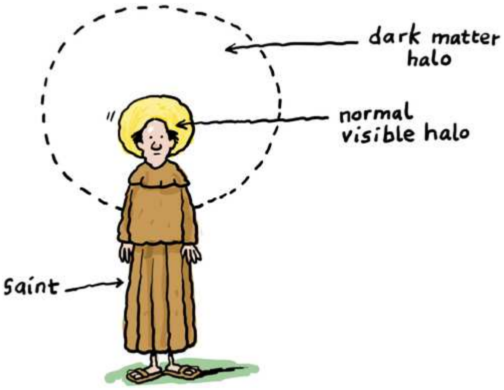
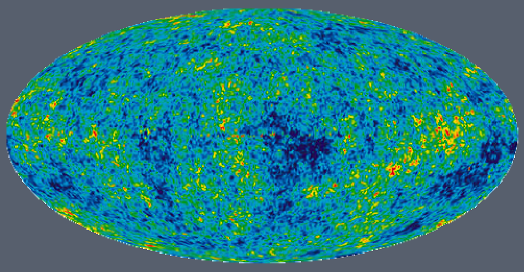
The
University
Of
Sheffield.



NON-BARYONIC DARK MATTER

Susan Cartwright

University of Sheffield

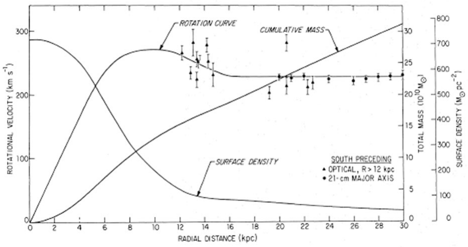


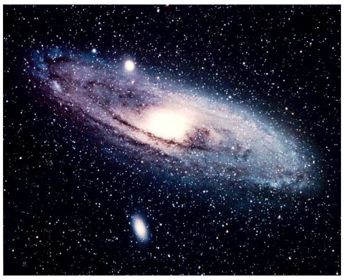
DARK MATTER

- Astrophysical Evidence
- Candidates
- Detection

THE ASTROPHYSICAL EVIDENCE

- Rotation curves of spiral galaxies

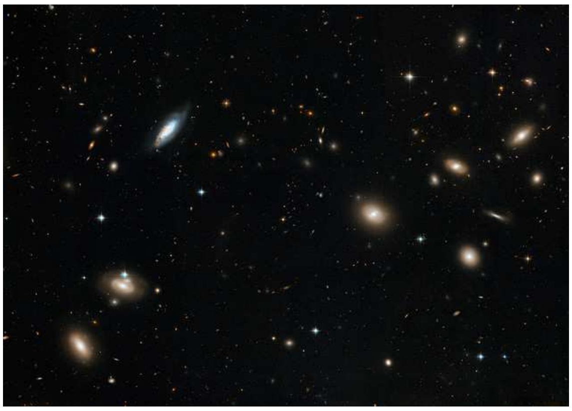




  - flat at large radii: if mass traced light we would expect them to be Keplerian at large radii, $v \propto r^{-1/2}$, because the light is concentrated in the central bulge
    - and disc light falls off exponentially, not $\propto r^{-2}$ as required for flat rotation curve

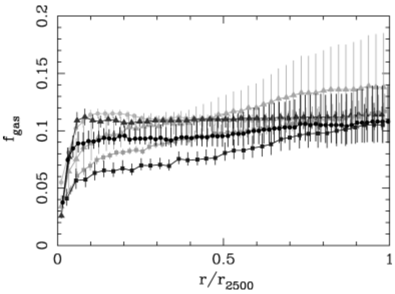
THE ASTROPHYSICAL EVIDENCE

- Dynamics of rich clusters
  - Zwicky (1933!) noted that the velocities of galaxies in the Coma cluster were too high to be consistent with a bound system

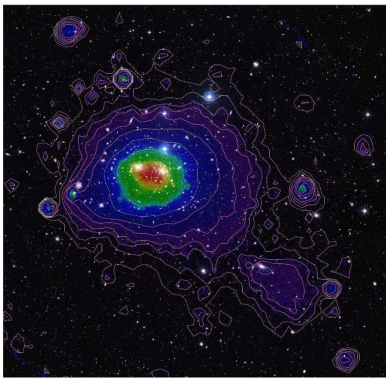


THE ASTROPHYSICAL EVIDENCE

- Dynamics of rich clusters
  - mass of gas and gravitating mass can be extracted from X-ray emission from intracluster medium



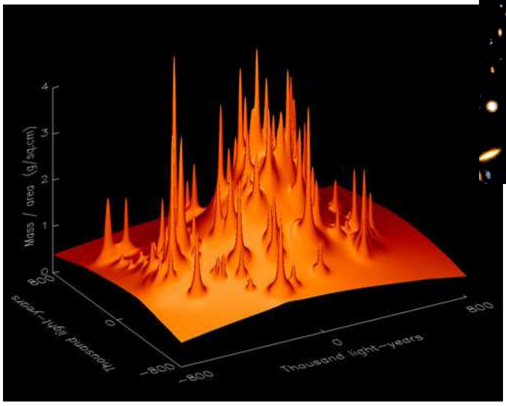
Allen et al., *MNRAS* **334** (2002) L11



