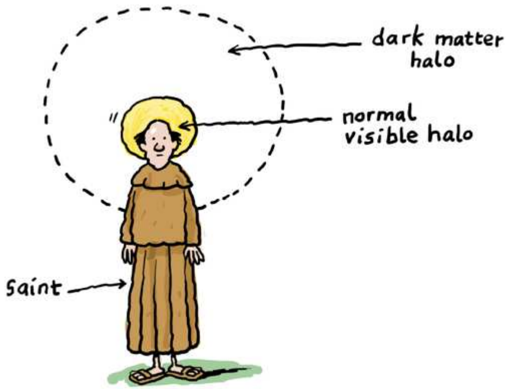
The University Of Sheffield.



ASTROPARTICLE PHYSICS LECTURE 4

Susan Cartwright
University of Sheffield

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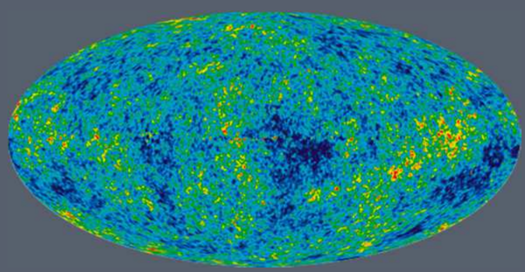


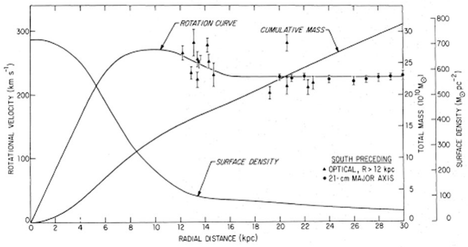
DARK MATTER

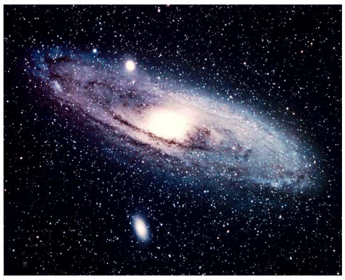
Astrophysical Evidence
Candidates
Detection

2

The Astrophysical Evidence

- Rotation curves of spiral galaxies



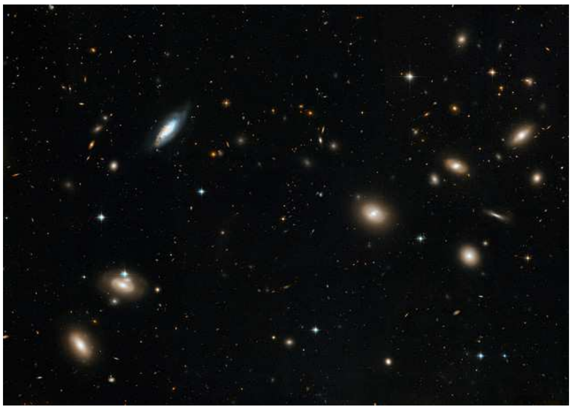


  - flat at large radii: if mass traced light we would expect them to be Keplerian at large radii, $v \propto r^{-1/2}$, because the light is concentrated in the central bulge
    - and disc light falls off exponentially, not $\propto r^{-2}$ as required for flat rotation curve

3

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



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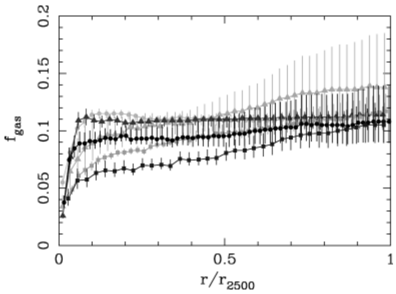
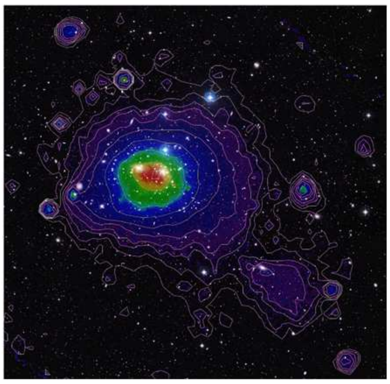
The Astrophysical Evidence

