Physics beyond the standard model and dark matter

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Why beyond?

Humans are driven to explore the unknown, discover new worlds, push the boundaries of our scientific and technical limits, and then push further. Curiosity and exploration are vital to the human spirit. The intangible desire to explore and challenge the boundaries of what we know and where we have been has provided benefits to our society for centuries. (NASA)

Why beyond the standard model?

- Unification of all interactions – SM does not include gravity
- Neutrino masses - in SM neutrinos are massless
  - Evidence for neutrino oscillation -> neutrino masses, $\Sigma m < 0.23$eV
  - RH neutrino - Dirac or Majorana?
- Origin of SM parameters in SM
  - Masses described by Higgs mechanism but why these values?
  - Value of gauge couplings, Higgs parameters
- Why 3 generation of fermions, flavour structure?
- Only one Higgs? (minimality)
- Hierarchy problem
  - Why gravity so weak, weak scale vs Planck scale, corrections to Higgs mass

Why beyond the standard model?

- Stability of vacuum
  - Assuming SM valid up to Planck scale, m_H implies vacuum unstable (metastable) : at some scale $\lambda < 0$ (λH^4)
- Strong CP problem
  - No CP violation in QCD, e.g. electric dipole moment of neutron very small -> CP phase $< 10^{-9}$ (fine-tuning)
  - Possible explanation : global U(1) symmetry - axions
- Dark matter
- Dark energy
  - Acceleration of expansion of Universe
- Baryon – antibaryon asymmetry
  - Why nore matter than anti-matter in the Universe, electroweak baryogenesis?
  - Baryon number violation, CP violation, departure from equilibrium

Why beyond the standard model?

- Although large number of experimental results are in perfect agreement with SM predictions, still a few (some non-compelling) unexplained phenomena
  - Muon g-2 : a long standing discrepancy, BNL (3σ)

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (287 \pm 80) \times 10^{-11}$$

  - Radius of proton
    - New measurement of radius of proton with muons – radius 4% smaller than with electrons
  - B decays, new source of b-s$\mu^+\mu^-$ transition?
    - R_K=B(B^+->$K^+\mu^+\mu^-$)/ B(B^+->$K^+e^+e^-$)

$$R_K^{\rm exp} = 0.745^{+0.090}_{-0.074}({\rm stat}) \pm 0.036({\rm syst}).$$

    - Decay rate for B^0->$K^{0*}\mu^+\mu^-$ exceed SM prediction (LHCb)

At which scale?

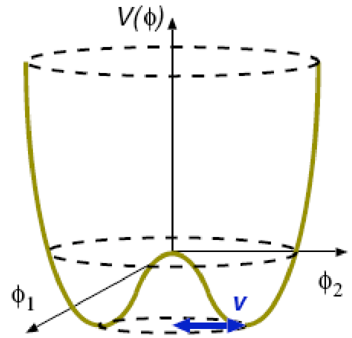
- Planck scale for sure 10^{19}GeV
- GUT scale 10^{15}GeV
- Intermediate scale : see-saw mechanism 10^{12}GeV
- TeV scale (at least we can explore this)

Hierarchy problem and dark matter are two of most compelling motivation for TeV scale new physics

Hierarchy problem

- Higgs potential in SM

$$V = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{4}\left(\phi^\dagger \phi\right)^2$$



- Minimum :

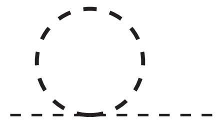
$$\frac{\partial^2 V}{\partial \phi^\dagger \phi} = 0 \rightarrow \quad \mu^2 = \frac{\lambda v^2}{4}$$

$$\phi \rightarrow \phi + \frac{v}{\sqrt{2}}$$

- In the SM, after symmetry breaking mass of W/Z relate to Higgs vev, M_W=gv/2 : v~246 GeV
- Higgs mass : $m_h^2 = v^2\lambda/2$
- Loop level : SM renormalizable -> finite results are expected for all higher order corrections, even when virtual momentum goes to infinity (or at least until scale of new physics)
- For sure new physics at Planck scale (gravity)
  - Cut-off Λ -> M_P

Hierarchy problem

- If scale of new physics is M_{pl}, then problem with SM beyond tree
- Self interaction



$$\lambda(\phi^\dagger\phi)^2$$

$$\lambda \int d^4k \frac{1}{k^2 - m_H^2} \rightarrow \lambda\Lambda^2$$

- Quadratic divergence : corrections to potential

$$\mu_{phys}^2 = \mu^2 + \lambda\Lambda^2$$

- μ_{phys} related to Higgs mass -> O(100) GeV, Λ ~M_{pl}
- Bare value of μ^2 must almost cancel $\lambda\Lambda^2$ → fine-tuning
- Affects Higgs mass
- Clearly less severe fine-tuning if new physics below Planck scale , fine-tuning acceptable if new scale one order of magnitude above weak scale (subjective)

Solution to hierarchy problem

- Eliminate quadratic dependence on high scale present in theories with fundamental scalars
  - Eliminate elementary scalars : ‘technicolour’ - disfavoured
  - Include elementary scalars but control quadratic divergences
    - Symmetries can remove dangerous divergences
      - QED, unbroken gauge theory keeps photon massless
      - Chiral symmetry keeps electron massless
      - Supersymmetry protects Higgs mass
- Bring ‘Planck mass’ to lower scales (extra dimension)
- Introduce new physics at some ‘low’ scale, e.g. 10TeV

Dark matter

Dark matter : the beginning

- In 1933: Fritz Wicky, a Swiss astronomer measured velocity dispersion in COMA cluster to estimate the cluster mass. He found mass was 400 times larger than the visible mass (deduced from luminosity estimation) He postulated the existence of a kind of matter that does not emit light → dark matter
- He was criticized (too much uncertainty) and forgotten BUT this result was confirmed later on many scales

In 1970 : Vera Rubin , US astronomer, measures the rotation velocity of spiral galaxies

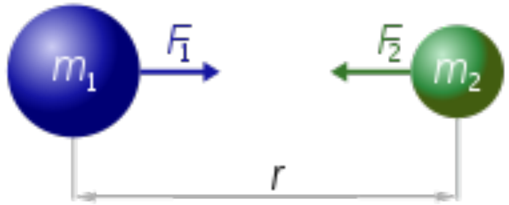
Velocities tend to a constant at large distances –presence of non-luminous matter can explain this

Ever since that time evidence for dark matter at different scales (galaxies, clusters, cosmology) has been accumulating

- The amount of mass needed is more than luminous mass
  - The galactic scale
  - Scale of galaxy clusters
- Dark matter is required to amplify the small fluctuations in Cosmic Microwave background to form the large scale structure in the universe today - Cosmological scales

What constitutes dark matter : is it a new weakly interacting particle? (BSM)

Rotation curves of galaxies



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

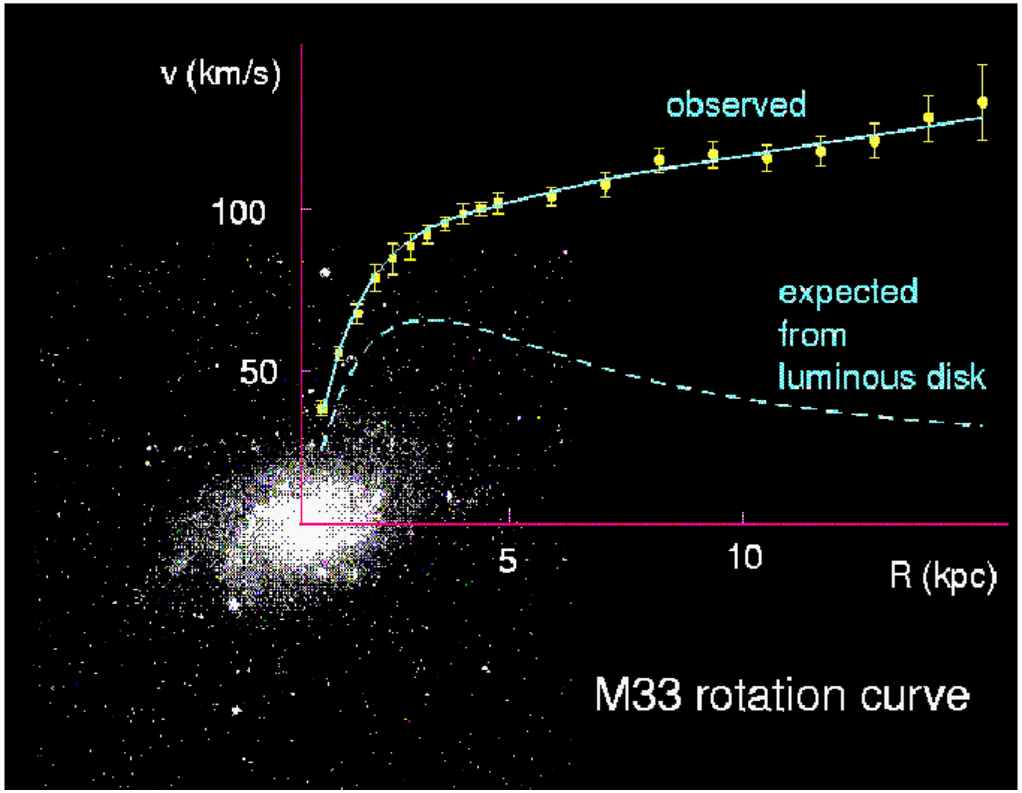
$$M(r) = 4\pi \int_0^r \rho(a) a^2 da$$

- Newton: inside a solid sphere of constant density the gravitational force varies linearly with distance r from the center
- For a sphere of constant density $M \sim r^3$ -> $v \sim r$
- Outside sphere ($r > r_{luminous}$), M constant -> velocity decreases