ROSAT X-ray image of Coma cluster overlaid on optical.
MPI (ROSAT image);
NASA/ESA/DSS2 (visible image)

THE ASTROPHYSICAL EVIDENCE

- Dynamics of rich clusters



Mass map of CL0024+1654 as determined from the observed gravitational lensing.
Tyson, Kochanski and Dell'Antonio, *ApJ* **498** (1998) L107

THE ASTROPHYSICAL EVIDENCE: THE BULLET CLUSTER

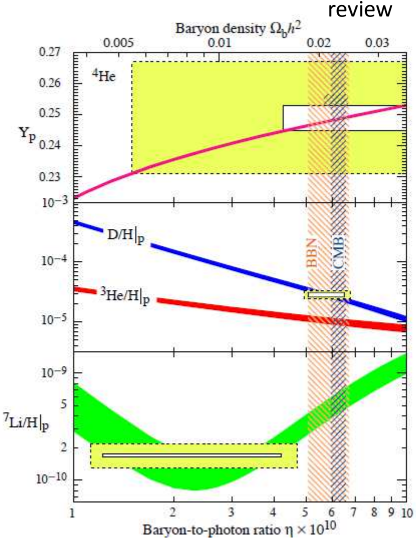
- Mass from lens mapping (blue) follows stars not gas (red)
  - ➔ dark matter is **collisionless**

Composite Credit:
X-ray: NASA/CXC/CfA/
M. Markevitch et al.;
Lensing Map:
NASA/STScI; ESO WFI;
Magellan/U.Arizona/
D.Clowe et al
Optical: NASA/STScI;
Magellan/U.Arizona/
D.Clowe et al.

NON-BARYONIC DARK MATTER

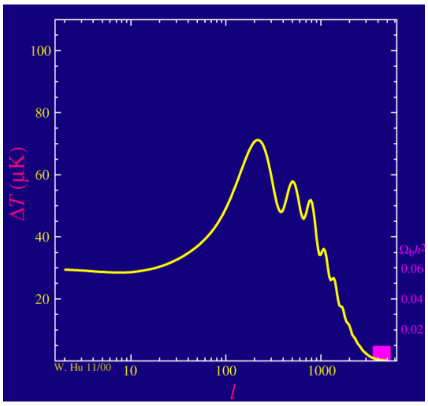
- Density of baryonic matter strongly constrained by early-universe nucleosynthesis (BBN)
  - density parameter of order 0.3 as required by data from, e.g., galaxy clusters is completely inconsistent with best fit
    - note here cosmologists' $h = H_0/100$ km s^{-1} Mpc^{-1} ≈ 0.7
    - do not confuse with Planck's constant!

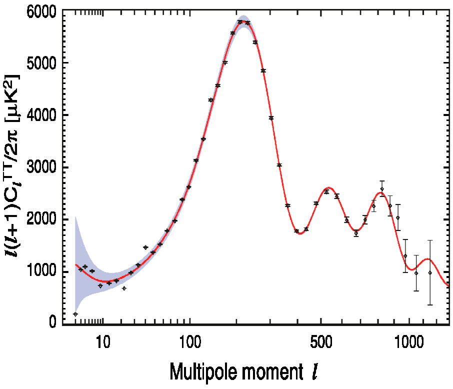
PDG review



NON-BARYONIC DARK MATTER: COSMOLOGY

Ratio of odd/even peaks depends on Ω_b



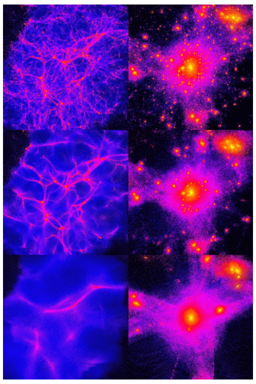


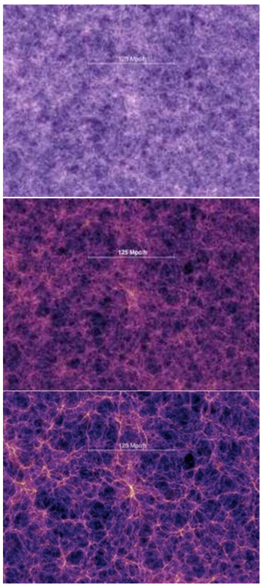
Wayne Hu

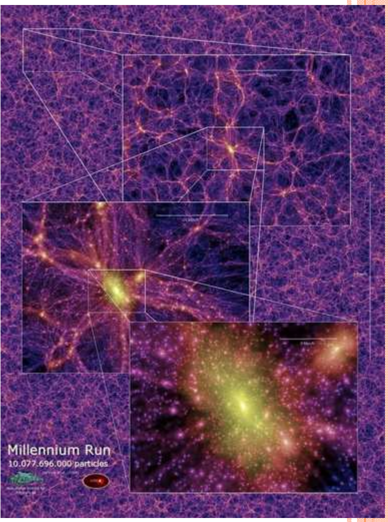
LARGE SCALE STRUCTURE

Relativistic (**hot**) dark matter makes structure top-down—non-relativistic (**cold**) bottom-up.

Real world looks like **cold** dark matter.

