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评 述　华中师范大学百廿校庆专辑

中微子和暗物质物理的关联研究

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摘要　中微子质量起源和暗物质本质是粒子物理和宇宙学前沿的重要科学问题, 相关研究是探索超出粒子物理标准模型新物理的重要途径. 近二十多年来, 中微子和暗物质理论和实验研究均取得了重要进展. 本文简单介绍了中微子和暗物质理论和实验研究的进展和展望, 特别是两者之间的交叉关联研究.

关键词　中微子, 暗物质, 超出标准模型新物理

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1 引言

粒子物理标准模型是极其成功的理论, 但依然不够完善. 两个需要额外粒子自由度和相互作用的重要问题是中微子质量起源机制和暗物质本质. 中微子和暗物质是两个源于20世纪30年代为解释贝塔衰变中“缺失的能量”和星系团中“缺失的质量”而分别被提出的理论假设[1,2], 至今已接近百年历史. 在“中微子假说”提出后, 共有三种不同类型的中微子在实验上得以发现, 分别称为电子中微子、缪子中微子和陶中微子, 它们成为了粒子物理标准模型中基本粒子的一部分. 另一个关于中微子的理论猜测是中微子在传播过程中会发生振荡现象[3], 该现象在实验上得以证实, 意味着中微子具有极其微小的质量和存在代之间的混合, 其质量起源指向需要超出标准模型的新的自由度或新的相互作用. 众多的天文和宇宙学证据已明确地表明宇宙中八成以上的物质是非重子物质, 主要由所谓的冷暗物质组成. 虽然目前人们还没有揭示暗物质粒子的真实面目, 但可断定占其主体部分的暗物质粒子并非来自粒子物理标准模型中. 过去的几十年中, 中微子和暗物质实验极大地深化了人们对自然规律的认知, 包括粒子物理标准模型和宇宙学标准模型的建立. 在今后的一二十年内, 随着更多、更大、更先进的相关实验投入运行, 将提供中微子和暗物质相关物理参数和其他相关物理的更精确测量, 这必将更一步地提高人们对中微子和暗物质物理的相关认识, 以及对探索超出标准模型的新物理提供重要实验参考. 中微子和暗物质相关物理是当前粒子物理重要前沿研究领域, 人们试图厘清中微子质量起源机制和暗物质的本质. 作为超出标准模型物理的两个重要探针, 它们之间是否具有内在关联性是非常吸引人的有趣问题. 本文尝试简单介绍中微子物理和暗物质物理的交叉关联研

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究, 大致结构如下: 第2节简单介绍中微子混合与质量机制以及主流的暗物质粒子模型: 第3节介绍中微子物理与暗物质物理的关联研究, 主要包括相关理论模型构建; 第4节介绍利用中微子实验探测暗物质的相关唯象研究; 最后是本文总结.

2 中微子和暗物质

2.1 中微子混合与质量起源

中微子物理对标准模型的建立起了重要的作用, 如弱相互作用下宇称不守恒和中微子二分量理论催生了弱相互作用的V-A理论. 在粒子物理的标准模型中, 中微子被认为是一类无质量的粒子. 关于中微子拥有非零质量且在传播时存在混合的假设最早在二十世纪六十年代被提及[3], 并被用来解释太阳中微子的理论预测和实验观测偏差[4]. 中微子传播过程中存在味道之间的振荡现象最早于1998 年由日本的Super-Kamiokande实验给出[5]. 该实验通过探测大气中的中微子, 比较直接从大气中射入探测器的下行中微子和从地球背面通过穿越地球到达探测器的上行中微子事例数, 发现下行中微子和上行中微子中不同味道的中微子事例数之比是不同的, 从而判断出中微子在飞行过程中存在振荡现象. 此后中微子振荡现象分别在太阳中微子、反应堆中微子和加速器中微子实验中得到验证.

实验上人们已经发现了三种类型的中微子, 通过Z^0粒子的不可见衰变模式, LEP实验也基本上确定了轻的中微子代数为三代. 可在标准模型的框架中嵌入中微子质量考察三代中微子的混合和振荡, 中微子混合矩阵一般称为PMNS矩阵$U_{\rm PMNS}$, 具有三个混合角$(\theta_{12},\theta_{23},\theta_{13})$和Dirac相角$\delta_{\rm CP}$. 若中微子为Majorana类型粒子, 则还包含两个Majorana相角, 但在中微子振荡实验中难以测量. 通过近几十年众多中微子实验的努力, 中微子物理到了所谓的“精确”时代, 相关物理参数的整体数值拟合结果为[6,7]

