The Future of Particle Cosmology (after LHC Run II)

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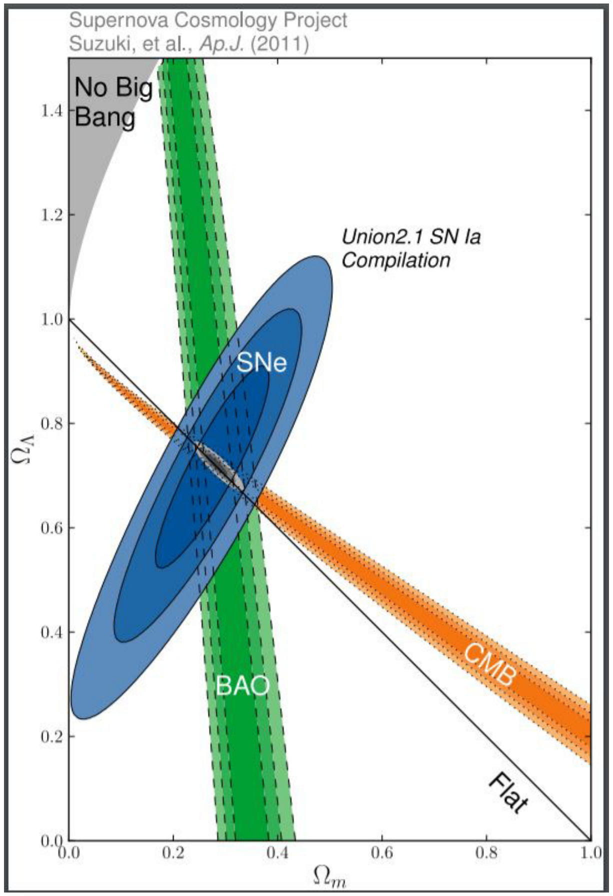
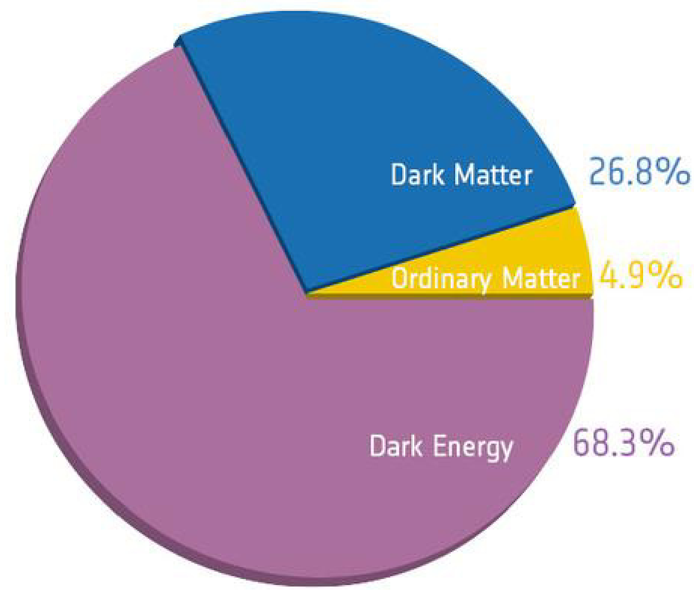
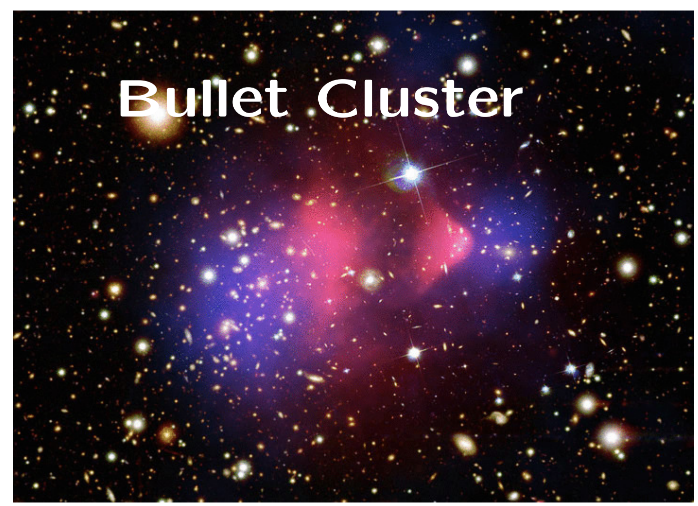
Lecture 3: Dark Matter and Particle Physics



Planck





95% of Cosmos: unknown!