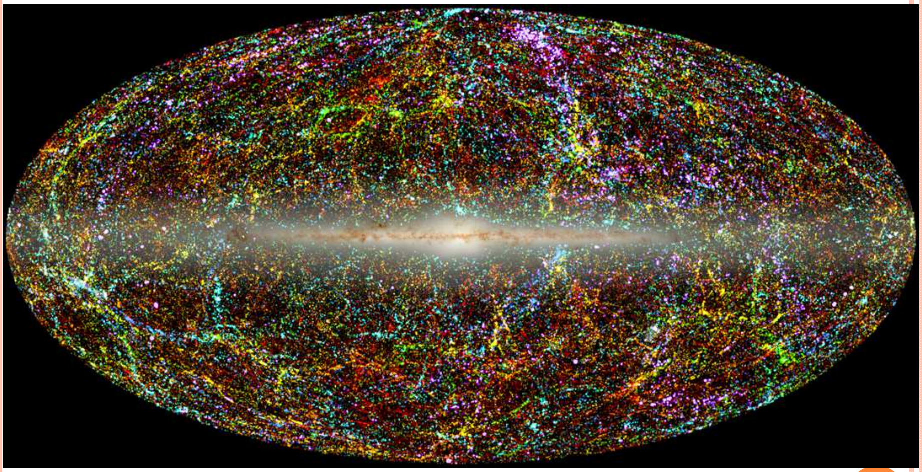






VIRGO Consortium
Millennium Simulation
http://www.mpa-garching.mpg.de/galform/millennium/

2MASS Galaxy Survey



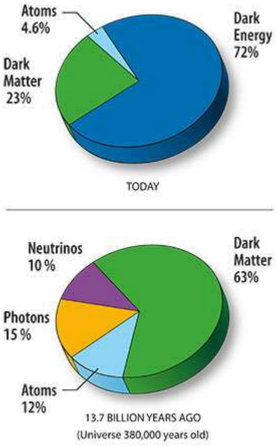
Local galaxies ($z < 0.1$; distance coded by colour, from blue to red)

Statistical studies, e.g. correlation functions, confirm visual impression that this looks much more like cold than hot dark matter

Brief Summary of Astrophysical Evidence

- Many observables concur that $\Omega_{m0} \approx 0.3$
- Most of this must be non-baryonic
  - BBN and CMB concur that baryonic matter contributes $\Omega_{b0} \approx 0.05$
  - Bullet Cluster mass distribution indicates that dark matter is collisionless
- No Standard Model candidate
  - neutrinos are too light, and are “hot” (relativistic at decoupling)
    - hot dark matter does not reproduce observed large-scale structure

→ *BSM physics*



DARK MATTER

Astrophysical Evidence

Candidates

Detection

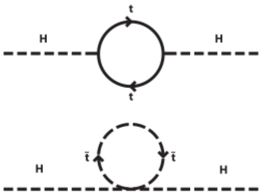
DARK MATTER CANDIDATES

	WIMPs	SuperWIMPs	Light $\tilde{G}$	Hidden DM	Sterile ν	Axions
Motivation	GHP	GHP	GHP/NPFP	GHP/NPFP	ν Mass	Strong CP
Naturally Correct Ω	Yes	Yes	No	Possible	No	No
Production Mechanism	Freeze Out	Decay	Thermal	Various	Various	Various
Mass Range	GeV-TeV	GeV-TeV	eV-keV	GeV–TeV	keV	μeV–meV
Temperature	Cold	Cold/Warm	Cold/Warm	Cold/Warm	Warm	Cold
Collisional				√		
Early Universe		√√		√		
Direct Detection	√√			√		√√
Indirect Detection	√√	√		√	√√	
Particle Colliders	√√	√√	√√	√		

GHP = Gauge Hierarchy Problem; NPFP = New Physics Flavour Problem
√ = possible signal; √√ = expected signal

Jonathan Feng, *ARAA* **48** (2010) 495 (highly recommended)

Particle Physics Motivations

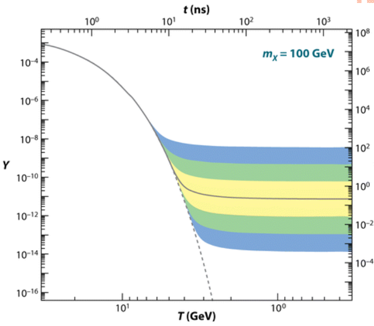


- Gauge Hierarchy Problem
  - in SM, loop corrections to Higgs mass give

$$\Delta m_h^2 \approx \frac{\lambda^2}{16\pi^2}\int^{\Lambda}\frac{d^4p}{p^2} \approx \frac{\lambda^2}{16\pi^2}\Lambda^2$$

    and there is no obvious reason why $\Lambda \neq M_{\mathrm{Pl}}$
    - (Planck mass $M_{\mathrm{Pl}} = (\hbar c/G)^{1/2} \approx 1.2\times10^{19}$ GeV = mass scale for quantum gravity)
    - supersymmetry fixes this by introducing a new set of loop corrections that cancel those from the SM
    - new physics at TeV scale will also fix it (can set $\Lambda \sim 1$ TeV)
- New Physics Flavour Problem
  - we observe conservation or near-conservation of B, L, CP
    - and do not observe flavour-changing neutral currents
  - new physics has a nasty tendency to violate these
    - can require fine-tuning or new discrete symmetries, e.g. *R*-parity

