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基于伽马射线的类轴子粒子探测及暗物质子晕搜寻研究

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目前已经有很多观测证据表明宇宙中存在着大量暗物质, 其能量密度占据了目前宇宙总能量密度的1/4. 根据高精度的数值模拟和引力透镜观测, 我们已经对从矮星系到星系团中的暗物质空间分布有了较好的理解, 但是对于暗物质究竟是什么我们还一无所知.

由此, 物理学家提出了很多假想的粒子模型. 其中比较著名的粒子模型有: 弱相互作用大质量粒子(WIMP)、轴子和类轴子(ALP). 弱相互作用大质量粒子只存在弱相互作用和引力相互作用, 可以相互湮灭(或者衰变)成稳定的高能粒子, 包括伽马光子、带电粒子和中微子. 从而使我们可以通过探测其湮灭(或者衰变)产生的高能粒子来间接探测弱相互作用大质量粒子. ALP可以在电磁场中与光子相互转化, 这一特性使得我们可以通过寻找伽马射线能谱中的光子-类轴子振荡结构来间接探测类轴子. 本文中的研究主要是利用公开的费米大面积望远镜(Fermi Large Area Telescope, Fermi-LAT)的数据和已发表的大气切伦科夫望远镜High Energy Stereoscopic System (H.E.S.S.)能谱数据, 对暗物质粒子(轴子和类轴子、弱相互作用大质量粒子)进行间接探测.

银河系中广泛存在着磁场, 因此在河内源的能谱中可能存在着由光子和类轴子相互转化而形成的振荡结构. 首先我们选取了3个在银盘上且非常明亮的超新星遗迹作为目标源(分别是IC443、W44和W51C), 利用Fermi-LAT对这3个超新星遗迹的观测来寻找光子-类轴子振荡信号. 在IC443的能谱中, 我们找到了疑似的振荡结构, 但是其对应的类轴子参数空间已经被太阳轴子望远镜CAST (CERN (European Centre for Nuclear Research) Axion Solar Telescope)排除. 我们猜测, 由于IC443是个空间延展的源, 其能谱中出现的疑似的振荡结构可能是来自不同区域伽马射线辐射叠加的结果. 然后我们选取了10个明亮的位于银盘上的TeV源, 利用H.E.S.S.发表的能谱数据继续搜寻类轴子. 然而我们并没有找到明显的光子-类轴子振荡信号, 随后计算出了对类轴子参数空间的限制. 这是首次利用天文观测数据在高质量区域(100 neV)对解释河外TeV伽马射线反常弱吸收的类轴子模型参数空间进行排除.

我们还利用Fermi-LAT伽马射线观测, 搜寻了来自暗物质子晕结构的弱相互作用大质量粒子湮灭信号. 目前有大量数值模拟的结果显示, 像银河系这样的星系中存在大量的暗物质子晕结构. 暗物质粒子可以湮灭或者衰变产生伽马射线. 因此质量足够大且距我们足够近的暗物质子晕可能会以稳定延展伽马射线源的形式出现, 同时没有其他波段的对应天体. 以此为标准, 我们找到了一个可能的暗物质子晕候选体3FGL J1924.8−1034, 但是由于Fermi-LAT角分辨率的局限, 我们不能排除它是由两个(及以上)邻近点源组成的可能.

由于高的质光比, 矮椭球星系一直被认为是暗物质间接探测的理想目标. 我们搜寻了银河系附近矮椭球星系的伽马射线辐射, 来探测弱相互作用大质量粒子的信号. 分析发现来自Reticulum II方向的伽马射线信号是随时间稳步增长的. 随后我们对所有目标源进行了联合分析, 得到的联合伽马射线信

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号已经超过了4σ的局域置信度. 在暗物质间接探测中, 主要困难在于如何把暗物质湮灭或衰变产物的信号从天体物理背景中分离出来. 如果是搜寻具有某些独特特征的能谱, 如线谱和箱型能谱, 在这方面遇到的困难就要小一些, 因为通常的天体物理辐射过程难以出现这种特殊结构的能谱. 在本文的工作中, 我们还利用了Fermi-LAT数据来搜寻暗物质粒子可能产生的特征能谱(包括线谱和箱型能谱)信号. 我们分别在银河系卫星星系和银河系内的暗物质子晕结构(通过N体模拟)寻找潜在的线谱信号. 由于没有发现明显信号, 我们随后计算出了暗物质湮灭成两个光子的湮灭截面的相应上限. 随后我们还在矮椭球星系中, 研究了由暗物质湮灭或衰变所产生的中间粒子衰变发出的箱型伽马射线能谱信号.