- 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

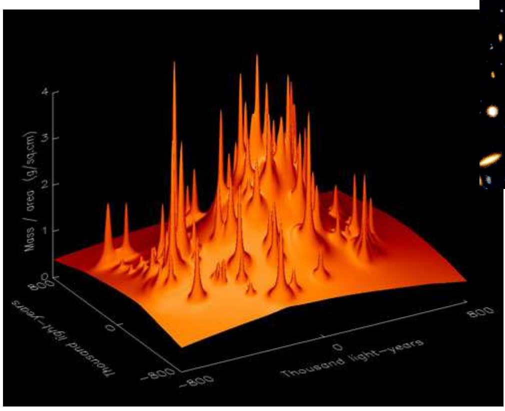


ROSAT X-ray image of Coma cluster overlaid on optical.
MPI (ROSAT image);
NASA/ESA/DSS2 (visible image)

5

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

6

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.

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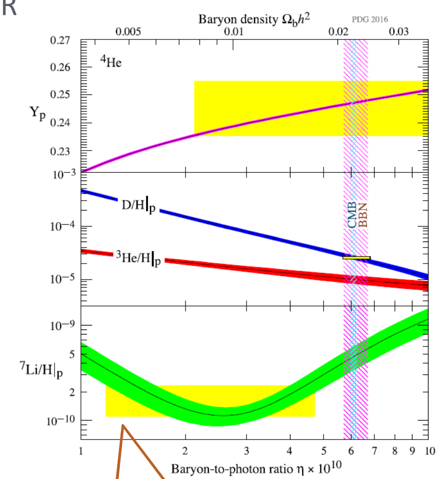
Non-Baryonic Dark Matter

- 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

PDG review

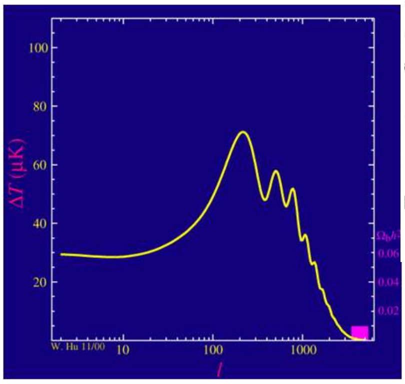


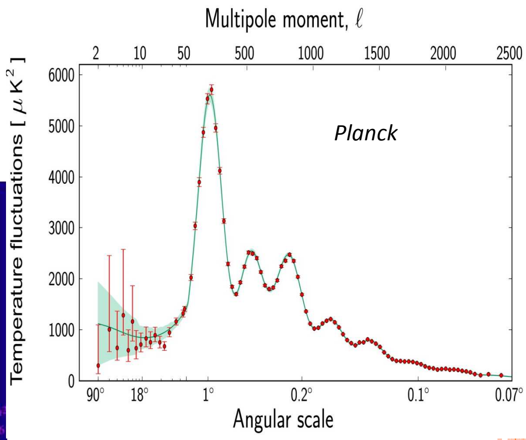
"The lithium problem": possible new physics??

8

NON-BARYONIC DARK MATTER: COSMOLOGY

Ratio of odd/even peaks depends on Ω_b





Wayne Hu

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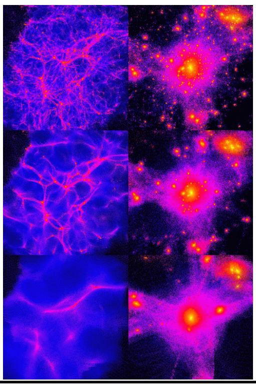
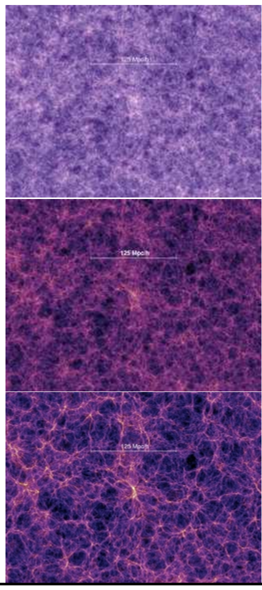
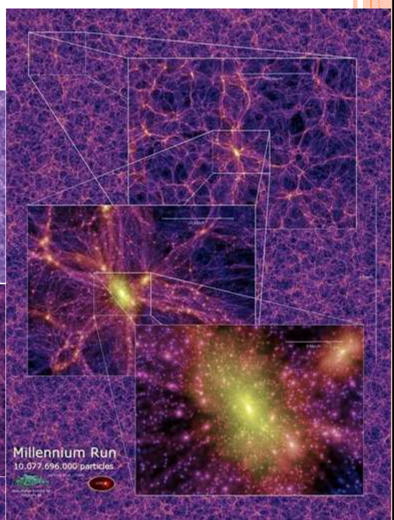
LARGE SCALE STRUCTURE

