Seeing the invisible: the mystery of Dark Matter

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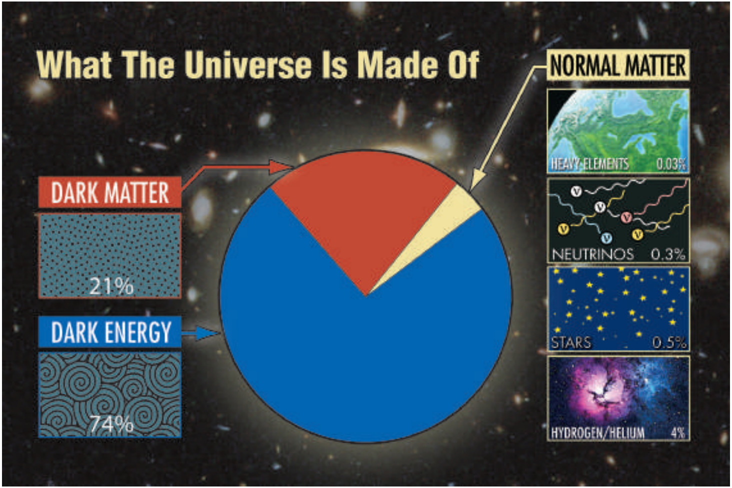
Overview

The energy budget of the Universe



Evidence for Dark Matter - Cluster scales

- 1933: Fritz Zwicky estimates mass of Coma Cluster from velocity dispersion
- Virial Theorem:
  $U \sim K \implies M \sim \frac{\sigma^2 R}{G}$
- Luminous mass not sufficient ("dunkle materie")
- ...but his work was essentially ignored for 40 years!

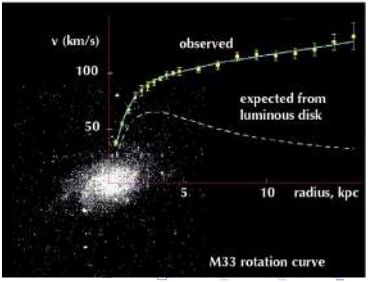
Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln",

Helv. Phys. Acta 6 (1993) 110-127

Evidence for Dark Matter - Galactic scales

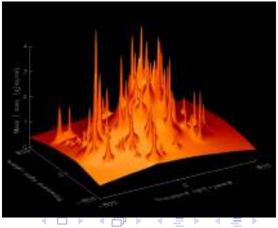
- 1970: Vera Rubin measures galactic rotation curves
- Flat at large radii, far beyond range of luminous matter!
- Expected from Keplerian motion: $v \propto \frac{1}{\sqrt{r}}$
- Requires presence of dark matter halo, far more extended than observed stellar disk

Rubin, Ford, “Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions”, ApJ 159 (1970) 379-403



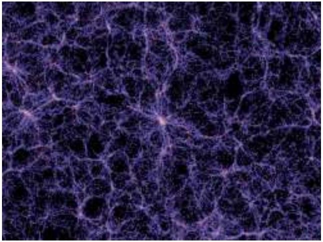
Evidence for Dark Matter - Gravitational lensing

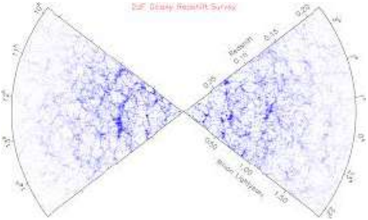
- Strong lensing: easily visible distortions (Einstein rings, arcs, multiple images)
- Weak lensing: small effect, elliptical distortions
- Microlensing $\implies$ fraction of DM in compact objects $< 10\%$
- $\rho_{\text{DM,local}} \approx 0.3 \ \frac{\text{GeV}}{\text{cm}^3}$



Evidence for Dark Matter - Large Scale Structure

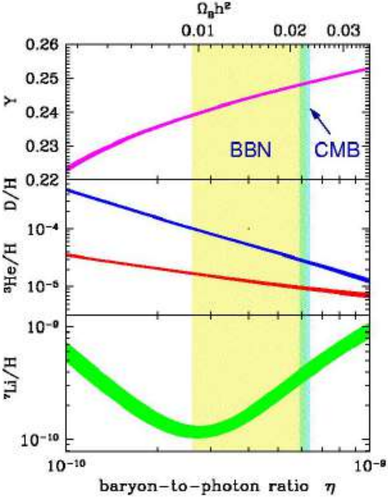
- N-body simulations: a substantial amount of “cold” DM is required to form the observed LSS
- $\delta_{\text{CMB}} \sim 10^{-5} \implies \delta_{\text{today}} \sim \delta_{\text{CMB}} z_{\text{CMB}} \sim 10^{-2}$ (c.f. actual overdensity in LSS, $\sim 10^2$)
- Power spectrum depends on the amount of matter (baryons + DM)
- Large scale surveys (e.g. 2dFGRS, SDSS) indicate $\Omega_m \approx 0.29$





Evidence for Dark Matter - Big Bang Nucleosynthesis

- When $T \sim 1$ MeV, protons and neutrons fuse to Helium
- Helium fraction (Y_p) heavily dependent on baryon-to-photon ratio (η), weakly dependent on total amount of matter (baryons + DM)
- $\eta \propto \Omega_b h^2$
- Observations infer $\Omega_b \approx 0.04$
- DM **must** be non-baryonic!

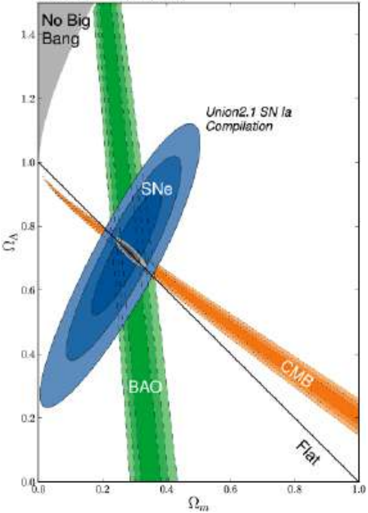


Evidence for Dark Matter - Concordance cosmology

- CMB acoustic peaks
- CMB anisotropy spectrum sensitive to physics affecting the baryon-photon acoustic oscillations
- $\Omega_{\mathrm{DM}} h^2 = 0.1197 \pm 0.0022$

  Planck 2015, XIII, [arXiv: 1502.01589]
- Excellent agreement with BBN: $\Omega_{\mathrm{b,CMB}} h^2 = 0.02222 \pm 0.00023$, $\Omega_{\mathrm{b,BBN}} h^2 = 0.0214 \pm 0.0020$
- The fit is so amazing that you could remove any one dataset and would still infer the same cosmology!

