Dark matter at colliders

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Outline

- Evidence
- Relic density
- Status of searches
- WIMPs at colliders
  - From simplified to UV complete models
- Other DM candidates
- Conclusions

Dark matter : evidence

- In 1933 Fritz Zwicky measured velocity dispersion in COMA cluster to estimate the cluster mass and found orbital velocities about factor 10 larger than expected from the mass of galaxies in clusters. He postulated the existence of some kind of matter which does not emit light - > dark matter

- He was criticized and forgotten, BUT this result was later confirmed on many scales
    - The galactic scale (rotation curves)
    - Scale of galaxy clusters
        - Mass to light-ratio : virial theorem, gravitational lensing
        - Bullet cluster
    - Cosmological scales
        - Dark matter is required to amplify the small fluctuations in Cosmic microwave background to form the large scale structure in the universe today
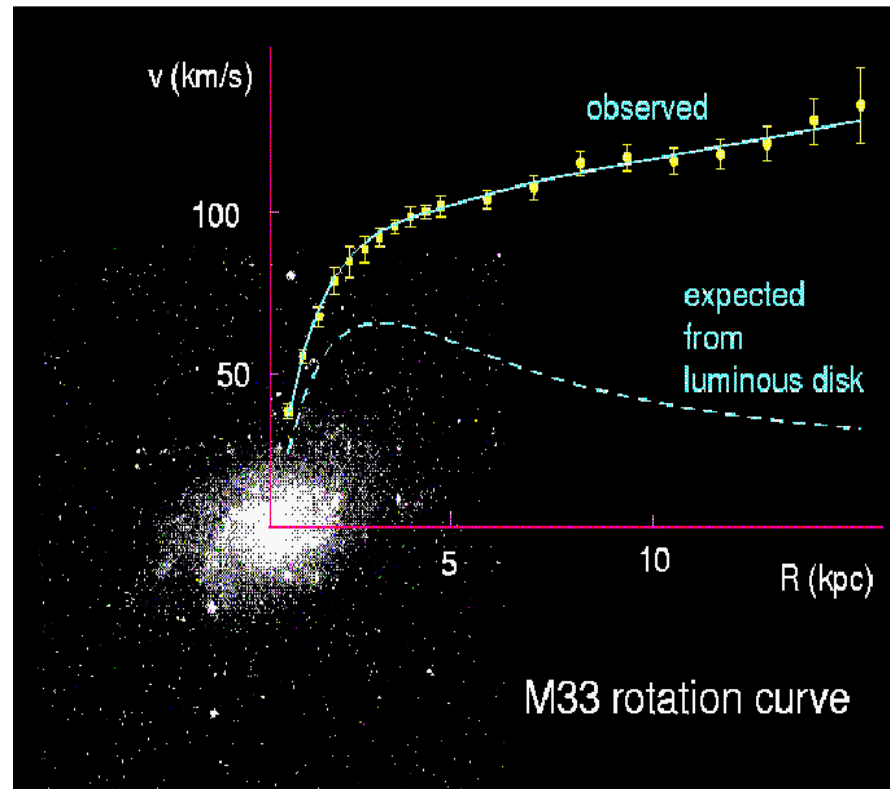
Rotation curves of galaxies

Newton's law :

For a sphere of constant density $M \sim r^3$ -> $v \sim r$

Outside sphere ($r > r_{luminous}$), M constant -> velocity decreases

$$v(r) = \sqrt{\frac{GM(r)}{r}} \, ,$$

But that is not what is observed…

M33 rotation curve

Explanation halo has a $M \sim r$: a large part of the mass is in outer part of galaxy (dark matter halo) rather than in visible disk

Bullet Cluster

- Collision of two clusters : direct evidence of dark matter
- Comparison of X-ray images of luminous matter with measurements of the cluster's total mass through gravitational lensing.
- Total mass peak offset by Xray peak (hot gas that forms most of baryonic matter)– 8σ
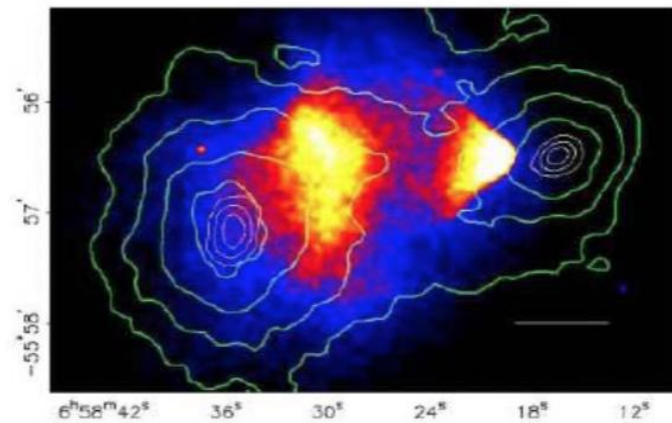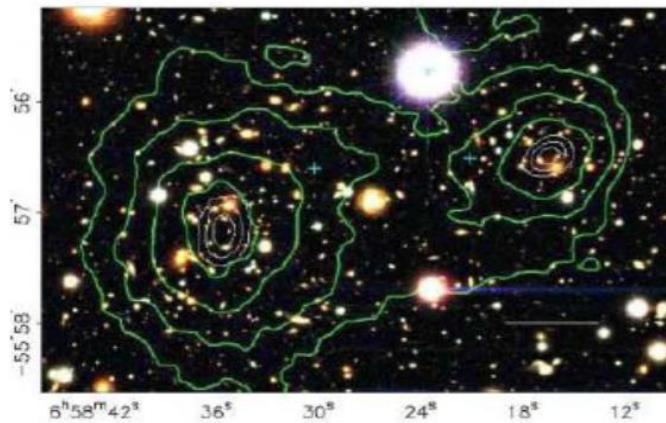
- Two small clumps of luminous matter slowed down by the collision
- Two clumps of collisionless matter (not slowed down) – DM

