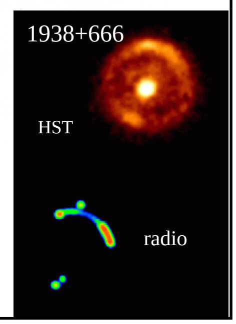
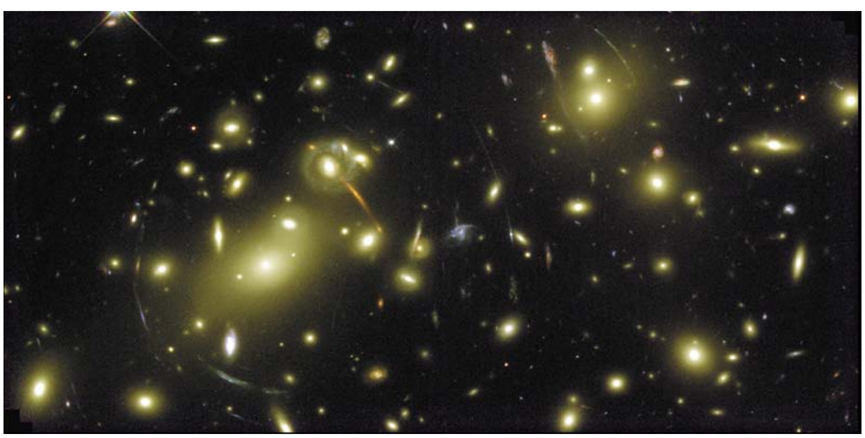
Observations of lensed objects

- Extended background source (e.g. a galaxy)
  - ==> arcs or rings
- Weak lensing: $\theta >> \theta_E$
  - images slightly extended
  - currently being exploited to look for cluster halos, dark galaxies, etc.
- Strong lensing: $\theta < \theta_E$
  - multiple images formed
  - weak central image usually not seen


The “Einstein Cross”

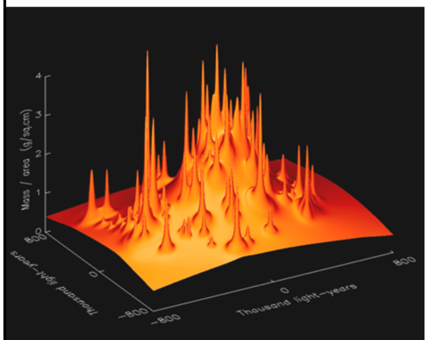


Weak (and not-so-weak) Lensing
Abell 2218



- Foreground cluster distorts images of numerous background galaxies.
- Use to determine total mass of foreground cluster.
- Shows that 85% of mass is Dark Matter.

The Remarkable Case of CL0024+1654



- Single distant blue galaxy
  - $z \sim 1.2 - 1.8$
- Lensed by foreground cluster
  - $z = 0.39$
- 8 different grav. images of blue galaxy.
- Allows detailed analysis of mass distribution in cluster.
- 83% of mass is non-luminous Dark Matter.
- $M/L = 270h$ (390*h* after allowing for stellar evolution to $z = 0$)

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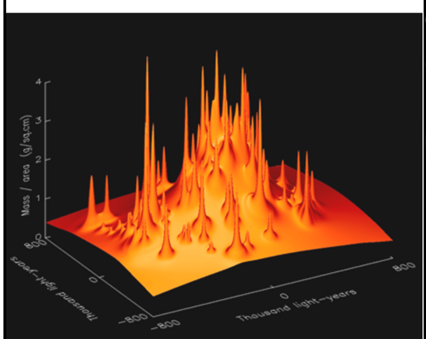