Supernova Cosmology Project
Suzuki, et al., Ap.J. (2011)



Dark Matter candidates - A ten-point test

- Correct relic density?
- Cold?
- Neutral?
- Consistent with BBN?
- Leaves stellar evolution unchanged?

Taoso, Masiero, Bertone, 2007

- Compatible with self-interaction constraints?
- Consistent with direct DM searches?
- Compatible with γ-ray constraints?
- Compatible with other astrophysical bounds?
- Can be probed experimentally?

Leading paradigm: ΛCDM. Cold, collisionless, non-interacting DM around spiral galaxies is in the form of a roughly spherical halo, much more extended than the luminous matter and responsible for the flat rotation curves.

ΛCDM - Problems on small scales

Simulations of collisionless, cold, dissipationless DM agree perfectly with observations on large scales but are problematic on small scales ($< \mathrm{Mpc}$)

- "*Core vs cusp problem*": N-body simulations predict a cuspy profile (NFW profile). Observations suggest a core? de Blok, 2009
- "*Missing satellite problem*": N-body simulations predict too much substructure (read; dwarf galaxies) Klypin, Kravtsov, Valenzuela, Prada, 1999
- "*Too-big-to-fail problem*": N-body simulations predict too dense subhalos which are not observed. Springel et al., 2008

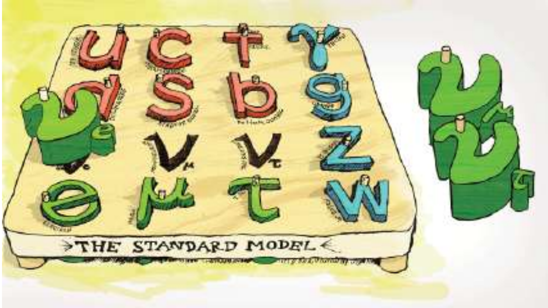
Problems could be alleviated by self-interacting DM (SIDM)? Need a mean free path $\sim \mathcal{O}(\mathrm{kpc} - \mathrm{Mpc})$, with cross-section Spergel, Steinhardt, 1999

$$\sigma_\chi = 8.1 \times 10^{-25} \left(\frac{m_\chi}{\mathrm{GeV}} \right) \left(\frac{\lambda}{\mathrm{Mpc}} \right)^{-1}$$

Or discrepancies are simply due to baryonic effects?

The Standard Model - any Dark Matter candidate?

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + \bar{\psi}_i\mathcal{Y}_{ij}\psi_j + |D_{\mu}\phi|^2 - V(\phi)$$



The Standard Model has one potential DM candidate: the neutrino...

The Standard Model - no Dark Matter candidates!

...which, unfortunately, does not work!

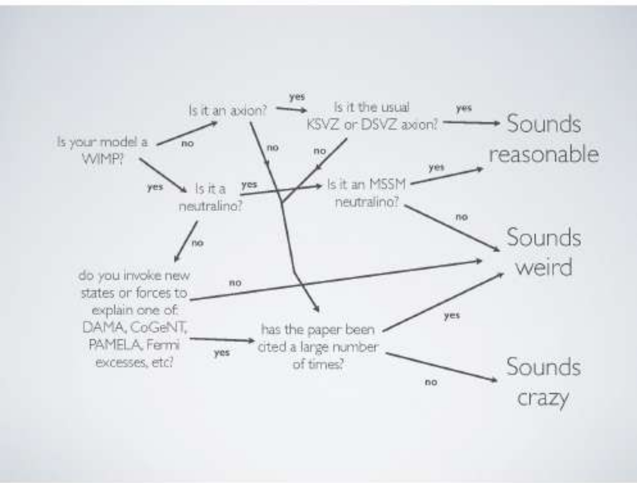
- Neutrinos simply do not make up enough mass in the Universe

  $$\Omega_\nu \approx \frac{\Sigma_i m_{\nu,i}}{46 \text{ eV}} < 0.02$$

  given bounds on the sum of neutrino masses $\Sigma_i m_{\nu,i} < 0.7 \text{ eV}$
- Neutrinos are "hot" DM, suppress structure formation below their free-streaming scale
- The Standard Model has no Dark Matter candidates. This alone is evidence for new physics!

Dark Matter candidates - The good, the bad, the ugly

Luckily (or unluckily) for us, there is no shortage of DM candidates...



Courtesy: Neal Weiner, DM@LHC 2014

Dark Matter candidates - A huge zoo

...there's actually a whole zoo of them!

Kusenko, Rosenberg, C 13-07-29.2, arXiv: 1310.8642

Dark Matter candidates - MACHOs (which do not work)

- Massive Astrophysical Compact Halo Object Paczynski, 1986
- Very dim astrophysical objects, composed of baryonic matter (red dwarfs, white dwarfs, brown dwarfs, black holes, neutron stars, isolated planets, etc.)
- Ruled out by gravitational lensing experiments ($\Omega_{\text{MACHO}} \lesssim 0.1\Omega_{\text{DM}}$)

  Alcock et al. 2000, Tisserand et al. 2007, Wyrzykowski et al. 2009
- Ruled out because non-baryonic (recall BBN and CMB) Freese et al., 1995-1999

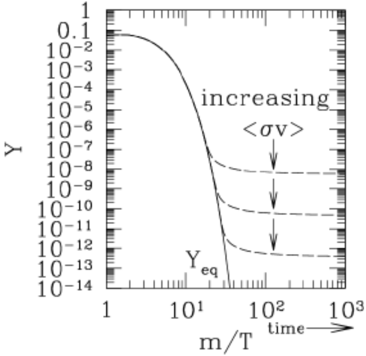
Dark Matter candidates - WIMPs (χ)

- Weakly Interacting Massive Particles
- Interact with SM fields only through the weak force
- Stability on cosmological timescales is usually achieved by making the WIMP the lightest member of a matter sector charged under a discrete symmetry (e.g. R-parity in SUSY)
- Typically acquire mass m_χ at the EWSB scale (GeV - few TeV), if members of $SU(2)_L$ multiplets and not protected by any other symmetry $\implies$ heavy enough to account for DM!
- WIMPs are **thermal relics**: produced thermally in the early Universe through chemical decoupling from the primordial plasma ($\Gamma \ll H$)
- Typically decouple at temperature $T \sim \frac{m_\chi}{20} \implies$ non-relativistic at decoupling, hence cold!