Cosmic microwave background
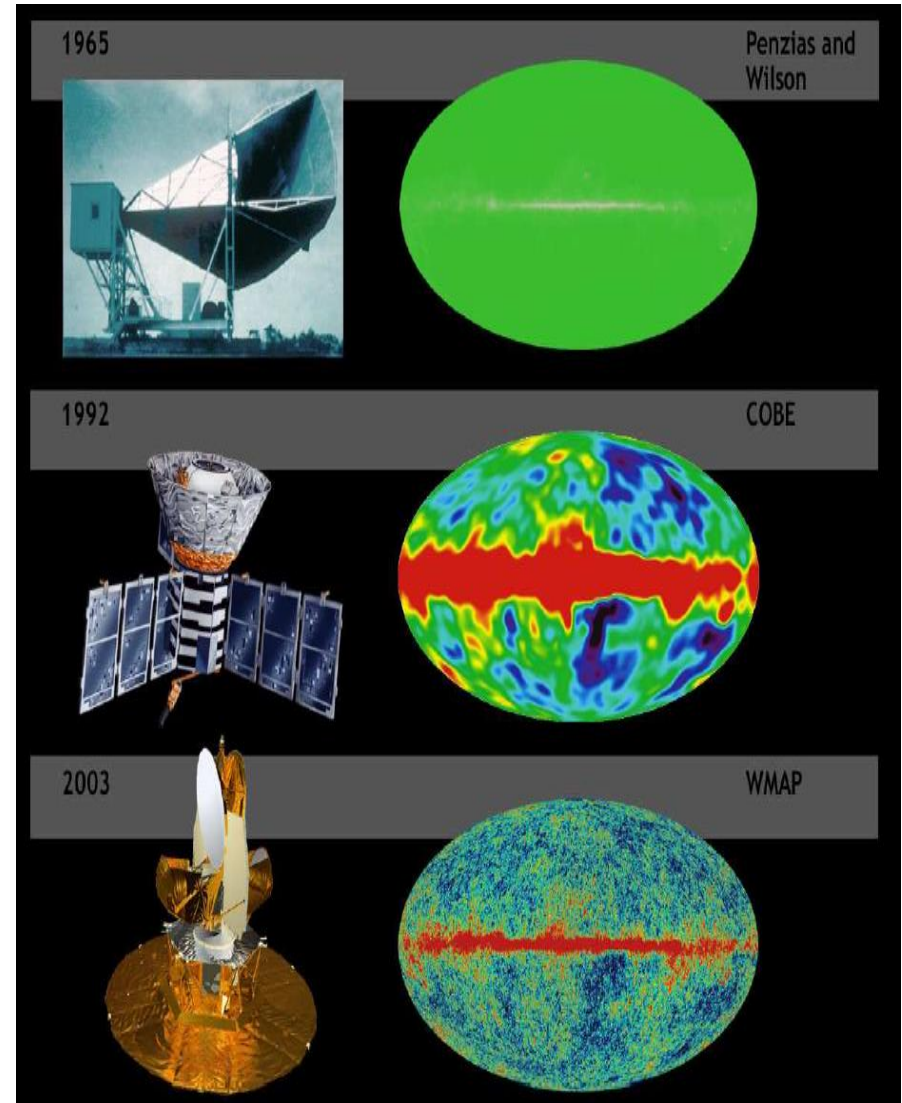## and total amount of dark matter in the universe

Background radiation originating from propagation of photons in early universe (once they decoupled from matter) predicted by Gamow in 1948

Discovered Penzias&Wilson 1965

CMB is isotropic at 10^{-5} level and follows spectrum of a blackbody with T=2.726K

Anisotropy to CMB tell the magnitude and distance scale of density fluctuation when universe was 1/1000 of present scale

Study of CMB anisotropies provide accurate testing of cosmological models, puts stringent constraints on cosmological parameters

Cosmic microwave background
and total amount of dark matter in the universe

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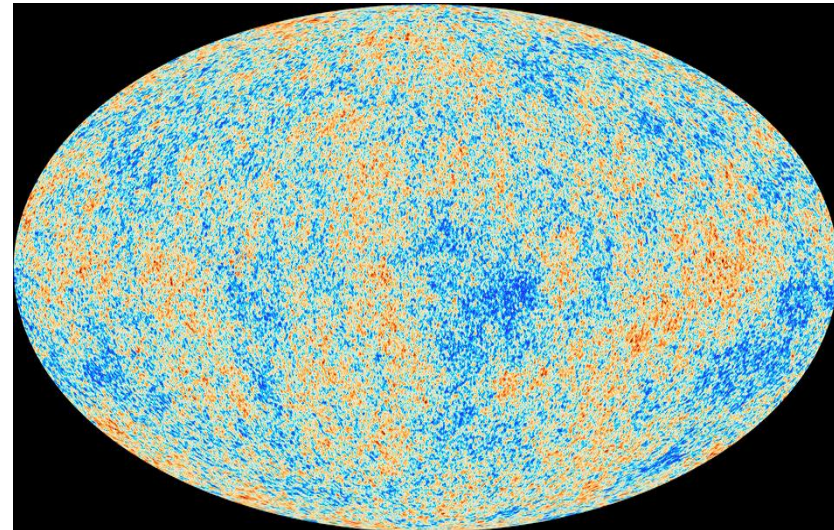
PLANCK

Discovered Penzias&Wilson 1965

CMB is isotropic at 10^{-5} level and follows spectrum of a blackbody with T=2.726K

Anisotropy to CMB tell the magnitude and distance scale of density fluctuation when universe was 1/1000 of present scale (time of last scattering)

SM is in plasma at high T-> it cannot generate such fluctuations -> cold dark matter

Density fluctuations

- Small anisotropy observed in sky

- All information contained in CMB maps can be compressed in power spectrum

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{\ell=2}^{+\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell \equiv <|a_{\ell m}|^2> \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.$$

- T fluctuation relate to fluctuations in gravitation potential at time of last scattering

- CMB anisotropy maps contain information on cosmological model parameters (Ω_B, Ω_M, Ω_Λ, Ω_ν ..) - best fit location and height of peaks
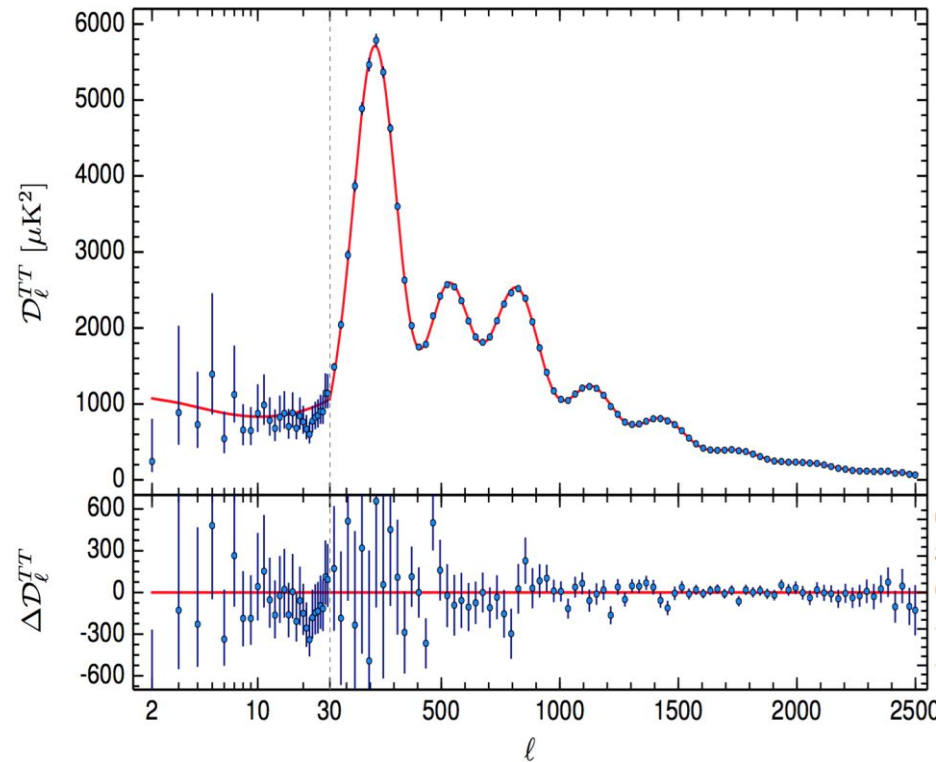

PLANCK 2015

[1] Parameter	[5] 2015F(CHM)
$100\theta_{MC}$	1.04094 ± 0.00048
$\Omega_b h^2$	0.02225 ± 0.00023
$\Omega_c h^2$	0.1194 ± 0.0022
H_0	67.48 ± 0.98
n_s	0.9682 ± 0.0062
Ω_m	0.313 ± 0.013
σ_8	0.829 ± 0.015
τ	0.079 ± 0.019
$10^9 A_s e^{-2\tau}$	1.875 ± 0.014

