Decaying Superheavy Dark Matter and Subgalactic Cosmic Structure

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- Collisionless dark matter and subhalo problem at kpc scale
- Ultra high energy cosmic rays with $E > 10^{11}$ GeV
- Decaying superheavy dark matter of mass $10^{11-13}$ GeV
- Kuzmin-Rubakov model $X \rightarrow Y +$ quarks + leptons
- $X & Y$ particles and subgalactic structure of the Universe
- Other implications -- direct detection of dark matter
  -- instanton-induced $X$ decay
  & dark energy

astro-ph/0306437 with Chung-Hsien Chou
### “Best” Cosmological Parameters

*C.L. Bennett et. al (WMAP), astro-ph/0302207*

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>+ uncertainty</th>
<th>− uncertainty</th>
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<tr>
<td>Total density</td>
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<td>EOS of quintessence</td>
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<td>Hubble constant</td>
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<td>Age of universe (Gyr)</td>
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The favored candidates for dark matter

- For over a decade, the favored candidates for dark matter have been hypothetical elementary particles that are long-lived, cold and collisionless.

- **Long-Lived**: the lifetime must be comparable to or greater than the present age of the Universe, about 14-billion years.

- **Cold**: the particles are *non-relativistic at the onset of the matter-dominated epoch* so that they are immediately able to cluster gravitationally.

  - Because clustering occurs on length scales smaller than the Hubble horizon and the Hubble horizon was much smaller at matter domination than today, the first objects to form-clumps or halos dark matter were much tinier than the than the Milky Way and much less massive.

  - Hot, relativistic particles would be moving too fast at matter domination to gravitationally cluster, and would resulting in a dramatically different distribution of structure inconsistent with observation.
The favored candidates for dark matter (2)

♦ Collisionless: the interaction cross-section between dark matter particles (and between dark matter and ordinary matter) is so small as to be negligible for densities found in dark matter halos.

♦ Several reasons in favor of CCDM:
  • Numerical simulations of structure formation with cold, collisionless dark matter agree with most observations of structure.
  • For a special subclass known as WIMPs (weakly interacting massive particles), there is a natural explanation for why they have the requisite abundance.
  • There are specific appealing candidates for the dark matter particles in models of fundamental physics.

♦ But we cannot claim to understand the evolution of structure in the Universe, if we do not know the nature of the dark matter and how it fits within our models of fundamental physics.
Test of CCDM at many different physical scales

- The largest scales (thousands of Mpc) are seen in the CMB itself. These measure the primordial distribution of energy and matter when their distribution was nearly uniform and there was no structure.

- Large-scale structure seen in the distribution of galaxies ranging from few Mpc to $10^3$ Mpc. Typically, these measurements span concentrations of dark matter ranging from small to intermediate.

- Over all of these scales, observation and theory are consistent inspiring great confidence in the overall picture.

- However, on smaller scales, from 1 Mpc down to the scales of galaxies, kpc, and below, there is confusion. Either the results of the tests are uncertain, or they indicate disagreement with the naive expectation of the theory.
Cracks in the foundation

- Substructure, small halos and galaxies orbiting within larger units, may not be as common as is expected on the basis of numerical simulations of cold collisionless dark matter.

- The density profile of dark matter halos should exhibit a "cuspy" core in which the density rises sharply as the distance from the center decreases, in contrast to the central regions of many observed self-gravitating systems.

- There is a discrepancy between the predicted high densities and the observed much lower densities in the inner parts of dark matter halos, ranging from those in giant clusters of galaxies \( (M \geq 10^{15} M_{\text{solar}}) \) to those in the smaller dwarf systems observed \( (M \leq 10^9 M_{\text{solar}}) \).
**Cuspy halo problem**

- Numerical simulations of CCDM halos show cuspy halo density profiles well fit with the generalized Navarro-Frenk-White (NFW) form,

\[
\rho(r) = \rho_c \left( \frac{r}{r_c} \right)^{-\alpha} \left( 1 + \frac{r}{r_c} \right)^{\alpha-3},
\]

with \( \alpha \approx 1 - 1.5 \) and \( r_c \) is the core radius, \( \rho_c \) is the mean density of the Universe at the time the halo collapsed, and the concentration parameter \( c \equiv \frac{r_{200}}{r_c} \approx 20 \), where \( r_{200} \) is the radius within which the mean density \( \rho_{200} \) is 200 times the present mean density of the Universe.