The WIMP miracle: survival of the weakest (or less sociable)

Solve the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle \sigma v \rangle (n^2_{\chi,\text{eq}} - n^2_\chi) \implies \Omega_\chi h^2 \approx 0.1 \frac{3 \times 10^{-26}\ \text{cm}^3\text{s}^{-1}}{\langle \sigma v \rangle}$$



Courtesy: Graciela Gelmini and Paolo Gondolo

Caveats to the WIMP miracle picture

- WIMP miracle roughly independent of m_χ, but:
  - Upper limit from unitarity + not overclosing the Universe: $m_\chi \lesssim 120\ \mathrm{TeV}$ Griest, Kamionkowski, 1990
  - Lower limit from not overclosing the Universe: $m_\chi \gtrsim 2\ \mathrm{GeV}$, known as "Lee-Weinberg limit" Lee, Weinberg, 1977
- Care has to be taken when solving the Boltzmann equations in the presence of
  - Coannihilations with other particles close in mass
  - Resonance annihilations (e.g. "Sommerfeld enhancement")
  - Thresholds Griest, Seckel, 1991; Profumo, TASI Lectures 2012 [arXiv: 1301.0952]
- "WIMPless" miracle: if $\frac{g'^4}{m_X^2} \sim \sigma_{\text{ew}}$ then $\Omega_\chi \approx \Omega_{\text{DM}}$! Naturally occurs in gauge-mediated SUSY breaking Feng, Kumar, 2008

Why are WIMPs so appealing?

- Naturally appear in many extensions of the SM: lightest neutralino in SUSY, gravitino in SUGRA, lightest Kaluza-Klein particle in UEDs, branons in LEDs, T-odd particles in Little Higgs
- Mechanism producing them allows for their detection (more later)
- We expect new physics at the weak scale! Hierarchy problem: why is the Higgs so light (125 GeV)? Mass of fundamental scalars not protected by any symmetry (cf. fermions [chiral symmetry], vectors [gauge symmetry]). Corrections to m_H at 1-loop:

$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi\langle H\rangle^2}(2m_W^2 + m_Z^2 + m_H^2 - 2m_t^2)$$

Why is m_H not at the GUT or Planck scale? Tuning of $(m_H)_0$ against $\delta m_H \implies$ "hierarchy problem"! Introduce new physics at $\Lambda \sim \mathrm{TeV}$ to stabilize the EW scale (technicolor, SUSY, extra dimensions,...)

Dark Matter candidates - Asymmetric Dark Matter

- Dark Matter and baryonic energy densities very similar:

  $$\Omega_{\rm DM} \simeq 5\Omega_{\rm b} \implies m_{\rm DM} n_{\rm DM} \simeq 5 m_{\rm b} n_{\rm b}$$

  $m_{\rm b} \sim \mathrm{GeV}$ (proton) comes from $\Lambda_{\rm QCD}$, $n_{\rm b}$ comes from baryogenesis, i.e. from the initial baryon asymmetry $\frac{n_{\rm b}-n_{\bar{\rm b}}}{n_s} \sim 10^{-10}$: the visible sector is asymmetrical (basically no antiparticles).
- WIMPs are symmetric (i.e. both particles and antiparticles are present) thermal relics: the similar abundance to baryons (produced non-thermally) is then just a massive coincidence!
- Asymmetric DM: baryogenesis and DM genesis are related, so that $n_{\rm DM} \sim n_{\rm b}$. If $m_{\rm DM} \sim 5\ \mathrm{GeV}$, right relic abundance
- DM is an asymmetric relic: only DM particles present today, DM antiparticles all annihilated away

Asymmetric Dark Matter - ingredients

Ingredients are the 3 Sakharov conditions

Sakharov, 1967

- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium

Courtesy: Kimmo Kainulainen

Actually, the SM possesses all the required conditions, but in too small amount: need new physics! Many implementations of baryogenesis (and DM genesis): leptogenesis, co-genesis, pangenesis, Affleck-Dine mechanism, and too many others!

Good reviews: Petraki & Volkas, Int.J.Mod.Phys. A28 (2013) 1330028, arXiv: 1305.4939; Zurek, Phys.Rept. 537 (2014), 91-121, arXiv: 1308.0338

Dark Matter candidates - The rest of the zoo

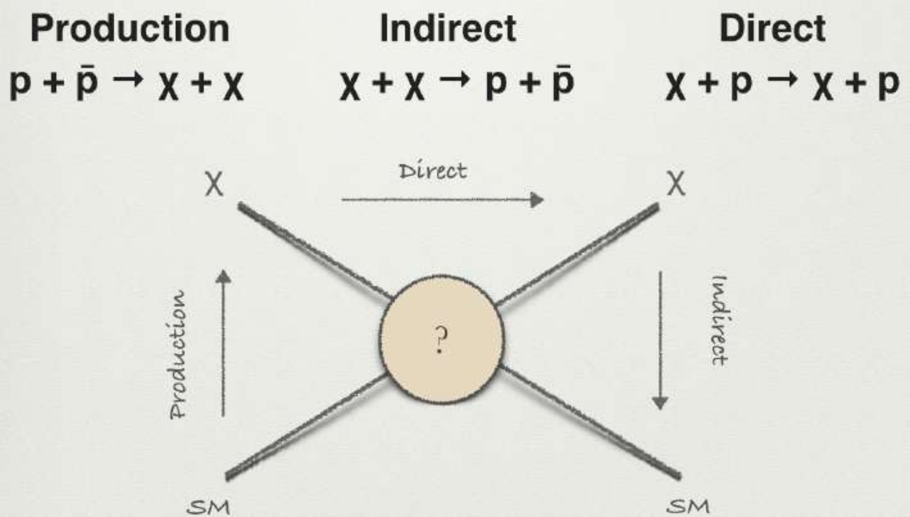
Just a laundry list, browse the arXiv to find out more!