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

- Observations show that velocity does not decrease

Rotation curves of galaxies



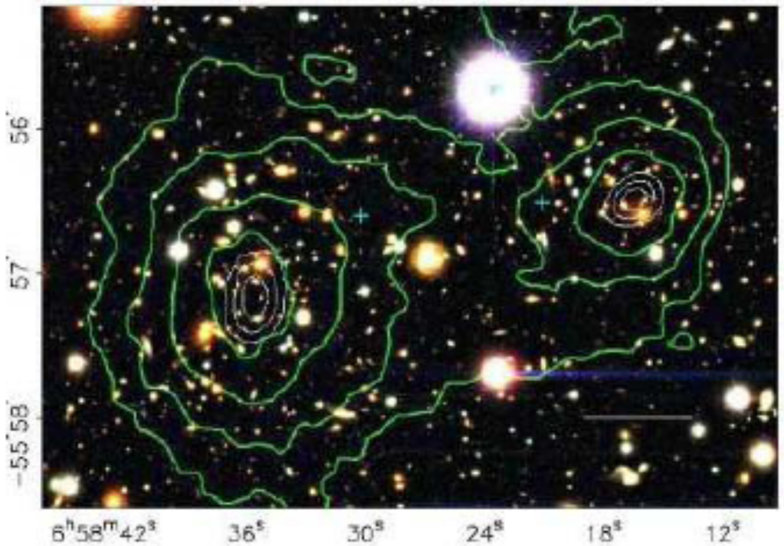
Explanation halo has a M ~ r : a large part of the mass is in outer part of galaxy (dark matter halo) rather than in visible disk

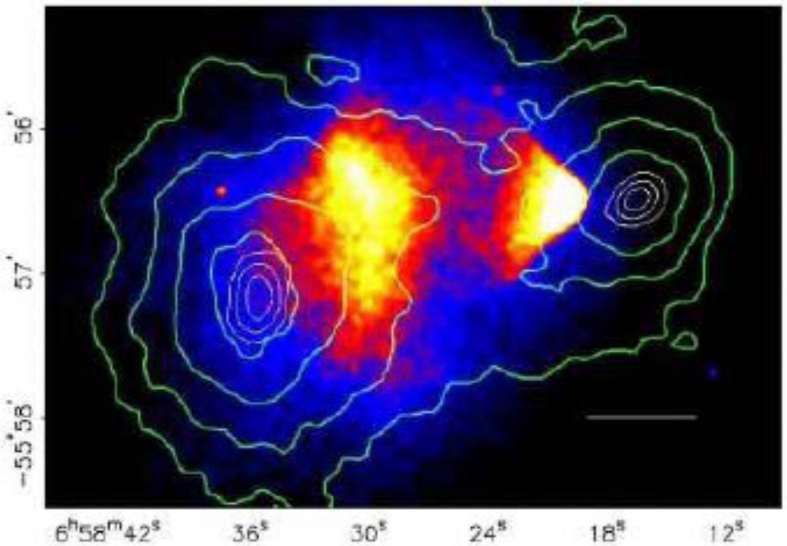
Bullet Cluster

- 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.
- Involves the observation of the distortion of light from background galaxies by the cluster's gravity -- the greater the distortion, the more massive the cluster (lensing).
- Two small clumps of luminous matter slowed down by the collision (interactions)
- Two large clumps of collisionless matter (not slowed down by the collision) – dark matter

Bullet cluster

- Total mass peak offset from X-ray peak (hot gas that forms most of baryonic mass) by 8 σ
- Most of mass in form of collisionless DM





Cosmic microwave background

and total amount of dark matter in the universe

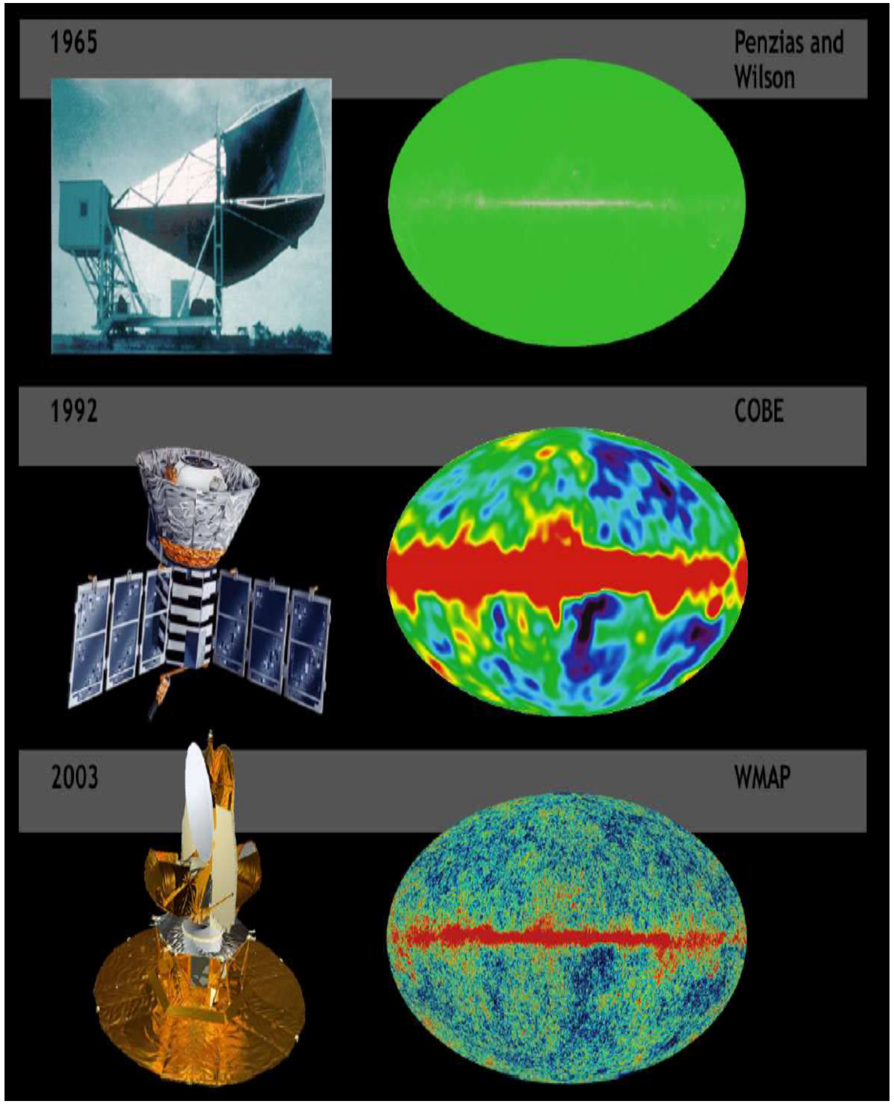
Background radiation originating from propagation of photons in early universe (once they decoupled from matter) predicted by Gamow in 1948