- However, observations indicate flat core density profiles with \( \alpha \lesssim 0.5 \) and smaller concentrations with \( c \approx 6 - 8 \).
Alternatives to cold, collisionless dark matter

- Strongly Self-Interacting dark matter (SIDM): (Spergel, Steinhardt 2000)
- Warm dark matter (WDM): (Colin, Avila-Reese, Valenzuela 2000; Bode, Ostriker, Turok 2001)
- Repulsive dark matter (RDM): (Goodman 2000)
- Fuzzy dark matter (FDM): (Hu, Barkana, Gruzinov 2000)
- Decay dark matter (DDM): (Cen 2001)
- Massive Black Holes (BH): (Lacey Ostriker 1985)
- .......
Energy spectrum of UHECR

- UHECR flux as measured by the HiRes-I and HiRes-II detectors, and the AGASA experiment.
The Greisen-Zatsepin-Kuzmin cutoff

- The CMB radiation field has profound consequences for UHECR: there would be a cutoff in the spectrum of proton around $6 \times 10^{19}$ eV due to photo-pion production on the microwave background (GZK cutoff).

- The principle reactions of protons $p$ with background photons $\gamma_{2.7K}$ are

$$p + \gamma_{2.7K} \rightarrow n + \pi^+$$
$$\rightarrow p + \pi^0$$
$$\rightarrow p + e^+ + e^-$$

- The dominant background photons are microwaves, which have a peak energy of $6 \times 10^{-4}$ eV and a photon density of about 400 per cm$^3$.

<table>
<thead>
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<th></th>
<th>Threshold energy</th>
<th>mean free path</th>
<th>energy loss</th>
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<tbody>
<tr>
<td>photo-pion production</td>
<td>$6 \times 10^{19}$ eV</td>
<td>$\sim 6$Mpc</td>
<td>$\sim 20%$</td>
</tr>
<tr>
<td>pair production</td>
<td>$\sim 10^{18}$ eV</td>
<td>$\sim 1$Mpc</td>
<td>$\sim 0.1%$</td>
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</table>
Origin of UHECR: acceleration mechanism and sources

- The Hillas diagram showing size and magnetic field strengths of possible sites of particle acceleration.
Non-acceleration origin of cosmic rays above $10^{20}$ eV

- Basic idea: the UHECR are from the decay products of some superheavy X particles.

- Three basic conditions must be satisfied:
  - The X particles must decay in recent cosmological epoch, or equivalently at non-cosmological distances ($\leq 100$ Mpc) from Earth.
  - The X particles must be sufficiently massive with mass $m_X \gg 10^{11}$ GeV.
  - The number density and rate of decay of the X particles must be large enough to produce detectable flux of UHECR particles.

- Sources of X particles:
  - Cosmic topological defects: (cosmic strings, decaying vortons, monopoles, cosmic necklaces,...)
  - Metastable superheavy relic particles.
  - Evaporation of primordial black holes.
  - ...
**UHECR from decays of metastable superheavy relic particles**

- Assuming sizable hadronic component (jets) among the decay products, the flux $F$ of protons or photons of energy $E$ on the Earth is estimates as

$$
\frac{dF}{dlnE} = \frac{1}{4\pi} \frac{n_X}{\tau_X} R_{p,\gamma} N_j \frac{dN_{p,\gamma}(E)}{dlnE}
$$

where $N_j$ is the number of jets; $R_{p,\gamma}$ is the effective distance to X-particle; $n_X$ is the number density of X-particle at the scale $R_{p,\gamma}$, $\tau_X$ is the X-particle lifetime and $\frac{dN}{dlnE}$ is the fragmentation function.

- Another relation is

$$
m_X \langle n_X \rangle = \Omega_X \rho_{crit}
$$

where $\langle n_X \rangle$ : average number density of X-particle and $\Omega_X \lesssim 1$. 

From these constraints, one can obtain

\[ 10^{-33} \lesssim \frac{n_X}{s} \lesssim 10^{-21}; \quad \Rightarrow \quad 10^{10} \text{yr} \lesssim \tau_X \lesssim 10^{22} \text{yr}. \]

The unconventionally long lifetime of the superheavy particle (\(10^{10} - 10^{22}\) years) might require novel particle physics mechanisms of their decays, such as non-perturbative instanton effects or quantum gravity (wormhole) effects. (Kuzmin and Rubakov 1998) (Berezinsky, Kachelriβ, Vilenkin 1997)
The Kuzmin-Rubakov model

- KR considered an extended standard model with a new $SU(2)_X$ gauge interaction and two left-handed $SU(2)_X$ fermionic doublets $X$ and $Y$ and four right-handed singlets.