- Axions (strong CP problem) Peccei, Quinn, 1977
- Sterile neutrinos (heavy ν_R?) Dodelson, Widrow, 1994
- Hidden sector DM (often with an $U(1)'$, e.g. mirror DM, atomic DM) Ibarra et al., 2008, Kaplan et al., 2009, Cline et al., 2012, Cyr-Racine et al., 2013, Foot & SV 2014, Pearce et al., 2014
- SuperWIMPs (late WIMP decays) Feng, Rajaraman, Takayama, 2003
- Other very exotic candidates: WIMPzillas, RAMBOs, CHAMPs, SIMPs, D-matter, cryptons, Q-balls, GUT-balls, technibaryons,...
- Non-particle DM: MOND, mimetic gravity,... Milgrom, 1983; Chamseddine, Mukhanov, 2013

Good reviews:Feng, arXiv: 1003.0904; Scott, arXiv: 1110.2757 (PhD thesis); Garrett, Duda, arXiv: 1006.2483; Bergström, arXiv: 1205.4882; Gelmini, TASI 2014 lectures [arXiv: 1502.01320]; Bertone, Hooper, Silk, arXiv: 0404175 [hep-ph]; Kusenko, Rosenberg, C 13-07-29.2, arXiv: 1310.8642

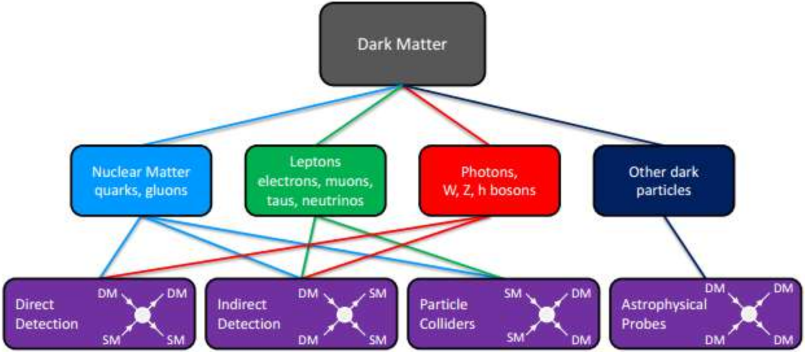
Dark Matter searches - Overview

At least in the case of WIMPs, the same mechanism that produces them allows for us to search them, by exploiting crossing symmetry



Dark Matter searches - Overview

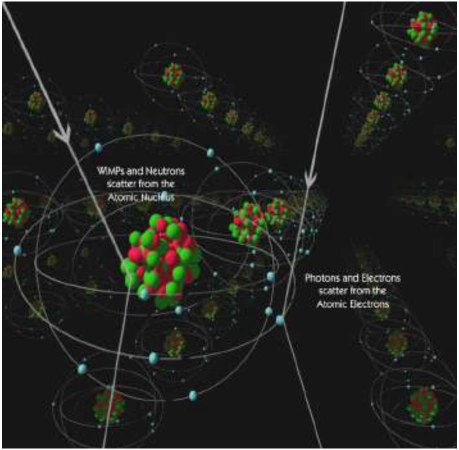
A broader view



Dark Matter searches - Direct Detection

Principle: place a large detector underground, minimize the background, look for signatures of halo DM recoiling off nucleus Goodman, Witten, 1985

Three main signals: ionization, scintillation, vibration (phonons)



Dark Matter direct detection - Signatures

DM with mass $m \sim 100\ \mathrm{GeV}$, nucleus with mass $M \sim\ 100\mathrm{GeV}$, DM typical velocity $v \sim 10^{-3}c$. Typical recoil energy (elastic scattering)

$$E_R = \frac{2\mu^2 v^2}{M} \cos^2 \theta_{\text{lab}} \sim 10\ \mathrm{keV}$$

Counts per day per kg of detector mass per keV recoil energy

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{mM} \int_{v_{\text{min}}<v<v_{\text{esc}}} d^3v\ \frac{d\sigma}{dE_R} v f(\mathbf{v}, t)$$

$\rho_\chi \simeq 0.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}$, $v_{\text{min}} = \sqrt{\frac{2ME_R}{2\mu^2}}$, $\mu = \frac{mM}{m+M}$, $f(\mathbf{v}, t)$ DM velocity distribution, usually assumed truncated Maxwellian ("Standard Halo Model").

Look for an excess over known background. Good experiments can bring the background down to ~ 0.1 counts/kg/day/keV

Dark Matter direct detection - The particle physics

Particle physics enters in the cross-section:

$$\frac{d\sigma}{dE_R} = \sigma(E_R)\frac{M}{2\mu^2 v^2}$$

Two types of interaction cross-sections

- Spin-independent: DM couples to the nuclear density, e.g. through scalar ($\bar{\chi}\chi\bar{p}p$) or vector ($\bar{\chi}\gamma_\mu\chi\bar{p}\gamma^\mu p$) bilinears $\implies$ A^2 enhancement

$$\sigma^{SI}(E_R) = \left[Z + (A-Z)\left(\frac{f_n}{f_p}\right)\right]^2 \left(\frac{\mu^2}{\mu_p^2}\right)\sigma_{\chi p}F^2(E_R)$$

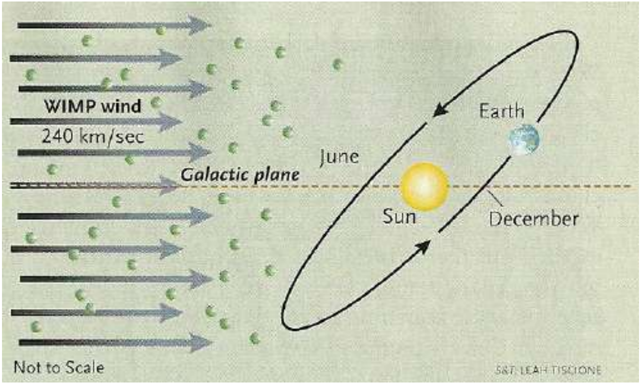
- Spin-dependent: DM couples to the nuclear spin density, e.g. through pseudoscalar ($\bar{\chi}\gamma_5\chi\bar{p}\gamma_5 p$) or pseudovector ($\bar{\chi}\gamma_\mu\gamma_5\chi\bar{p}\gamma^\mu\gamma_5 p$) bilinears

$$\sigma^{SD}(E_R) = 32\mu^2 G_F^2\frac{J_T+1}{J_T}\left[\langle S_p\rangle a_p + \langle S_n\rangle a_n\right]^2 F_{SD}^2(E_R)$$