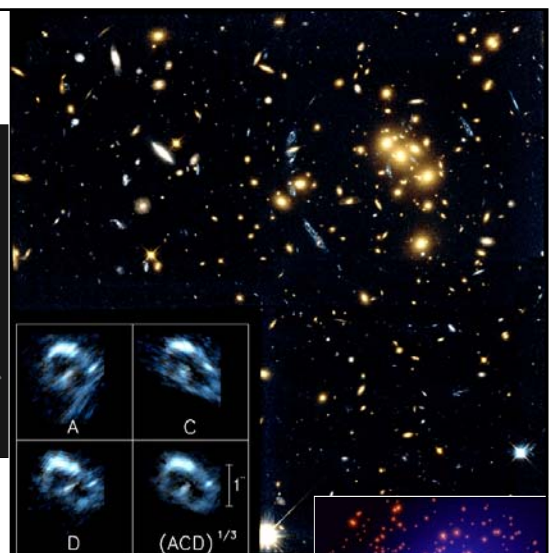

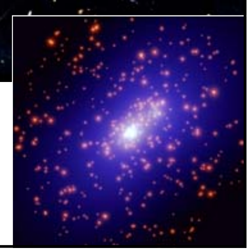

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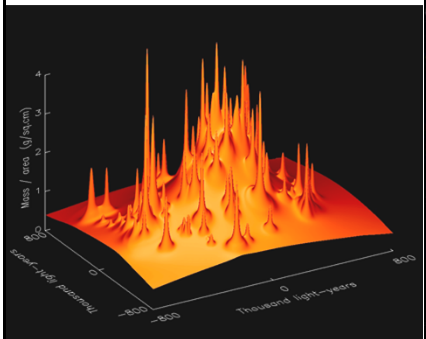
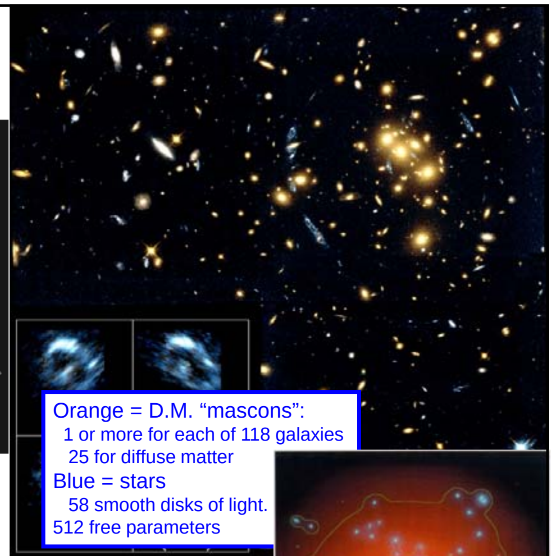
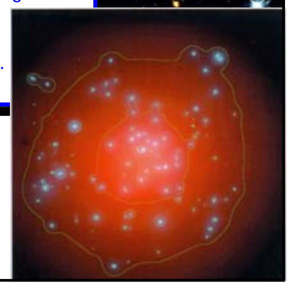




Orange = D.M. “mascons”:
1 or more for each of 118 galaxies
25 for diffuse matter
Blue = stars
58 smooth disks of light.
512 free parameters



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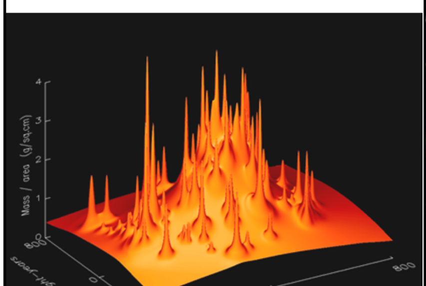

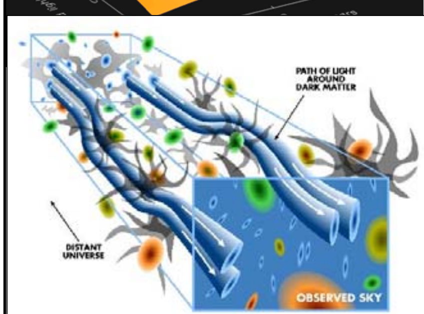

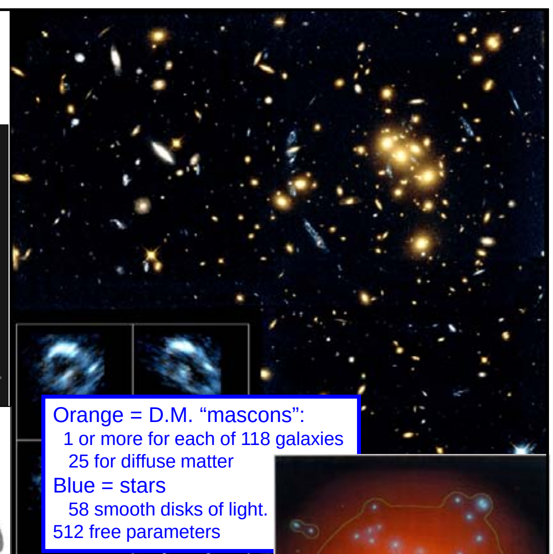

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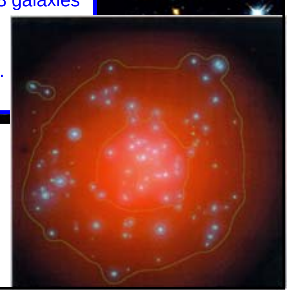


stribution in cluster.
Matter.