- All new particles are singlets of the standard model, while some conventional quarks and leptons may carry non-trivial $SU(2)_X$ quantum numbers.

- The $SU(2)_X$ is assumed to be broken at certain high energy scale, giving large masses $m_{X,Y}$ to all $X$ and $Y$ particles.

- $X$ and $Y$ are assumed to carry different global symmetries, so there is no mixing between them.

- However, $SU(2)_X$ instantons induce effective interactions violating global symmetries of $X$ and $Y$.

- Assume $m_X > m_Y$, then the instanton effects lead to the decay

$$X \rightarrow Y + \text{quarks} + \text{leptons}$$

with a long lifetime roughly estimated as $\tau_X \sim m_X^{-1}e^{4\pi/\alpha_X}$, where $\alpha_X$ is the $SU(2)_X$ gauge coupling constant.
DCDM and subgalactic structure of the Universe

- We can show that the KR model that has attempted to explain the presence of UHECR with energies beyond the GZK cutoff can easily provide a DCDM solution for the problem of subgalactic structure formation in the CCDM model. (Chou and Ng astro-ph/0306437)

- We study the effect of DCDM to the original NFW profile with $\alpha = 1$.

- Defining $x = r/r_{200}$, it gives the halo mass profile $M(x) = M_{200} F(x)$ that is the mass within $x$ and the associated rotational velocity $V(x) = V_{200} \left[ F(x)/x \right]^{1/2}$, where $M_{200} = M(x = 1)$, $V_{200} = V(x = 1)$, and

$$F(x) = \left[ \ln(1 + cx) - \frac{cx}{1 + cx} \right] / \left[ \ln(1 + c) - \frac{c}{1 + c} \right].$$
Solid (dashed) curves represent respectively from up to down the rotation curves (mass profiles) for the $X$ halo which is from the NFW profile in the CCDM model, the $Y$ halo in the DCDM model, and the case in which $X$ decays into relativistic particles. The $x$-axis ($y$-axis) is in unit of $r_{200}$ of the $X$ halo ($V_{200}$ for solid curves and $M_{200}$ for dashed curves).
Dark matter in galaxies

- Observed rotation curve of the nearby dwarf spiral galaxy M33, superimposed on its optical image.
Observational test (1): astrophysics side

- In the DCDM model in which $X$ DM decay into relativistic particles, not only halo core density is lowered but also small dwarf galaxies are darkened due to core expansion and subsequent quenched star formation.

- This model predicts that the small-scale power at higher redshift is enhanced compared to the CDM model as well as the gas fraction in clusters should decrease with redshift. The latter can be tested by X-ray and Sunyaev-Zel’dovich effect observations.

- If $X$ particles decay into non-relativistic stable massive $Y$ DM, the $Y$ DM provides well fits to the rotation curves of low-mass galaxies and does not necessarily produce a significant reduction of the central DM density of certain dwarf.

- Remarkably, the subhalo astrophysics at kpc scales may provide a hint to understand the mass difference between $X$ and $Y$ in the KR model at energy scale of about $10^{13}\text{GeV}$.
Observational test (2): UHECR side

- To test models of superheavy particles directly in terrestrial particle accelerators is quite impossible.

- Superheavy particles decay into ultra high-energy quark and lepton jets which fragment predominantly into photons with a small admixture of protons.

- The ultra high-energy neutrino flux accompanying the UHECR is near the detection limit of the on-going AMANDA neutrino experiment and will be severely constrained by the upgraded AMANDA and next generation neutrino telescope IceCube.

- Because of the off-center location of the Solar system in the Galactic halo, some amount of anisotropy in the arrival directions of UHECR is expected.

- The particle spectra and the arrival directions of UHECR produced from decays of superheavy particles in the Galactic halo can provide crucial tests.
Observational test (3): dark matter side

- Instanton mediated decay processes typically lead to multiparticle final states.

- Thus $X$ particle decays will produce a relatively large number of quark jets with a fairly flat energy distribution and rather hard leptons as compared to typical perturbative decays of superheavy particles.

- This may leave a distinct signature in the predicted UHECR spectrum which may help in distinguishing the KR model from other DCDM models.