WIMPs



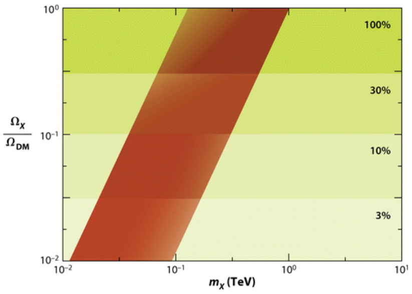
Feng JL. 2010.
Annu. Rev. Astron. Astrophys. 48:495–545

- Weakly Interacting Massive Particles
  - produced thermally in early universe
  - annihilate as universe cools, but "freeze out" when density drops so low that annihilation no longer occurs with meaningful rate
    - "target volume" per particle in time Δt is $\sigma_A v \Delta t$, where σ_A is cross-section
    - so annihilation rate is $n_f\langle\sigma_A v\rangle$ where n_f is number density
  - freeze-out occurs when $H \approx n_f\langle\sigma_A v\rangle$, and in radiation era we have $H \propto T^2/M_{Pl}$ (because $\rho \propto T^4$ and $G \propto 1/M_{Pl}^2$)
  - can estimate relic density by considering freeze-out

$$n_f \approx (m_X T_f)^{3/2} e^{-m_X/T_f} \approx \frac{T_f^2}{M_{Pl}\langle\sigma_A v\rangle}$$

WIMP RELIC DENSITY

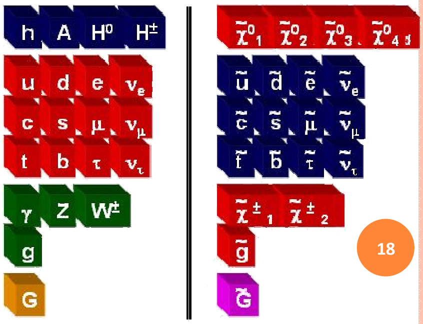
- Converting to Ω gives $$\Omega_\chi = \frac{m_\chi n_0}{\rho_c} \approx \frac{m_\chi T_0^3}{\rho_c}\frac{n_f}{T_f^3} \approx \frac{x_f T_0^3}{\rho_c M_{Pl}}\langle\sigma_A v\rangle^{-1}$$ where $x_f = m_\chi/T_f$
  - and typically $\langle\sigma_A v\rangle \propto 1/m_\chi^2$ or v^2/m_χ^2 (S or P wave respectively)
- Consequence: weakly interacting massive particles with electroweak-scale masses "naturally" have reasonable relic densities
  - and therefore make excellent dark matter candidates



Feng JL. 2010.
Annu. Rev. Astron. Astrophys. 48:495–545

SUPERSYMMETRY (SUSY)

- Extension to Standard Model in which all fermions have partner particles that are bosons, and vice versa
  - if this were an exact symmetry we'd see twice as many particles
    - therefore it is a "broken" symmetry—sparticles much more massive than SM particles
- Slightly extended "normal" particle content
  - need to generate SUSY masses leads to extra Higgs particles
- Some SUSY particles are mixed states
  - neutralinos χ are mixed partners of Z, γ, h and H



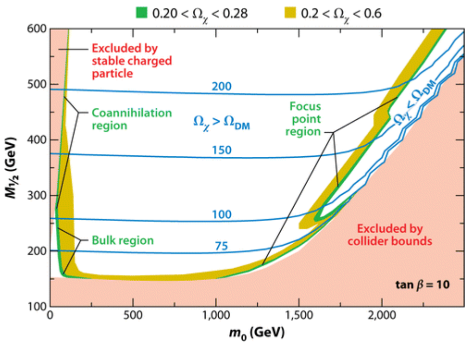
Supersymmetric WIMPs

- Supersymmetry solves the GHP by introducing cancelling corrections
  - predicts a complete set of new particles
    - well-defined interactions, but unknown masses (10 GeV – few TeV)
  - NPFP often solved by introducing *R*-parity—new discrete quantum number
    - then lightest supersymmetric particle is stable
    - best DM candidate is lightest neutralino (mixed spartner of W^0, B, H, h)
  - far too many free parameters in most general supersymmetric models
    - so usually consider constrained models with simplifying assumptions
    - most common constrained model: mSUGRA
      - parameters m_0, $M_{1/2}$, A_0, tan β, sign(μ)
    - mSUGRA neutralino is probably the best studied DM candidate

SUSY WIMPs

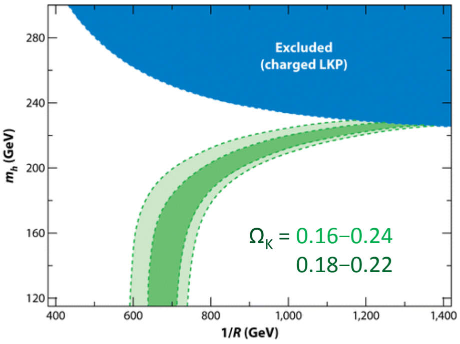
this means that particle = antiparticle

- Neutralinos are Majorana fermions and therefore self-annihilate
  - Pauli exclusion principle implies that $\chi_1\chi_1$ annihilation prefers to go to spin 0 final state
  - $f\bar{f}$ prefers spin 1
    - therefore annihilation cross-section is suppressed
    - hence Ω_χ tends to be too high
    - parameter space **very** constrained by WMAP