PLANCK, A&A 2015
arXiv:1502.01589

- Large dark energy component (assume to be cosmological constant)

- Precise evaluation of dark matter component - $\Omega_{cdm} = \rho_{cdm}/\rho_c$ (ratio of DM density to critical density)

- Baryon density in agreement with BBN (.019-.024) – form only a small component of matter
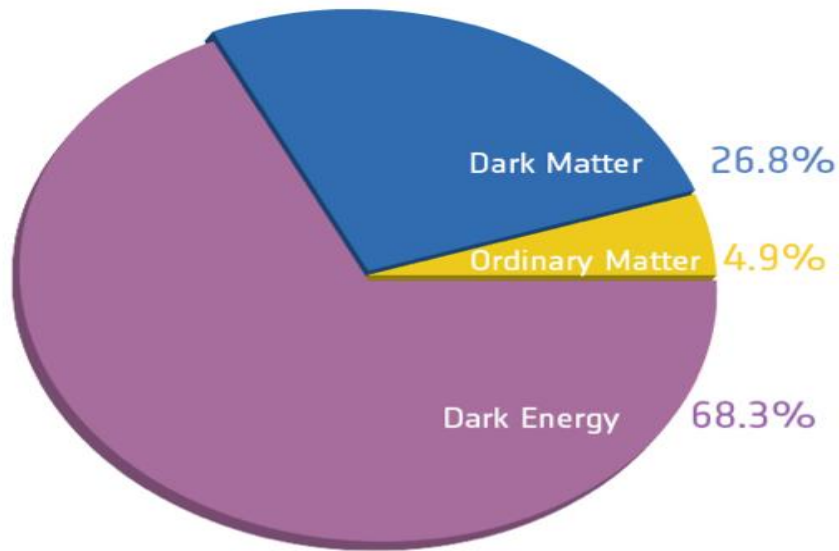
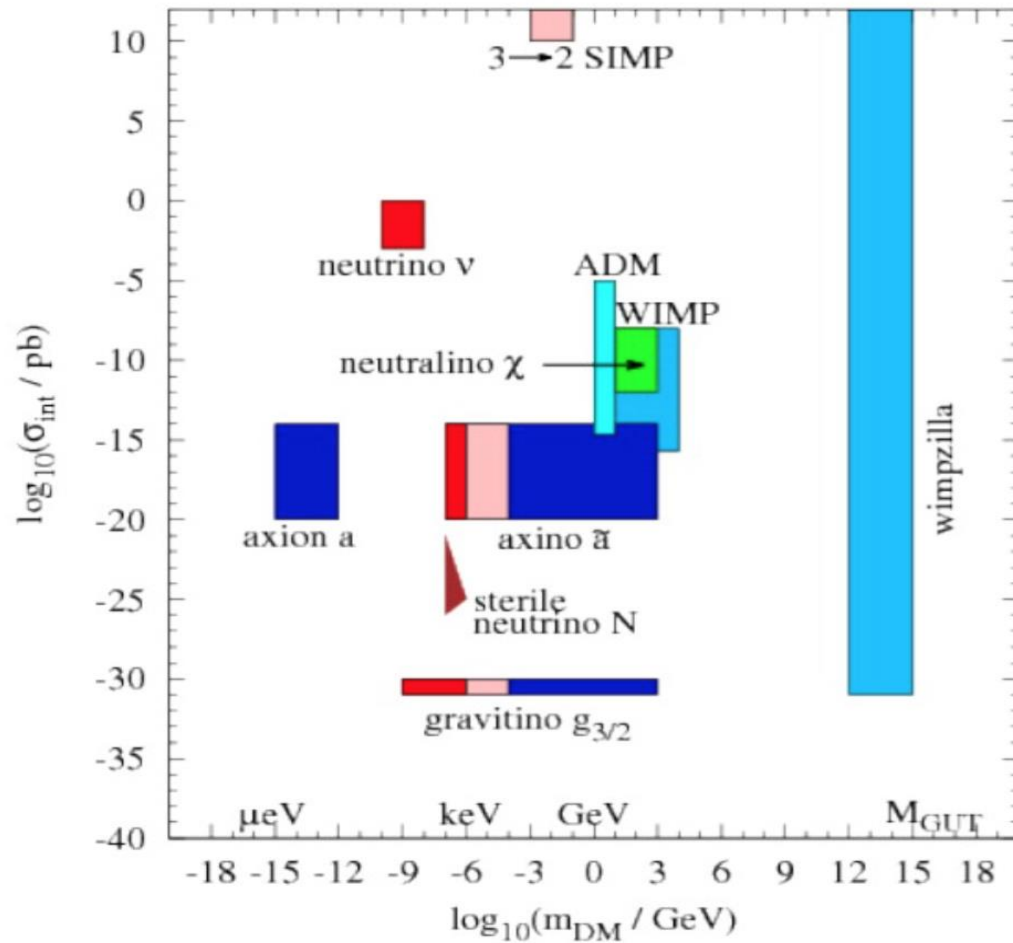WMAP and PLANCK

Universe is made of 27% cold dark matter.

*Cold: nonrelativistic during structure formation

Hot (relativistic) dark matter excluded because smooths out structures

DM particles nonrelativistic during time of last scattering –> M>10keV : neutrino cannot be main DM component

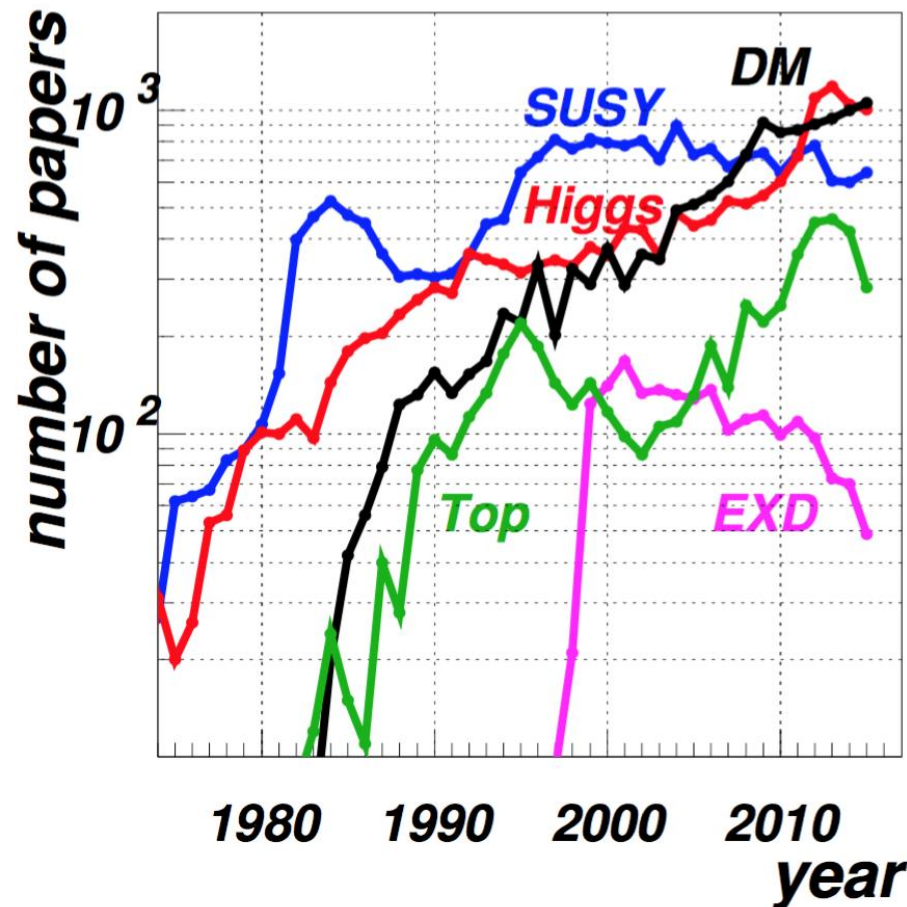Is DM a new particle, what are its properties?

