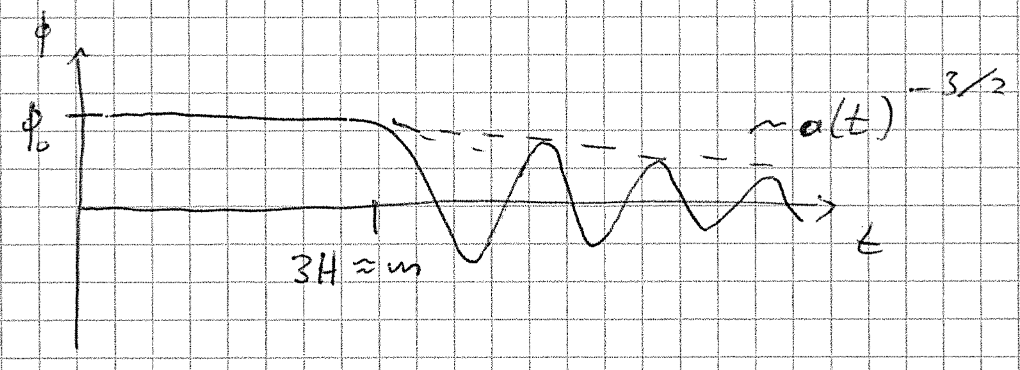
with

$$3H \dot{\phi}_0 \approx -2 \phi_0$$

$$\Rightarrow \quad -\frac{3}{2} \frac{da}{a} \approx \frac{d\phi_0}{\phi_0}$$

$$\Rightarrow \quad \phi_0(t) \sim a(t)^{-3/2}$$

Oscillation with frequency m and amplitude $\phi_0(t)$



Energy stored in field proportional to $\phi_0(t)^2 \sim a^{-3}$

Just like non-relativistic matter!

Coherently oscillating field
$\quad \cong$ Collection of particles at rest

* Analogy to quantum mechanics:

Consider ground state $|0\rangle$ of harmonic oscillator

$$\hat{a}\,|0\rangle = 0$$

Annihilation operator $\hat{a} = \sqrt{\frac{m\omega}{2}}\left(\hat{x} - \frac{i}{m\omega}\hat{p}\right)$

Construct coherent oscillation with amplitude x_0:

$$|x_0\rangle = \hat{T}(x_0)\,|0\rangle$$

translation operator $[\hat{T}(x_0), \hat{x}] = x_0$

$$\hat{a}\,|x_0\rangle = \hat{a}\,\hat{T}(x_0)\,|0\rangle$$

$$= \hat{T}(x_0)\left(\hat{a} + \sqrt{\frac{m\omega}{2}}\,x_0\right)|0\rangle$$

$$= \sqrt{\frac{m\omega}{2}}\,x_0\,|x_0\rangle$$

$\Rightarrow$ $|x_0\rangle$ is eigenstate of $\hat{a}$, but not of the number operator

$$\hat{N} = \hat{a}^{+}\hat{a}$$

Expectation value of $\hat{N}$:

$$\langle\hat{N}\rangle = \langle x_0|\,\hat{N}\,|x_0\rangle$$

$$= \langle x_0|\,\hat{a}^{+}a\,|x_0\rangle$$

$$= \frac{m\omega}{2}\,x_0^2$$

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$\Rightarrow$ Number of excited quanta prop. to x_0^2

Calculate relic abundance:

$$\Omega h^2 \sim m^2 \phi_0(\text{today})^2$$

$$\phi_0(\text{today}) \simeq \phi_0 \cdot \left(\frac{a(t_1)}{a(\text{today})}\right)^{3/2}$$

where $3H(t_1) = m$

Radiation domination:

$$a(t_1) \sim t_1^{1/2}$$
$$H(t_1) \sim t_1^{-1}$$

$$\Rightarrow \phi_0(\text{today}) \sim m^{-3/4}$$

$$\Rightarrow \Omega h^2 \sim m^{1/2} \phi_0^2$$

Restoring missing factors:

$$\Omega h^2 \approx 0.1 \sqrt{\frac{m}{1\ \mu eV}} \left(\frac{\phi_0}{10^{13}\ GeV}\right)^2$$