- If the $Y$ particle interacts weakly with ordinary matter, it may scatter with the target nucleus with mass $m_N$ in a detector and deposit a huge amount of energy of order $m_N (1 - \delta)^{-2}$ in the detector.

- This deposit energy is much larger than that of a typical halo DM particle which is about $m_N v_X^2$.

- This may give a new thought to the direct detection of halo DM. (Chou and Ng, astro-ph/0306437)
Cosmological constant from degenerate vacua (1)

- Idea: consider a field theory model whose perturbative vacuum states are labelled by $|+\rangle$ and $|−\rangle$ with $\langle+|−\rangle = 0$ at the lowest order.

- Although the transition from $|+\rangle$ to $|−\rangle$ is classically forbidden, there is an instanton solution which describes this quantum tunnelling.

- The true ground state, with tunnelling effect taken into account, is

$$|S\rangle = \frac{|+\rangle + |−\rangle}{\sqrt{2}}$$

- From dilute instanton approximation we have

$$\langle S | e^{-\mathcal{H}T} | S \rangle = \exp \left( -\rho_0 V T + k V T e^{-S_0} \right),$$

and the energy density of true ground state is

$$\rho_S = \rho_0 - m^4 e^{-S_0}.$$  

- Assuming $\rho_S = 0$ we find a non-vanishing vacuum energy density

$$\rho_0 = m^4 e^{-S_0}$$

in either of the perturbative vacuum states $|+\rangle$ or $|−\rangle$. 
Cosmological constant from degenerate vacua (2)

- Consider an $SU(2)$ gauge theory whose perturbative vacuum states $|n\rangle$ are classified in terms of winding number $n$.
- The Euclidean action of one instanton solution is $S_0 = \frac{8\pi^2}{g^2}$.
- The true ground state in the presence of quantum tunnelling is

$$|\theta\rangle = \sum_{n=-\infty}^{\infty} e^{in\theta} |n\rangle.$$

- Based on the dilute instanton approximation

$$\langle \theta'| e^{-\mathcal{H}T} |\theta\rangle = \exp \left(2KVTe^{-S_0}\cos\theta\right) \delta(\theta - \theta').$$

- Assuming $\theta = 0$ vacuum is the true ground state, the vacuum energy density in each perturbative vacua is found to be

$$\langle n | \rho_v | n\rangle = 2Ke^{-S_0}.$$

- However, the factor $K$, in the case of pure $SU(2)$ gauge theory, is divergent due to the contribution of arbitrary large instantons.
Cosmological constant from degenerate vacua (3)

-To obtain a physical cutoff, ’t Hooft introduced an $SU(2)$ doublet scalar field $\Phi$ with potential $V[\Phi] = \frac{\lambda}{2}(|\Phi|^2 - \frac{M^2}{2})^2$.

-Then the prefactor is given by $K \approx \left(\frac{8\pi}{g^2}\right)^4 \frac{M^4}{2}$ and we find

$$\rho_\nu \approx M^4 \left(\frac{8\pi}{g^2}\right)^4 e^{-\frac{8\pi^2}{g^2}}$$

$$\Gamma \approx M^4 \left(\frac{8\pi}{g^2}\right)^4 e^{-\frac{16\pi^2}{g^2}}$$.

-Demanding that $\rho_\nu = 10^{-12} M_G^4$ and $\Gamma H_0^{-4} \lesssim 1$, we find

$$\frac{\pi}{\alpha} + 2 \ln \alpha = 60 \ln 10 + 2 \ln (M/M_G), \quad \text{and} \quad M \gtrsim \alpha M_G.$$  

-If the above inequality is marginally satisfied, we find $\alpha = 1/44.4$ and $M = 5 \times 10^{16}$ GeV.

-The observed tiny dark energy can be realized by the interplay of high energy physics between grand unification and Planck scales and inflationary cosmology.  (J. Yokoyama 2002)
Summary

- The collisionless cold dark matter (CCDM) model predicts overly dense cores in dark matter halos and overly abundant subhalos.

- The idea that CDM are decaying superheavy particles which produce ultra-high energy cosmic rays with energies beyond the Greisen-Zatsepin-Kuzmin cutoff may simultaneously solve the problem of subgalactic structure formation in CCDM model.

- In particular, the Kuzmin-Rubakov’s decaying superheavy CDM model may give an explanation to the smallness of the cosmological constant and a new thought to the CDM experimental search.