A wide variety of DM candidates

… many publications

Because of strong evidence for DM, has become one of main motivation for BSM

A. Belyaev

Part 1 : WIMPs

Basics

- Number density of weakly interacting particle in gas

$$n_\chi = \frac{g}{(2\pi)^3} \int f(\mathbf{p}) d^3\mathbf{p}$$

- g: number of internal degrees of freedom (e.g. spin)
  - g=2 (fermions, photons), 3 (massive vector), 1(scalar)
- f: phase space distribution function

$$f(\mathbf{p}) = exp\left(\frac{E-\mu}{T} \pm 1\right)^{-1}$$

- μ : chemical potential, $E^2 = p^2 + m^2$ (c=1), +1(fermion) -1(boson)
- In relativistic limit (T>>m) and T>>μ

$$n_A(T)_{T \gg m,\mu} = \frac{\zeta(3)}{\pi^2} g_A T^3 \quad \text{(bosons)}$$

$$n_A(T)_{T \gg m,\mu} = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_A T^3 \quad \text{(fermions)}$$

- n ~T^3, as many μ than photons

- In non relativistic limit $m \gg T$ (also $T \gg \mu$) expansion in p^2/m^2

$$n_\chi^{eq} \approx g(m_\chi T/2\pi)^{\frac{3}{2}} exp(-m_\chi/T).$$

- The number density is Boltzmann suppressed.
- If expansion of the Universe was so slow that thermal equilibrium was maintained -> number density of weakly interacting particles today would be exponentially suppressed
- Similarly can also compute energy density

$$\rho_A(T) = \frac{g_A}{(2\pi)^3} \int E(\vec{p}) f(\vec{p}) d^3p = \frac{g_A}{2\pi^2} \int_{m_A}^{\infty} \frac{(E^2 - m_A^2)^{1/2}}{e^{(E-\mu_A)/kT} \pm 1} E^2 dE$$

$$\rho_A(T)_{T \gg m,\mu} = \frac{\pi^2}{30} g_A T^4 \quad \text{(bosons)}$$

$$\rho_A(T)_{T \ll m_A} = g_A m_A \left(\frac{m_A T}{2\pi}\right)^{3/2} e^{-(m_A - \mu_A)/T}$$

$$\rho_A(T)_{T \gg m,\mu} = \frac{7}{8} \frac{\pi^2}{30} g_A T^4 \quad \text{(fermions)}$$
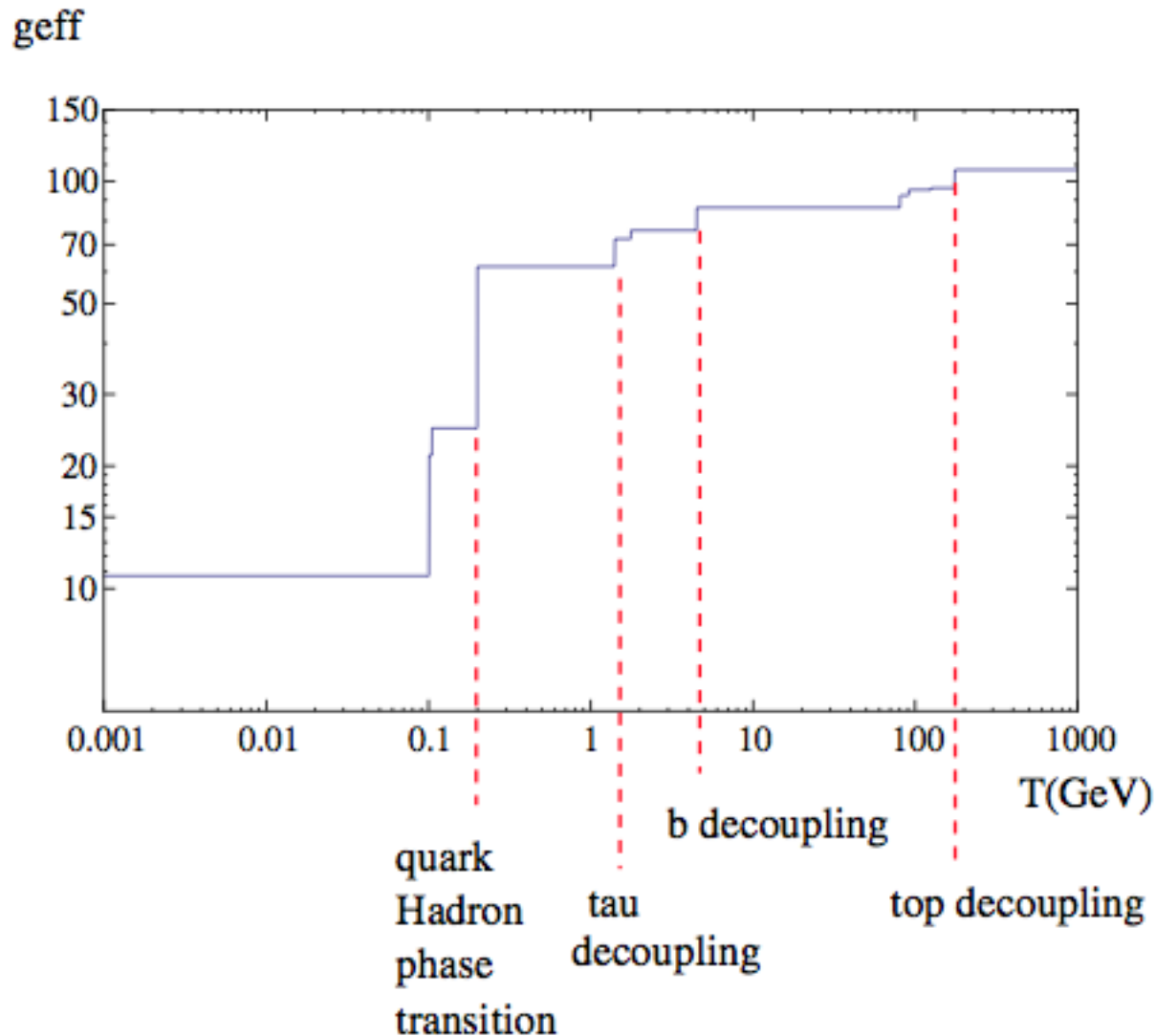
Degrees of freedom

- Primordial plasma is mix between different particles : some relativistic others not