Example: The QCD axion

$\phi_0 = f_a$ $\quad$ ↳ solves strong CP problem

$m = \frac{m_\pi^2}{f_a}$ (+ finite temperature corrections)

$$\Rightarrow \Omega h^2 \approx 0.3 \left(\frac{f_a}{10^{12}\ GeV}\right)^{7/6}$$

4. Phenomenology of WIMPs

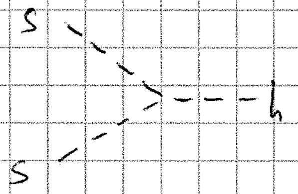
4.1 Case study: Scalar singlet dark matter (SSDM)

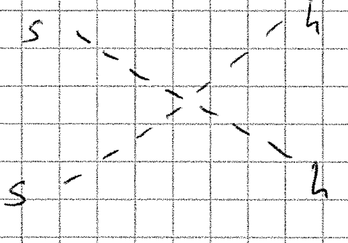
↳ Arguably simplest WIMP model

Consider scalar boson s that is completely neutral
(no strong, weak, EM charge)

$\Rightarrow$ No couplings to SM fermions or gauge bosons.

$\Rightarrow$ But: Can couple to Higgs boson h:





* QFT: Couplings arise from

$$\mathcal{L} \supset \frac{1}{2} \lambda_{hs} \, s^2 \, H^+ H$$

↑ Higgs doublet

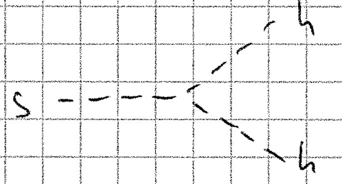
After spontaneous symmetry breaking

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

↑ Higgs boson ↑ Higgs vev

$$\Rightarrow \mathcal{L} \supset \underbrace{\frac{1}{2}\lambda_{hs}\, s^2 v^2}_{\text{mass term}} + \underbrace{\lambda_{hs}\, v\, s^2 h}_{\text{trilinear term}} + \underbrace{\frac{1}{2}\lambda_{hs}\, s^2 h^2}_{\text{quartic term}}$$

Note: No vertices involving single scalar boson



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Otherwise s is unstable

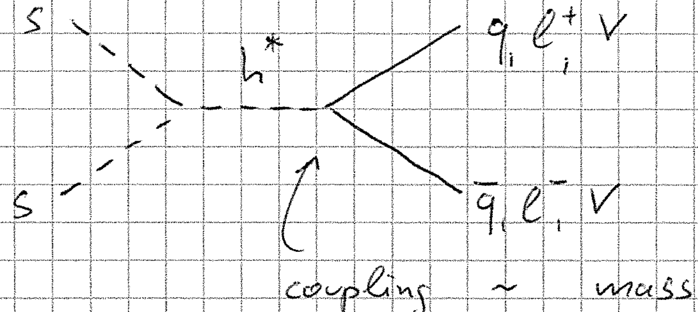
$\Rightarrow$ Two parameters:

m_s: Singlet mass

λ_{hs}: Higgs coupling

4.1.1 ~~5.1.4~~ Relic density

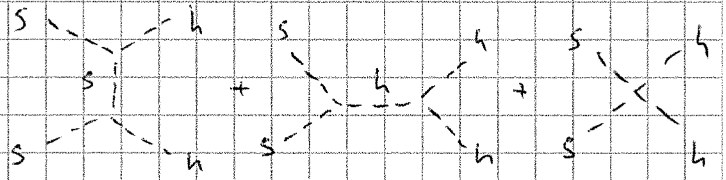
$$\Omega h^2 \approx \frac{3 \cdot 10^{-27}\ \mathrm{cm}^3\, \mathrm{s}^{-1}}{\underbrace{\langle \sigma v \rangle}_{\text{DM annihilation cross section}}} \overset{!}{=} 0.12$$