Dark Matter direct detection - Annual modulation

An $\mathcal{O}(10\%)$ annual modulation in the count rate is expected due to the motion of the Earth around the Sun. Count rate maximum in June, minimum in December

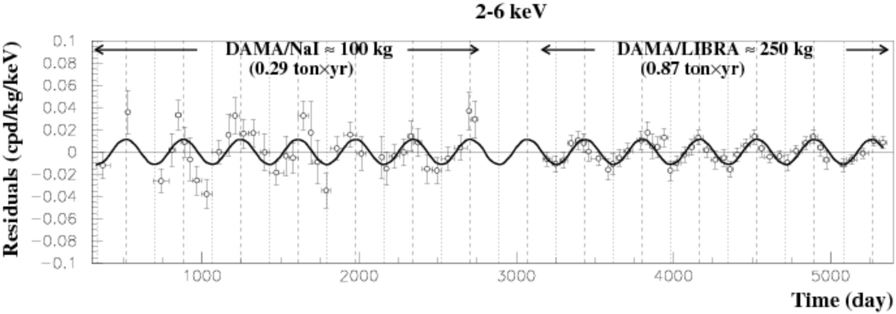
Drukier, Freese, Spergel, 1986



DAMA: a controversial claim of detection

The DAMA experiment located under the Gran Sasso claims a $\sim 9\sigma$ detection of DM. The annual modulation phase is consistent with DM

Bernabei et al., 2003; Bernabei et al., 2010



Looks all nice and convincing. But...

DAMA: a controversial claim of detection

...DAMA's observation has not been confirmed by other experiments! (more later)

- Region of parameter space required to explain DAMA inconsistent with positive results (few) from other experiments and negative results (many) from others still
- Experiment is not replicable
- Raw data has not been made public

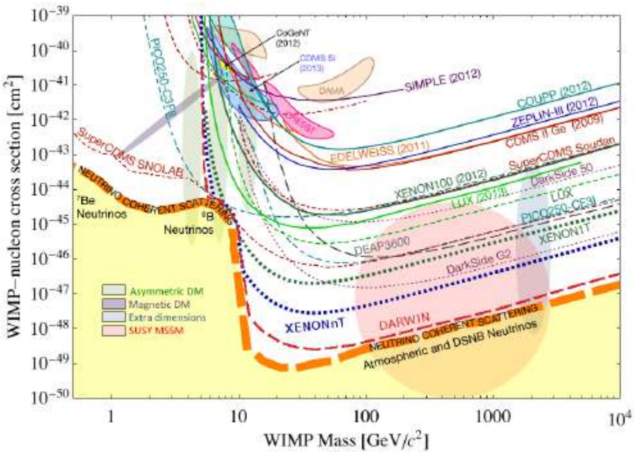
("Public? What does that mean?" [quot.])

Dark Matter direct detection - Experimental status

- DAMA: annual modulation of *something* at 9.3σ in 14 years of data
- CoGeNT: had an excess of events at low energies, including an annual modulation at 2.3σ. More careful analyses suggest no excess
- CRESST: had an unexplained $\sim 2\sigma$ excess at low energies. Upgraded to CRESST-II, excess disappeared.
- CDMS-II: saw an excess in the Si but not Ge component. Upgrades to CDMSlite and SuperCDMS (both Ge) find no excess
- XENON: no excess in XENON10 or XENON100
- LUX: no excess seen. By far kills all above claims

Dark Matter direct detection - Confusion of the mind

The claims of detection are not mutually compatible, and are mostly excluded by upper limits from experiments which have not seen anything!



Dark Matter direct detection - Caveats to the standard picture

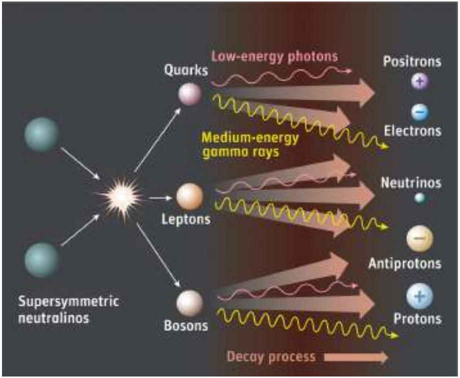
There are ways of getting around the confusing situation described

- "Halo-independent methods" bypass uncertainty on $f(\mathbf{v}, t)$ Fox, Kribs, Tait, 2010; Fox, Liu, Weiner, 2010; McCabe, 2011; Gondolo, Gelmini, 2012; Frandsen et al., 2013
- Change the particle physics of DM. Many examples:
  - inelastic (endothermic or exothermic) DM Tucker-Smith, Weiner, 2001
  - momentum dependent DM Chang, Pierce, Weiner, 2009
  - resonant DM Bai, Fox, 2009
  - luminous DM Feldstein, Graham, Rajendran, 2010
  - isospin violating DM Chang et al., 2010; Feng et al., 2011; Frandsen et al., 2011
  - magnetic inelastic DM Chang, Weiner, Yavin, 2010
  - ...and many others!
- DAMA has a poor background discrimination, events could be due to $\sim \mathrm{MeV}$ DM recoiling against electrons Foot, 2014

Dark Matter searches - Indirect detection

Look for products of DM annihilation or decay

- γ-rays - *Fermi*-LAT, HESS, MAGIC, Veritas, CTA
  - produced through loop suppressed ann's → monochromatic line
  - bremsstrahlung (FSR or VIB)
  - continuum from secondary decay (e.g. $\chi\chi \rightarrow \bar{q}q \rightarrow \pi^{\pm}\pi^{0}$, $\pi^{0} \rightarrow \gamma\gamma$)
- anti-protons - PAMELA, AMS-02
- anti-deuterons - GAPS
- neutrinos - IceCube, ANTARES, KM3NeT
- positrons - *Fermi*-LAT, ATIC,