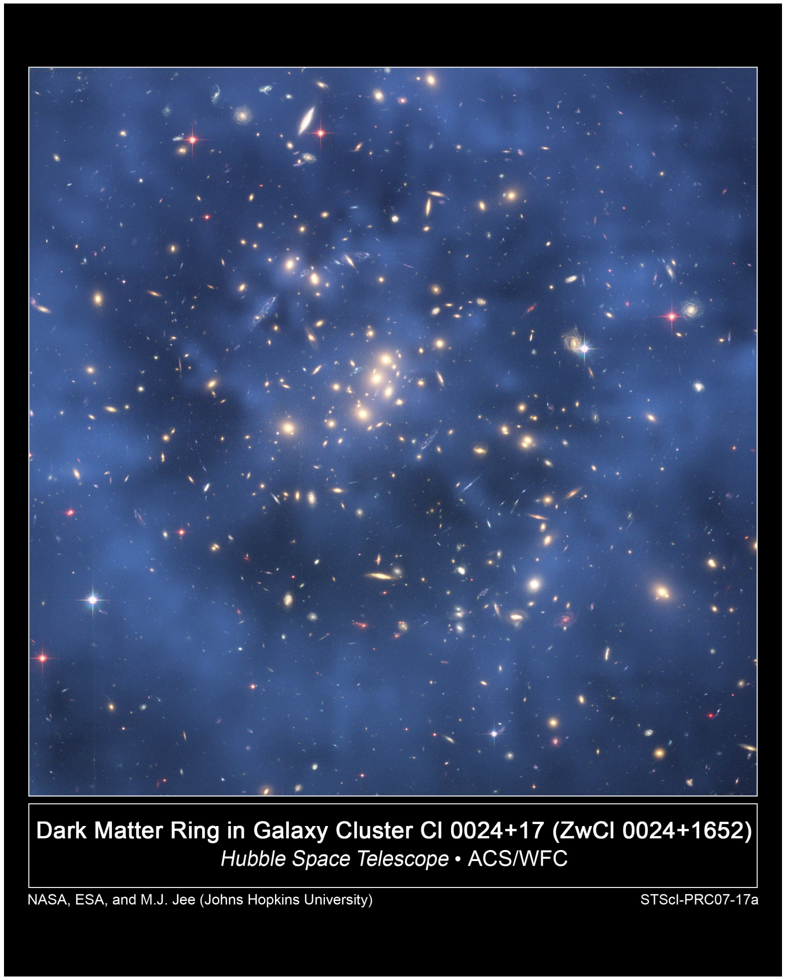
Cosmic acceleration (dark energy):
Could be vacuum energy; no dynamics

Dark matter (DM)

- $\Omega_{\mathrm{DM}} \sim 0.27$, fraction of critical energy density
- Robust evidence from cosmology and astrophysics
  - CMB, BBN, rotation curves of galaxies, lensing, Bullet Cluster, . . .
- **Unknown origin**
  - Feeble interactions with atoms, light
  - Self-interactions not strong ($\sigma \lesssim 1$ barn)
  - Local energy density $\rho_{\mathrm{DM}} \sim 0.3$ GeV cm^{-3}
  - Not explained in SM

Strongly motivates new physics

So far, evidence limited to gravity effects



How do you look for something of unknown nature?

Possible DM mass scale: 10^{-22} *eV* $\lesssim M_{\rm DM} \lesssim 10^{68}$ *eV*

(Spanning ultra light bosons to primordial black holes: $\sim$ 90 orders of magnitude!)

Searches often guided by *theoretical motivation*

- New physics to address unresolved questions in SM

  - Strong CP problem (QCD)

  - CP violating effects highly suppressed in QCD by $\bar{\theta} \lesssim 10^{-9}$

  - The hierarchy problem in SM:

  - Quantum corrections to Higgs potential comparable to UV scales

  - Why is $M_H \sim 10^2$ GeV small compared to *e.g.* $M_{\text{Planck}} \sim 10^{19}$ GeV?

- SM extensions often introduce/require new symmetries

- Symmetry $\rightarrow$ Charge conservation

$\Rightarrow$ Stable or long-lived particles: DM candidates

Some well-known extensions of SM:

- Strong CP

- Peccei-Quinn (PQ) symmetry, broken at $f_{\text{PQ}} \gg M_W$

- Light **axion** (pseudo-Goldstone boson), m_a from non-perturbative QCD

- Couplings suppressed by $1/f_{\text{PQ}}$

- QCD axions could be dark matter for $m_a \sim \mu$eV; $f_{\text{PQ}} \sim 10^{12}$ GeV

- Hierarchy

- New weak scale physics ($M_{\text{new}} \gtrsim M_H$): supersymmetry, strong dynamics, . . .

- Often requires an unbroken **parity** (*e.g.* R-parity in SUSY) to avoid problems

- Lightest parity-odd particle stable

- **Weakly Interacting Massive Particles** (WIMPs)

Quick Review of QCD Axion

- QCD: $\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$ allowed by all good symmetries

- Strong CP problem: Why is $\bar{\theta} = \theta + \arg[\det(M_q)] \lesssim 10^{-10}$

neutron EDM: $d_n < 0.30 \times 10^{-25}$ e cm (90% CL), PDG2016

- If $\exists\, m_q = 0$ $(q = u)$ can rotate θ away

- Disfavored by phenomenology, lattice

- Assume a $U(1)$ anomalous under $SU(3)_c$ Peccei and Quinn, 1977

- Broken $U(1)$: massless Goldstone, *axion a*, decay constant f_a

Wilczek, 1978; Weinberg, 1978

- QCD anomaly: $m_a \neq 0$ from non-perturbative instanton effects

- Potential $V_a \sim m_u \Lambda^3_{\text{QD}} \left(1 - \cos\frac{a}{f_a}\right) \Rightarrow m_a^2 \sim m_u \Lambda^3_{\text{QCD}}/f_a^2$