- Energy density of relativistic species much larger than non-relativistic ones (can be neglected)

$$\rho(T) = \frac{\pi^2}{30}T^4 \sum_{i=all\ species} \frac{30}{\pi^2}\left(\frac{T_i}{T}\right)^4 \frac{g_i}{2\pi^2}\int_{x_i}^{\infty}\frac{(\epsilon^2 - x_i^2)^{1/2}\epsilon^2 d\epsilon}{e^{\epsilon - \mu_i/T}\pm 1} = g_\rho(T)\frac{\pi^2}{30}T^4$$

$$g_\rho(T) \simeq \sum_{b=bosons} g_b\left(\frac{T_b}{T}\right)^4 + \frac{7}{8}\sum_{f=fermions} g_f\left(\frac{T_f}{T}\right)^4$$

- T_b and T_f = photon temperature of the bath if they are relativistic and in equilibrium

geff

150
100
70
50
30
20
15
10

0.001   0.01   0.1   1   10   100   1000

T(GeV)

quark
Hadron
phase
transition

tau
decoupling

b decoupling

top decoupling

SM particles : 6 quarks (3 colors), 3 massive leptons, 3 neutrinos
3 massive vector (W,Z), 9 massless vector (8 gluons+photons), one real scalar
Today, g~3 (only 2 relativistic species : photons and neutrinos)

Relic density of WIMPs

- Assume a new stable (very long-lived) neutral weakly-interacting particle

- Will be in thermal equilibrium when T of Universe much larger than its mass

- Equilibrium abundance maintained by processses

$$\chi\bar{\chi} \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, W^+W^-, ZZ$$

- As well as reverse processes, inverse reaction proceeds with equal rate

Boltzmann equation

- Describes interactions of wimp with photons and other relativistic particles in thermal bath before they decouple

- Number of part χ/unit volume -> creation – annihilation

$$\frac{1}{R^3}\frac{d\left(n_A R^3\right)}{dt} = \langle\sigma v\rangle_{B\to A} n_B^2 - \langle\sigma v\rangle_{A\to B} n_A^2$$

$$\frac{dn_\chi}{dt} + 3H n_\chi = -\langle\sigma v\rangle\left((n_\chi)^2 - (n_\chi^{eq})^2\right)$$

Depletion of χ due to annihilation

Creation of χ from inverse process

$$H = \dot{R}/R$$

H: Hubble expansion rate
R: scale factor of the Universe

- If T>m,☐Wimps abundant, H negligible, χ relativistic and in thermal equilibrium with other particles like photons - rapidly annihilating in SM particles (vice-versa) $n \sim n_{eq} \sim T^3$

- As Universe expands T drops below m, n_{eq} drops exponentially, production rate is suppressed (particles in plasma do not have sufficient thermal energy to produce $\chi\chi$) χ start to decouple – can only annihilate $dn/dt=\sigma v\, n^2$

- Eventually rate of annihilation drops below expansion rate $\Gamma< H$ – not enough χ for annihilation - > fall out of equilibrium and freeze-out (production of wimps ceases) $dn/dt=-3Hn$

- This happens at $T_{FO}\sim m/20$, LSP decouples, density depends only on expansion rate
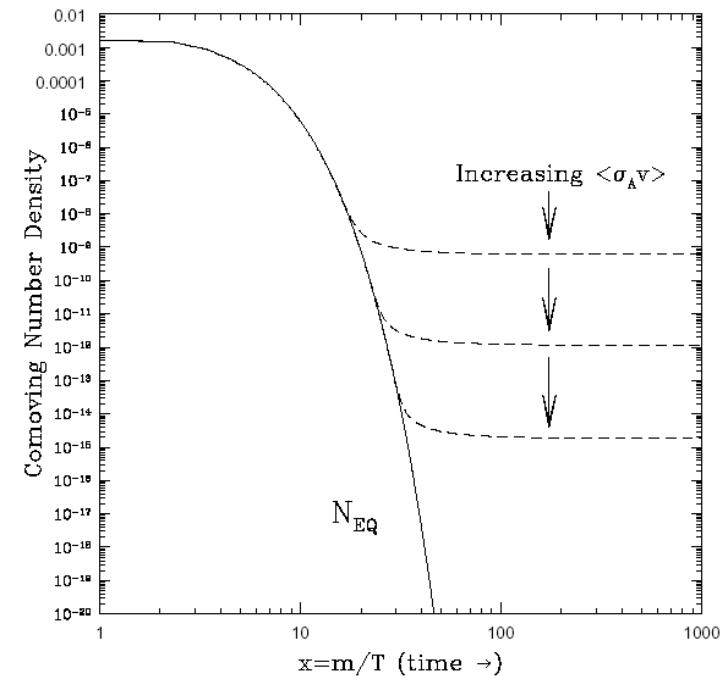
$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

Solving Boltzmann equation

- Y: ratio of number density to entropy density, s

$$\frac{dY}{dt} = \frac{d}{dt}\left(\frac{n}{s}\right) = \frac{dn}{dt}\frac{1}{s} - \frac{n}{s^2}\frac{ds}{dt}$$

- $R^3 s$ is constant in absence of entropy production

$$\frac{ds}{dt} = -3Hs \qquad\qquad \frac{dY}{dt} = \frac{dn}{dt}\frac{1}{s} + 3H\frac{n}{s}$$

- Evolution eq.

$$\frac{dY}{dt} = -s\langle\sigma v\rangle\left(Y^2 - Y_{eq}^2\right)$$

- Or in terms of entropy density

$$\frac{dY}{ds} = \frac{1}{3H}\langle\sigma v\rangle_T (Y^2 - Y_{eq}(T)^2)$$

- or x=m/T

$$\frac{dY}{dx} = -\frac{m}{x^2}\frac{1}{3H}\frac{ds}{dT}\langle\sigma v\rangle\left(Y^2 - Y_{eq}^2\right)$$

- Energy and entropy density parametrized with eff. degrees of freedom geff, heff

$$\rho = g_{eff}(T)\frac{\pi^2}{30}T^4 \quad s = h_{eff}(T)\frac{2\pi^2}{45}T^3$$

- Integrating on s from T=inf. to T=T_0 (photon temperature of the Universe today) gives Y_0

- Relic density at present

$$\Omega_\chi = \frac{m_\chi n_\chi}{\rho_{\text{crit}}} = \frac{m_\chi s_0 Y_0}{\rho_{\text{crit}}}$$