Discovered Penzias&Wilson 1965

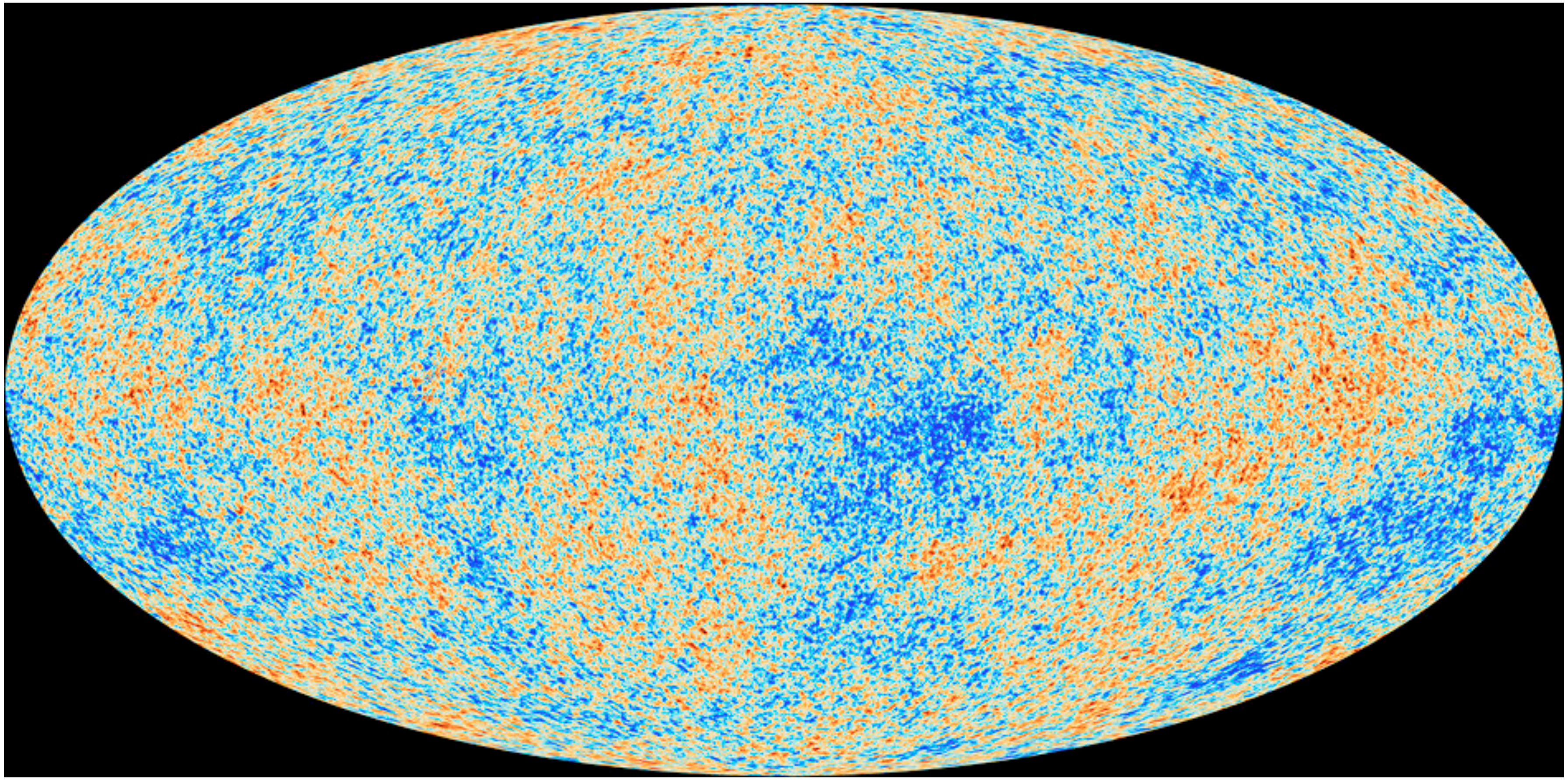
CMB is isotropic at 10^{-5} level and follows spectrum of a blackbody with T=2.726K

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



The Universe by PLANCK (ESA)



Density fluctuations

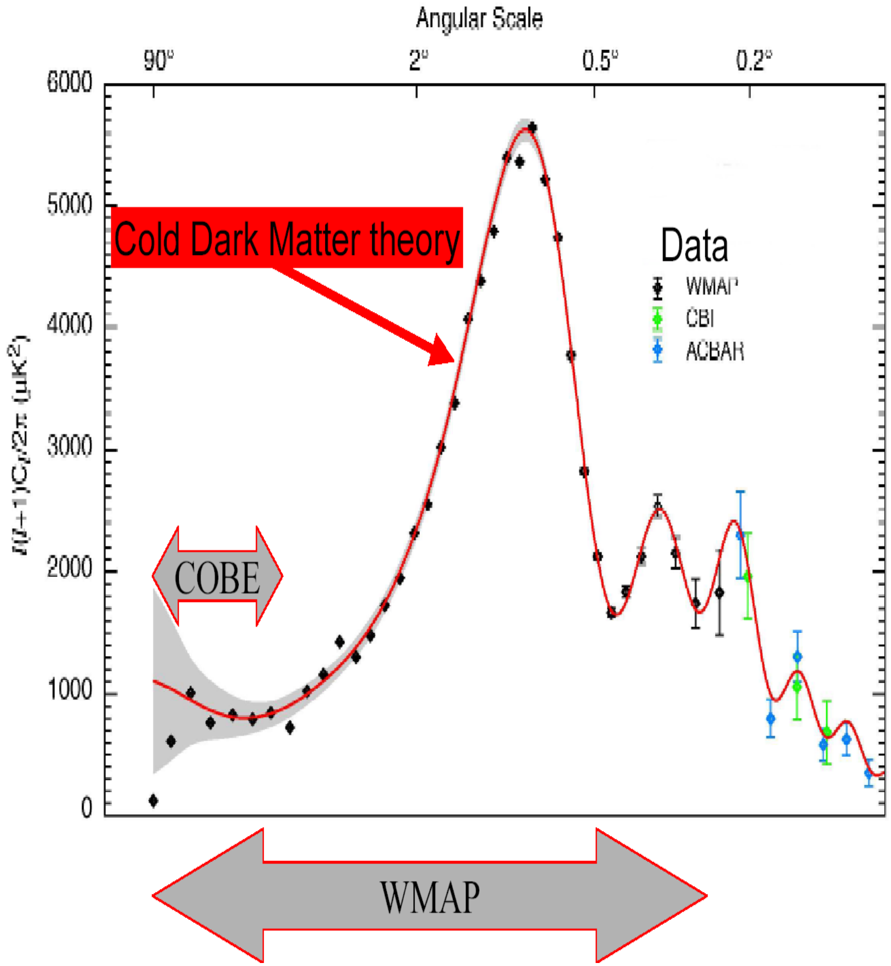
- Small anisotropy observed in sky

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

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

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

- To extract information from CMB anisotropy maps. Start from cosmological model with small number of parameters and find best fit



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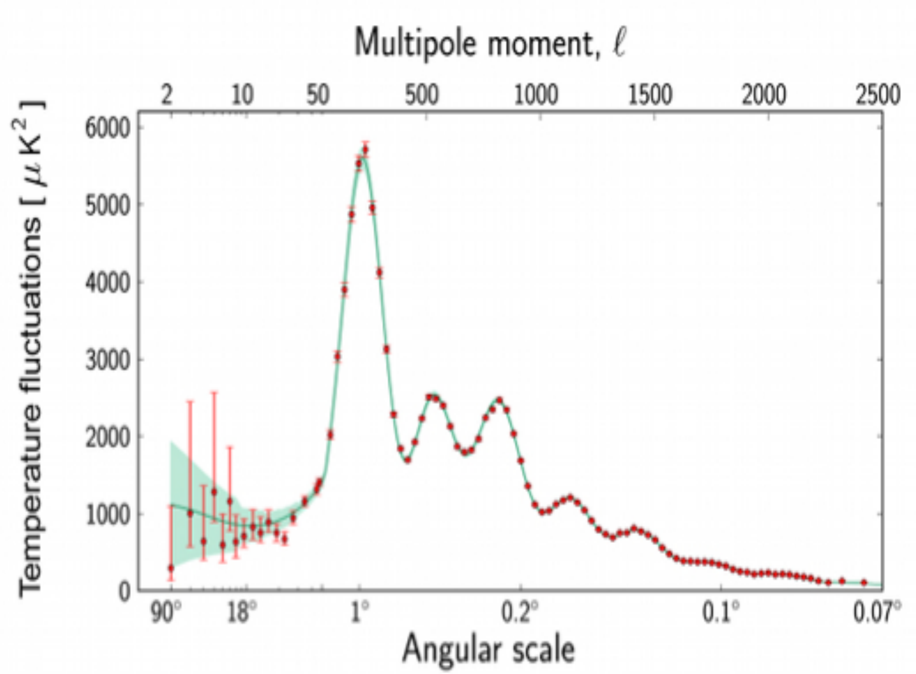


PLANCK 2013

Cosmological model

- Cosmological model parameters ΛCDM

$$\Omega_m, \Omega_b, \Omega_\Lambda, \Omega_r, \Omega_\nu, \Delta^2_R, n \quad \tau, H$$

Hubble parameter

Density perturbations (how the universe deviates from homogeneity)

Ionization optical depth : Related to probability that a given photon scatters once

- Universe is flat when no cosmological constant and energy density is critical density

$$\rho_{crit} = \frac{3H^2}{8\pi G_N}$$

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}$$

- $\Omega_i = \rho_i/\rho_c$ $\Omega_M = \rho_M/\rho_c$ $\Omega_\Lambda = \Lambda/3H^2$
- $\Omega_M = \Omega_B + \Omega_{cdm} + \Omega_\nu$

Parameter	*Planck* Best fit	*Planck* 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020
σ_8	0.8344	0.834 ± 0.027
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$
H_0	67.11	67.4 ± 1.4

PLANCK, A&A 2013
arXiv:1303.5076

- Large dark energy component (assume to be cosmological constant)
- Precise evaluation of dark matter component
- Baryon density in agreement with BBN (.019-.024)

- In supernovae: relation between observed flux and intrinsic luminosity of an object which depends on the distance