Dark Matter

Galaxy clusters, typical values

- 85% Dark Matter
- 15% Normal Matter
  - 14% hot intergalactic gas
  - ~1% stars in galaxies

About 85% of gravitationally interacting matter is invisible.

- Detected solely by its gravitational effects.
- Line of evidence reaching back to Zwicky (1933)
- Baryonic matter constrained by BBN (Big Bang Nucleosynthesis), WMAP
  - $\Omega_B = .04$
  - This includes large component of invisible Baryons
- But $\Omega_{Matter} = 0.27$

What *is* Dark Matter?

CO
pp. 896-898
pp. 1232-1233

Candidates

- Cold dark matter
  - "cold" means v << c
  - Leading candidate: Weakly Interacting Massive Particles (WIMPs)
- Hot dark matter
  - "hot" means v ~ c
  - Leading candidate: neutrinos
- Baryonic dark matter
  - Black dwarfs, black holes, failed stars, etc.
  - Massive Compact Halo Objects (MACHOs)
- General Relativity is wrong
  - MOND
  - Other alternate theories of gravity

MOdified Newtonian Dynamics (MOND)

- Invented as ad-hoc explanation of flat rotation curves for galaxies

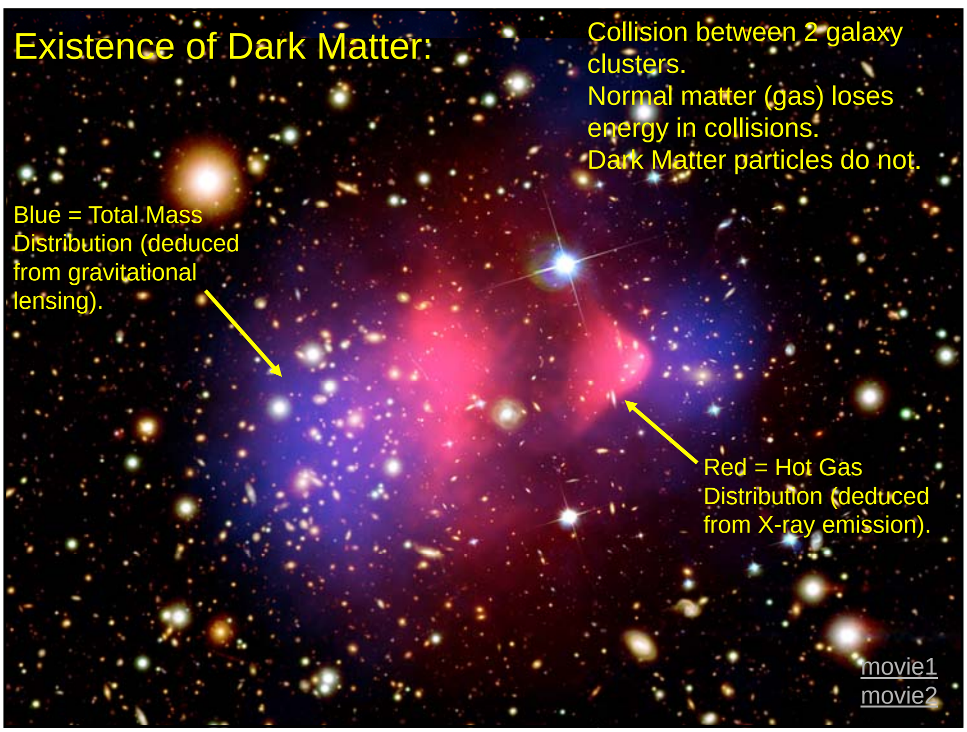
  Suppose that F_{grav} falls off slower than r^{-2}

- Originally not relativistically covariant
  - But there is now a version that does this

- Cannot also explain temperature, density structure of galaxy clusters.

- Dark matter simultaneously explains:
  - Flat rotation curves
  - Gravitational lensing results
  - Structure formation (coming attraction)

We don't want to trade it in for something that only explains one of these.