- s_0 : today's entropy at T=2.726K s_0=2889.2 cm^{-3}

- H= 100 h km/s/Mpc

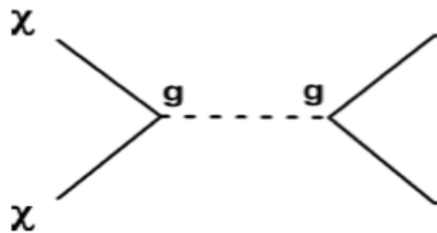- G= Newton's constant= 6.67X 10^{-11}m^3/kg/s^2 (G$^{-1/2}$=M_{Pl}=1.22 10^{19}GeV)

$$\Omega_\chi h^2 = 2.755 \times 10^8 \frac{m_\chi}{GeV} Y_0$$

Dark matter: a WIMP?
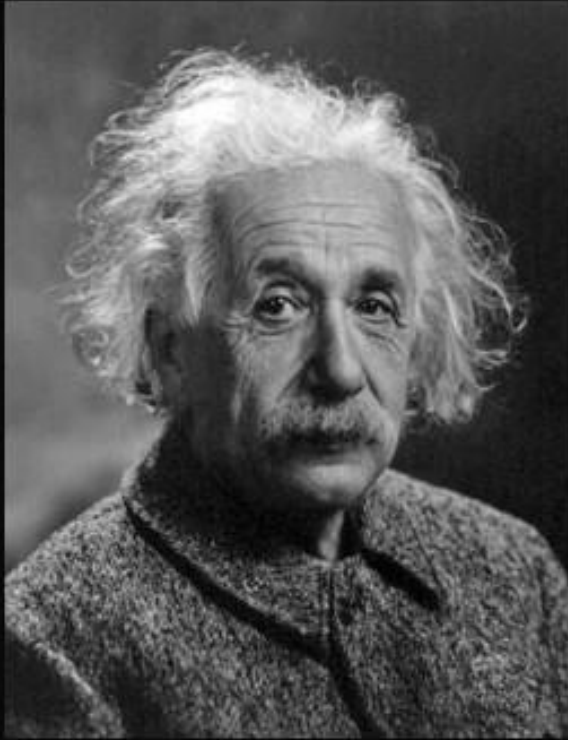
In standard scenario, relic abundance

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \ .$$

Depends only on effective annihilation cross section, a WIMP at EW scale has 'typical' annihilation cross section for $\Omega h^2 \sim 0.1$ (WMAP,PLANCK)

$$\langle \sigma v \rangle \sim \frac{g^4}{32\pi m_{DM}^2}$$

$\sim 3 \ 10^{-26} \text{ cm}^3/\text{s}$ (or $\sigma \sim 1\text{pb}$)

Remarkable coincidence : particle physics independently predicts particles with the right density to be dark matter (WIMP miracle)
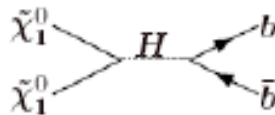
There are only two ways to live your life. One is as though nothing is a miracle. The other is as though everything is a miracle.

(Albert Einstein)

Miracle?

- Relic density puts strong constraint on combination of mass/couplings

- Will any weakly interacting particle lead to the 'miracle' ?

- Resonance

$$\sigma v \propto m_{\tilde{\chi}}^2 / (4m_{\chi}^2 - m_H^2)^2$$

  - much weaker coupling required when $2m_\chi \sim m_H$

- New channels : increase of cross section if W/Z/h/t channels kinematically open, also larger cross sections for spin 1

- t-channel : enhancement when small mass splitting
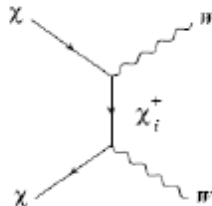
- Coannihilation : when many 'dark' particles nearly degenerate

Coannihilation

If M(NLSP)~M(LSP) then $\qquad \chi + X \rightarrow \chi' + Y$

maintains thermal equilibrium between NLSP-LSP even after new particles decouple from standard ones

Relic density then depends on rate for all processes

$$\chi\chi \rightarrow XY$$
$$\chi\chi' \rightarrow XY \qquad\qquad \text{X,Y: SM particles}$$
$$\chi'\chi' \rightarrow XY$$

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{i,j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{eq} n_j^{eq} \right)$$
$$- \sum_{j \neq i} \langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{eq} n_X^{eq} \right) - \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{eq} n_X^{eq} \right)$$

Coannihilation

All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes

$$n = \sum_{i=1}^{N} n_i$$

Important processes are those involving particles close in mass to LSP

$$\frac{n_i}{n} \approx \frac{n_i^{eq}}{n^{eq}} \quad \sim\text{exp(-}\Delta m/T)$$

Generalisation of Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right)$$

where

$$< \sigma v > = \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T \left(\sum_i g_i m_i^2 K_2(m_i/T) \right)^2}$$

Exp(- ΔM)/T

Coannihilation

Contribution of coannihilation processes strongly suppressed with increasing mass difference - for comparable cross sections : few percent

When coan process more efficient than LSP annihilation → reduces the relic density (typically happens in most SUSY cases)

When coann process less efficient than LSP annihilation-> increases the relic density (typical for UED models)

If coannihilation is what gives the correct relic density -> other astro signatures which only rely on DM annihilation typically suppressed

WIMPs are not the only possibility (see tomorrow)

Probing the nature of dark matter
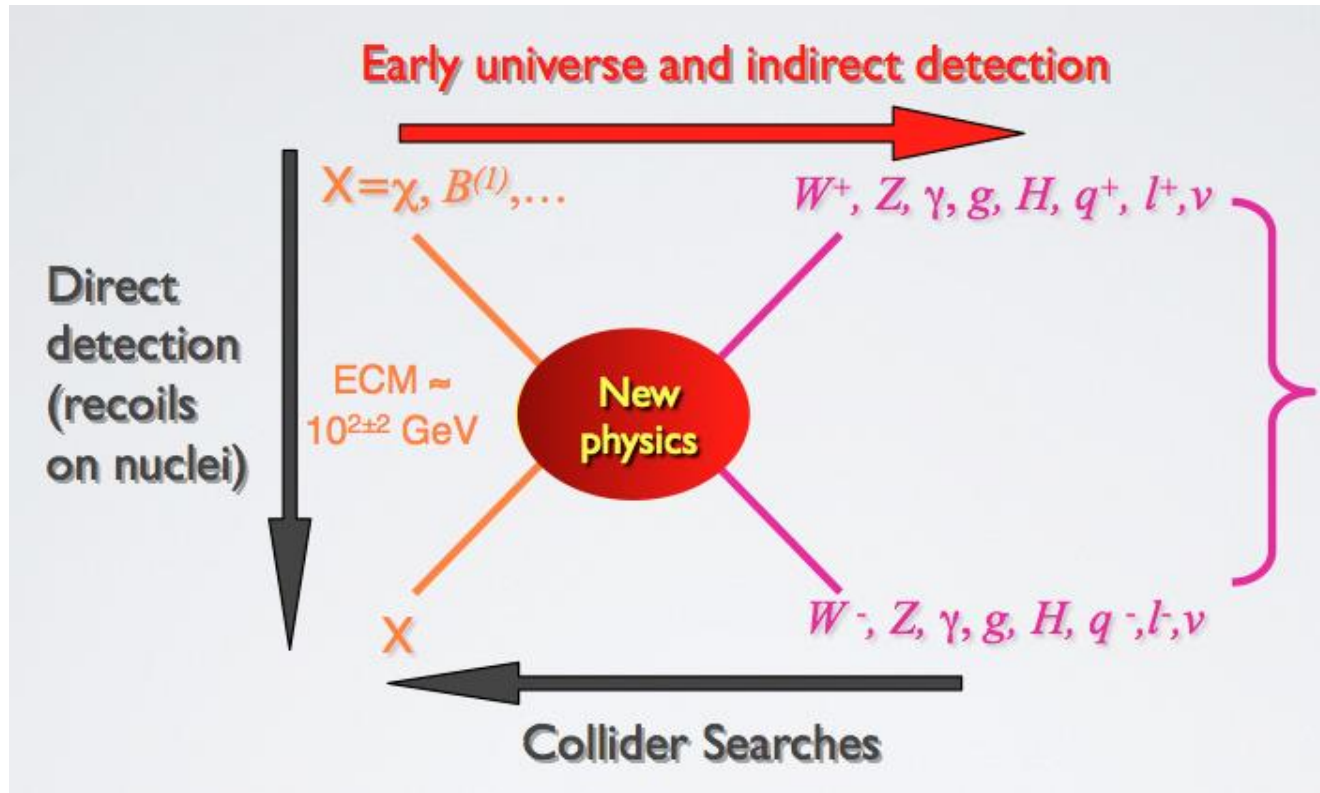
- All determined by interactions of WIMPS with Standard Model
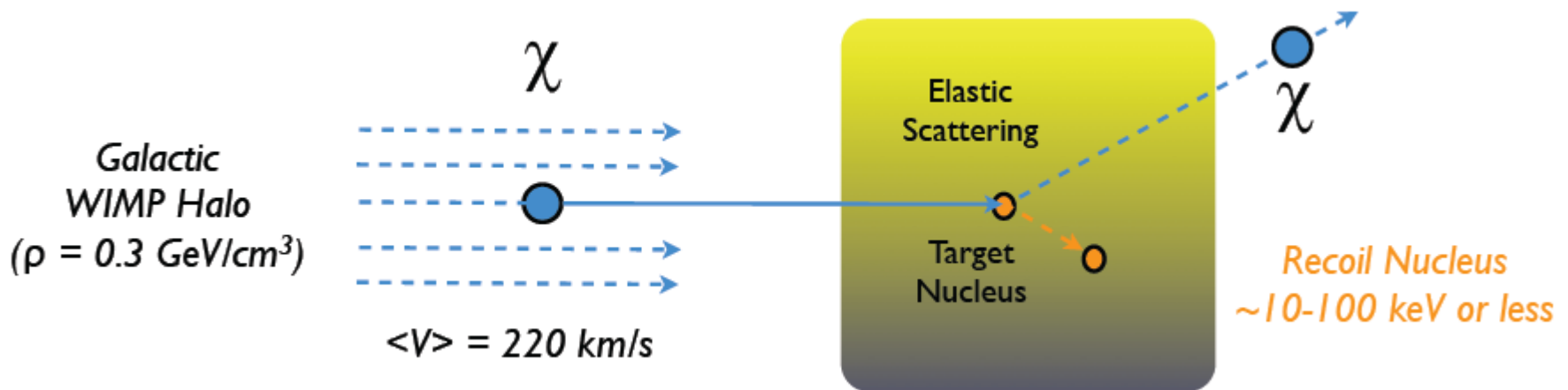- Specified within given particle physics model