Probe Axion-like Particles (ALPs) and Search for Dark Matter Subhalo with the Gamma-ray Observations

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The presence of a large amount of dark matter (DM) in the Universe has already been convincingly established. DM is believed to make up a quarter of the energy density of the current Universe. Thanks to high-resolution numerical simulations made possible by modern supercomputers and the gravitational lensing observations, the distribution of DM in structures ranging from dwarf galaxies to clusters of galaxies has been understood better than before. But the nature of DM remains unknown.

Various hypothetical particles have been proposed, such as weakly-interacting massive particles (WIMPs), axion, axion-like particles (ALPs), sterile neutrino and gravitino. WIMPs may be able to annihilate with each other (or alternatively decay) into stable high-energy particle pairs, including gamma-rays, charged particles and neutrinos. ALPs and photons can convert to each other in electromagnetic fields through the Primakoff process, which could result in the detectable spectral oscillation phenomena in the gamma-rays observation. My research mainly focused on the indirect detection of dark matter, such as ALPs and WIMPs, using publicly available Fermi Large Area Telescope (Fermi-LAT) data and the the published data of High Energy Stereoscopic System (H.E.S.S.) observation.

The conversion between photons and ALPs in the Milky Way magnetic field could result in the detectable oscillation phenomena in the gamma-ray spectra of the Galactic sources. First, we search for such oscillation effects in the spectra of supernova remnants caused by the photon-ALP conversion, using the Fermi LAT data. The inclusion of photon-ALP oscillations yields an improved fit to the γ-ray spectrum of IC443, which gives a statistical significance of 4.2σ in favor of such spectral oscillation. However, the best-fit parameters of ALPs are in tension with the CAST (CERN (European Centre for Nuclear Research) Axion Solar Telescope) limits. Secondly, we use the H.E.S.S. observations of some TeV sources in the Galactic plane to exclude the highest ALP mass region (i.e., ALP mass $m_{\rm a} \sim 10^{-7}$ eV) that accounts for the anomalously weak absorption of TeV gamma-rays for the first time.

A Milky Way-like galaxy is predicted to host tens of thousands of galactic DM subhalos. Annihilation of WIMPs in massive and nearby subhalos could generate detectable gamma-rays, appearing as unidentified, spatially-extended and stable gamma-ray sources. We search for such sources in the third Fermi Large Area Telescope source List (3FGL) and report the identification of a new candidate, 3FGL J1924.8−1034. 3FGL J1924.8−1034 is found spatially-extended at a high confidence level of 5.4σ. No significant variability has been found and its gamma-ray spectrum is well fitted by the dark matter annihilation into $b\bar{b}$ with a mass of ~ 43 GeV. All these facts make 3FGL J1924.8−1034 a possible dark matter subhalo candidate. However, due to the limited angular resolution, the possibility that the spatial extension of 3FGL J1924.8−1034 is caused by the contamination from the other un-resolved point source can not be ruled out.

The Milky Way dwarf spheroidal galaxy is considered one of the most ideal targets for indirect detection of dark matter due to their high dark matter density and low astrophysical backgrounds. We search for gamma-ray emission from nearby Milky Way dwarf spheroidal galaxies and candidates with Fermi-LAT data. Intriguingly, the peak TS (Test Statistic) value of the weak emission from Reticulum II rises continually. We also find that the combination of all these nearby sources will result in a more significant ($> 4\sigma$) gamma-ray signal. A commonly encountered obstacle in indirect searches for dark matter is how to disentangle possible signals from astrophysical backgrounds. Gamma-ray features, in particular monochromatic gamma-ray lines and boxlike spectral features, provide smoking gun signatures. We analyze the Fermi LAT observation of Milky Way satellites and the local volume dark matter subhalo population (with N-body simulation) to search for potential line signals, respectively. The corresponding upper limits on the cross section of DM annihilation into two photons are derived, without significant signal found. Then we study the box-shaped DM signals, which is generated by the decay of intermediate particles produced by DM annihilation or decay, with Fermi-LAT observations of dwarf spheroidal galaxies.