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/

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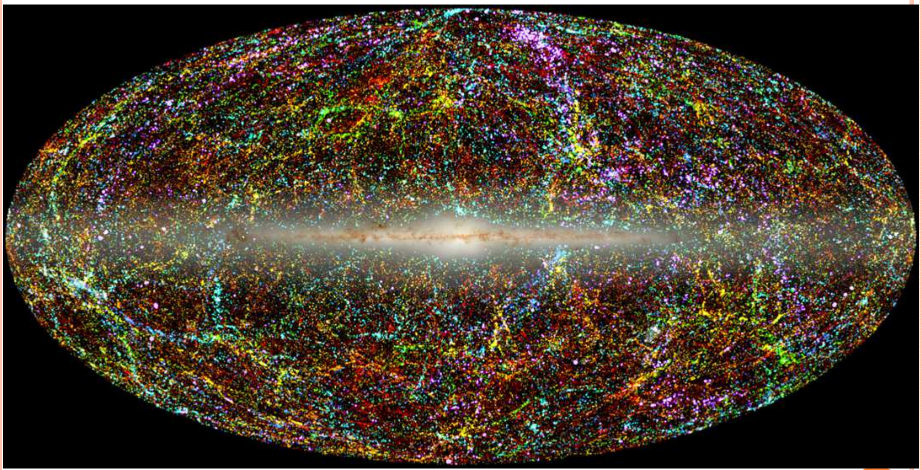
2MASS Galaxy Survey



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

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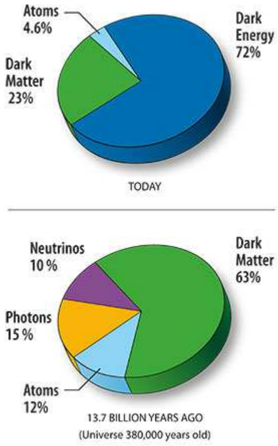
Brief Summary of Astrophysical Evidence

- 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*



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Dark Matter

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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)

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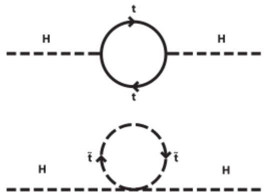
PARTICLE PHYSICS MOTIVATIONS



- 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 $\Lambda \neq M_{Pl}$
    - 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

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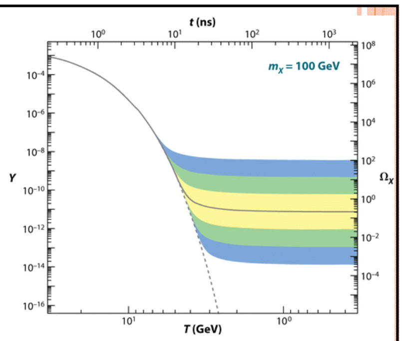
WIMPS



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

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

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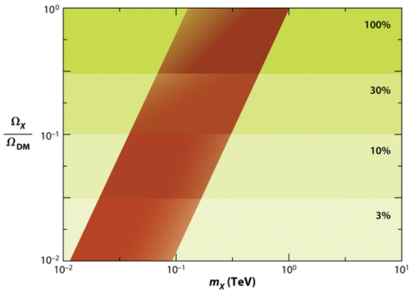
WIMP Relic Density