Constraints on WIMPs

- Reproduce the measured relic density assuming standard cosmological model

- Limits from astroparticle searches

  - Direct detection (Xenon,LUX, PandaX, CDMS Cresst, DAMIC, DAMA….)

  - Indirect detection (FermiLAT, HESS, Magic, AMS …) in particular with photons, positrons, antiprotons etc..

  - Neutrinos (IceCUbe)

- Hints in astroparticle searches

  - DAMA/CoGenT, CDMS-SI, Fermi-LAT Galactic Center, PAMELA, AMS02

- Collider constraints (model dependent – stability at collider scale only)

Direct detection

- Elastic scattering of WIMPs (weakly interacting massive particle) off nuclei in a large detector
- Measure nuclear recoil energy, E_R
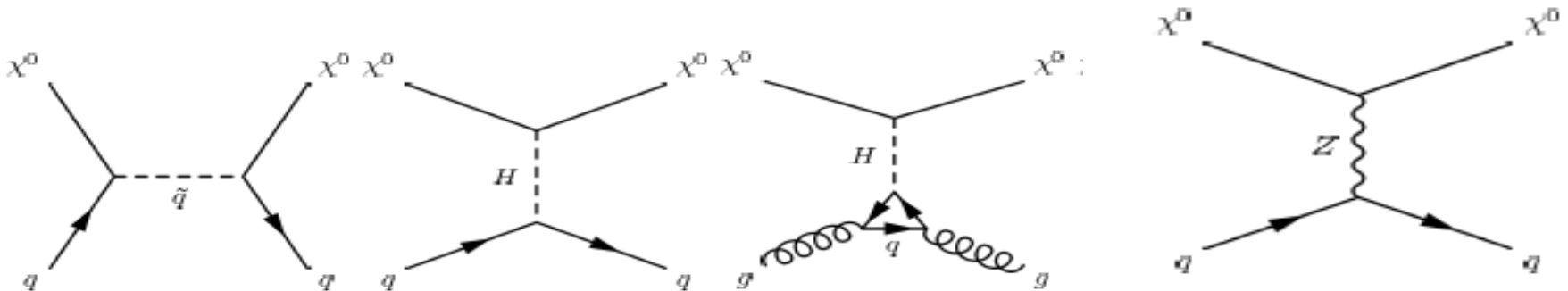
- Best way to prove that WIMPs form DM

Galactic WIMP Halo (ρ = 0.3 GeV/cm^3)

χ

<V> = 220 km/s

Elastic Scattering

Target Nucleus

χ

Recoil Nucleus ~10-100 keV or less

Direct detection

- Particle physics : effective Lagrangian for WIMP-nucleon and wimp-quark amplitude *at small momentum transfer (~100MeV)*

- For Majorana fermion

- For Dirac fermion

$$\mathcal{L}_N = \lambda_N \overline{\chi}\chi \overline{N}N + \xi_N \overline{\chi}\gamma_\mu \gamma_5 \chi \overline{N}\gamma^\mu \gamma_5 N$$

$$\mathcal{L}_F = \lambda_{N,e}\bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o}\bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \quad \text{(for SI)}$$

For Dirac fermions Z exchange contributes to SI and SD

WIMP-quark to WIMP-nucleon

- Coefficients for effective Lagrangian for WIMP – quark scattering – computed from fundamental Lagrangian, same as WIMP- nucleon : introduce coefficients relate WIMP-quark operators to WIMP nucleon operator (Scalar, vector…)
  - Extracted from experiments or computed from lattice
  - Recent progress in lattice –> reduce theoretical uncertainties
- Example : scalar coefficients, contribution of q to M_N(heavy quark contribution expressed in terms of gluonic content)

$$\langle N | m_q \overline{\psi}_q \psi_q | N \rangle = f_q^N M_N$$

$$\lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p} \qquad \qquad f_Q^N = \frac{2}{27}\left(1 - \sum_{q\leq 3} f_q^N\right)$$

Numerical values $f_d{}^p = 0.0191$, $f_u{}^p = 0.0153$, $f_s{}^p = .0447$, $f_Q{}^p = 0.07$
Large contribution from heavy quarks

WIMP-nucleus

- Rates (SI and SD) depends on nuclear form factors and velocity distribution of WIMPs + local density