Dark Matter Indirect detection - νs from the Sun

Dark Matter can accumulate in the Sun at a rate

$$\frac{dN}{dt} = C_\odot - A_\odot [N(t)]^2 - E_\odot N(t)$$

Evaporation negligible for $m_\chi \gtrsim 3\ \mathrm{GeV}$, capture and annihilation rates

$$C_\odot = \frac{\rho_\chi}{m_\chi} v_\chi \left(\frac{M_\odot}{m_p} \right) \sigma_{\chi p} \quad , \quad A_\odot = \langle \sigma v \rangle \left(\frac{4\pi G \rho_\odot m_\chi}{3 T_\odot} \right)^{\frac{3}{2}}$$

Solution

$$\Gamma_A = \frac{1}{2} A_\odot [N(t)]^2 = \frac{C_\odot}{2} \left(\frac{t}{t_{\mathrm{eq}}} \right)^2 \underset{t \gg t_{\mathrm{eq}}}{\approx} \frac{C_\odot}{2}$$

Bottom-line: at equilibrium the annihilation rate is directly related to the cross-section for scattering off protons!

Dark Matter indirect detection - Photons

Received flux from a direction ψ within a solid angle $\Delta\Omega$:

$$\phi_\gamma = \frac{\Delta\Omega}{4\pi}\left\{\frac{1}{\Delta\Omega}\int d\Omega \int_{\text{l.o.s.}} dl(\psi)\ \rho_\chi^2\right\}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma} \equiv \frac{\Delta\Omega}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\mathcal{J}$$

$$\frac{dN^\gamma_{\gamma\gamma}}{dE} = 2\delta(E - m_\chi) \quad , \quad \frac{dN^\gamma_{\gamma Z}}{dE} = \delta\left(E - m_\chi + \frac{m_Z^2}{4m_\chi}\right)$$

Bergström, Snellmann, 1988; Bergström, Ullio 1997

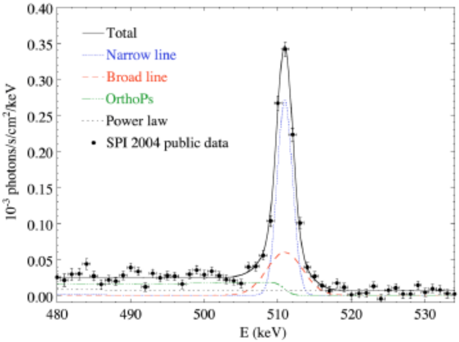
Some possible targets

- Galactic center: large signal, large background
- Galactic halo: moderate signal, moderate background
- Dwarf galaxies: low statistics, low background
- Clusters: low signal, low background, large modelling uncertainty
- Dark clumps: low statistics, low background

Dark Matter indirect detection - Claims

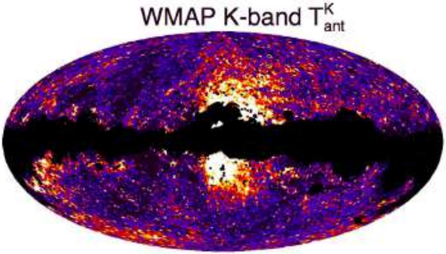
- INTEGRAL 511 keV line
- "WMAP Haze"
- Extended GeV excess
- 130 GeV line ("Weniger line")
- PAMELA excess

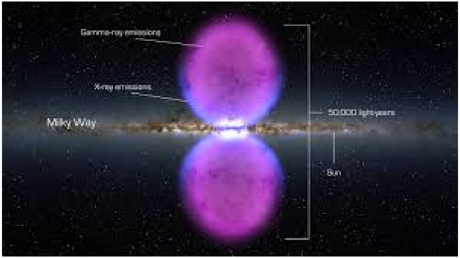
Dark Matter indirect detection - The INTEGRAL 511 keV line



- Clearly due to non-relativistic e^+e^- annihilation
- DM proposals
  - Light DM (LDM): $\chi\chi \to e^+e^-$, $m_\chi \sim \text{ MeV}$
  - EXciting DM (XDM): $\chi' \to \chi e^+e^-$, $m_{\chi'} - m_\chi = \delta \sim \text{ MeV}$
- 2008: emission shown to not be spherically symmetric, and consistent with a population of pulsars

Dark Matter indirect detection - The “WMAP haze”

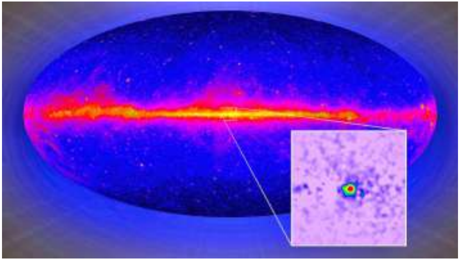




- Excess microwave emission, inner 20 degrees, $\sim$ 1 kpc

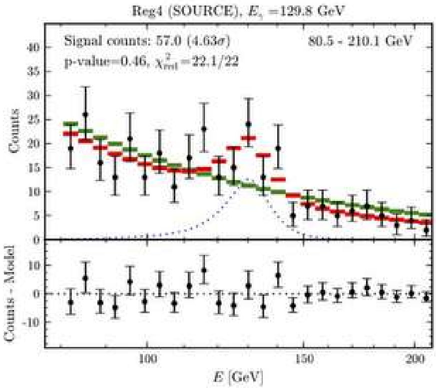
  Finkbeiner, 2003; Dobler, Finkbeiner, 2007
- DM explanation: produced by synchrotron radiation from e^+e^- (accelerated by B fields) produced by DM annihilation
- 2009: explained by “Fermi bubbles” Dobler *et al.* 2009; Su, Slatyer, Finkbeiner 2009

Dark Matter indirect detection - Galactic center excess



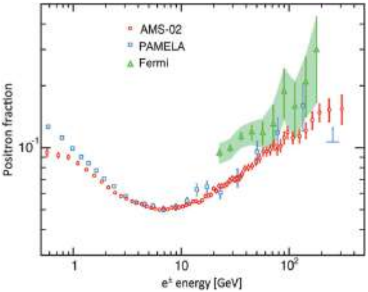
- Unexplained excess of GeV photons, peaks at 2-3 GeV Hooper, Linden 2011
- Could be explained by DM annihilation: $\chi\chi \rightarrow \tau^+\tau^-$ $(m_\chi \sim 7-12\ \mathrm{GeV})$ or $\chi\chi \rightarrow \bar{b}b$ $(m_\chi \sim 22-45\ \mathrm{Gev})$, $\langle\sigma v\rangle \simeq 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$
- Could be due to unresolved millisecond pulsars Abazajian, Kaplinghat 2012