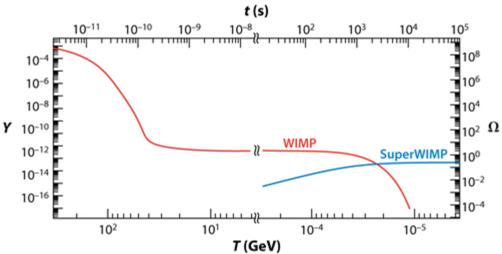


KALUZA-KLEIN WIMPS

- In extra-dimension models, SM particles have partners with the *same* spin
  - “tower” of masses separated by R^{-1}, where R is size of compactified extra dimension
  - new discrete quantum number, *K*-parity, implies lightest KK particle is stable
    - this is the potential WIMP candidate
    - usually B^1
  - annihilation not spin-suppressed (it’s a boson), so preferred mass higher



SUPERWIMPS

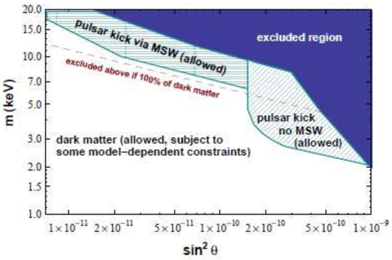


- Massive particles with superweak interactions
  - produced by decay of metastable WIMP
    - because this decay is superweak, lifetime is very long (10^3–10^7 s)
    - WIMP may be neutralino, but could be charged particle
      - dramatic signature at LHC (stable supermassive particle)
  - candidates:
    - weak-scale gravitino
    - axino
    - equivalent states in KK theories
- these particles cannot be directly detected, but indirect-detection searches and colliders may see them
  - they may also have detectable astrophysical signatures

LIGHT GRAVITINOS

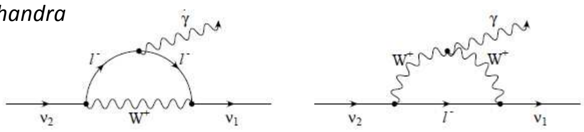
- Expected in gauge-mediated supersymmetry breaking
  - in these models gravitino has $m < 1$ GeV
    - neutralinos decay through $\gamma\tilde{G}$, so cannot be dark matter
  - gravitinos themselves are possible DM candidates
    - but tend to be too light, i.e. too warm, or too abundant
    - relic density in minimal scenario is $\Omega_{\tilde{G}} \approx 0.25\ m_G/(100\ \text{eV})$
      - so require $m_G < 100$ eV for appropriate relic density
      - but require $m_G > 2$ keV for appropriate large-scale structure
  - models which avoid these problems look contrived

Kusenko, DM10



STERILE NEUTRINOS

- Seesaw mechanism for generating small ν_L masses implies existence of massive right-handed sterile states
  - usually assumed that $M_R \approx M_{GUT}$, in which case sterile neutrinos are not viable dark matter candidates
  - but smaller Yukawa couplings can combine with smaller M_R to produce observed ν_L properties together with sterile neutrino at keV mass scale—viable dark matter candidate
    - such a sterile neutrino could also explain observed high velocities of pulsars (asymmetry in supernova explosion generating "kick")
    - these neutrinos are not entirely stable: $\tau >> 1/H_0$, but they do decay and can generate X-rays via loop diagrams—therefore potentially detectable by, e.g., *Chandra*



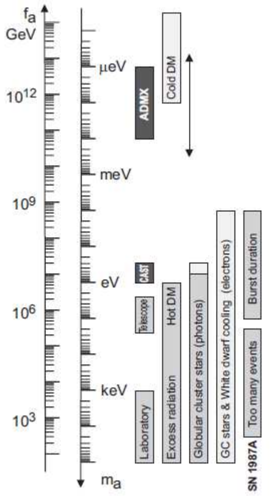
STERILE NEUTRINOS

- Production mechanisms
  - oscillation at $T \approx 100$ MeV
    - $\Omega_\nu \propto \sin^2 2\vartheta\, m^{1.8}$ from numerical studies
    - always present: requires small mass and very small mixing angle
      - not theoretically motivated: some fine tuning therefore required
  - resonant neutrino oscillations
    - if universe has significant lepton number asymmetry, $L > 0$
  - decays of heavy particles
    - e.g. singlet Higgs driving sterile neutrino mass term
- Observational constraints
  - X-ray background
  - presence of small-scale structure
    - sterile neutrinos are “warm dark matter” with Mpc free-streaming