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

Nuclear form factors

Particle physics + quark content in nucleon

DM velocity distribution
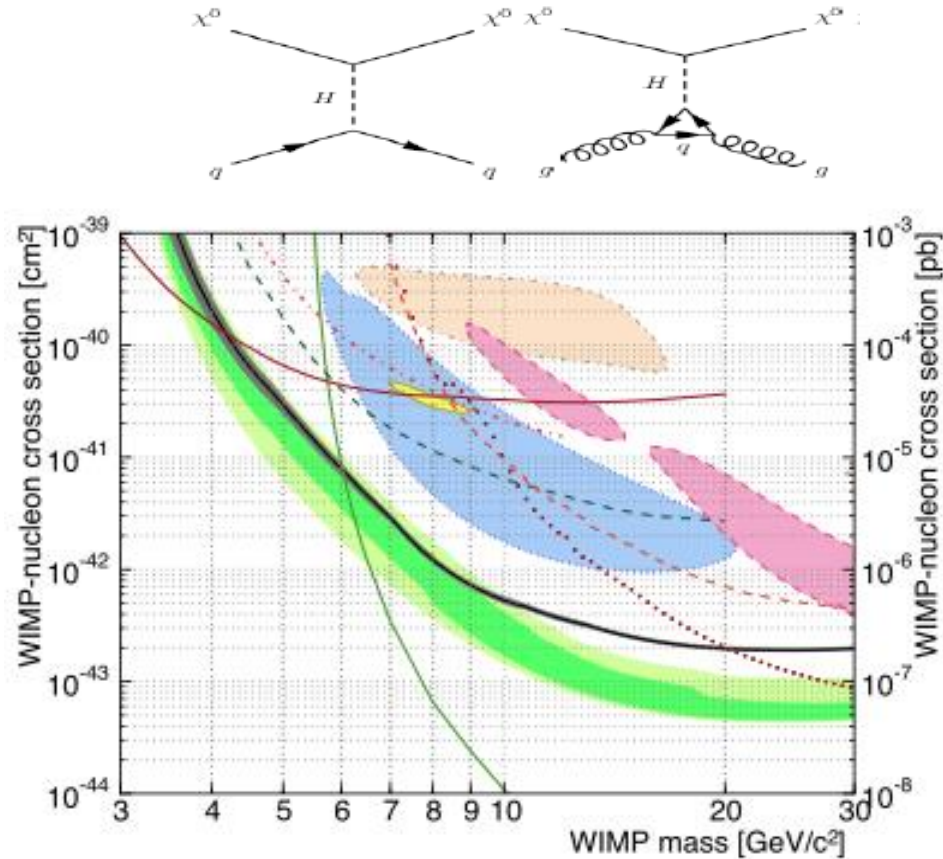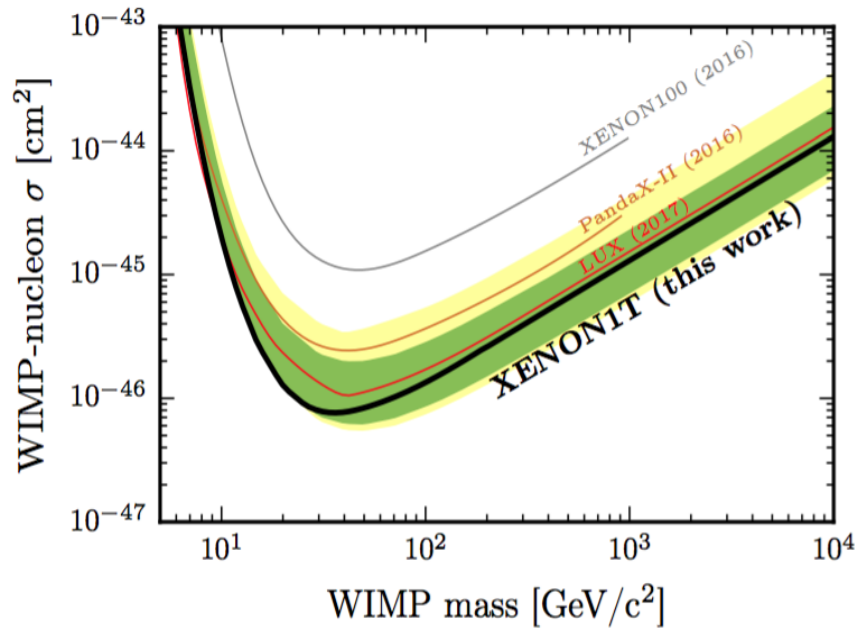
$$I(E) = \int_{v_{min}(E)}^{\infty}\frac{f(v)}{v}dv$$

$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

- For easy comparison between expt, assume $\lambda_p=\lambda_n$

$$\sigma_p^{SI} = \frac{4\mu_\chi^2}{\pi}\lambda_p$$
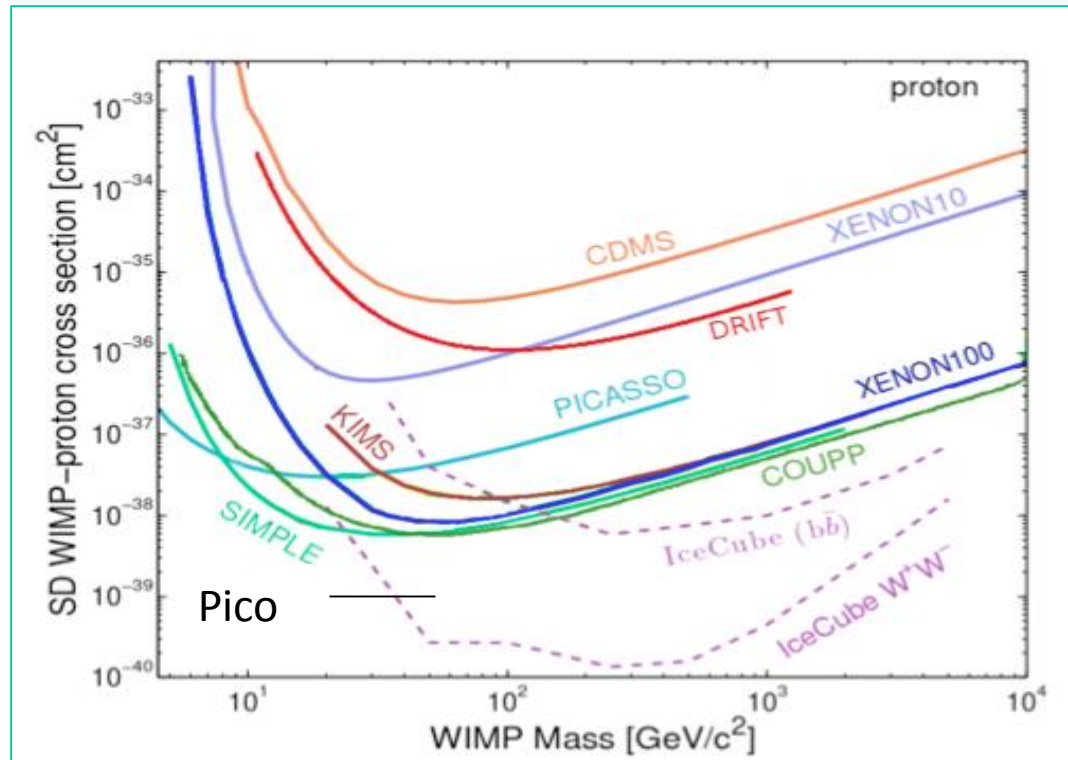
Spin independent

Elastic scattering of DM
off nucleons in a large detector

Much improved limit on SI cross section – Xenon1T (1705.06655)- and at low mass CDMS

Assuming $f_p=f_n$, rules out CDMS-Si, CoGENT, DAMA..

Limits spin dependent

Pico: 1503.00008

Cross sections probed are much larger than for SI
Just reaching the sensitivity to probe more popular DM model (MSSM)