$$\Delta m^2_{21} = 7.41^{+0.21}_{-0.20}\times 10^{-5}\,{\rm eV}^2\,,$$
$$\Delta m^2_{31(2)} = 2.511^{+0.028}_{-0.027}\,(-2.498^{+0.032}_{-0.025})\times 10^{-3}\,{\rm eV}^2\,,$$
$$\theta_{12}/^\circ = 33.41^{+0.75}_{-0.72}\,,\ \theta_{23}/^\circ = 49.1^{+1.0}_{-1.3}\,(49.5^{+0.9}_{-1.2})\,,$$
$$\theta_{13}/^\circ = 8.54^{+0.11}_{-0.12}\,(8.57^{+0.12}_{-0.11})\,,\ \delta_{\rm CP}/^\circ = 197^{+42}_{-25}\,(286^{+27}_{-32})\,.$$

其中, 括号内的部分代表的是中微子质量为逆序列时的拟合结果, 没有括号则代表正序列和逆序列的结果相同. 中微子质量具有这两种顺序是由于目前实验上还没有确定m_3和$m_{1,2}$的相对大小. 对于中微子的绝对质量大小, 目前实验上所能给出的最强的上限来自KATRIN实验$m_\nu < 0.8$ eV[8], 更强的限制则是来自于宇宙学, 给出了中微子质量总和的上限为$\sum m_\nu \lesssim 0.1$ eV[9–11].

目前绝大部分中微子振荡实验均符合三味中微子混合的理论, 但是MiniBooNE和LSND的结果显示, 可能存在更多类型的中微子, 质量量级为eV, 其不直接参与任何标准模型相互作用, 但与标准的中微子之间存在混合, 从而可以通过弱带电流与带电轻子发生耦合, 这样的中微子被称为eV量级的惰性中微子. 实验上暂时没有观测到其存在的明确信号, RENO, NEOS和大亚湾Daya Bay实验对于3+1模型, 即三代标准中微子加上一代惰性中微子的模型, 给出了很强的限制[12–15].

中微子存在振荡意味着它们具有非零的微小质量, 因此需要超出标准模型的新物理机制来提供中微子的质量起源. 中微子质量一般通过两种机制来实现, 一种是中微子为Dirac粒子, 其质量来源于希格斯机制, 另一种是中微子为Majorana粒子, 即中微子是其自身的反粒子, 通过跷跷板机制获得质量, 目前暂时还无法确定中微子是哪种类型的粒子.

若中微子是Dirac粒子, 在标准模型中引入右手中微子ν_R, 其质量可以由汤川耦合项$(y_\nu\overline{L_L}\tilde{\Phi}\nu_R+{\rm h.c.})$导出, 在自发性对称破缺后, 希格斯粒子获得真空期待值v, 赋予中微子Dirac质量$M^D_\nu = y_\nu v$. 对于Majorana中微子, 可在标准模型框架下引入三代重的单态Majorana右手中微子N_R, 使得中微子质量项除了Dirac质量项外还有破坏轻子数的Majorana质量项$\overline{N^c_R}M_N N_R$. 在对称性破缺后, 中微子质量在(ν_L, N^c_R)的基矢下可以写成一个6×6的方块矩阵, 在对矩阵进行块状对角化后, 可以得到轻的Majorana中微子的质量矩阵为$M^M_\nu = -M^D_\nu M^{-1}_N M^{DT}_\nu$. 可以看出, 当$M_N$足够大时, 可以自然地得到微小的Majorana中微子质量, 这样的机制被称为第一类型跷跷板机制[16–19].

更一般地, 若中微子为Majorana类型粒子, 其质量可以通过破坏轻子数两个单位的五维(Weinberg)算符$f_{ij}(\overline{L^{ic}_L}i\sigma_2\Phi)(\Phi^T i\sigma_2 L^j_L)/\Lambda + {\rm h.c.}$来生成[20], 这个算符在树图层次上有且仅有三种实现的方式[21], 分别被

称为第一类、第二类和第三类跷跷板模型, 如图1所示. 第一类跷跷板模型如前文所述, 引入的是单态右手中微子. 第二类模型引入的是三重态的希格斯粒子[22–26], 而第三类模型引入的是三重态费米子[27]. 此外, 在此基础上, 一些模型考虑了加入两种以上新的粒子, 例如混杂型跷跷板模型[28–31], 考虑加入单态右手中微子和三重态希格斯粒子; linear[32], inverse[33,34], double[35]跷跷板模型中, 则是考虑加入惰性中微子S_L和单态右手中微子N_R.