- Converting to Ω gives $\Omega_X = \frac{m_X n_0}{\rho_c} \approx \frac{m_X T_0^3}{\rho_c} \frac{n_f}{T_f^3} \approx \frac{x_f T_0^3}{\rho_c M_{Pl}} \langle \sigma_A v \rangle^{-1}$ where $x_f = m_X/T_f$
  - and typically $\langle \sigma_A v \rangle \propto 1/m_X^2$ or v^2/m_X^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

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Supersymmetric WIMPs

- Supersymmetry solves the GHP by introducing cancelling corrections
  - predicts a complete set of new particles
  - 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

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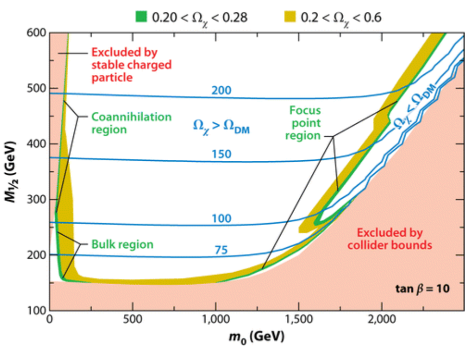
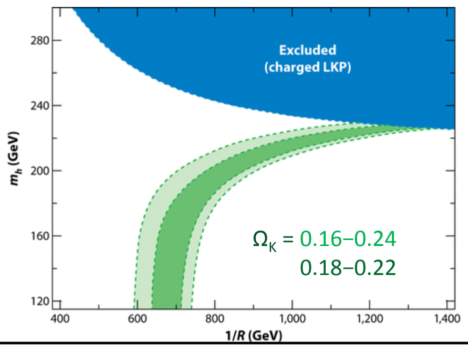
SUSY WIMPs

- 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

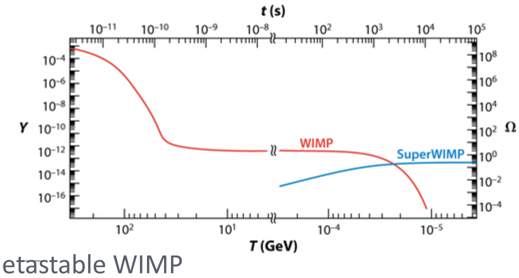


KALUZA-KLEIN WIMPs

- 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

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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

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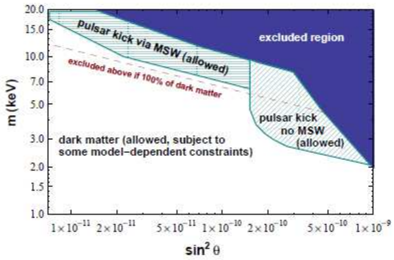
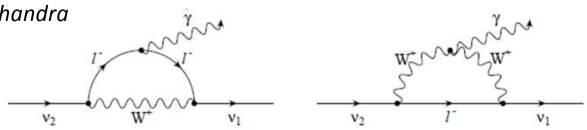
Kusenko, DM10



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*



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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

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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

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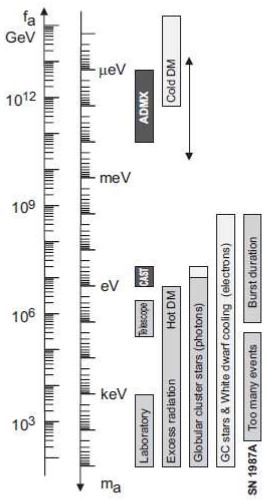
Axions



Georg Raffelt, hep-ph/0611350v1

- Axion mass is $m_a \approx 6$ μeV $\times f_a/(10^{12}$ 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 μeV $< m_a <$ 6 meV

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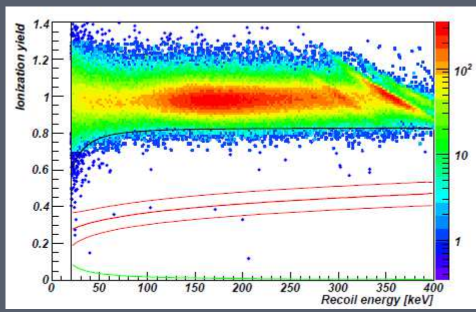