AXIONS

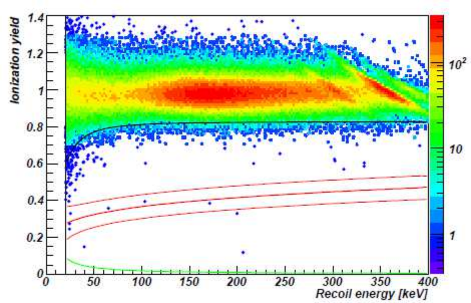
- Introduced to solve the “strong CP problem”
  - SM Lagrangian includes CP-violating term which should contribute to, e.g., neutron electric dipole moment
    - neutron doesn’t appear to *have* an EDM ($<3\times10^{-26}$ e cm, cf. naïve expectation of 10^{-16}) so this term is strongly suppressed
  - introduce new pseudoscalar field to kill this term (Peccei-Quinn mechanism)
    - result is an associated pseudoscalar boson, the axion
- Axions are extremely light (<10 **m**eV), but are cold dark matter
  - not produced thermally, but via phase transition in very early universe
    - if this occurs before inflation, visible universe is all in single domain
    - if after inflation, there are many domains, and topological defects such as axion domain walls and axionic strings may occur

AXIONS



Georg Raffelt, hep-ph/0611350v1

- Axion mass is $m_a \approx 6\ \mu\text{eV} \times f_a/(10^{12}\ \text{GeV})$ where f_a is the unknown mass scale of the PQ mechanism
- Calculated relic density is $\Omega_a \approx 0.4\ \vartheta^2\ (f_a/10^{12}\ \text{GeV})^{1.18}$ where ϑ is initial vacuum misalignment
  - so need $f_a < 10^{12}$ GeV to avoid overclosing universe
  - astrophysical constraints require $f_a > 10^9$ GeV
  - therefore $6\ \mu\text{eV} < m_a < 6\ \text{meV}$



DARK MATTER

Astrophysical Evidence

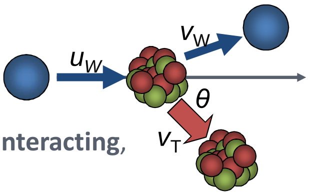
Candidates

Detection

Detection of Dark Matter Candidates

- Direct detection
  - dark matter particle interacts in your detector and you observe it
- Indirect detection
  - you detect its decay/annihilation products or other associated phenomena
- Collider phenomenology
  - it can be produced at, say, LHC and has a detectable signature
- Cosmology
  - it has a noticeable and characteristic impact on BBN or CMB
- Focus here on best studied candidates—WIMPs and axions

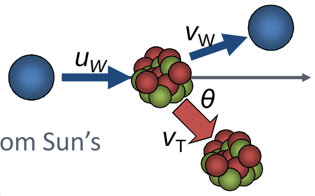
Direct Detection: WIMP-Nucleus Interaction



- Key points:
  - it doesn't happen very often: **Weakly Interacting**, remember?
  - it is **non-relativistic**: WIMPs are bound in Galactic halo, so have velocities ~220 km/s ($v/c \sim 10^{-3}$)
  - it is **elastic scattering**—momentum and KE conserved
- If we assume that spin plays no role, we can model this as collision of two hard spheres of masses M_W, M_T
  - we find that $v_T = \dfrac{2M_W}{M_W + M_T} u_W \cos\theta$
    - assuming nucleus initially at rest, $u_T = 0$
    - maximal for head-on scattering ($\cos\theta = 1$), and for $M_W = M_T$
    - u_W and its likely direction can be calculated by modelling the halo

de Broglie wavelength of particle with 1 TeV mass is $h/p \approx 10^{-15}$ m ≈ nuclear radius

WIMP-NUCLEUS INTERACTION



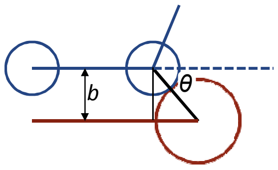
- Basic numbers:
  - local density of DM can be deduced from Sun’s orbital velocity via

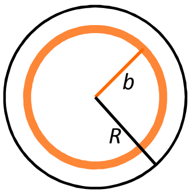
$$\rho(R_{Sun}) = \frac{1}{4\pi R_{Sun}^2}\frac{dM_r}{dr}\bigg|_{R_{Sun}} = \frac{1}{4\pi R_{Sun}^2}\frac{V^2}{G}$$

  - this gives 0.3–0.5 GeV/cm^3 depending on exactly what you assume for V and R_{sun} (neither of which is very well known)
  - WIMP rest energy expected to be in range 10–1000 GeV
    - so, between 0.3 and 50 particles per litre in solar neighbourhood
    - note that this assumes halo is an isothermal sphere—it might not be!
  - Kinetic energy of WIMP $\frac{1}{2}M_W V^2 \approx 2.7$–270 keV if $V \sim 220$ km/s
    - best case scenario: **all** of this transferred to nucleus—but this will not normally happen (requires $\cos\theta = 1$ *and* $M_W = M_T$)

WIMP-NUCLEUS INTERACTION: ENERGY SPECTRUM

- Scattering angle depends on impact parameter *b*
  - $\sin\theta = b/(R_W + R_T) = b/R$
  - Probability of impact parameter between b and $b + db$ is area of shaded region divided by total area $= 2\pi b\,db / \pi R^2 = (2b/R^2)\,db$





