PeV neutrino signals from decaying topological dark matter

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September 10, 2019

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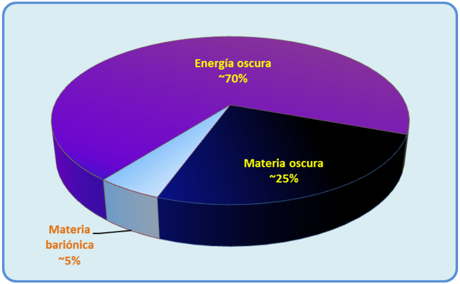
Introduction

Introduction

- The dark matter problem → ΛCDM



- Proposal for a dark matter candidate:
  Topological defects → monopoles: non-thermal production

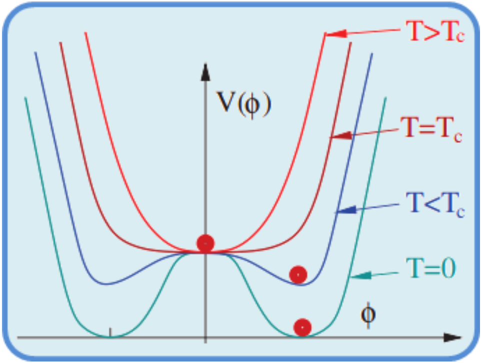
Second order phase transitions

Symmetry breaking process:

$$\langle\phi\rangle = 0,\ \ T > T_c \ \longrightarrow\ \langle\phi\rangle \neq 0,\ \ T < T_c$$

Landau-Ginzburg potential

$$V(\phi) = (T - T_c)m\phi^2 + \frac{\lambda(T)}{2}\phi^4$$



Correlation length and relaxation time diverge at T_c

$\rightarrow$ critical exponents

Abundance of topological defects

Kibble mechanism

- Non-thermal production of monopoles in phase transitions$\rightarrow$ density
- Based in causality: separation between regions $d \leftrightarrow ct$
- One monopole is produced on each correlated volume (ξ^3)

Kibble's estimate: one TD per horizon

$$n_M \sim \xi^{-3},\ \xi \simeq H^{-1}(T_c) \ \Rightarrow \ n_M \simeq H^3$$

Radiation dominated universe:

$$H = 1.66\sqrt{g_*}\,\frac{T^2}{M_P}\ , \qquad \text{entropy: } s = \frac{2\pi^2}{45} g_{*s} T^3$$

$$\frac{n_M}{s} \simeq 107 \left(\frac{T_c}{M_P}\right)^{\mathbf{3}} \longleftarrow$$

Kibble-Zurek mechanism

- Takes into account the finite timescales available for the transition
- Correlation length ξ, relaxation time τ
- Tested in laboratory: condensed matter and other systems

Parametrization of the divergences: critical exponents

$$\begin{cases} \xi = \xi_0 |\epsilon|^{-\nu} \\ \tau = \tau_0 |\epsilon|^{-\mu} \end{cases} , \qquad \epsilon \equiv \frac{T_c - T}{T_c} \text{ (proximity to } T_c\text{)}$$

Zurek's estimate → *quenching* process: $\Delta t \propto \Delta T$

$$\begin{cases} t - t_c = \tau_Q \, \epsilon(t) \\ \tau(t_*) = t_* - t_c \end{cases} \Rightarrow \xi(t_*) = \xi_0 \left(\frac{\tau_Q}{\tau_0} \right)^{\frac{\nu}{\mu+1}}$$

Radiation dominated universe ($T \propto t^{-1/2}$): $\tau_Q \xrightarrow[t \to t_c]{} 2t_c = H^{-1}(T_c)$

Initial conditions: $\xi_0 \simeq \tau_0 \sim 1/(T_c\sqrt{\lambda})$

Kibble-Zurek mechanism

With $\xi \leftrightarrow H(T_c)$, $s(T_c) \to n_M \simeq \xi^{-3}$, and assuming $g_* \simeq 106, \lambda \simeq 0.5$:

- General case

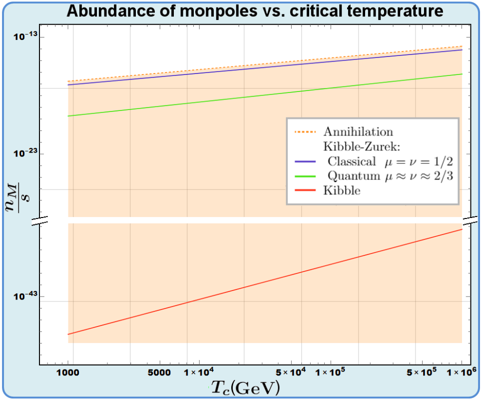
$$\frac{n_M}{s} \simeq 0.007 \left(\frac{24\, T_c}{M_P}\right)^{\frac{3\nu}{\mu+1}} \leftarrow$$

- Classical case ($\nu = 1/2$)

$$\frac{n_M}{s} \simeq 0.1 \left(\frac{T_c}{M_P}\right) \leftarrow$$

- *Quantum case* ($\nu = 2/3$)

$$\frac{n_M}{s} \simeq 0.35 \left(\frac{T_c}{M_P}\right)^{\frac{6}{5}} \leftarrow$$



$$\left.\frac{n_M}{s}\right|_{quantum} \sim 10^{-2} \left.\frac{n_M}{s}\right|_{classical}$$

Other bounds for the abundance of monopoles

Standard monopoles

- Annihilation: important for high abundances $\rightarrow$ dissapearance

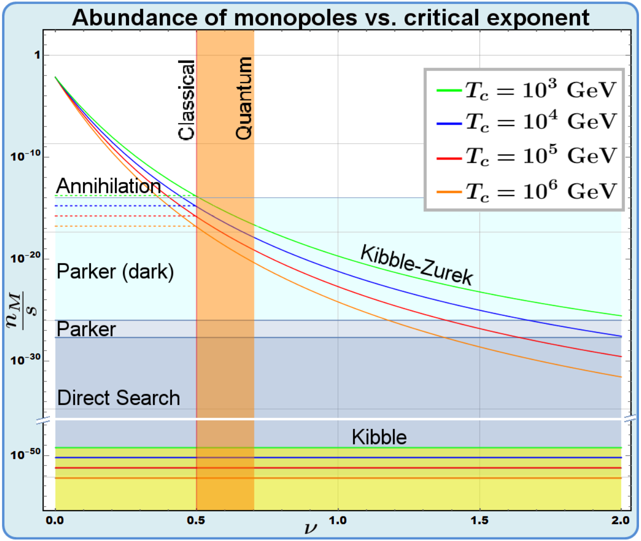
$$\frac{n_M}{s} \simeq 3.4 \cdot 10^{-22}\, x_c \left(\frac{T_c}{\mathrm{GeV}}\right)$$

- Parker limit (insterstellar magnetic fields): $\frac{n_M}{s} < \frac{B}{8\pi q \tau_g} \simeq 10^{-26}$
- Direct searches: MACRO experiment $\rightarrow \frac{n_M}{s} \lesssim 10^{-28}$

Dark monopoles $\Rightarrow$ suppressed *dark* charge: $q \rightarrow \chi q$, $\chi \sim 10^{-12}$

- Annihilation: *dark plasma*?, no significant annihilation processes?
- Parker limit: $\frac{n_M}{s} \rightarrow \frac{1}{\chi}\frac{n_M}{s} \lesssim 10^{-14}$
- Direct searches: cross section $\propto q^2 \rightarrow \chi^2 q^2$

Abundance of monopoles



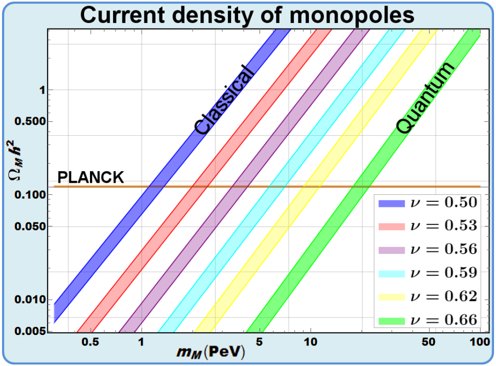
Current density of monopoles

$$\Omega_M h^2 = \frac{s_0 m_M}{\rho_c h^{-2}} \frac{n_M}{s} \simeq 2.8 \cdot 10^{14} \left(\frac{m_M}{\mathrm{PeV}}\right) \frac{n_M}{s}$$