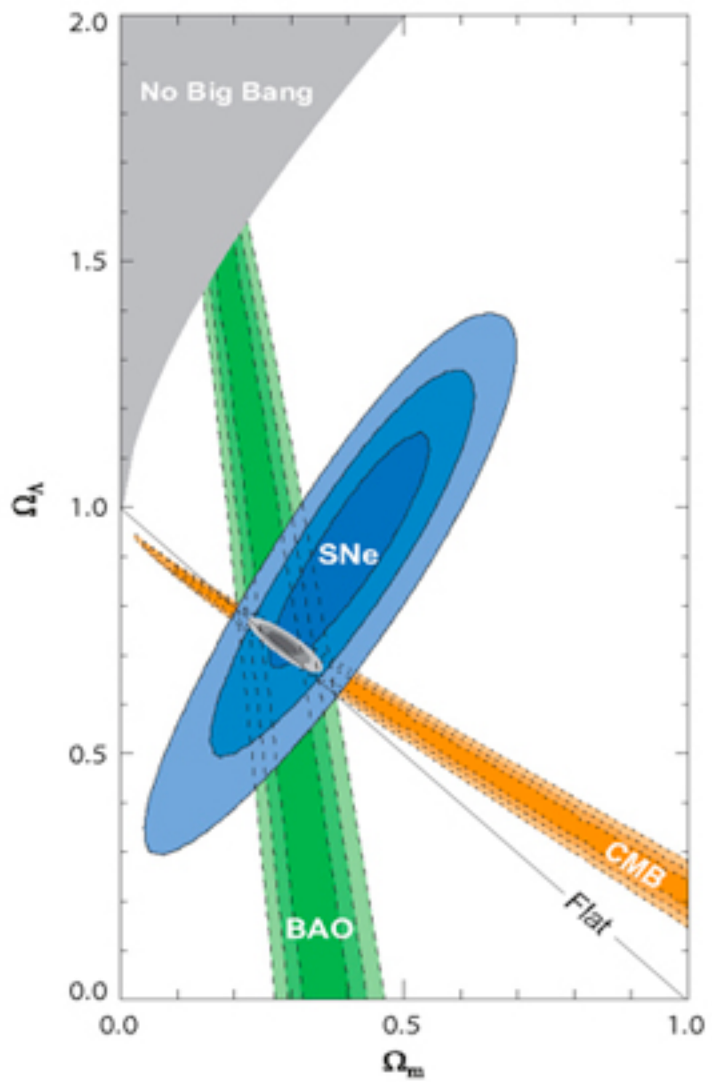
$$D_L = (1+z) r_e(z)$$

- z: redshift

$r_e(z)$ depend on the cosmological parameters Ω_m , Ω_Λ

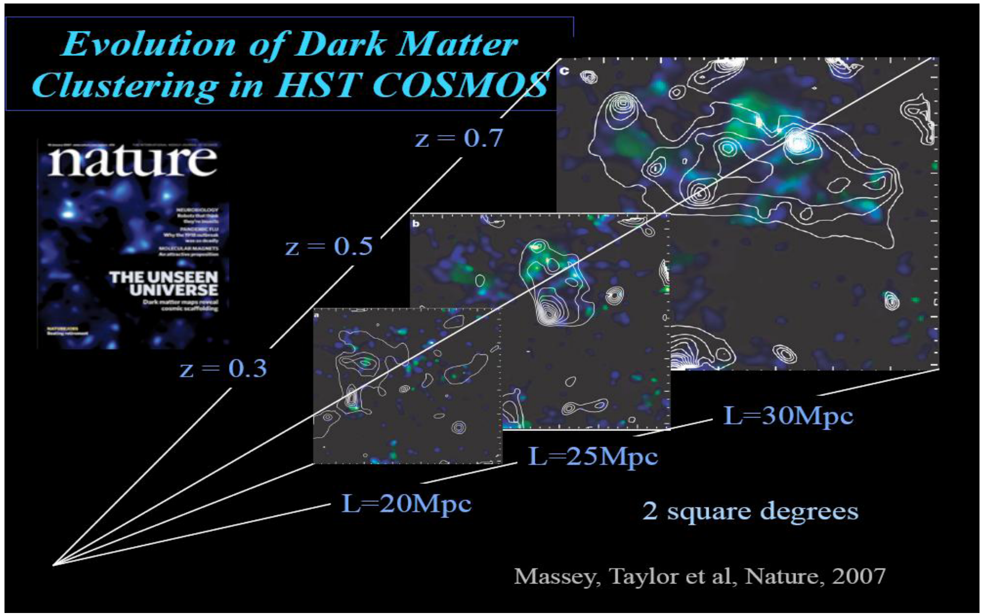
Observations of supernovae at large redshift constrain a combination of Ω_m , Ω_Λ nearly orthogonal to the one of WMAP

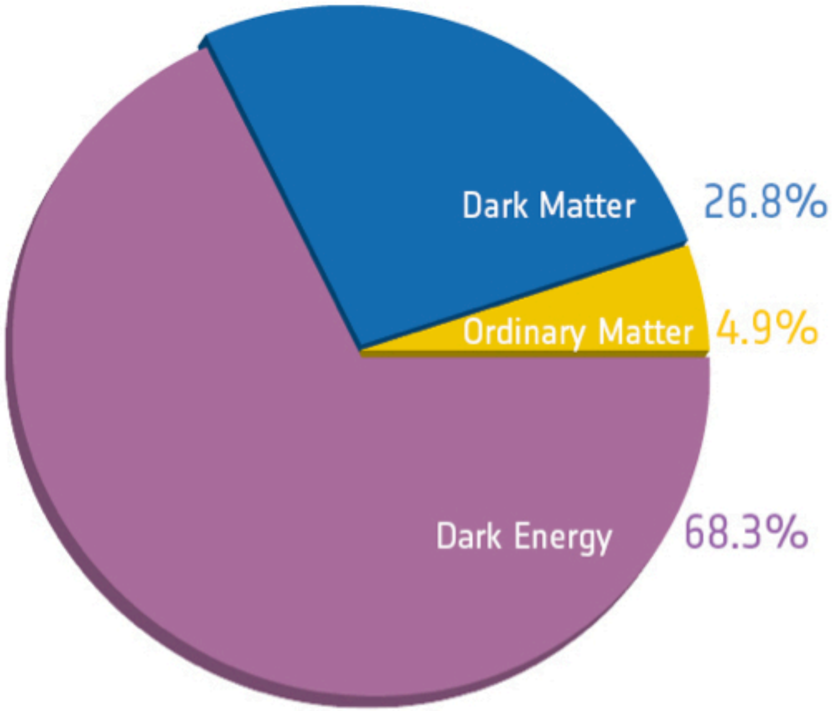
- Measurement of matter density is also obtained by measurements of clusters of galaxies e.g Sloan Digital Sky Survey (SDSS)



Dark matter

- At different scales evidence for dark matter
- Baryons form a small component of matter as shown from CMB and BBN
- CMB gives precise estimate of amount of dark matter
- Galaxy formation provide further evidence that dark matter exists





Universe is made of 27% cold dark matter. Can it be a new particle?

RELIC DENSITY OF WIMPS

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

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

- 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

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

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

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 $\chi\chi$) particles 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 $T_{FO}\sim m/20$

Relic density of wimps

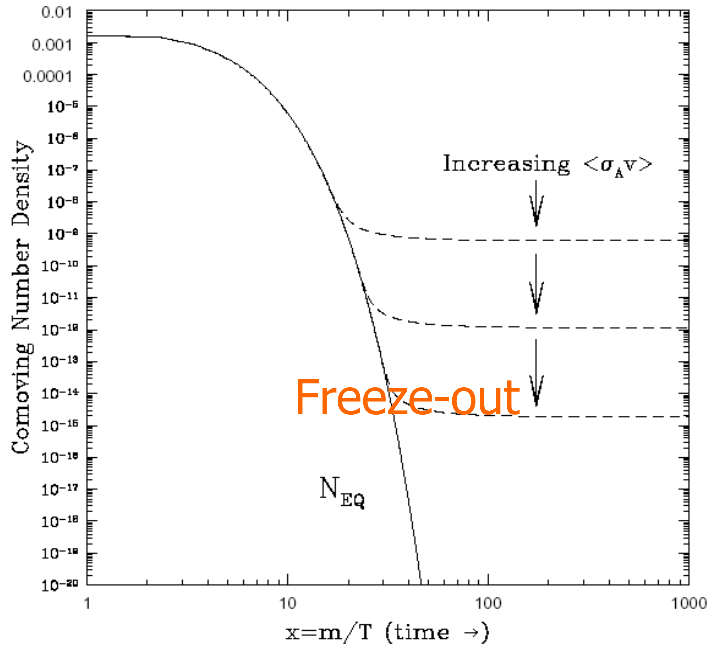
In early universe WIMPs are present in large number and they are in thermal equilibrium

As the universe expanded and cooled their density is reduced through pair annihilation

Eventually density is too low for annihilation process to keep up with expansion rate

Freeze-out temperature

LSP decouples from standard model particles, density depends only on expansion rate of the universe



$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

Dark matter: a WIMP?