Dark Matter indirect detection - The 130 GeV line ("Weniger line")



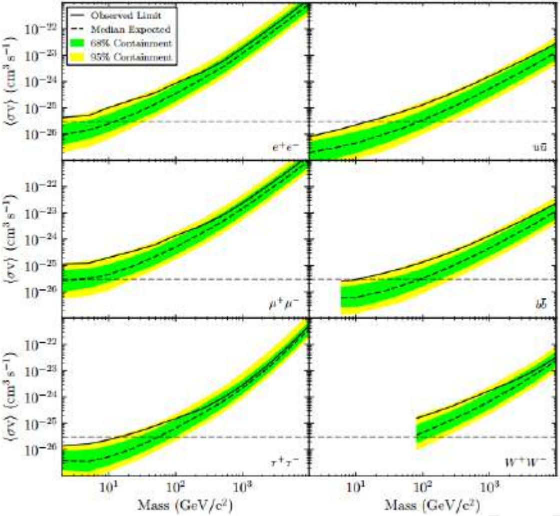
- 3.5σ line found at 130 GeV in *Fermi*-LAT data $(\chi\chi \to \gamma\gamma)$ Weniger, 2012
- Hint of a second 111 GeV line $(\chi\chi \to \gamma Z)$ Su, Finkbeiner 2012
- Not found where it should be (dwarf galaxies), found where it should not be (Earth's Limb, vicinity of the Sun)
- Probably a detector effect, situation far from being clear

Dark Matter indirect detection - The PAMELA excess



- Excess known since "HEAT" (1980s)
- 2008: PAMELA reports an excess in the e^+ fraction between 10 and 100 GeV
- Confirmed by *Fermi*-LAT and AMS-02
- No corresponding $\bar{p}$ excess found
- Supernova remnants? Pulsars?
- No endpoint observed (would be a probe of m_χ)
- DM explanation is complicated: leptophilic DM? Sommerfeld enhancement? Huge boost factor?
- $\chi\chi \to \phi\phi \to (\mu^+\mu^-, \tau^+\tau^-, 4\mu, 4\tau, \pi\text{s}) \to e^+e^-$ $(m_\chi < 1\ \text{GeV})$
- Huge modelling uncertainties

Dark Matter indirect detection - *Fermi*-LAT upper limits from dwarf galaxies



Dark Matter searches - Collider searches

Goal: produce and search for DM at colliders

Dark Matter collider searches - Search strategies

- Most obvious search strategy $[(SM)(SM) \to \chi\chi]$ is invisible
- Search for missing transverse energy $[(SM)(SM) \to \chi\chi Y]$, where Y is unavoidably produced at least as ISR
- Popular search channels are high $\mathbf{p}_T$ mono-(something) plus large missing transverse energy (MET): $Y = jet, \gamma, W^{\pm}, Z, H$

Advantages

- Do not suffer from threshold effect for low-mass DM
- Complementary to direct and indirect searches
- Do not suffer from astrophysical uncertainties

Disadvantages

- PDF suppression for high DM masses and some uncertainty in PDFs → can be cured by using a lepton collider (e.g. ILC)
- Signal may be due to an "impostor" stable on collider but not cosmological timescales
- For typical WIMPs large BGs

Dark Matter collider searches - EFT

Write down all possible effective vertices for DM coupling to quarks and gluons. For a Dirac fermion DM 14 possible effective vertices:

- $D_1 = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$
- $D_2 = \frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$
- $D_3 = \frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$
- $D_4 = \frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$
- $D_5 = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
- $D_6 = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$
- $D_7 = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$
- $D_8 = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
- $D_9 = \frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$
- $D_{10} = \frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$
- $D_{11} = \frac{\alpha_s}{4\Lambda^3}\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$
- $D_{12} = \frac{i\alpha_s}{4\Lambda^3}\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$
- $D_{13} = \frac{i\alpha_s}{4\Lambda^3}\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$
- $D_{14} = \frac{\alpha_s}{4\Lambda^3}\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$

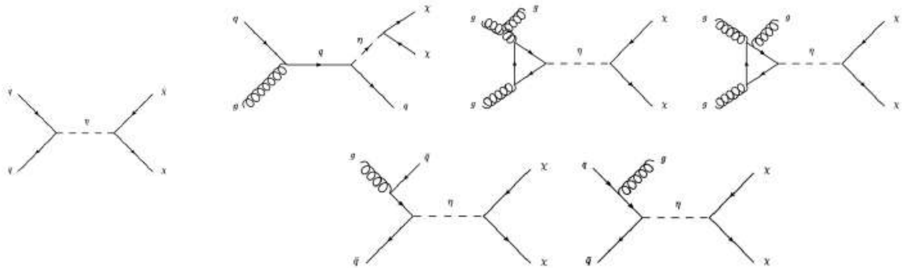
Askew, Chauhan, Penning, Shepherd, Tripathi, 2014

Downsides: assumes that new particles are much heavier than the scales at which we are probing these interactions. Also, does not consider interference between different operators and does not deal with light mediators.