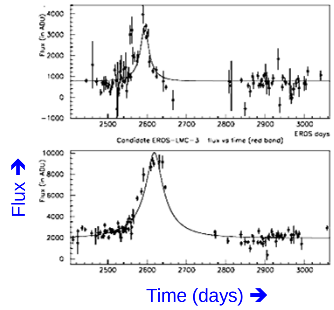


Baryonic Dark Matter

- Candidates include black holes, neutron stars, brown dwarfs, cool white dwarfs, etc.
- Use gravitational lensing to search for MACHOS
  - cross section is Einstein radius

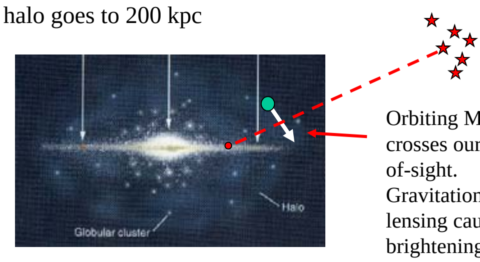
    $\theta_E = (M/M_{sun})^{1/2}\ (D/10\ \text{kpc})^{1/2}$ mas
  - variability timescale

    $t \sim 0.2\ (M/M_{sun})^{1/2}\ (D/10\text{kpc})^{1/2}\ (v/200\ \text{km/s})^{-1}$ yr
  - ==> if entire mass of MW is in Machos,
    still need to observe 10^6 sources to find one microlensed background source at any given time.



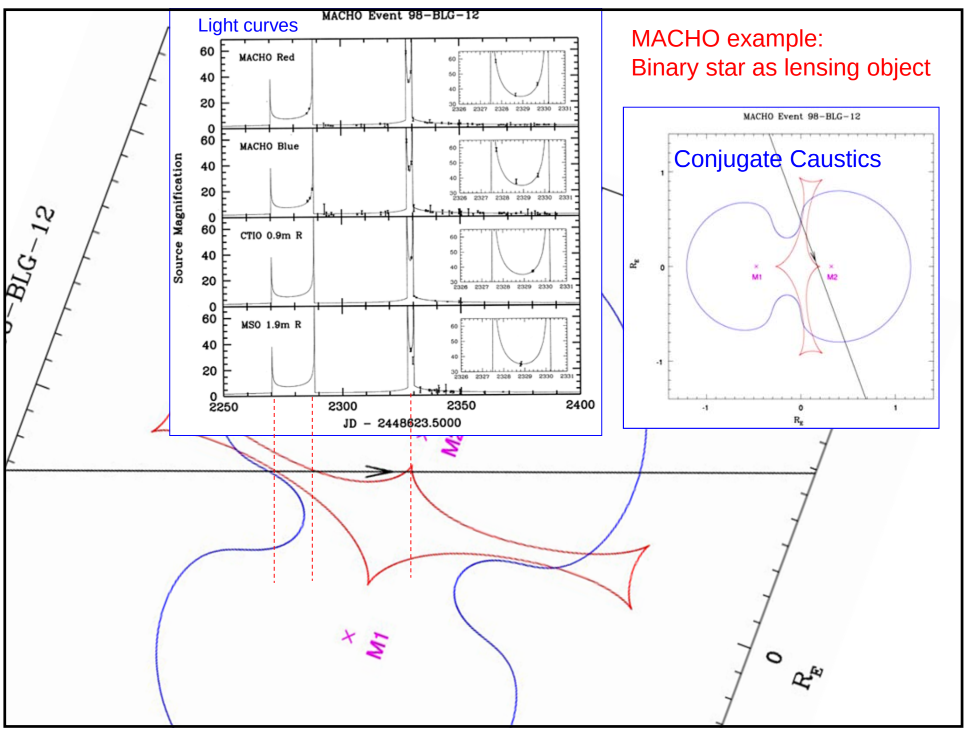
- Using LMC, SMC stars as background sources
  - LMC at 50 kpc, but MW halo goes to 200 kpc

- Two major searches
  - MACHO team
  - EROS



Orbiting MACHO crosses our line-of-sight. Gravitational lensing causes brightening.

MACHO example:
Binary star as lensing object



The Result for MACHOs

Astron. Astrophys. 355, L39–L42 (2000)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Not enough stellar mass Machos in the Galactic halo *

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Abstract. We combine new results from the search for microlensing towards the Large Magellanic Cloud (LMC) by EROS2 (Expérience de Recherche d'Objets Sombres) with limits previously reported by EROS1 and EROS2 towards both Magellanic Clouds. The derived upper limit on the abundance of stellar mass MACHOs rules out such objects as an important component of the Galactic halo if their mass is smaller than $1 M_\odot$.