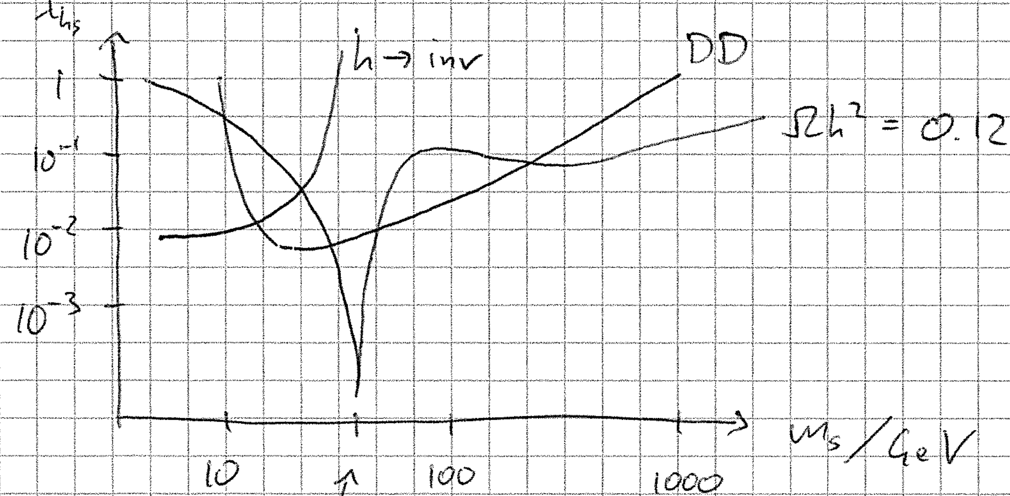
For $m_s \lesssim m_W$: $\sigma \approx \sigma(ss \to b\bar{b})$

For $m_s \gtrsim m_h$: $\sigma \approx \sigma(ss \to W^+W^-)$

$$+ \sigma(ss \to ZZ)$$
$$+ \sigma(ss \to hh)$$



For given m_s : Unique λ_{hs} yields $\Omega h^2 = 0.12$



$m_s = m_h/2 \Rightarrow$ resonant enhancement

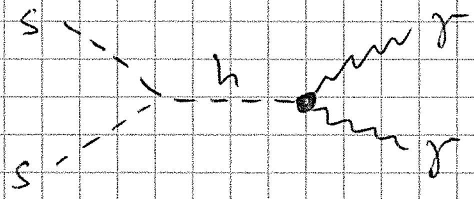
4.1.2 Searching for SSDM

- Indirect detection:

  DM annihilations stop after freeze-out **<u>except</u>** in regions of high density (e.g. Galactic centre)

  ↳ Look for anomalous emission

  Example: Gamma rays

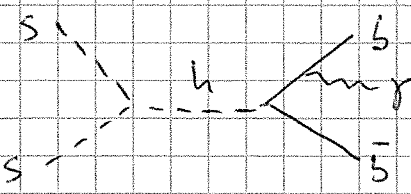


$\uparrow$ $v/c \ll 1$ $\qquad\qquad$ $\uparrow$ $E_\gamma \approx m_s$

⇒ Mono-energetic gamma-ray line (weak signal, very low BG)

⇒ Strong constraints (Fermi-LAT)

Can also look for continuum

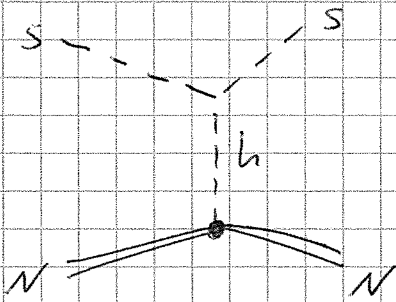


(Bremsstrahlung)

or for other final states (positrons, anti-protons)

- Direct detection

Higgs couples to nuclei proportionally to mass

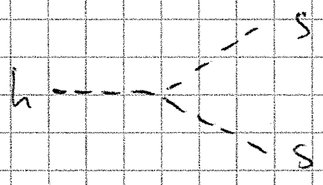


$\sigma \sim \lambda_{hs}^2 \, m_N^2$

$\Rightarrow$ Strong bounds from Xe-based experiments

- Collider experiments

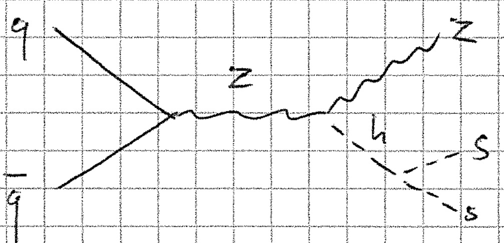
For $m_s < m_h/2$, Higgs can decay into DM:

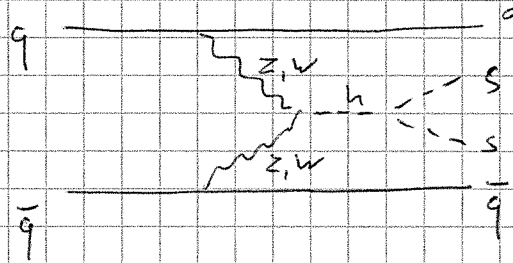


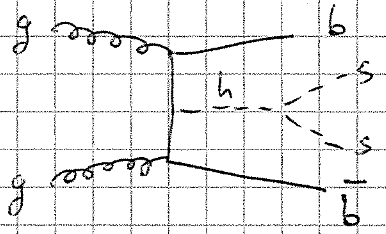
} invisible at colliders

How to observe?

$\rightarrow$ Look for Higgs produced together with something else







Invisible Higgs decay

$\Rightarrow$ Apparent violation of momentum conservation ("missing transverse momentum")

$\Rightarrow$ Can constrain invisible decays

LHC run 2: $BR(h \to inv) \lesssim 25\%$

4.1.3 Summary

Two viable regions

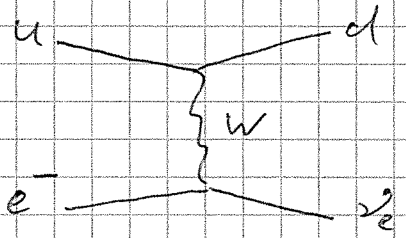
1) $m_s \approx m_h/2$ (difficult to probe)

2) $m_s \gtrsim 300$ GeV (probed by XENON1T)

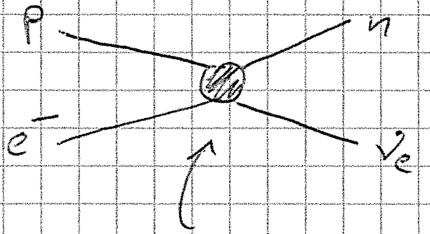
4.2 Model-independent approaches

Idea: At sufficiently low energies the ~~detaila~~ model-specific details do not matter

Example: Weak interactions



$\downarrow$ low energies



(4-fermion interaction)

$$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{m_W^2} = 1.17 \cdot 10^{-5} \text{ GeV}^{-2}$$

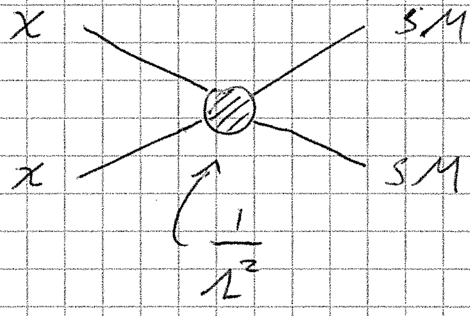
$\Rightarrow$ Effective field theory (EFT)

$\hookrightarrow$ beta decay

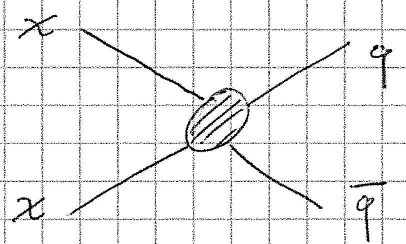
$\hookrightarrow$ neutrino scattering

$\hookrightarrow$ ...

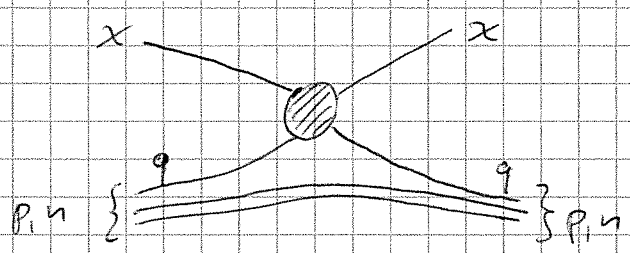
In analogy:



