Dark Matter Candidates

95 orders of magnitude uncertainty

- and it's worse than that!
- but we do have good clues
Dark Matter in General
What are its Properties?

- Dark matter required to explain galaxy potentials
- Newtonian gravity from luminous / baryonic material does not explain structures larger than kpc in size
- Dark matter must not have other (as yet) observable effects
- What properties are implied by these few requirements?
  - mass
  - interaction strength
  - density – this we know well

- Optically dark
  - unobserved (yet) from radio to gamma-rays
- Collisionless
  - mean free path for self-interaction > kpc
- Cold
  - non-relativistic at epoch of matter-radiation equality
- Fluid
  - dwarf galaxies $1e8 \ M_{\odot}$
  - discreteness issues
- Dust-like
  - pressureless at scales > kpc
# Dark Matter Properties I

- **Optically dark**
  - electromagnetic interactions must be very weak
  - charge, dipole moments small
  - OR
  - particles very heavy
  - this is not hard – zero charge is certainly allowed

- **Collisionless**
  - At kpc scales – self-interaction cross sections < barn for GeV
  - this is also not hard

- **Cold**
  - thermal relics must be more massive than keV to satisfy this
  - non-thermal relics are unconstrained

- **Fluid**
  - For 1e5 - 1e6 solar mass particles, galactic disks are heated too much – discreteness of dark matter is a problem
  - For 1e4 solar mass particles – poisson noise in power spectrum of density fluctuations
Dark Matter Properties II

- **Dust-like**
  - pressure support of any kind
  - quantum mechanics!
  - galactic velocities are 300 km/s
  - DeBroglie wavelength < kpc – particles must be localized in galaxies
  - 1e-23 eV – yes, electron-volts

- **Summary of mass range**
  - 1e6 solar masses = 2e39 g
  - 1e-23 eV = 1e-56 g
  - 95 orders of magnitude!
  - can this be right? alas yes.
  - only 70 for thermal relics!

- **OK, so no luck so far in constraining the mass**
- All we know about interaction cross sections is that they can't be very large
- Luckily, we do know something
  - density of cold dark matter is well known
  - CMB (e.g. WMAP)
  - LSS (e.g. SDSS)
  - BBN + cluster baryon fraction
  \[ \Omega_{\text{CDM}} h^2 = 0.113^{+0.008}_{-0.009} \ (7-8\%) \]
  \[ \rho = 1.19 \ h^2 \ \text{GeV m}^{-3} \]
Dark Matter Candidates - A Terribly Incomplete Survey

- Thermal Relics – equilibrium at early times
  - SUSY – neutralino
  - SUSY – gravitino
  - Neutrino
    - standard model + “sterile”
    - right-handed
- Non-thermal Relics – everything else
  - Axion
  - Primordial Black Holes
    - Planck mass and larger
  - ???

- This list is by no means complete – I will focus on several classes
  - SUSY is perhaps the favored source of dark matter candidates
  - Axions are the favored solution to the strong CP problem
  - Neutrinos are the least good candidate, but are known to actually exist
  - Primordial black holes are a possibility – difficult to form

- There is a dirty little secret – if it’s relevant it’s more interesting than dark matter
Thermal Relics I

- Thermal equilibrium in the early-enough universe
- Interaction rate becomes smaller than expansion rate – freeze-out
- Calculation of the relic density is straightforward – Boltzmann equation
  \[
  \frac{dn}{dt} + 3H n = -\langle \sigma v \rangle (n^2 - n_{eq}^2)
  \]
- Relativistic particles in equilibrium have \( n \sim T^3 \) - same as out of equilibrium
  - relic density insensitive to details of freeze-out
- Non-relativistic particles are Boltzmann-suppressed
  - equilibrium density falls exponentially with temperature
- Large annihilation rates – small relic density, etc.
- What is the scaling for relic density vs. cross-section?
  - relativistic freeze-out
    \[
    \Omega h^2 \approx \frac{m}{100 \text{ eV}} \cdot \frac{10}{g^*}
    \]
  - non-relativistic freeze-out
    \[
    \Omega h^2 \sim \left( \frac{m}{\text{TeV}} \right)^2
    \]
- Weak Interaction Scale!

\[ dn = -\langle \sigma v \rangle (n^2 - n_{eq}^2) \]
Illustrate with a simple model for a “neutrino” annihilating through a wide “Z” boson

\[ \sigma v \propto \frac{m^2}{(s-m_Z^2)^2 + m_Z^4} \]

Acceptable regions at 10 eV (hot) and 100 GeV (cold)

Thermal relic of 100 GeV seems a well-motivated candidate

This is intriguing as this is exactly the scale of the weak interaction

Weakly Interacting Massive Particles - WIMPs
Supersymmetry I

- Extend the Standard Model by adding partners to all states – spins differ by $\frac{1}{2}$
- Matter fermions – scalars
- Gauge bosons – spin $\frac{1}{2}$
- Higgs bosons – spin $\frac{1}{2}$
- Graviton – spin 3/2
- SUSY is broken! Breaking at the weak scale solves hierarchy problem
- R-parity imposed – superpartners interact in pairs – lightest is stable
- Neutral superpartners
  - sneutrino
  - neutralino – gauge and Higgs
  - gravitino
  - axino
- Smeutinos have large cross sections – ruled out
- Neutralinos are the favored candidate
- Gravitinos
  - warm dark matter $\sim$ keV
  - SuperWIMPs $\sim$ GeV
- Axinos – hypothetical partner of hypothetical particle
Supersymmetry II