- Dynamical relaxation of $\bar{\theta} \to 0$

- Astrophysics (emission from stars, supernovae, . . .): $f_a \gtrsim 10^8$ GeV

- Axion: oscillating field for $m_a(T) \gtrsim 3H(T)$ (CDM behavior)

• Assume $a/f_a \lesssim 1$: axion potential approximated by the m_a^2 term

• Axion equation of motion: $\ddot{a} + 3H(t)\,a + m_a^2(t) = 0$
m_a temperature (time) dependent

• For $H = \dot{R}/R\,, \dot{m}_a/m \ll m_a$: $a(t) \approx A(t)\cos(m_a t)$,

where $d(m_a A^2)/dt = -3H(m_a A^2) \Rightarrow n_a = \frac{1}{2} m_a A^2 \propto R^{-3}$ (CDM)

Preskill, Wise, Wilczek, 1983; Abbot, Sikivie, 1983; Dine, Fischler, 1983

- $\Omega_a \propto f_a^{1.18} (A_i/f_a)^2$ with A_i initial amplitude

- Cosmology yields upper bound $f_a \lesssim 10^{12}$ GeV (overclosure)

• Bound assumes initial amplitude $A_i \sim f_a$

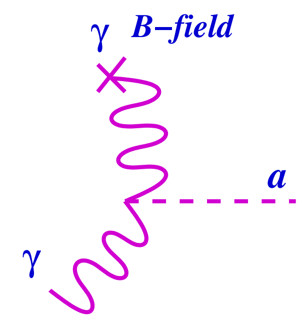
- For $f_a \sim 10^{12}$ GeV axions could be good DM candidates

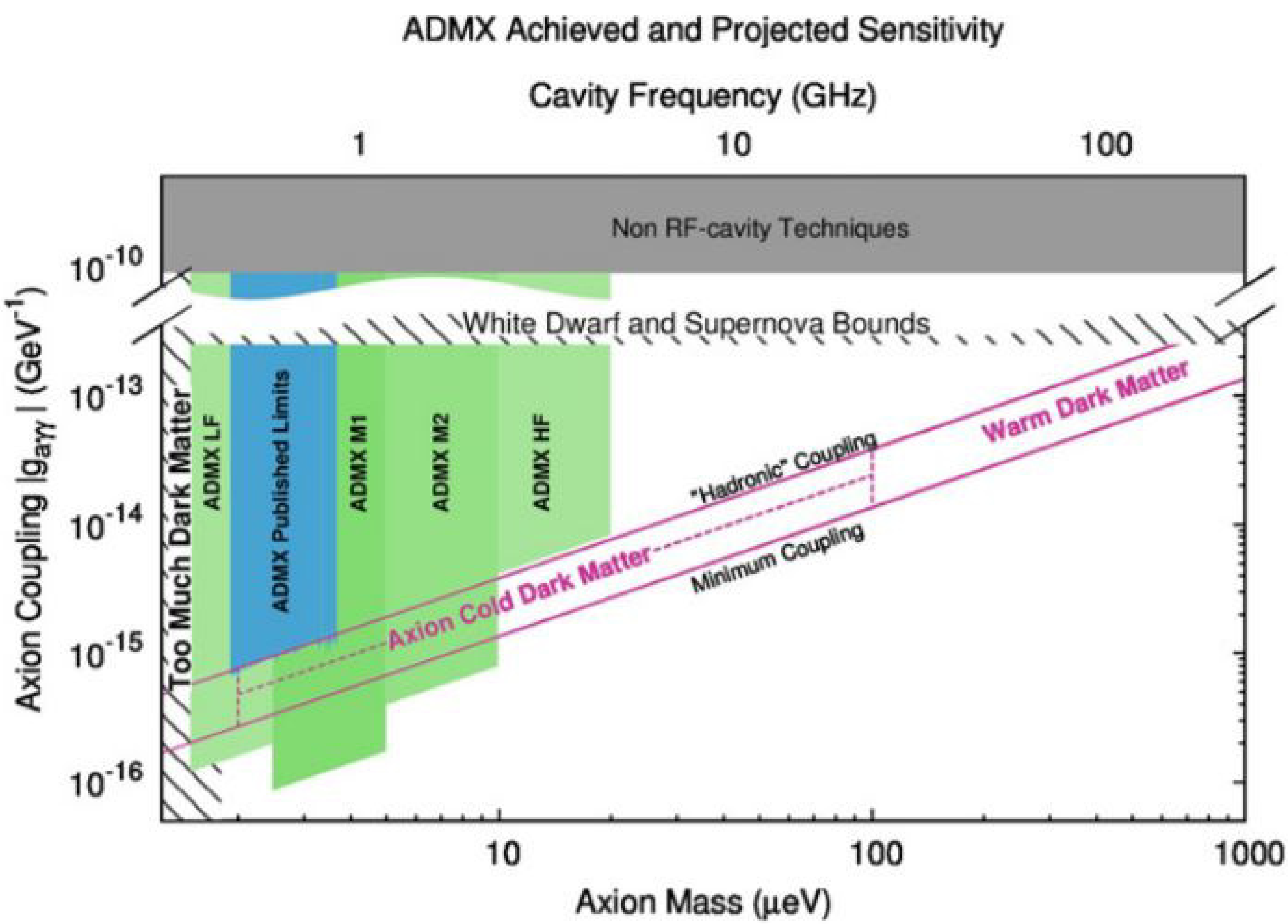
$f_a \to M_{GUT}$ requires $\mathcal{O}(10^{-3})$ or better tuning of A_i^2

