Very Heavy Dark Matter and Multi-Messenger Astronomy

Kohta Murase
(Yukawa Institute for Theoretical Physics, Kyoto)

CCAPP DM workshop (17/Oct/2008)
Outline

Purpose:
High-energy astronomy and heavy dark matter

• Two illustrative examples of VHDM:
  Top down scenario for UHECRs
  Metastable gravitino

• Astrophysical sources and discussions
Motivation

- Thermal Relics: well-known unitarity bound $M_x < 100$ TeV

- Nonthermal production of relics is possible
e.g., topological defects, very heavy dark matter
$M_x >> 100$ TeV is possible (e.g., SHDM for UHECRs, $M_x < M_{GUT}$)

- $M_x \sim M_{SUSY} > \text{TeV}$ may be possible (e.g., split SUSY)

- Indirect detection via CRs, gammas and nus (beyond LHC)
Annihilation $\vec{\sigma}$ cross section is small, difficult to see at VHE range
Decay (metastable DM) $\vec{\tau}$ could be detected depending on $\Omega x$, $\tau x$, $Mx$

$\tau x < t_H$: Influence on BBN and CMB (e.g., Kawasaki et al., 2005, PRD)
$\tau x > t_H$: Late time decay, and particles may be observed
Observations of CRs, gammas and nus can lead to best constraints on $\tau x$ and $Mx$

Origin of late time Decay $\vec{\tau}$ e.g., soft break of preservation symmetry
Window of High-Energy Astronomy

High-Energy Gamma Rays
Milagro, HAWC
(HESS, VERITAS, CTA)
TeV-PeV $\gamma$s

Neutrinos
IceCube/KM3Net
TeV-EeV $\nu$s

Cosmic Rays
Auger, TA, EUSO,
KASKADE, PAMERA etc.
HE $\mu$s and nuclei
EeV-ZeV $\nu$s
VHE $\gamma$s and HE $\mu$s
General Aspects

• $M_x$, $\tau_x$ and abundance ($\sim \Omega x \sim \Omega m \sim 0.3$) (which are related by a specific production mechanism)

$$I_{SHDM}(E) = \frac{1}{M_x \tau_x} D(E)n_X(R)$$

• Spectrum of decay products $D(E)$ depends on the model (e.g., SHDM decay including quarks, gravitino decay, sneutrino decay etc.)

• Spectra mediated by propagation of SM particles in the universe (e.g., magnetic field, pair production, inverse Compton for $\gamma$s/leptons) (e.g., magnetic field, Bethe Heitler and $p\gamma$ processes for protons)

• Effect of cosmic evolution for extragalactic DM

$$J_{EG}(E) = \frac{c}{4\pi} \int_0^\infty dz \left| \frac{dt}{dz} \right| Q_{inj}(E_g(E, z)) \frac{dE_g(E, z)}{dE}$$

• Importance of the Galactic halo ($\tau_x \gg t_H$) (typically by $\sim 10$ than extr. flux)

$$n_X(R) = \frac{n_0}{(R/R_s)^\alpha(1 + R/R_s)^{3-\alpha}}$$
Example 1: VHDM as UHECR sources

VHDM is considered to explain both of the UHECRs and DM

- “Super Heavy Dark Matter” (SHDM)

  (e.g., Lemaitre 1950, Berezinsky+ 1997, Kuzmin & Rubakov 1998)

They can nonthermally be produced in the early universe

  (e.g., Chung+ 1999, Kuzmin & Tkachev 1998)

For gravitational production

\[ \Omega_X h^2 \approx \frac{T_R}{10^8 \text{ GeV}} \left\{ \begin{array}{ll}
\left( \frac{m_X}{H_I} \right)^2, & m_X \ll H_I \\
\exp\left(-\frac{m_X}{H_I}\right), & m_X \gg H_I
\end{array} \right. \]

Two Scenarios

- Topological defect (e.g., monopole, cosmic string)
- Long-Lived super heavy dark matter \( M_X > \text{ZeV} \)

\[ \dot{n}_X(t) = \kappa m_X^p t^{-4+p}, \]
Top Down Scenario (cont.)

- $M_x \sim 10^{13-16}$ GeV ($> M_{\text{SUSY}}$) $> Q_{\text{had}} \sim$ GeV
- Parton cascade after decay $\rightarrow$ many pions leading to $\gamma_s$ & $\nu_s$
- Parton evolution can be calculated by DGLAP eq. or MC codes
- Final spectra depend on decay modes
- SUSY QCD leads to final spectra flatter
- (Some uncertainty may also come from CGC)
- Neutrinos and gamma rays are dominant than baryons
Original Top Down Scenario