In standard scenario, relic abundance

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

Depends only on effective annihilation cross section – calculable in specific particle physics model

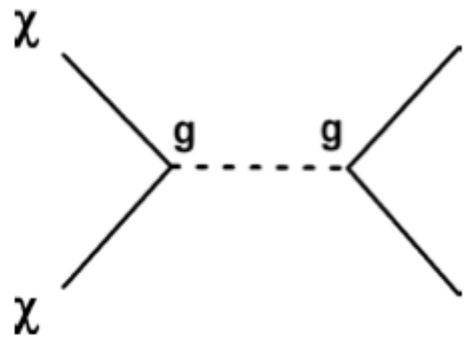
A WIMP has 'typical' annihilation cross section for $\Omega h^2 \sim 0.1$ (WMAP)

With WMAP cosmology has entered precision era, can quantify amount of dark matter. PLANCK satellite launched in 2010 will go one step further. This strongly constrain some of the proposed solutions for cold dark matter

Has motivated many direct/indirect searches for dark matter

WIMPS

- This value of the cross section is typical of weak interaction process → weakly interacting particle will give naturally the correct amount of dark matter to explain the measured relic density



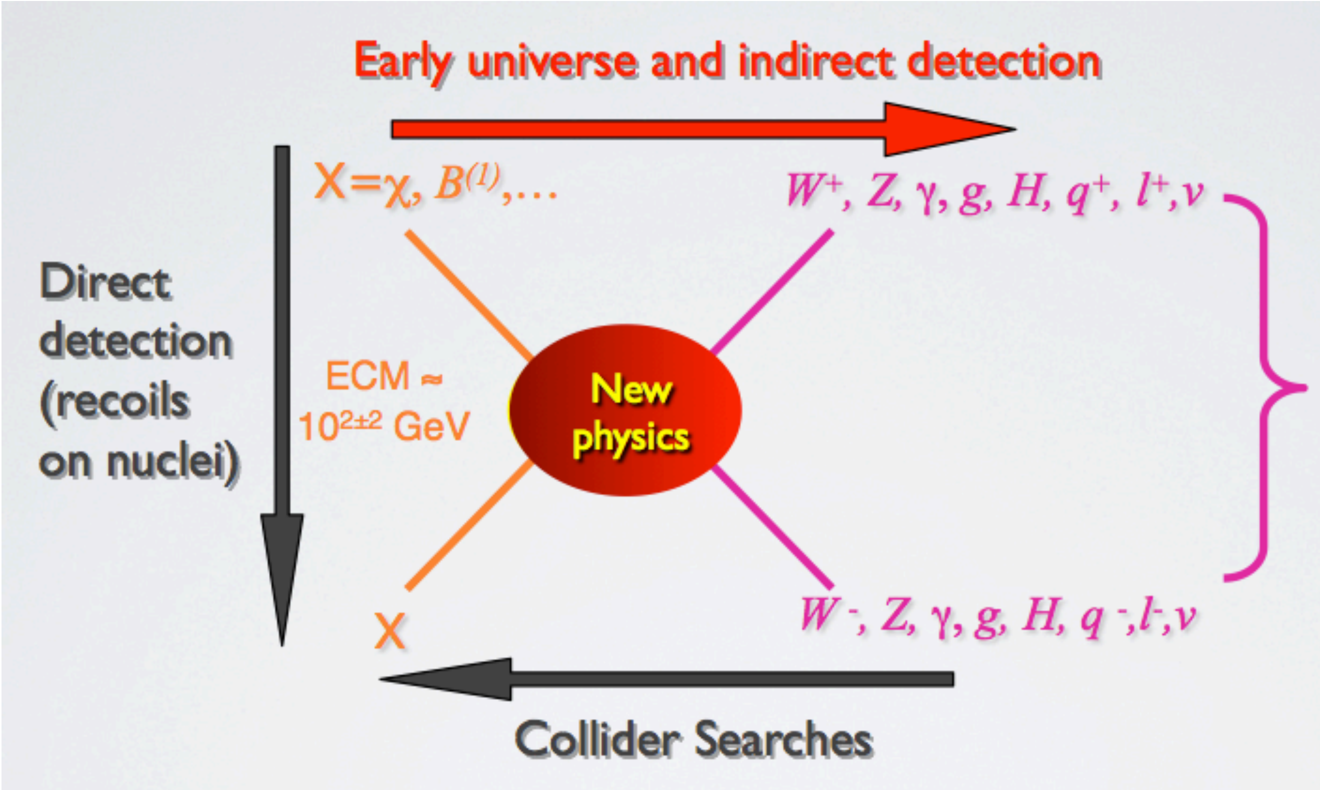
$$< \sigma v > \sim \frac{g^4}{32\pi m_{DM}^2}$$

- With g~0.2 (weak : g~0.6) m~100GeV $\sigma v = 1.6 \times 10^{-9}\ \mathrm{GeV}^{-2}$
- $\sigma v = 1.6\ 10^{-9}\ \mathrm{GeV}^{-2} \times (.389\ \mathrm{GeV}^2\ \mathrm{mb})\ (10^{-27}\ \mathrm{cm}^2/\mathrm{mb})\ 3 \times 10^{10}\mathrm{cm/s}$ =
  = $2\ 10^{-26}\mathrm{cm}^3/\mathrm{s}$ → $\Omega \sim .1$

Constraints on WIMPs

- Must reproduce the measured relic density assuming standard cosmological model
- Limits from astroparticle searches
  - Direct detection (LUX, CDMS, Xenon, Cresst, DAMIC, DAMA….)
  - Indirect detection (FermiLAT, HESS, Magic, AMS …) in particular with photons, positrons, antiprotons etc..
- hints in astroparticle searches
  - DAMA/CoGenT, CDMS-SI, Fermi-LAT Galactic Center, PAMELA, AMS02
- Collider constraints (model dependent – stability at collider scale only)

Probing the nature of dark matter



- All determined by interactions of WIMPS with Standard Model
- Specified within given particle physics model
- Collider : need trigger or decay of other particles

Direct detection

Eastic scattering of WIMPs off nuclei in a large detector

Measure nuclear recoil energy, E_R

Best way to prove that WIMPs form DM

Small transfer momentum – typically 100MeV

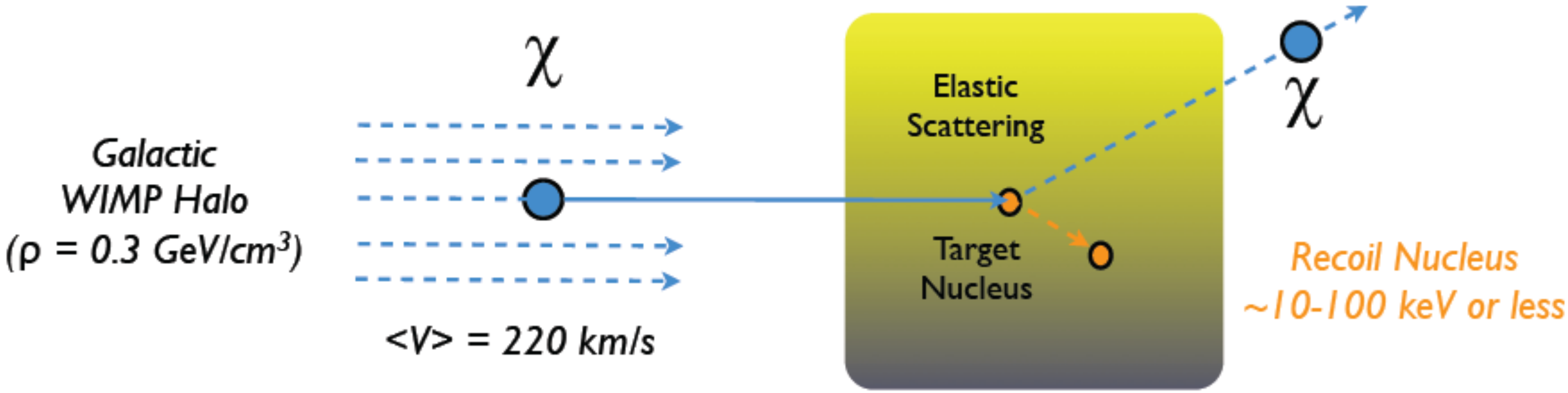
$E_R = q^2/2m_N$ q: transfer momentum

$E_R = \mu^2 v^2(1-\cos\theta)/m_N$

$\mu = m_\chi m_N/(m_\chi + m_N)$: reduced mass

100GeV WIMP, v=220km/s → $E_R < 27$keV

Direct detection



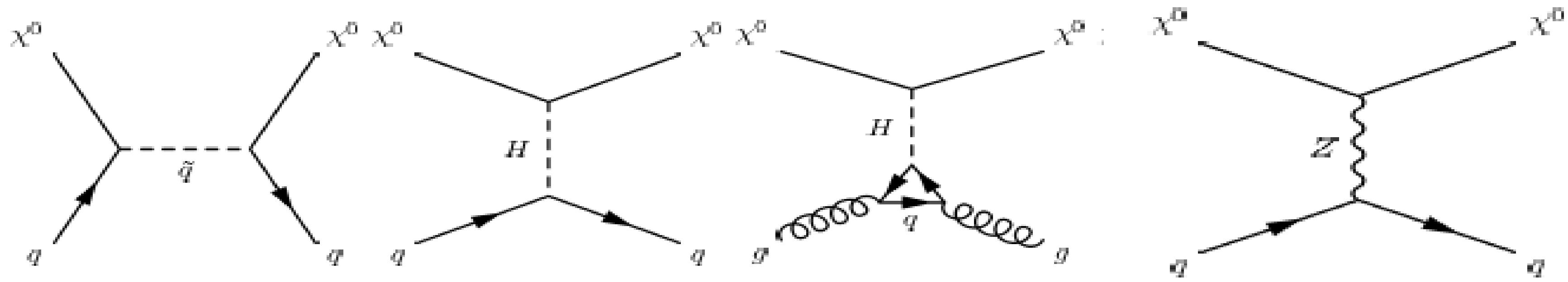
Two types of scattering

- Coherent scattering on A nucleons in nucleus, for spin independent interactions
  - Dominant for heavy nuclei
- Spin dependent int – only one unpaired nucleon
  - Dominant for light nuclei