- Axion DM search using a microwave cavity with background B-field

Haloscope concept: Sikivie, 1983

- Axion-photon coupling: $g_{a\gamma\gamma}\, a\, \vec{E}.\vec{B}$ $\qquad g_{a\gamma\gamma} \sim (\alpha/\pi)/f_{\rm PQ}$

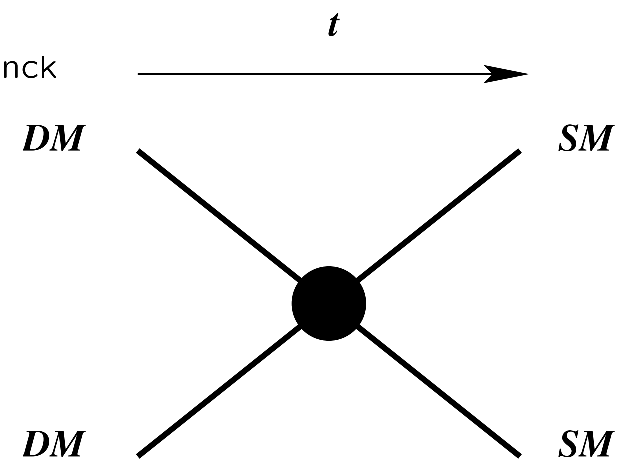




G. Rybka [ADMX Collaboration], Phys. Dark Univ. **4**, 14 (2014)

WIMPs

- Thermal relic density: annihilation, freeze-out



- Annihilation rate below Hubble scale $H \sim g_*^{1/2} T^2 / M_{\text{Planck}}$

- $\rho_{\text{WIMP}} \propto 1/\langle \sigma_{ann} v \rangle$ and $\sigma_{ann} \sim g^4/M^2$

- $g \sim g_{\text{weak}}$, $M \sim$ TeV $\Rightarrow \Omega_{\text{DM}} \sim \mathcal{O}(0.1)$

$\Omega_{\text{CDM}} \equiv \frac{\rho_{\text{CDM}}}{\rho_{\text{crit}}} = 0.258(11)$ (From PDG2016)

- Weak scale ($\sim$ TeV) theoretically motivated

- Motivation diminished if no new physics at LHC

- However, g^4/M^2 may be achieved otherwise (WIMPless Miracle)

Feng and Kumar, 2008

- **WIMPs: the main focus of DM searches**

- DAMA/LIBRA, CDMS, Xenon10, CDMSII, Xenon100, LUX, Fermi GST...

Thermal Relic Density

See, *e.g.*, HD, Lewis, 1309.6640

- Annihilation cross section: $\sigma_{\text{ann}}\, v_{\text{rel}} = a + b\, v_{\text{rel}}^2$

a (b) dominant: s (p)-wave

- Thermal average: $\langle \sigma_{\text{ann}}\, v_{\text{rel}} \rangle = a + 6b/x$ with $x \equiv m_{\text{dm}}/T$

- In general: $\langle \sigma_{\text{ann}}\, v_{\text{rel}} \rangle = \sum_j a_j\, x^{-j}$

- Relic density:

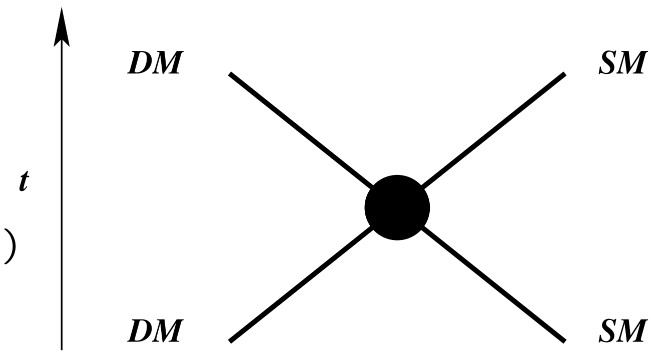
$$\boxed{\Omega h^2 = \frac{5.36 \times 10^{43} \text{cm}^3\, \text{GeV}\, s(0)}{M_{\text{Planck}}^3\, g_{*s}/\sqrt{g_*}} \frac{x_f}{\sum_j a_j\, x_f^{-j}/(j+1)}}$$