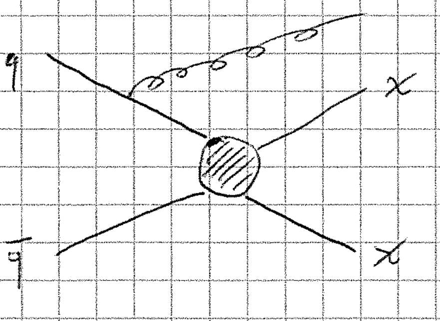
E.g. consider interactions with quarks



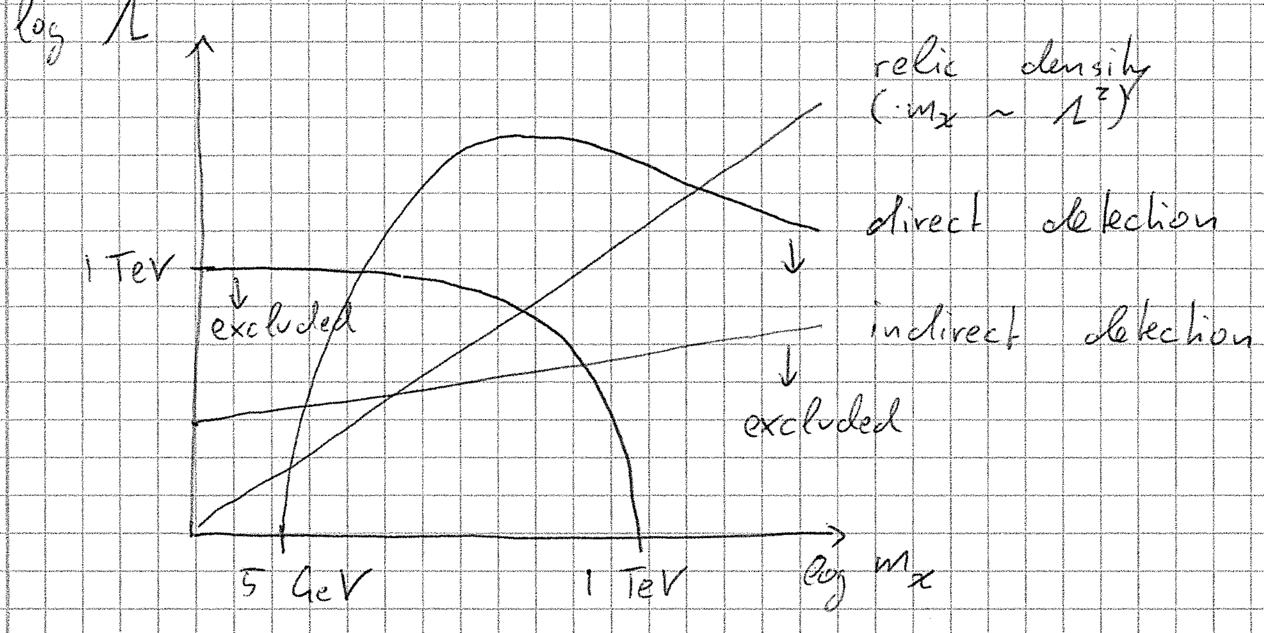
→ DM annihilation
- relic density
- indirect detection



→ DM scattering
- direct detection



→ DM production
- LHC searches (need initial state radiation)



$\Rightarrow$ Strong constraints on WIMPs below the TeV scale

4.3 Possible exceptions (incomplete)

Relic density:

- Resonant enhancement
- Co-annihilations ($\chi_1 \chi_2 \to SM\ SM$)

Direct detection:

- Momentum dependent interactions
  $\sigma \sim (q/m_\chi)^n \approx 10^{-3n}$ $(n = 2\text{-}4)$
- Inelastic scattering

Indirect detection:

- Velocity-suppressed (p-wave) annihilation

$$\sigma v \sim v^2 = 10^{-6}$$

LHC searches:

- EFT approach not valid
  ($m_{mediator} \ll 1$ TeV)

Or it's just not a WIMP:

- Axion
- Gravitino (super-WIMP)
- Asymmetric dark matter
- FIMPs (freeze-in mechanism)
- Sterile neutrinos
- ...

For experiments to decide!