Dark Matter

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- 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

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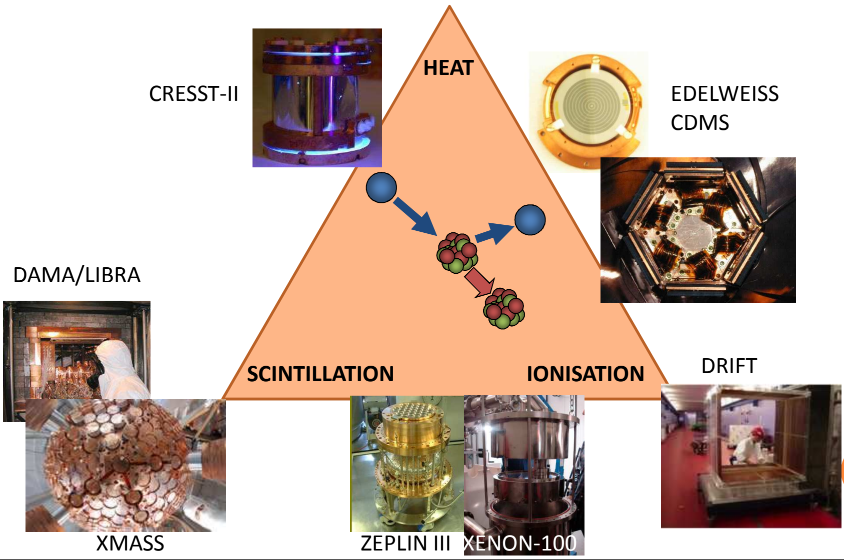
Direct Detection of WIMPs

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



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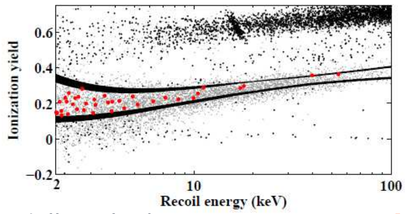
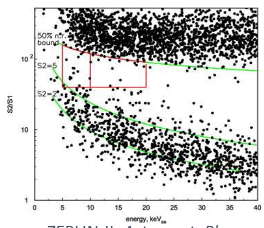
Direct Detection of WIMPs



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

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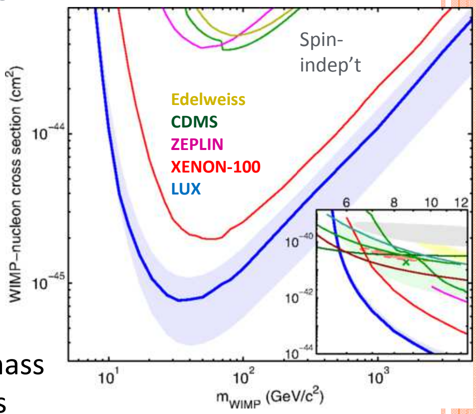
Direct Detection of WIMPs

Signals in inset: CoGeNT; CDMS; CRESST; DAMA/LIBRA

- 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
- Some claimed signals at low mass inconsistent with others' limits
  - requires very low mass and high cross-section
    - if real, may point to a non-supersymmetric DM candidate



Akerib et al., *PRL* **112** 091303
DMTools (Butler/Desai)

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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

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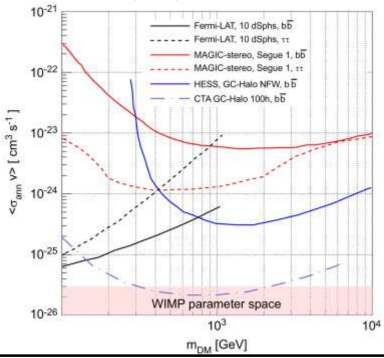
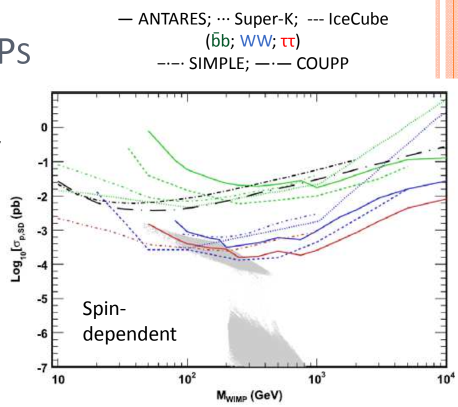
Indirect Detection of WIMPs