- Hard Spectrum ($dN/dE \sim E^{-1.9}$) and $dN/dE \sim E^{-2.6}$ at $10^{19}$ eV
- No GZK cutoff (coming from the halo) followed by AGASA data
- A significant fraction of UHECRs should be photons
- But... essentially excluded by Auger
• SH relics as DM may still be subdominant UHECR sources
• SHDM still predicts increase of a fraction of photons
Subdominant Top Down Scenario

• SH relics as DM may still be subdominant UHECR sources
• SHDM still predicts increase of a fraction of photons
• SHDM also predicts anisotropy even below $E_{GZK} \sim 10^{19.7}$ eV
• Constraints on lifetime ($\tau x > 10^{28.5}$ s around $Mx \sim 10^{22}$ eV)
Example 2: Gravitino Decay

- Soft break of R-parity → NLSP can decay before BBN metastable LSP
- Fragmentation of W/Z & products of $\tau$ at high-energies
Gravitino Decay (Cont.)

Halo $\nu$ flux & extragalactic $\nu$ flux

Example of extragalactic $\gamma$ flux

- Extension to higher Mx could be possible (split SUSY) (depending on SUSY breaking and production mechanism…)
- e.g., for $\tau_{3/2} \sim 10^{27}$ s ($E^2 \frac{dJ}{dE} \sim 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$), $M_{3/2} \sim 300$ TeV □ R-parity breaking Yukawa coupling $\sim 10^{-13}$
Astrophysical signals prevent us from finding DM signals

Active Galactic Nuclei
- The most massive BHs with large scale jets
  \[ M_{\text{BH}} \sim 10^{6-9} M_{\text{sun}} \]

Gamma-Ray Bursts
- The most violent explosions
  \[ E_{\text{GRB}} \sim 10^{51} \text{ergs} \]

Clusters of Galaxies
- The largest gravitationally bounded objects
  \[ r_{\text{vir}} \sim \text{a few Mpc} \]

Supernovae
- The violent explosions in our Galaxy
  \[ E_{\text{kin}} \sim 10^{51} \text{ergs} \]

CRs from these sources do exist in the Galactic and extragalactic space!
Astrophysical signals prevent us from finding DM signals

- **UHECRs**
  Observed astrophysical UHECRs (AGNs, GRB…)

- High-energy neutrinos
  Atmospheric neutrino background (HECRs)
  Many astrophysical possibilities (HECRs, AGNs, GRB…)

- High-energy gamma rays (and high-energy CRs)
  Many astrophysical possibilities (HECRs, AGNs, SNe…)
  Mediation during the propagation in the space

No DM signals \[ \Rightarrow \] constraints on properties of VHDM (e.g., \( \tau x \))
Neutrinos

- atmospheric nus (and possible charm mesons)
- extragalactic sources (pp/\gamma)
- cosmogenic nus (p\gamma)
- Galactic nus (pp)
- Galactic sources

Many astrophysical predictions are model dependent
We may have a chance to find DM signals in the future?
Anisotropy search at high energies
Extragalactic Gamma Rays

> TeV gamma rays are cascaded by CIB, CMB and CRB photons!

Resulting spectra are not sensitive to primary spectra

Murase+ (2009)

Kachelriess (2008)
Extragalactic Gamma Rays

> TeV gamma rays are cascaded by CIB, CMB and CRB photons!

Resulting spectra are not so sensitive to primary spectra

Signals diffuse out unless $B_{IG} < 10^{-16}$ G
Galactic Gamma Rays and Electron-Positrons

- Cascade of VHE photons is moderate below 100 TeV
- The magnetic field is important for propagation of protons/electrons
- Cascaded spectra complicated — search for non-cascaded component

EGRET data

Galactic gamma rays

CR electrons

Yoshida+ 2004

GALPROP (Strong et al.)
No DM Signals  □ Potential Constraints

Simple Case (with analytical consideration):
Mx is divided by $\nu s$, $\gamma s$ (and es)

\[ \frac{dN}{dE} \propto \delta(E-E_0) \]

Requirement:
DM Flux < exp. background flux

Lower limits on $\tau_x$

#1:
background flux is extrapolated to the unobserved range

#2:
can be important even when $\tau_x \sim t_H$
(e.g., Kanzaki+ 2007)

#3:
HE electron sources should be nearby

Gondolo (1992)
Possibly We Have a Chance to See Signals

Prediction of TD scenario rather than SHDM scenario
Demonstrating power of multi-messenger HE astronomy
Summary (Not Conclusion)

- VHDM is possible and they may decay at late time
- Their properties (e.g., lifetime) over the wide mass range can be tested by the multi-messenger astronomy
- Information: Spectrum, Composition, Anisotropy, (Corr.)

Ultra-High-Energy Cosmic Rays
Typically more important for $mx > ZeV$

High-Energy Neutrinos
Typically more important for $TeV < mx < ZeV$

High-Energy Gamma Rays and Electron-Positrons
Typically more important for $mx < TeV$

Possibly, some interesting treasure may be buried…?