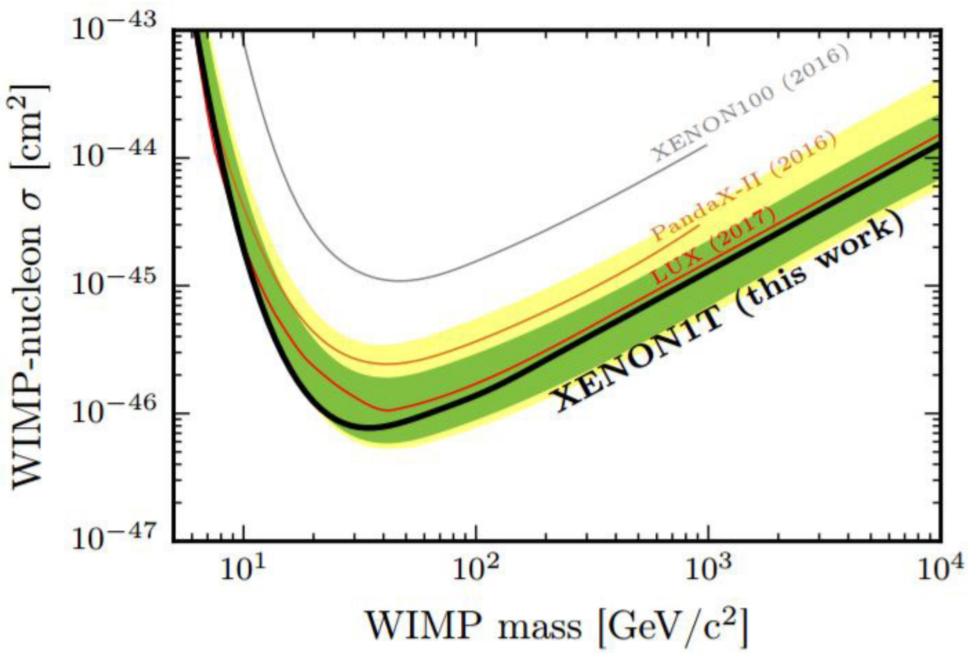
$H(0) = 100$ km/s Mpc h (Hubble constant today), entropy density $s(0) = 2889.2\ 1/\text{cm}^3$, $g_* \approx g_{*s}$ relativistic degrees of freedom, and x_f is value of x at freeze-out

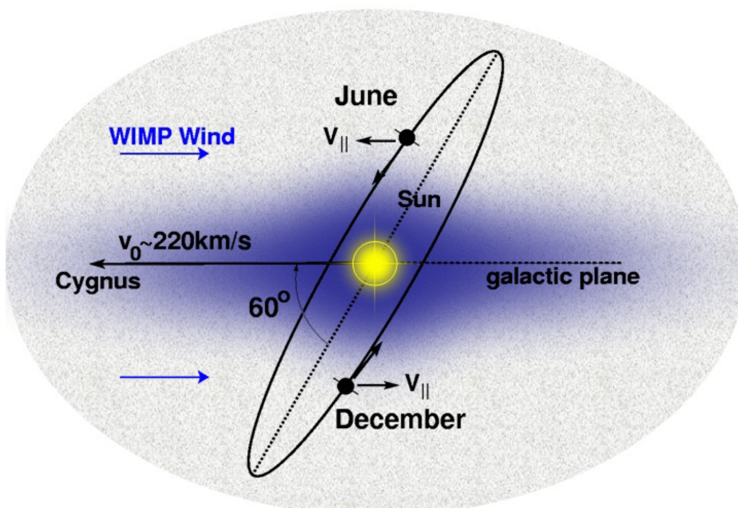
$x_f \approx \ln[0.038(\kappa/\sqrt{x_f\, g_*}) M_{\text{Planck}}\, m_{\text{dm}}\, \langle \sigma_{\text{ann}}\, v_{\text{rel}} \rangle]$ κ: DM internal degrees of freedom

Direct WIMP DM Searches

- Recoil off atomic nuclei (electrons)
  - Energy deposition (ionization, scintillation, . . .)
  - Motion of Sun within Galaxy: WIMP wind
  - Earth's motion: seasonal modulation (DAMA/LIBRA)







E. Aprile *et al.*, arXiv:1705.06655 [astro-ph.CO] (green, yellow: 1,2 σ limits, 90% C.L.)

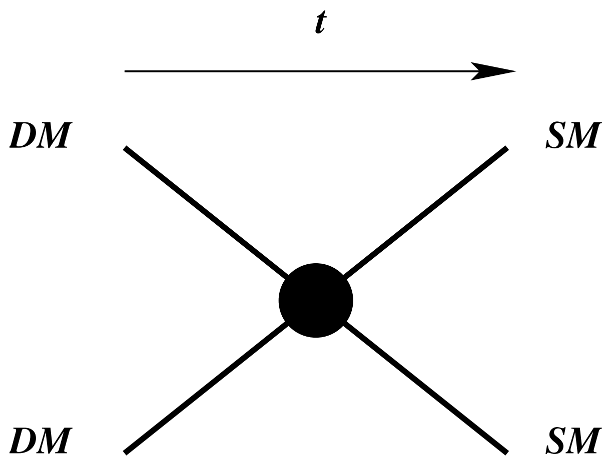
- General feature: $m_{\rm DM} \lesssim$ **few GeV** poorly constrained (low recoil energy)

Other avenues for WIMP search:

- Indirect searches: self-annihilation signals

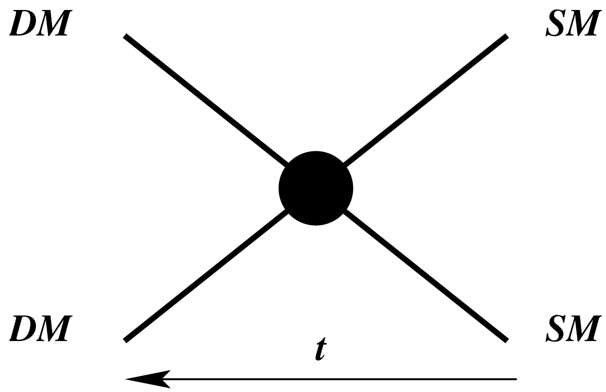
- Related to thermal relic density

- Complicated by astrophysical backgrounds

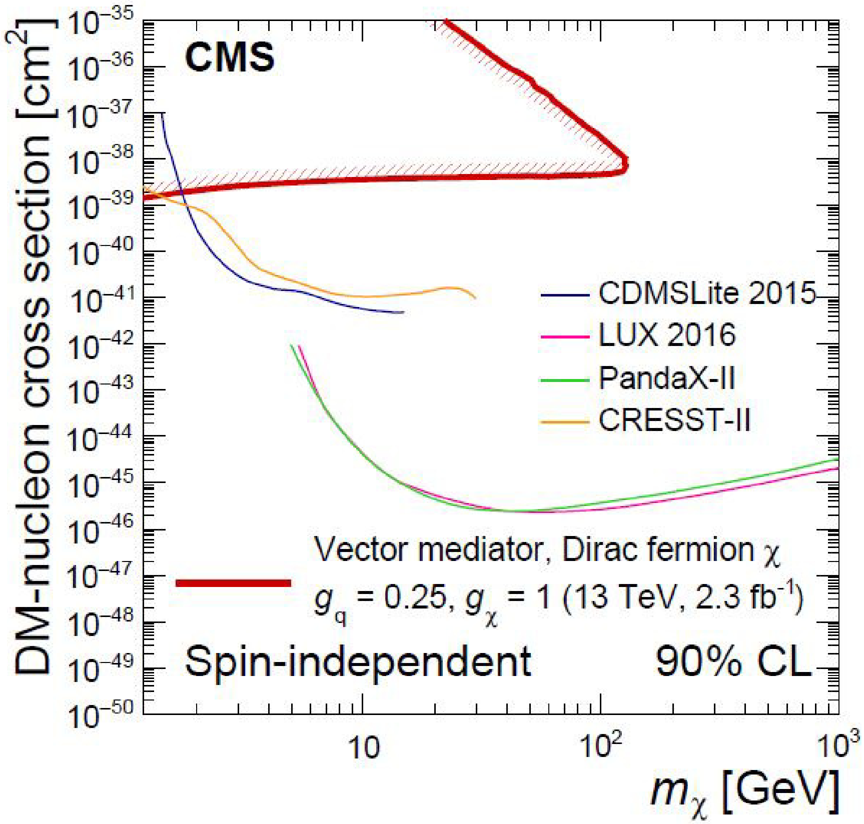


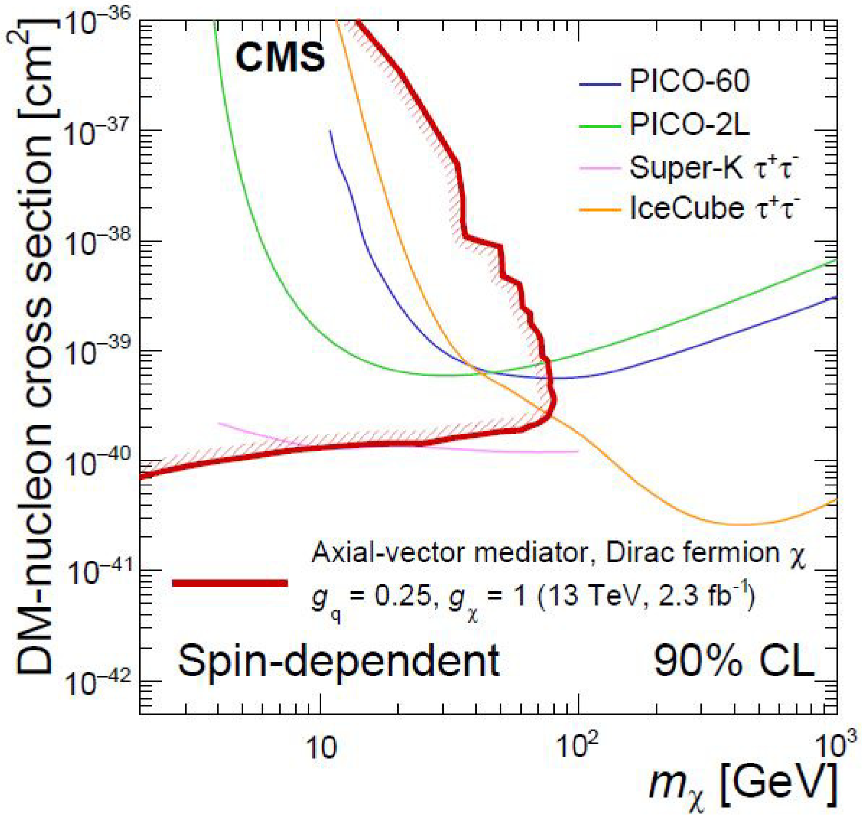
- Collider production: LHC

- Search for missing energy in events

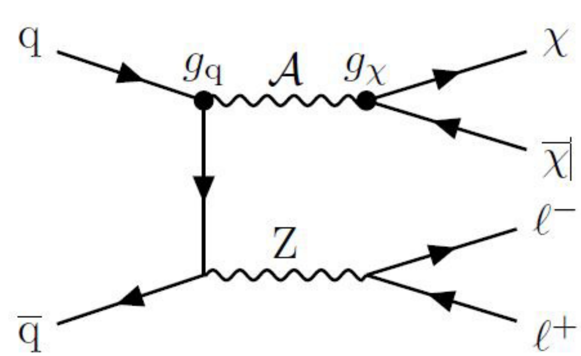


Plots and diagram from CMS Collaboration, 1701.02042

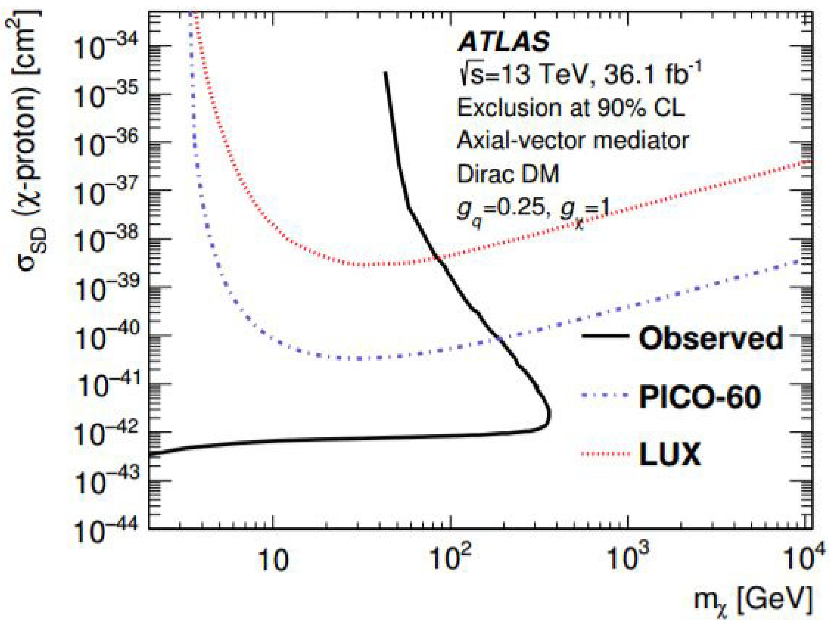