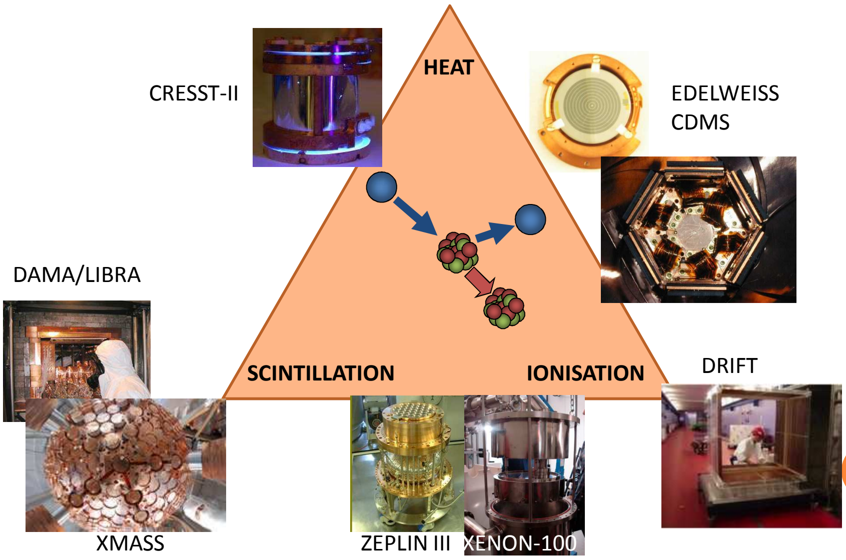
- Transferred energy is $\frac{1}{2}M_T v_T^2 = E_T$ where

$$E_T = \frac{M_T M_W}{(M_T + M_W)^2} E_W \cos^2\theta$$

- $P(\cos^2\theta) = P(b)/|d(\cos^2\theta)/db| = 1$
- *All values of recoil energy are equally likely*
  - and for a given halo model the only unknown is M_W

DIRECT DETECTION OF WIMPS

Basic principle: WIMP scatters elastically from nucleus; experiment detects nuclear recoil



HEAT

SCINTILLATION

IONISATION

CRESST-II

EDELWEISS
CDMS

DAMA/LIBRA

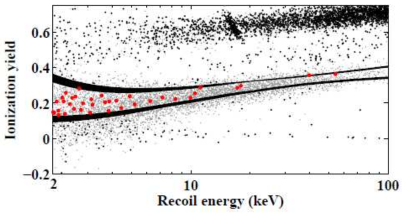
XMASS

ZEPLIN III

XENON-100

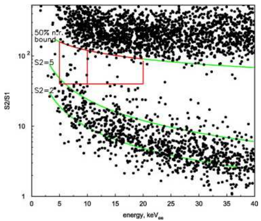
DRIFT

DIRECT DETECTION OF WIMPS



CDMS-II, *PRL* **106** (2011) 131302

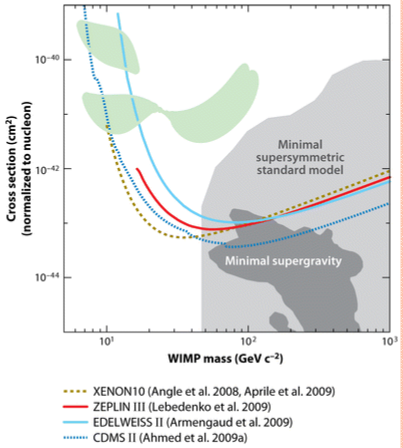
- Backgrounds
  - cosmics and radioactive nuclei (especially radon)
    - use deep site and radiopure materials
    - use discriminators to separate signal and background
- Time variation
  - expect annual variation caused by Earth's and Sun's orbital motion
    - small effect, ~7%
    - basis of claimed signal by DAMA experiment
  - much stronger diurnal variation caused by changing orientation of Earth
    - "smoking gun", but requires directional detector
    - current directional detector, DRIFT, has rather small target mass (being gaseous)—hence not at leading edge of sensitivity



ZEPLIN-II, *Astropart. Phys.* **28** (2007) 287

DIRECT DETECTION OF WIMPS

- Interaction with nuclei can be spin-independent or spin-dependent
  - spin-dependent interactions require nucleus with net spin
  - most direct detection experiments focus on SI, and limits are much better in this case
- Conflict between DAMA and others tricky to resolve
  - requires very low mass and high cross-section
    - if real, may point to a non-supersymmetric DM candidate



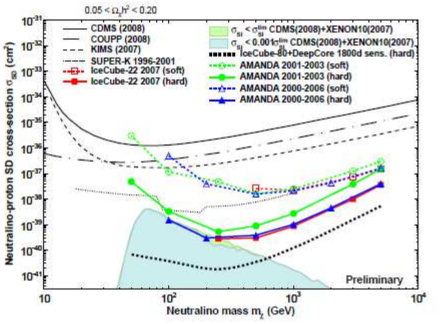
Feng JL. 2010. Annu. Rev. Astron. Astrophys. 48:495–545 DMTools (Butler/Desai)

INDIRECT DETECTION OF WIMPS

- After freeze-out, neutralino self-annihilation is negligible in universe at large
  - but neutralinos can be captured by repeated scattering in massive bodies, e.g. Sun, and this will produce a significant annihilation rate
    - number of captured neutralinos $N = C - AN^2$ where C is capture rate and A is $\langle \sigma_A v \rangle$ per volume
    - if steady state reached, annihilation rate is just $C/2$, therefore determined by scattering cross-section
  - annihilation channels include W^+W^-, $b\bar{b}$, $\tau^+\tau^-$, etc. which produce secondary neutrinos
    - these escape the massive object and are detectable by neutrino telescopes