Key words: Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content – galaxies: Magellanic Clouds

tion of the Galactic dark matter resides in planet-sized objects (Aubourg et al. 1995; Alcock et al. 1996; Renault et al. 1997; Renault et al. 1998; Alcock et al. 1998).

However a few events were detected with longer timescales. From 6-8 candidate events towards the LMC, the MACHO group estimated an optical depth of order half that required to account for the dynamical mass of the standard spherical dark halo; the typical Einstein radius crossing time of the events, t_E, implied an average mass of about $0.5 M_\odot$ for the lenses (Alcock et al. 1997a). Based on two candidates, EROS1 set an upper limit on

The Result for MACHOs

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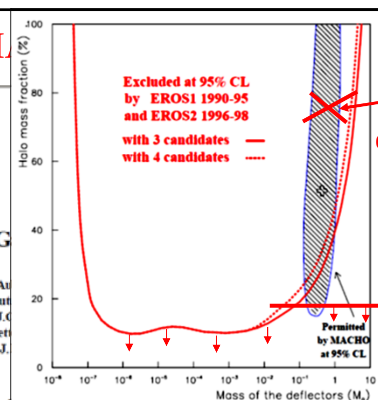
Letter to the Editor

Not enough stellar mass Machos in the Galactic halo

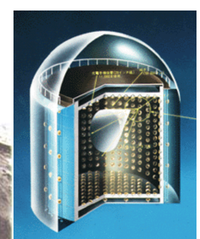


- MACHO Project:
  - 5.7 yrs, 11.9 million stars
  - 13-17 microlensed events
  - 2-4 expected from known stellar populations
- EROS
  - 3 events towards LMC, 1 towards SMC
- Fraction of MW halo in < 1 M_{sun} dark objects is < 20-40%.

- Hot Dark Matter (HDM)
  - "Hot" = particles moving at relativistic speeds.
  - Prime candidates for HDM are neutrinos.
    - there should be a cosmic background flux of neutrinos similar to CMB.
      - frozen out at $T \sim 10^{10}$K
  - predicted neutrino density = $3n_{photons}/11$
    - ~100 cm^{-3} at present time
    - ==> need $m_\nu > 10 eV/c^2$ for $\Omega_m = 0.2$

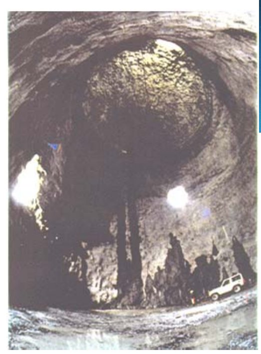
Neutrino mass

Measuring the Neutrino Mass

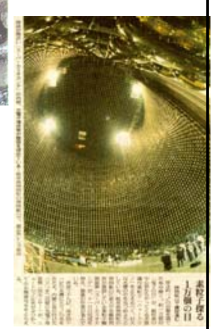


Super Kamiokande (Japan)

- Large chamber deep underground.
  - Neutrinos interact (weakly) with water.
  - 13,000 photocells detect resulting light.



- 1998: Found *neutrino oscillations*
  - Three types of neutrinos known.
  - Neutrinos change back and forth between types while in transit.
  - Can only happen if neutrinos have mass.

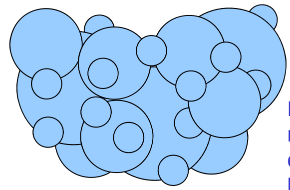


- But mass is small.
  - need $m_\nu > 10 eV/c^2$ for $\Omega_m = 0.2$
  - Mass differences are $\Delta m_\nu \sim 0.1$ eV/c^2
    (+ upper limit on electron neutrino: $m_\nu < 2.2$ eV/c^2)
  - Still….
    mass density of neutrinos ≅ mass density in visible stars

.

Hot & Cold Dark Matter

- Dark Matter = matter not coupled to electromagnetic field
  - unable to condense by dissipation



Early U. contained more small matter condensations than large ones.

- Hot Dark Matter (HDM)
  - relativistic for $T \sim 10^5$ K
  - can free-stream out of galaxy-sized matter concentrations.
  - erases small-scale structures early in life of universe.

    ➔ top-down structure formation, starting from large structures with 10^{13} M_{sun}.

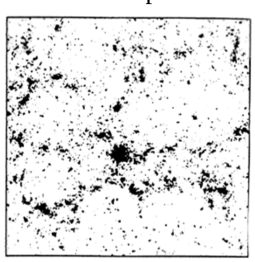
- Cold Dark Matter (CDM)
  - slow moving (non-relativistic)
  - does not erase small concentrations.
  - preponderance of low-mass structures predicted by inflation survive.