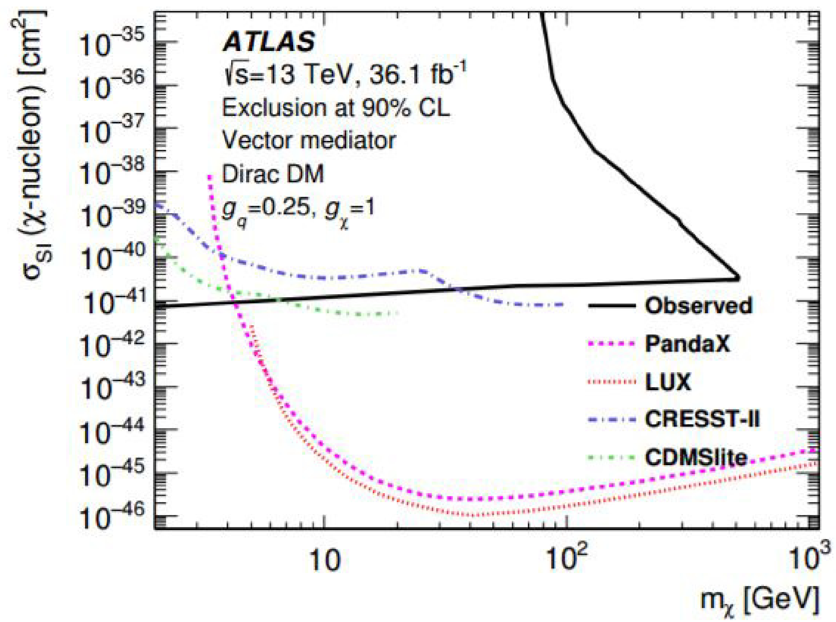


- Z + missing p_T search mode
- Limits based on a "simplified model"

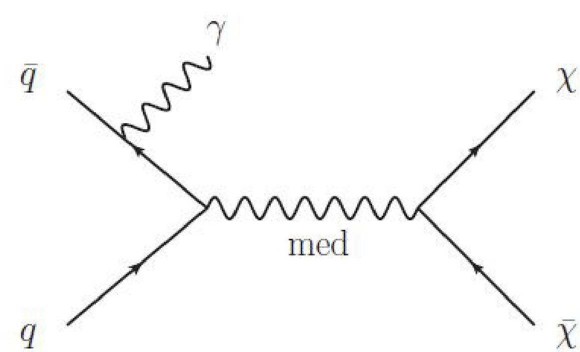


Plots and diagram from ATLAS Collaboration, 1704.03848





- γ + missing p_T search mode
- Limits based on a "simplified model"



Observation motivating DM theory

- Similar energy density of atoms and DM:
- $\Omega_{DM} \approx 5\Omega_B$. Planck, 2015

Why would two unrelated sectors have similar Ω?