PLANCK: $\Omega_M h^2 \simeq 0.12$

Kibble-Zurek:

$$\Omega_M h^2 \simeq 2 \cdot 10^{12} \left(\frac{1.97 \cdot 10^{-12}}{x_c}\right)^{\frac{3\nu}{\mu+1}} \left(\frac{m_M}{\mathrm{PeV}}\right)^{\frac{3\nu}{\mu+1}+1}$$



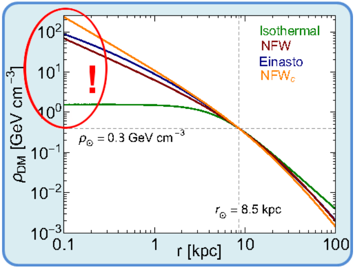
Dark matter decay signal $\rightarrow$ neutrinos

Neutrino fluxes: galactic halo

$$\frac{\mathrm{d}\Phi_{halo}}{\mathrm{d}E_\nu} = \frac{1}{4\pi m_M \tau_M} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int \rho_{halo}[r(s,l,b)] = D_{halo} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}$$

Navarro-Frenck-White profile

$$\rho_{halo}(r) = \frac{\rho_0}{\frac{r}{r_c}\left(1+\frac{r}{r_c}\right)^2}$$



$$D_{halo} = 1.3 \cdot 10^{-12} \left(\frac{\mathrm{PeV}}{m_M}\right) \left(\frac{10^{27}\ \mathrm{s}}{\tau_M}\right) (\mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr})^{-1}$$

$$oscillations: \ \Phi = (\nu_e + \nu_\mu + \nu_\tau)/3$$

Neutrino fluxes: extragalactic sources

Cosmological distances: homogeneity and isotropy $\rightarrow \rho_{eg} = \Omega_{DM}\rho_c$

$$\frac{\mathrm{d}\Phi_{eg}}{\mathrm{d}E_\nu} = \frac{\Omega_{DM}\rho_c}{4\pi m_M \tau_M} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu[(1+z)E_\nu]}{\mathrm{d}E_\nu}\,\mathrm{d}z =$$
$$= D_{eg} \int_0^\infty \frac{1}{\sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}} \frac{\mathrm{d}N_\nu[(1+z)E_\nu]}{\mathrm{d}E_\nu}\,\mathrm{d}z$$

ΛCDM cosmology: $D_{eg} = 1.6 \cdot 10^{-12} \left(\frac{\mathrm{PeV}}{m_M}\right) \left(\frac{10^{27}\ \mathrm{s}}{\tau_M}\right) (\mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr})^{-1}$

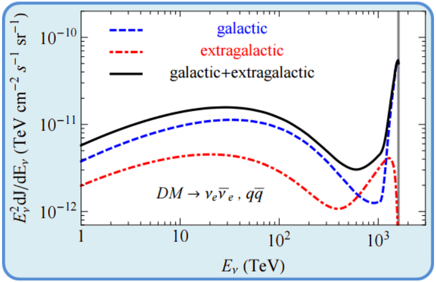
Neutrino spectrum

Two kinds of decay channels:

- hard: $M \to \nu\bar{\nu}, \ldots \Rightarrow$ spectrum with peak $\propto \delta\left(E_\nu - \frac{m_M}{2}\right)$, width due to electroweak corrections
- soft: $M \to q\bar{q}, \ldots \Rightarrow$ continuum

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = b_{hard}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\bigg|_{hard} + (1 - b_{hard})\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\bigg|_{soft}$$