Direct detection

- Particle physics : effective Lagrangian for WIMP-nucleon amplitude *at small momentum transfer (~100MeV)*
- For spin independent (Majorana fermion)

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



For Dirac fermions Z exchange contributes to SI and SD

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

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

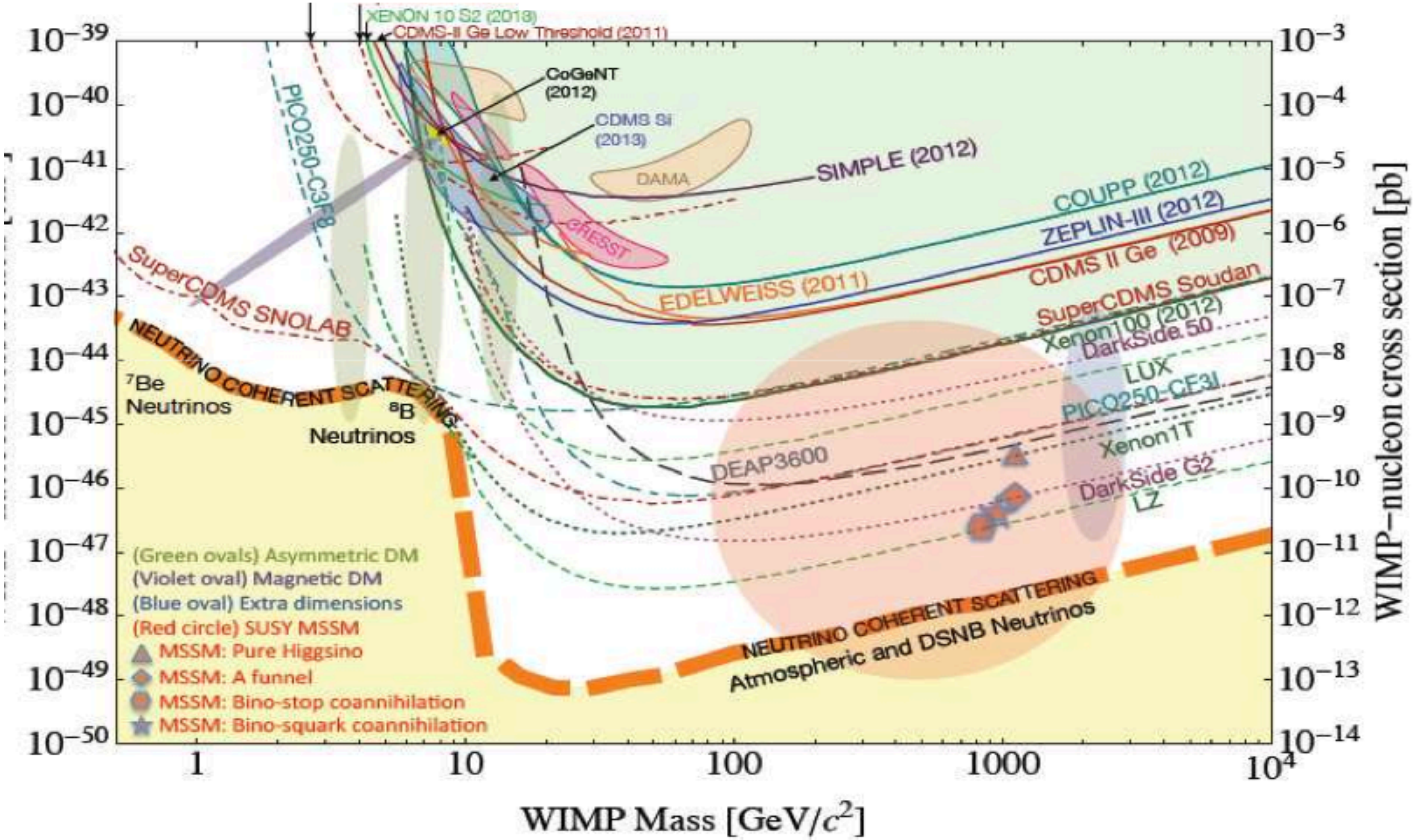
$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

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

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

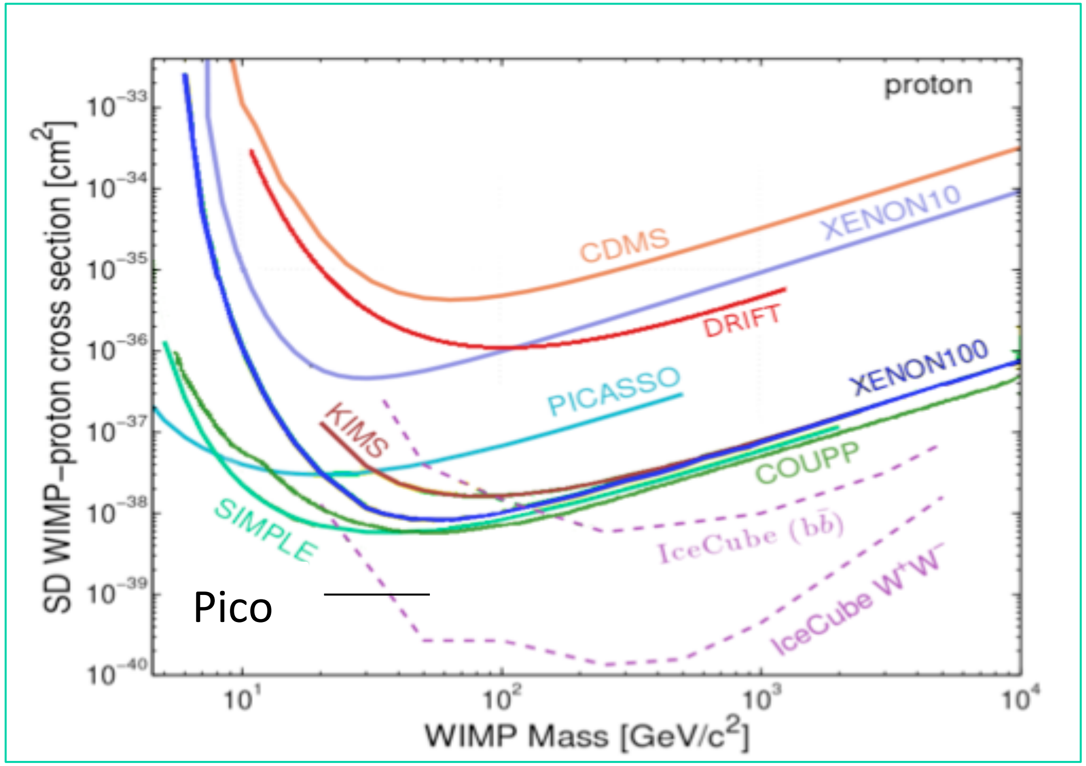
Spin independent results

Best limit : LUX , Akerib et al, arXiv:1310.8214



Limits spin dependent

Pico: 1503.00008

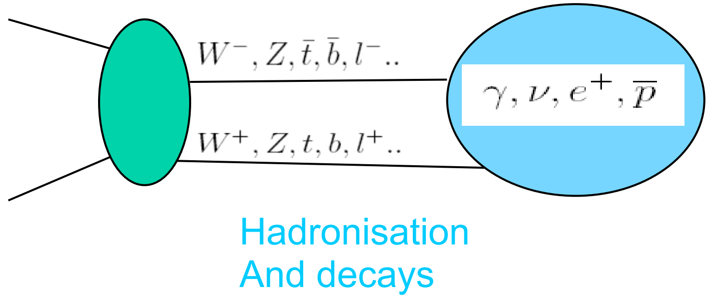


Cross sections probed are much larger than for SI

Just reaching the sensitivity to probe more popular DM model (MSSM)

Indirect detection

Annihilation of pairs of DM particles into SM : decay products observed



Searches for DM in 4 channels

- Antiprotons and Positrons from galactic halo/center
- Photons from GC/Dwarfs
- Neutrinos from Sun/GC