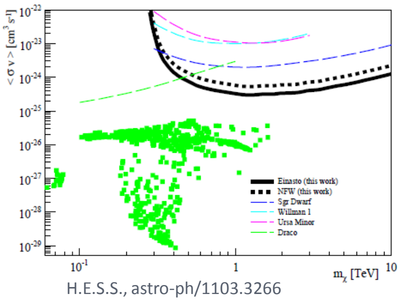
INDIRECT DETECTION OF WIMPS

- Relatively high threshold of neutrino telescopes implies greater sensitivity to “hard” neutrinos, e.g. from WW



Braun & Hubert, 31st ICRC (2009): astro-ph/0906.1615

- Also possible that neutralinos might collect near Galactic centre
  - in this region other annihilation products, e.g. γ-rays, could escape

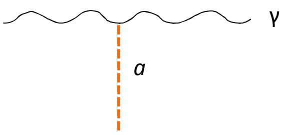


H.E.S.S., astro-ph/1103.3266

- search by H.E.S.S. found nothing
- signals at lower energies could be astrophysical not astroparticle

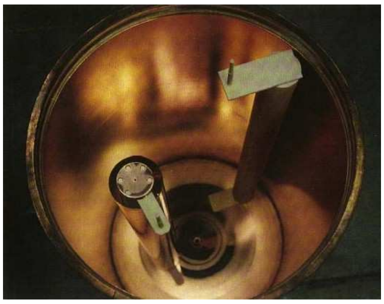
LHC DETECTION OF WIMPS AND SWIMPS

- WIMPs show up at LHC through missing-energy signature
  - note: not immediate proof of dark-matter status
    - long-lived but not stable neutral particle would have this signature but would not be DM candidate
    - need to constrain properties enough to calculate expected relic density if particle *is* stable, then check consistency
- SuperWIMP parents could also be detected
  - if charged these would be spectacular, because of extremely long lifetime
    - very heavy particle exits detector without decaying
      - if seen, could in principle be trapped in external water tanks, or even dug out of cavern walls (Feng: “new meaning to the phrase ‘data mining’”)
  - if neutral, hard to tell from WIMP proper
    - but mismatch in relic density, or conflict with direct detection, possible clues

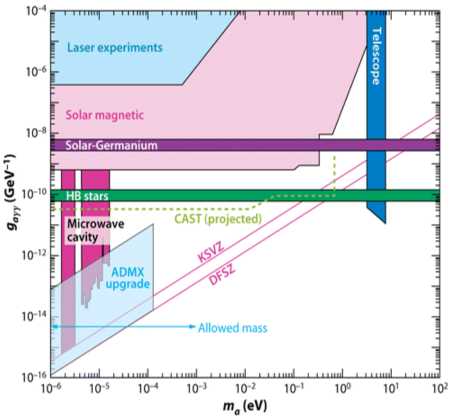


AXION DETECTION

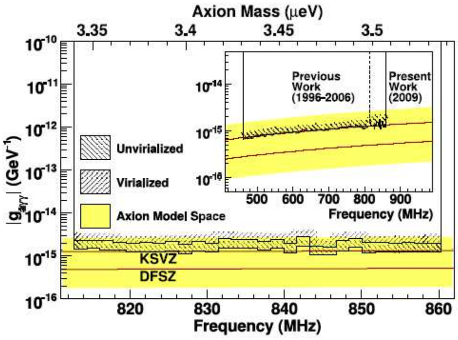
- Axions couple (unenthusiastically) to photons via $\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a\, \mathbf{E}\cdot\mathbf{B}$
  - they can therefore be detected using Primakoff effect (resonant conversion of axion to photon in magnetic field)
  - ADMX experiment uses very high *Q* resonant cavity in superconducting magnet to look for excess power
    - this is a scanning experiment: need to adjust resonant frequency to "see" specific mass (*very* tedious)
  - alternative: look for axions produced in Sun (CAST)
    - non-scanning, but less sensitive

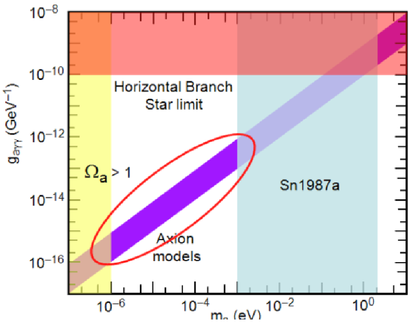


AXION DETECTION



Feng JL. 2010.
Annu. Rev. Astron. Astrophys. 48:495–545





DARK MATTER: SUMMARY

- Astrophysical evidence for dark matter is consistent and compelling
  - not an unfalsifiable theory—for example, severe conflict between BBN and WMAP on Ω_b might have scuppered it
- Particle physics candidates are many and varied
  - and in many cases are not *ad hoc* inventions, but have strong independent motivation from within particle physics
- Unambiguous detection is possible for several candidates, but will need careful confirmation
  - interdisciplinary approaches combining direct detection, indirect detection, conventional high-energy physics and astrophysics may well be required

THE END