Neutrino flux

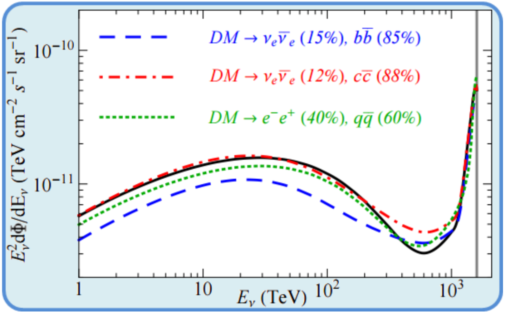


Flux characteristics:

- Peak $\sim$ PeV and cut
- *sub*-PeV dip
- Continuum $\sim 10 - 100$ TeV
- Galactic $\sim$ extragalactic

Numerical simulations:

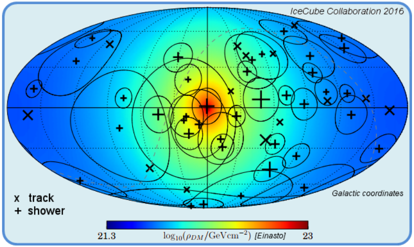
The spectral shape is the same for different choices of decay channels and parameters (specific particle model not needed)

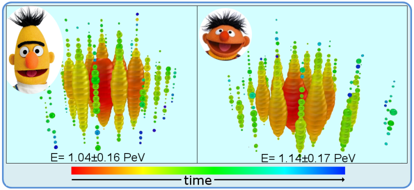


Comparison with IceCube results

Observed neutrino flux

For a 1347 days exposure: 53 HESE (High Energy Starting Events) observed



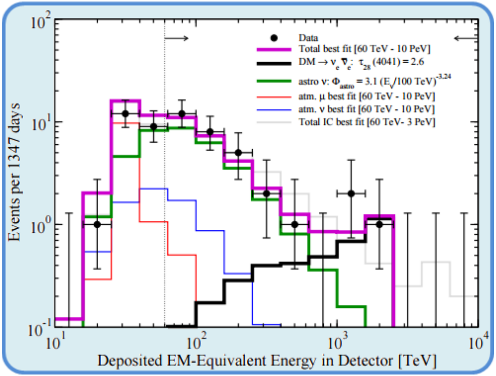


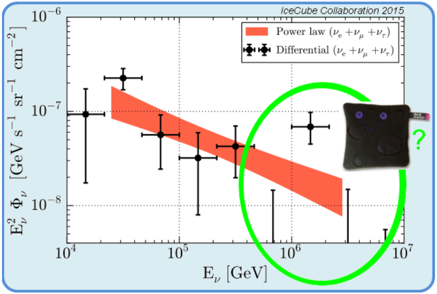
- Most events: *showers* $\rightarrow$ high angular uncertainty
- 2 events con $E_\nu \simeq \mathrm{PeV}$ observed
- Standard astrophysical sources: power law $\sim E^{-2}$
- Background: atmospheric showers from cosmic rays

Observed neutrino flux

Flux → events per energy bin

$$N_i = \int_{\Delta_i E_\nu} \left(\frac{\mathrm{d}\Phi_{halo}}{\mathrm{d}E_\nu} + \frac{\mathrm{d}\Phi_{eg}}{\mathrm{d}E_\nu} \right) \mathcal{E}(E_\nu)\, \mathrm{d}E_\nu$$





Characteristics of the observed flux: similar to those of the proposed model

Conclusions

Conclusions

Summary:

- (Dark) Monopoles $\rightarrow$ dark matter candidates
- Abundance estimations: Kibble-Zurek mechanism
- $m_M \sim \mathrm{PeV} \leftrightarrow$ abundance measured by PLANCK
- High energy neutrinos observed with IceCube
- Monopole decays $\rightarrow$ possible explanation for the neutrino flux
- Best fit: $m_M \simeq 3 - 4$ PeV ($\nu \simeq 0.56$) with a hard+soft spectrum

Future work:

- Improvement of statistics and precision of the data sets
- Angular distribution: preference for the dark matter model?
- Analysis of specific particle models for monopoles

Thank you for your attention