- Minimal Supersymmetric Standard Model – SM + extra Higgs doublet + partners
- More than 100 parameters
- Need some simplification
  - understanding SUSY breaking
- Most parameters are masses and mixings
  - strong constraints from FCNC
- Assumptions required
- Unifications of SUSY parameters at various scales
- Gaugino unification – masses unified at GUT scale
- Scalar unification – masses unified at GUT scale
- Flavor diagonal – no new mixing parameters
- Allow some Higgs freedom – this is only a few parameters
  - MSSM removes one SM parameter
  - Higgs quartic coupling - $g^2$
- Start here, perhaps relax more constraints
Supersymmetry III

- Minimal Supergravity
  - simplest SUSY breaking model
  - 4 parameters + one sign – gaugino mass, scalar mass, trilinear coupling, ratio of Higgs VEVs, sign of Higgs mass term
  - radiative EWSB

- This model has rich phenomenology
- Evolve RGEs between GUT and weak scales
- Gauginos (strong, weak, hypercharge – 6:2:1 in mass)

- Heavy squarks, light sleptons
  - gauge coupling run mass up, Yukawa couplings run it down
  - stau_R usually lightest sfermion

- Insist on neutralino LSP
  - this can be B-ino or Higgsino

- Regions of mSUGRA parameter space with acceptable relic density are special
  - coannihilations with stau
  - “focus point” - Higgsino LSP
  - Higgs resonances

- Perhaps a more general model is favored
Detecting SUSY Dark Matter

- **Accelerator searches – LHC**
  - discovery of superpartners and measurement of properties
  - connection to dark matter requires more
    - must be detected astrophysically
- **Direct detection**
  - deep underground to reduce cosmic ray backgrounds
  - particles in galactic halo – speeds of 300 km / s
  - elastic scattering deposits of order 10 keV
  - MANY experiments with different techniques
- **Neutrino telescopes**
  - WIMPs scatter into bound orbits – settle at the centers of massive objects (Earth, Sun)
  - annihilations greatly enhanced, neutrinos escape
  - AMANDA / IceCube (south pole) ANTARES (Mediterranean)
- **Cosmic / gamma rays**
  - annihilations in galactic halo
  - antiprotons, positrons
  - gamma ray continuum
  - gamma ray line – this is the most convincing signal
Axions

- Strong CP problem – strength of QCD parity violating term (theta) is undetermined
  - measured to be < 1e-9
- Promote coupling to (pseudo) scalar field – PQ symmetry
- This is the axion – drives theta to zero
- Naively it should couple like a neutral pion
- Axions generated in early universe – dark matter
- Mass scale is μeV – meV

- Coupling to 2 photons like pion
  - axion – photon conversion in magnetic field
  - low end of mass scale, these are microwaves
  - use high Q tunable cavities to look for resonant conversion
- Narrow axion line, fractional width 0.001 (300 km / s)
- Resolution is much better than this – study detailed velocity structure of our galactic halo
Neutrinos

- Neutrinos are dark matter!
  - though likely not dominant
- Hot dark matter – strong conflict with LSS
- Three neutrino species, all < few eV
  - tritium beta decay
  - two oscillation mass splittings
- Sterile neutrinos may have relevance for dark matter
- Light (TeV) right handed neutrinos are an acceptable candidate with some assumptions

- keV neutrinos could be warm dark matter – need a sterile state to explain oscillations
- Neutrinos are disfavored now, but perhaps unfairly
  - we know they exist!
  - we don't understand them!
- Precise LSS / CMB data have the potential to measure SM neutrino masses
- We live in a Cold+Hot dark matter universe – the question is how much hot?
Primordial Black Holes

- Forming black holes in the early universe is HARD
- Sound speed ~ light speed
  - gas pressure disallows structure growth
  - sound horizon is almost as large as light horizon
- Phase transitions – sound speed drops (bubble nucl., ...)
  - opportunity to form structures
- QCD phase transition
  - characteristic scale is of order solar mass
- Solar mass black holes can not be all of the dark matter – microlensing limits
- Making the heaviest allowed is difficult
- Lighter may be acceptable – not too light or evaporation timescale is too short
- Planck-scale remnants of evaporation?
- String inspired candidates
  - appropriately lumped here due to ignorance of gravity
The Dirty Little Secret

- Dark matter is postulated because Newtonian gravity fails at scales > dwarf galaxy
- Why not modify gravity at LOW energy?
- MOND - MOdified Newtonian Dynamics
  - accelerations have a fundamental lower bound
- Prescription with one free parameter describes spiral galaxies disturbingly well
- MOND cosmology?
  - many other observations must be explained
- Clusters require a different scale – perhaps the MOND parameter runs
- Gravitational lens mass estimates agree with dynamical ones
  - MOND must affect photons
  - need relativistic theory
- Scalar-tensor theories can have a MOND limit for matter, but they fail for photons
- Scalar-vector-tensor theory (Bekenstein) seems to work
  - cosmology may be acceptable
Conclusions and Outlook

- Dark matter candidates are nearly unconstrained in mass – 95 orders of magnitude allowed
- Cosmological density is the one good measurement – strong hint of new weak scale physics
- Extensive experimental program
  - Accelerator
  - Underground
  - Cosmic Ray
  - Axion search
  - Gravitational Lensing