- Relatively high threshold of neutrino telescopes implies greater sensitivity to "hard" neutrinos, e.g. from WW
- Also possible that neutralinos might collect near Galactic centre

Doro, *NIMPA* **742** (2014) 99





Zornoza & Lambard, *NIMPA* **742** (2014) 173

- in this region other annihilation products, e.g. γ-rays, could escape
- Limits from Fermi-LAT, MAGIC, H.E.S.S. not yet reaching expected signal, but CTA could come close

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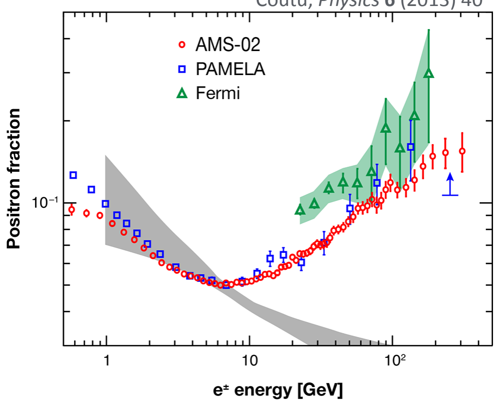
Indirect Detection of WIMPs

Coutu, *Physics* **6** (2013) 40



- Various experiments see positron fraction in cosmic rays rising with energy (unexpectedly)
  - This *could* be a signal of χχ annihilation
  - But there are also potential astrophysical sources, e.g. pulsar wind nebulae, microquasars
  - And there are no signals for γ-ray excess, which we might expect

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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

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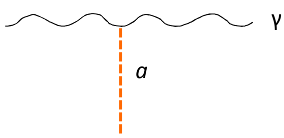
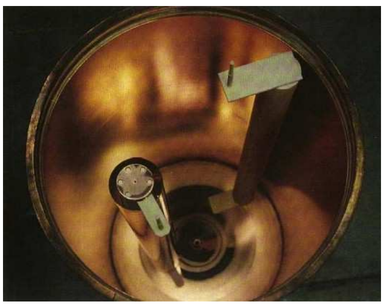
Axion Detection



- 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

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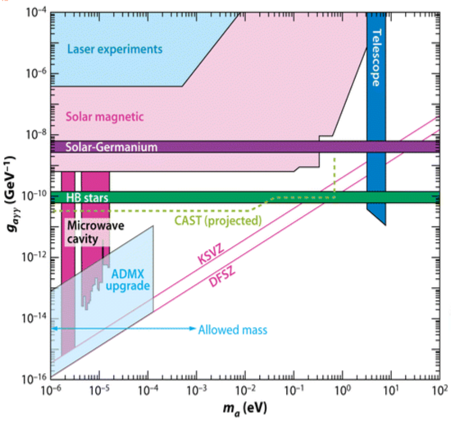
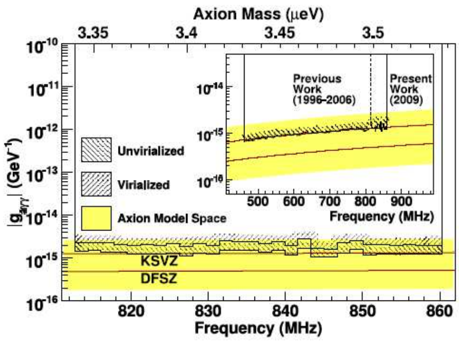
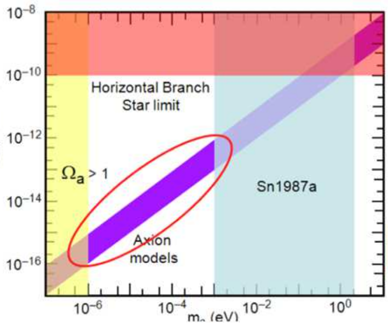
AXION DETECTION



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





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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

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THE END

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