Dark Matter collider searches - Simplified models

UV complete the effective operators using at most one new particle other than the DM. For example, for D_1, can insert an intermediate scalar particle

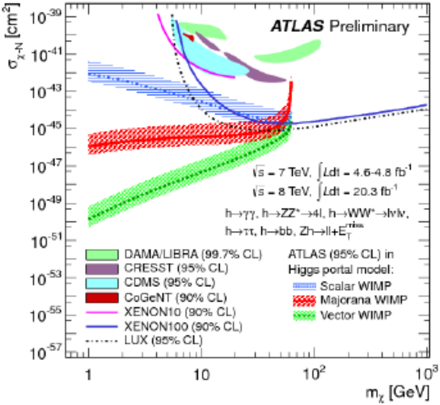
$$\mathcal{L} = i\bar{\chi}\left(\gamma^\mu D_\mu - m_\chi\right)\chi + \left(m_\phi^2\phi^\dagger\phi + g_\chi\phi\bar{\chi}\chi + g_q\frac{m_q}{m_\phi}\phi\bar{q}q + \text{h.c.}\right) \implies \Lambda = \frac{m_\phi}{\sqrt[3]{g_q g_\chi}}$$

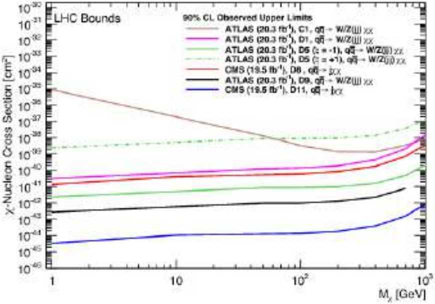


Courtesy: Millie McDonald

Dark Matter collider searches - Bounds

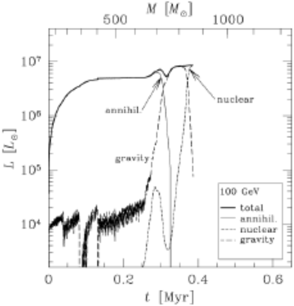
Set bounds in $\sigma_{\chi N} - m_\chi$ or $\Lambda - m_\chi$ parameter space and combine with bounds from direct detection. My personal opinion: this last one is a highly misleading and dangerous thing to do (ask me later if interested!)





Dark Matter astrophysical probes - Dark Stars

- Scattering and gravitational contraction allow stars to accrete DM
- DM can annihilate and dump/transport energy within the stars
- PopIII stars likely to be heavily influenced by DM Spolyar, Freese, Gondolo, 2008
  - Much higher DM density in the early Universe [$\propto (1+z)^3$]
  - First stars form in the center of DM halos
  - DM energy source can dominate over fusion
  - Can become very massive ($> 10^6 M_\odot$) and very luminous ($> 10^9 L_\odot$)
  - Progenitors of SMBHs?
  - Possibly detectable by JWST, and by impact on reionization

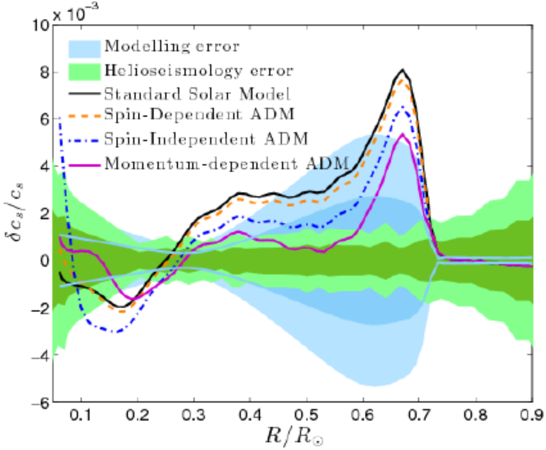


Dark Matter astrophysical probes - Impact on the Sun

Solar composition problem: the current Solar model with the revised abundances does not reproduce helioseismological observables

- 1998: GS98 abundances, perfect agreement with helioseismology Grevesse, Sauval, 1998
- 2005-2009: new abundances (AGS05 and AGSS09) with 30% lower metallicity cause terrible agreement with helioseismology Asplund, Grevesse, Sauval, 2004; Asplund, Grevesse, Sauval, Scott, 2009
  - Surface Helium fraction too low by 6σ
  - Radius of convective zone is too high by 15σ
  - Sound speed is off by as much as 10σ
  - Neutrino fluxes are potentially off
- 2010-today: captured DM can alter heat transport within the Sun and restore partial agreement. The simplest picture does not work. Perhaps q^2-ADM? Or more complicated scenarios? Frandsen, Sarkar, 2010; Cumberbatch, Guzik, Silk, Watson, West, 2010; Taoso, Iocco Meynet, Bertone, Eggenberger, 2010; Vincent, Scott, Serenelli, 2014; Vincent, Scott, Serenelli, 2015; Frandsen, Sarkar, Shoemaker, SV, 2015 (in preparation)

Dark Matter astrophysical probes - The Solar composition problem



Vincent, Scott, Serenelli, 2014

1E 0657-558...

...aka the Bullet Cluster for friends!

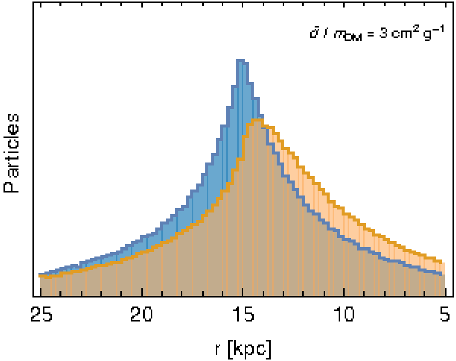
Sets a rough bound:

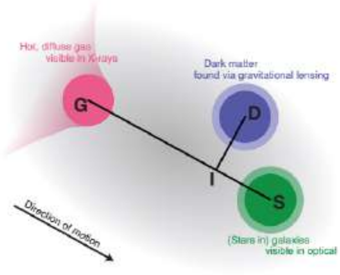
$$\frac{\sigma_\chi}{m_\chi} \lesssim 1 \; \frac{\mathrm{cm}^2}{\mathrm{g}} \simeq 2 \; \frac{\mathrm{barn}}{\mathrm{GeV}}$$

Randall et al., 2007

Dark Matter astrophysical probes

Can we measure DM self-interactions through offsets between luminous and DM in colliding clusters? Kahlhoefer, Schmidt-Hoberg, Frandsen, Sarkar, 2013





Measured recently in Abell 3827, although first analysis was plagued by a trivial mistake Massey et al., 2015; Kahlhoefer, Schmidt-Hoberg, Kummer, Sarkar, 2015

The mystery of Dark Matter - Conclusion

- Dark Matter exists - unlikely to be a simple modification to GR
- A compelling DM discovery requires evidence in multiple complementary channels
- Experimental situation highly confusing - controversial detection claims and an insufficient understanding of background
- Many theoretical candidates, perhaps new/different ideas required?

Stay tuned for more!

Thank you for your attention!