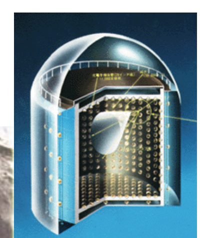
# Non-baryonic dark matter candidates

- Dark Matter = matter not coupled to electromagnetic field
  - unable to condense by dissipation
  - Hot vs. Cold Dark Matter
- Hot Dark Matter (HDM)
  - relativistic for $T \sim 10^5$ K
    - can free-stream out of galaxy-sized concentrations.
    - leads to top-down structure formation, starting at $10^{13}$ $M_{sun}$.
  - Prime candidates for HDM are massive 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 $m_\nu > 50 eV/c^2$ for $\Omega = 1$

Neutrino mass

# What *is* Dark Matter?



## 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 $m_\nu > 50 eV/c^2$ for $\Omega = 1$
  - Mass differences are $\Delta m_\nu \sim 0.1$ eV/$c^2$

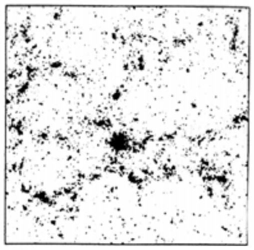
    (+ upper limit on electron neutrino: $m_\nu < 2.2$ eV/$c^2$)
  - Still….

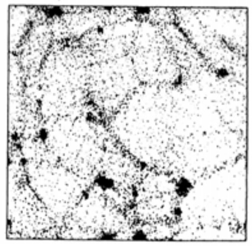
    mass density of neutrinos ≅ mass density in visible stars

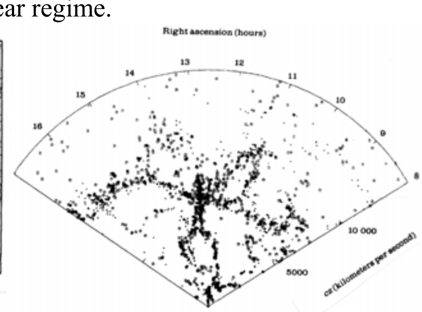
# N-body simulations ➔ CDM

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

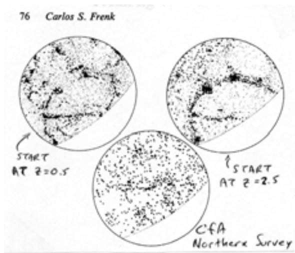



*Fig. 4.* Equal area projections of the galaxy distributions on the northern sky and in artificial catalogues made from *N*-body simulations. The top two diagrams correspond to neutrino dominated universes in which galaxy formation began at a redshift 0.5 (top left) and 2.5 (top right). In both cases $\Omega = 1$, 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.

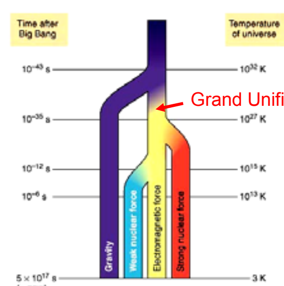
# Cold Dark Matter (CDM)

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

CDM Menu of the Day
Axions
Axinos
Gravatinos
Neutralinos
Wimpzillas
⋮

CDM candidates

- Axions
  - zero momentum
  - very light ==> huge number density needed to make up $\Omega_M$
  - should be detectable within a few years if present.
- WIMPs
  - Weakly Interacting Massive Particles
  - 50x proton mass
    - set by the weak interaction cross-section
- Leftovers from GUT era
  - Expansion, cooling of U
    ➔ frozen out of equilibrium reactions
  - Lots of theories ➔ lots of candidates



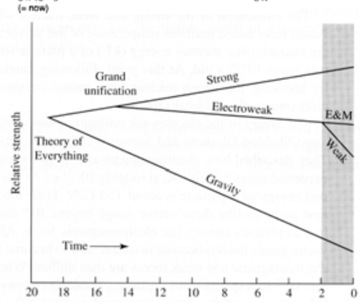



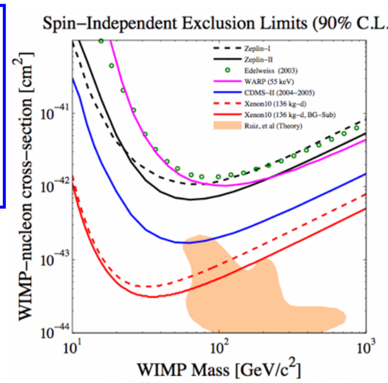

Fig. 30.2

# Cold Dark Matter in the Lab

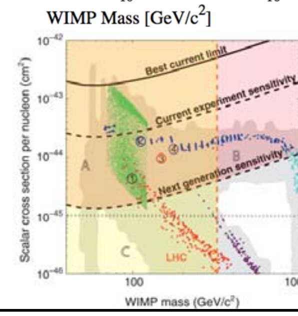
CDM candidates

- Axions
  - zero momentum
  - very light ==> huge number density needed to make up $\Omega_M$
- WIMPs
  - Weakly Interacting Massive Particles
  - 50x proton mass
    - set by the weak interaction cross-section
  - $\chi$ neutralino is best candidate

**CDM Menu of the Day**
Axions
Axinos
Gravatinos
Neutralinos
Wimpzillas
⋮




- Can be detected 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 ($m \sim 100\text{-}1000\ m_p$) already ruled out.




- Hope is to identify CDM, then manufacture it in CERN Large Hadron Collider