- Empirical motivation for common origin
- **DM from an asymmetry**: Kaplan, Luty, Zurek, 0901.4117

For reviews see, for example, HD, Mohapatra, 1203.1247; Petraki, Volkas, 1305.4939; Zurek, 1308.0338

$$n_B \approx n_{DM} \Rightarrow m_{DM} \approx 5m_p$$

- Like baryons, DM and $\overline{\text{DM}}$ annihilate efficiently, leaving asymmetry

- **Can lead to different search strategies**

- One does not typically expect annihilation indirect signals for ADM

Hylogenesis H.D., Morrissey, Sigurdson, Tulin, Phys.Rev.Lett. 105 (2010) 211304

Greek: *hyle "matter" + genesis "origin"*

- Generalized global B for both visible and hidden sectors

- Out-of-equilibrium, CP-violating decays of X_1, $\bar{X}_1$ into

(1) SM (quarks); (2) dark matter (Y, Φ): $X = X_1, X_2$

$$-\mathscr{L} \supset \frac{\lambda}{M^2}(X_L^\dagger s_R)(u_R d_R) + \zeta\, XY\Phi + H.C.$$

- **CPT**: $\Delta B(\text{SM}) = -\Delta B(\text{DM})$; $m_{Y,\Phi} \sim$ 2-3 GeV

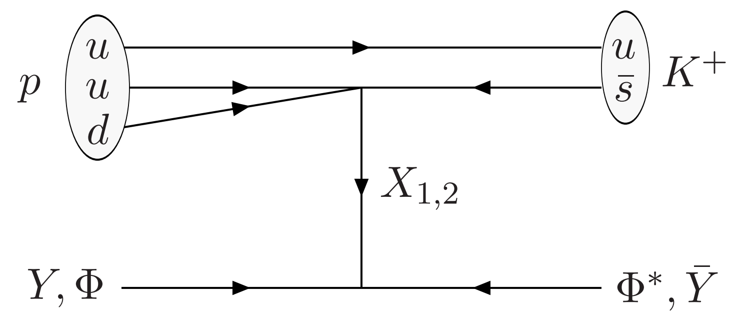
- Matter stability: symmetry and kinematics

- **Baryons (Quarks) and Anti-baryons (DM) can annihilate**:

Induced Nucleon Decay (IND) $\Rightarrow$ New approach to DM detection

Induced Nucleon Decay

- $YN \to \Phi^* M$ and $\Phi N \to \bar{Y} M$ (M a meson)



- Mimics standard $N \to M\nu$, but with *different kinematics*.

Decay mode	p_M^{SND} (MeV)	p_M^{IND} (MeV)
$N \to \pi$	460	800 - 1400
$N \to K$	340	680 - 1360
$N \to \eta$	310	650 - 1340

p_M monochromatic, negligible broadening from halo velocity.

- χPT estimate: $$\tau_N \approx 10^{32}\ \text{yr} \times \left(\frac{\Lambda_{IND}}{1\ \text{TeV}}\right)^6 \left(\frac{0.3\ \text{GeV/cm}^3}{\rho_{DM}}\right)$$

- Current bound on $p \to K^+\bar{\nu}$: $\tau_p > 5.9 \times 10^{33}$ yr   Super-Kamiokande Collaboration, 2014

★ Bound may not apply to IND due to different meson kinematics:

Less likely to be stopped, more Čerenkov radiation, boosted decay products.

Alternatives to CDM

- CDM simulations: predictions unsuccessful on scales $\lesssim 10$ kpc
- Too much small scale structure: missing satellites,...
- Cusp (simulations) versus core (observations) for DM profile

- It is possible that more details need to be included
- Effect of baryons on the DM density near galactic centers
- Self-interacting DM For a review, see Tulin and Yu, 1705.02358
- A new paradigm?

- We will briefly discuss an alternative scenario

- An alternative possibility: *Fuzzy DM (FDM)* Barkana, Gruzinov, 2000

- An ultra light axion of mass $m_a \sim 10^{-22}$ eV
- de Broglie wavelength ~ 1 kpc
- Can be thought of as coherent wave

- Quantum mechanics: FDM cores of ~ 1 kpc (solitons)

- Avoids problems of the CDM at small scales

- Axion potential $\mu^4 \cos(a/f_a) \Rightarrow m_a \sim \mu^2/f_a$

- QCD axion not a motivated option: $\mu \sim \Lambda_{\text{QCD}} \rightarrow f_a \gg 10^{19}$ GeV

- However, FDM may descend from string scale dynamics

Hui, Ostriker, Tremaine, Witten, 2016

- Decay constant $f_a \sim 10^{16-18}$ GeV ; $\mu \lesssim 1$ keV
- Mass generation from stringy instantons: $\mu^4 \sim M_{\text{Pl}}^2 M_{\text{UV}}^2 e^{-S}$
- $M_{\text{UV}} \sim M_{\text{SUSY}}$-$M_{\text{Pl}} \rightarrow S \sim 2\pi/\alpha_G \sim 100$-$200$

Summary

- DM may be motivated by solutions to other SM problems

- Models requiring new weak scale states (hierarchy problem) could naturally lead to thermal relics, WIMPs

- No new physics at LHC (and null direct detection results) can make the typical weak scale WIMPs less motivated

- Thermal relics may still be DM, but perhaps at lower masses with feeble couplings to SM

Different frameworks may also be invoked: asymmetric DM, ultra light bosons,. . .

- This is a challenging regime for conventional direct detection, collider searches

- New experiments may provide access to this sector, as we will outline in the next lecture