Rate for production of e^+,p,γ

- Dependence on the DM distribution (ρ) – not well known in center of galaxy
- Dependence on propagation

$$Q(x, \mathbf{E}) = \frac{<\sigma v>}{2}\left(\frac{\rho(\mathbf{x})}{m_\chi}\right)^2 \frac{dN}{dE}$$

Typical annihilation cross section

$$<\sigma v> = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

Indirect Detection

At freeze-out -> $$\langle \sigma v \rangle \approx 3 \times 10^{-26}$$

In galaxy where v->0.001c , σv can be different than at "freeze-out"

$$\sigma v = a + b v^2$$

σv(0) < σv(FO) if b dominates (e.g. in MSSM)

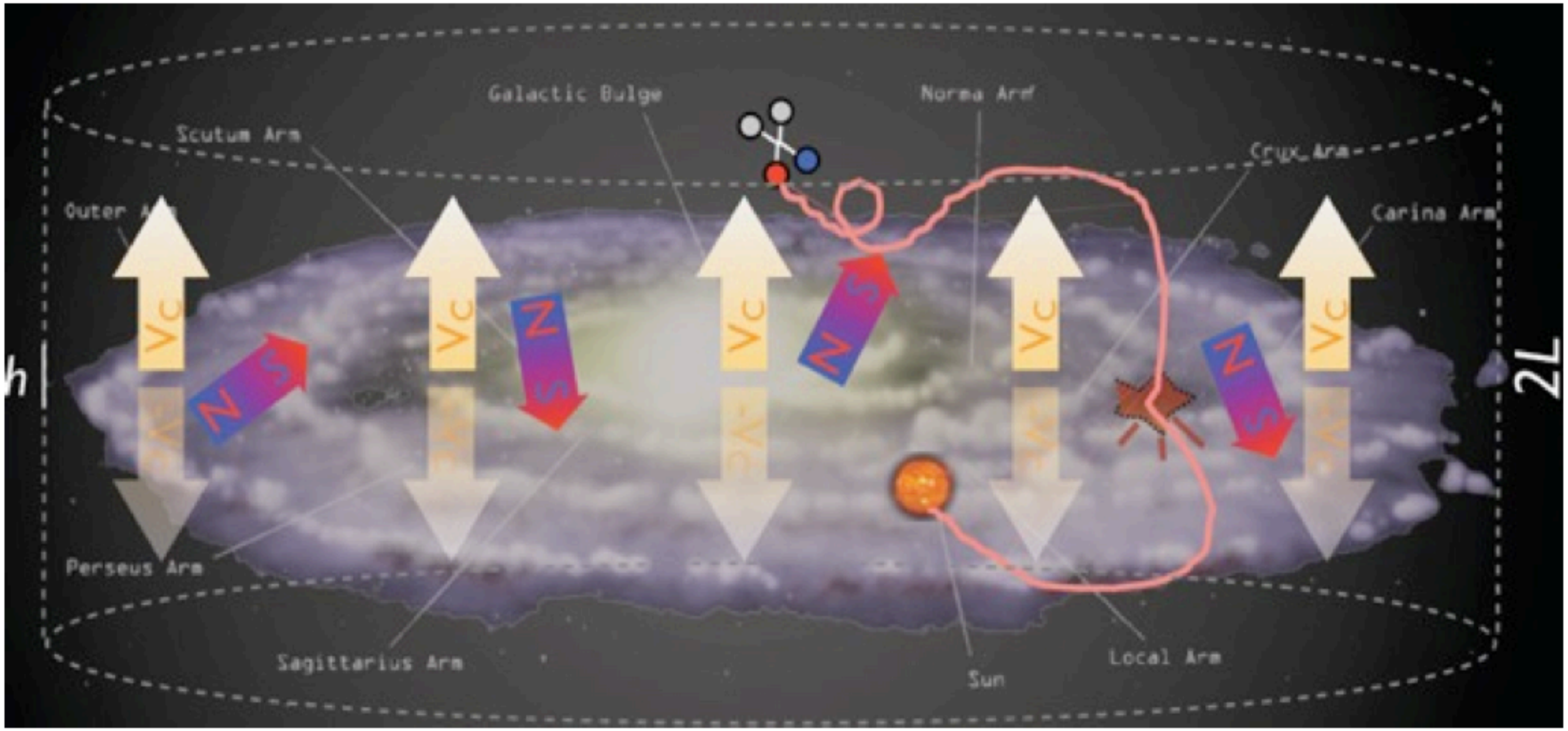
Also suppressed cross section if coannihilation dominant

Can have strong increase

- Sommerfeld enhancement (1/v term)
- Near resonance annihilation
- (strong enhancement at v->0 for Gamma,Delta<1)

$$v\sigma(v) \propto \frac{1}{(s-m_A^2)^2+\Gamma_A^2 m_A^2} = \frac{1}{16m_\chi^4}\frac{1}{(v^2/4+\Delta)^2+\Gamma_A^2(1-\Delta)/4m_\chi^2}$$

Propagation

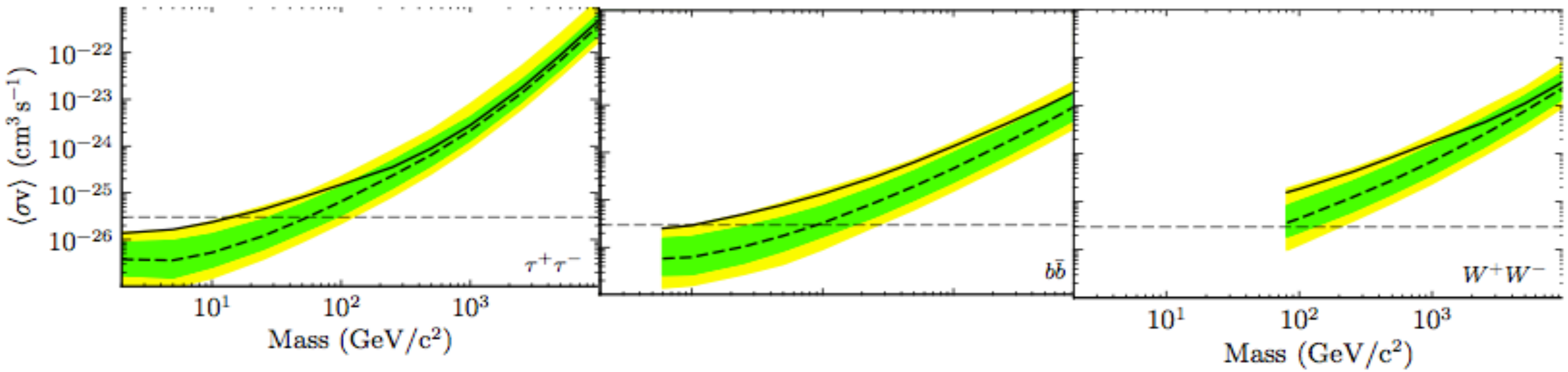


$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x},E)\,\nabla N] - \frac{\partial}{\partial E}[b(E)\,N] = q(\mathbf{x},E)$$

Source

Results - photons

- For light dark matter, FermiLAT probes cross sections expected of a thermal relic with photons from dwarf Spheroidal galaxies

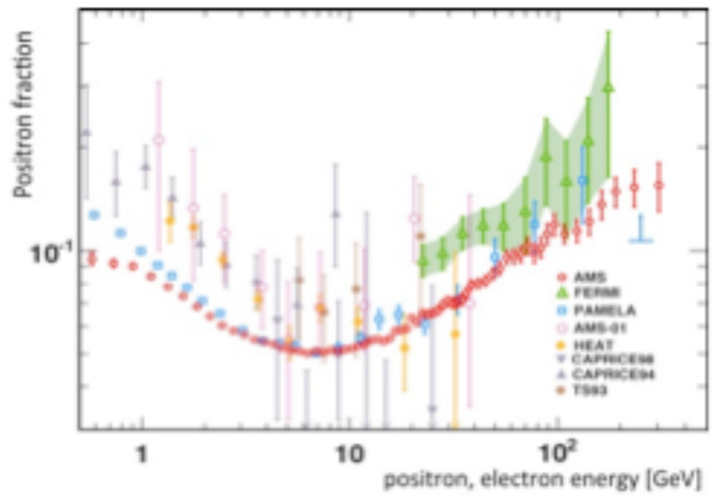


- Evidence of a gamma-ray line (from DM annihilation into two-photons) for m=130GeV weakening