    ➔ less massive concentrations form first (bottom up structure formation).

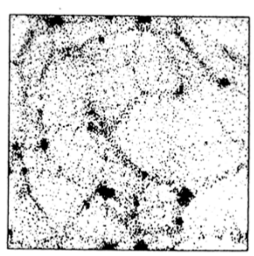
N-body simulations ➔ CDM

Standard CDM = SDCM, replaced by ΛCDM model

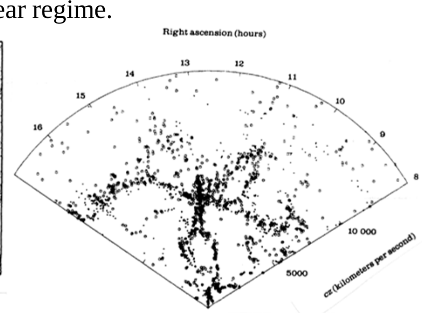
- Start with perturbation spectrum at time of decoupling
- Follow perturbations into highly non-linear regime.



CDM



HDM



- HDM models become too highly clustered over observed lifetime of galaxies

76 Carlos S. Frenk

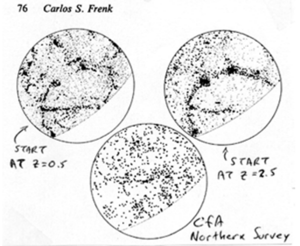


Fig. 4. Equal area projections of the galaxy distributions on the northern sky and in artificial catalogues made from *N*-body simulations. The top two diagrams correspond to neutrino dominated universes in which galaxy formation began at a redshift 0.5 (top left) and 2.5 (top right). In both cases $\Omega = 1$, but $h = 0.8$ for the model at the left, and $h = 0.5$ for the model at the right. The circles represent the "galaxies" while the dots represent the neutrino distribution. The bottom diagram is the CfA northern survey. The outer circle represents galactic latitude +40, and the empty regions lie at declinations below 0°. Even the model with a completely unrealistic epoch of galaxy formation is more strongly clustered than the data. This disagreement persists for any combination of model parameters.

Cold Dark Matter (CDM)

- slow moving.
- mass power spectrum from inflation only slightly modified by free streaming.
- less massive concentrations form first (bottom up).

CDM candidates

- Leftovers from Electroweak era
  - Expansion, cooling of U.
    ➔ frozen out of equilibrium reactions.
  - Lots of theories ➔ lots of candidates.
    - "Standard model" is not complete.
    - Supersymmetry (SUSY), or other extensions needed.
- Axions???
  - zero momentum.
  - very light ➔ huge number density needed to make up Ω_M
- WIMPs --- Weakly Interacting Massive Particles
  - Example: Neutralinos???
    - $\geq$ 50x proton mass
      - set by the weak interaction cross-section
    - predicted by SUSY

CDM
Menu of the Day
Axions
Axinos
Gravatinos
Neutralinos
Sneutrinos
⋮

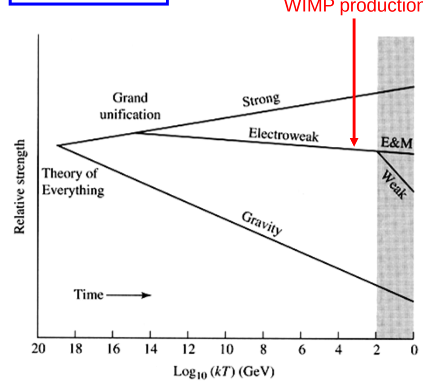


Fig. 30.2

Cold Dark Matter in the Lab

- Cosmological limits
  - Freezeout ➔ limit on n <σ*v*> (DM particles/vol; cross section x velocity)
  - $\Omega_m \propto nm$ (DM particle mass)
  - Crude estimate of <σ*v*> from particle physics symmetry arguments
    ➔ ballpark estimate of *m*, σ range.
- Trying to detect in lab through elastic scattering off various target nuclei
  - measure recoil energy imparted to target
  - look for seasonal variation due to Earth's orbital motion
  - these WIMPS are the MW halo
  - Massive neutrinos (m ~ 100-1000 m_p) already ruled out.
- Hope is to identify CDM, then manufacture it in Large Hadron Collider (or vice-versa)