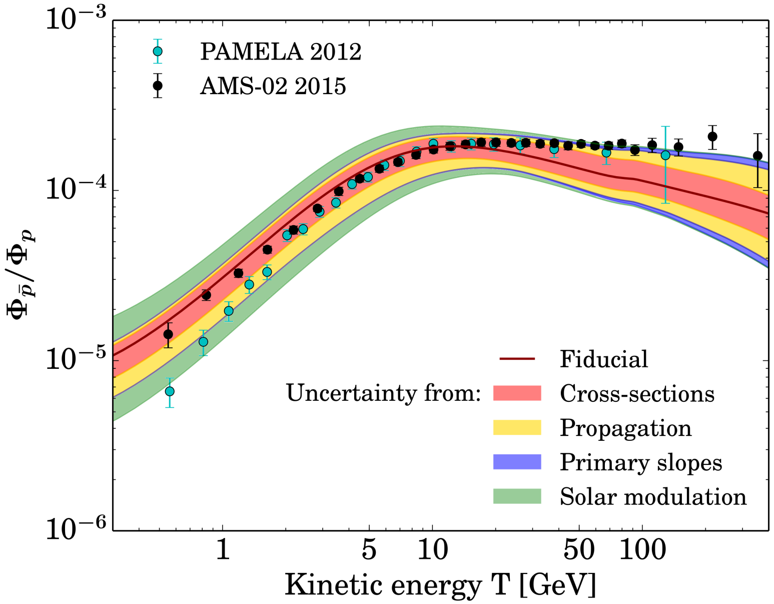
- Excess gamma-ray from 7^{o}X7^o region around the GC
- Compatible with DM of 30 GeV annihilating in bb
  - Hooper, Goodenough, PLB697(2011)

Results

- Large excess in positron fraction (from PAMELA and AMS)
- No excess in antiprotons (PAMELA)
- AMS compatible with background



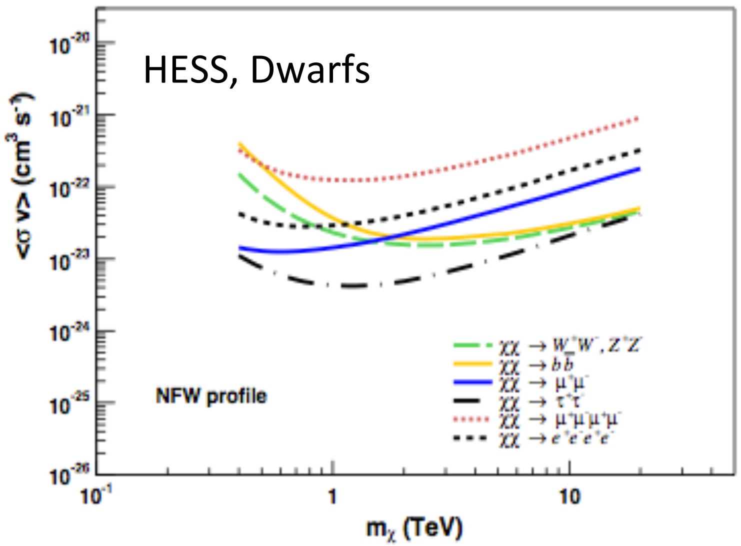
AMS, PRL113.121101



G.Gliesen et al, 1504.04276

Positron fraction excess

- Can this be DM?
- Model-independent approach
- For any channel large cross sections are required, 10^{-23} -10^{-21}cm^3/s
- With better measured total lepton flux from AMS02 – not possible to obtain good fit for pure leptophilic DM
- Large cross sections in tension with IceCube, photons, antiprotons
- Pulsars could be explanation



Abramowski et al, 1410.2589

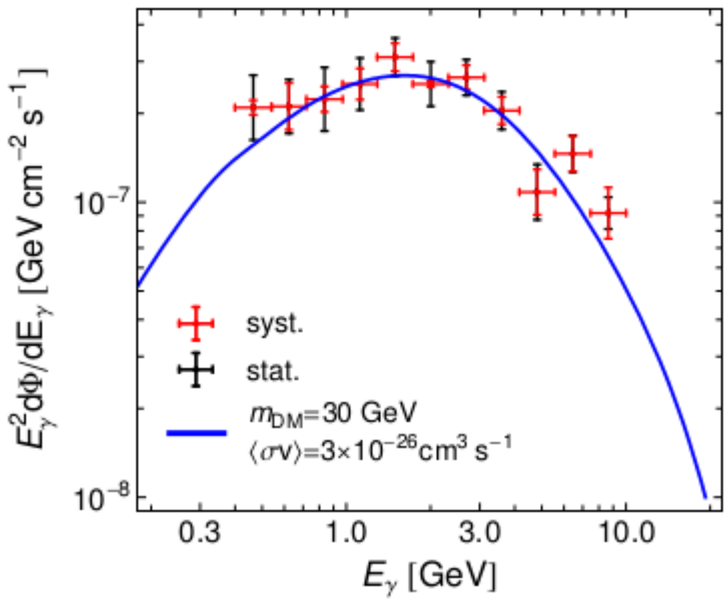
Final remarks

- Dark matter : no conclusive evidence from astroparticle, some constraints on particle physics from photon detectors
- Direct detection searches continue with more sensitive detectors -> constraints on physics beyond standard model
- WIMPs are not the only possibility : testable hypothesis at colliders
- Model that satisfies upper limit on relic density -> consistent but no explanation for dark matter
- Model that propose solution to hierarchy problem + dark matter : very attractive and testable at LHC : these two problems might be unrelated

The end

Gamma-ray excess

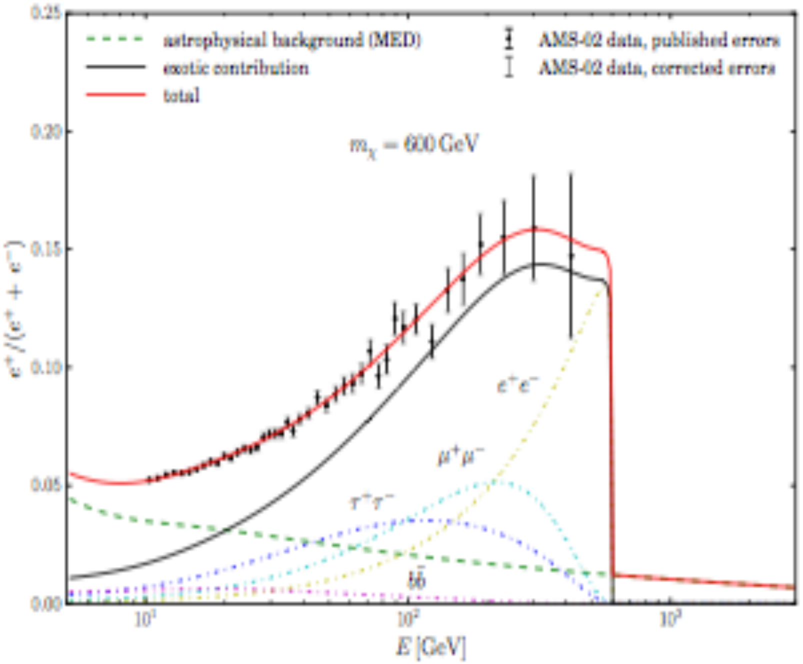
- Fermi-LAT : gamma-ray excess from 7°X7° region around the GC
  - Hooper, Goodenough, PLB697(2011)
- Compatible with DM of 30 GeV annihilating in bb
- Simple model compatible with this and no other signal (only constraint from antiproton Cirelli et al 1407.2173) :
  - Dirac fermion coupled to pseudoscalar(coupling proportional to mass)
  - Few constraints on pseudoscalar (even at LHC13)



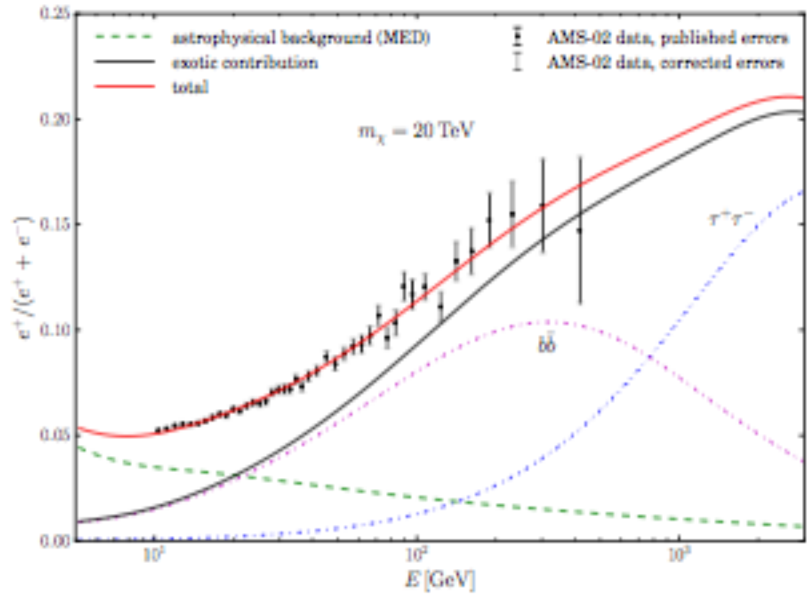
C. Boehm et al 1401.6458

Positron fraction excess

1.1 10^{-23} cm^3/s



1.1 10^{-21} cm^3/s



- Mixed channels : good fit for any mass 0.5-40TeV
- Cross sections are very large