Weinberg算符除了可在树图层次上实现, 也可以通过圈图的方式实现. 相较于树图而言, 由于圈图本身存在压低因子, 因此在实现中微子质量时, 新加入的粒子的质量可以更轻, 在高能对撞机搜寻上更有优势. 相关的研究工作有很多, 例如文献[21,23,36,37]在单圈图上实现中微子质量; 文献[23,38–45]对两圈图进行了讨论; 对于三圈图的分析和讨论, 相关的工作见文献[46–49]. 这些在圈图层次上实现中微子质量的模型, 又被称为辐射中微子质量模型, 相关的详细综述可参考文献[50]. 除了五维算符外, 微小的中微子Majorana质量也可以通过更高维算符产生, 相关的讨论可见文献[51–53].

另外, 对于Dirac中微子质量, 也可以通过类跷跷板机制来获得质量, 以避免“不自然”地引入过于小的汤川耦合系数. 在Dirac跷跷板模型中, 加入单态右手中微子ν_R和一个具有真空期待值的标量单态S, 另外还

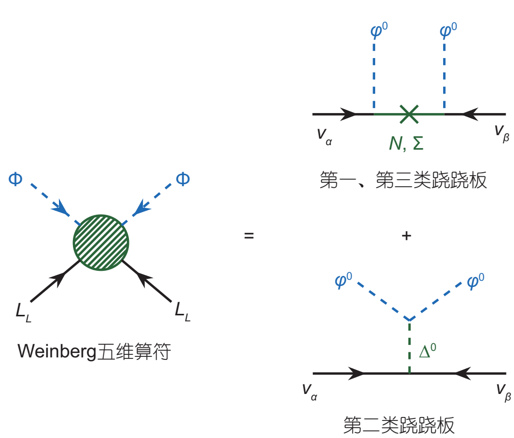

图 1 (网络版彩图)树图层次上的Majorana中微子跷跷板机制

Figure 1 (Color online) The tree level seesaw models for Majorana neutrinos.

需引入新的对称性Z_2. 在Z_2对称性下, 所有标准模型粒子为偶(+1), 所有新物理粒子为奇(−1), 使得树图层次上的汤川耦合项被禁戒, 中微子的Dirac质量通过一个五维算符$g_{ij}\overline{L_L^i}\tilde{\Phi}\nu_R^j S/\Lambda + \mathrm{h.c.}$导出. 相应地, 树图层次上对于算符实现也可以分为三类, 分别称为第一类、第二类和第三类Dirac跷跷板模型, 引入的粒子为单态费米子、二重态费米子或是二重态标量粒子, 相关的研究工作见文献[54–59]. 文献[60,61]中作者对算符做了系统分析, 文献[62–66]讨论了圈图层次上的算符实现.

2.2 暗物质及其探测

从暗物质的概念被提出后, 对暗物质的研究已有相当长的一段历史. 随着天文观测和宇宙学进入“精确”时代, 我们对暗物质的性质有了更深入的了解. 暗物质候选者应该具有如下的性质: (1) 不参与标准模型的强相互作用和电磁相互作用; (2) 在宇宙时间尺度上稳定; (3) 有合适的残余丰度; (4) 大部分由非重子物质和非相对论性粒子组成. 合格的暗物质候选粒子的质量范围区间可以很大. 质量小的暗物质候选粒子可以在eV量级以下, 比如轴子, 它是为解决强CP问题而提出的一种假想粒子, 其玻色-爱因斯坦凝聚物是理想的冷暗物质候选者, 相关的研究可以参考文献[67–69]. 暗物质候选者的质量也可以非常大, 例如原初黑洞[70–72]. 在暗物质粒子模型中, 最受欢迎的是弱耦合大质量粒子(WIMP)模型. WIMP的质量区间大致为GeV到TeV量级, 是冷暗物质的理想候选者, 它们在早期宇宙中与普通粒子处于热平衡, 当宇宙温度低于其质量时发生退耦, 粒子密度冻结. WIMP粒子恰好能够自然地解释暗物质在宇宙中的残余丰度, 被称为WIMP奇迹. WIMP粒子可以很好地内嵌在超出标准模型的新物理模型中, 同时现代实验探测技术也对这样的暗物质有较好的探测灵敏度, 所以受到了领域内广泛的关注. 关于暗物质粒子模型的相关总结可参考文献[73,74].

对于WIMP暗物质粒子的探测方式一般分为三种, 即对撞机探测、间接探测和直接探测. 在对撞机上暗物质粒子和中微子类似, 表现为消失的横动量. 间接探测则为探测星系中暗物质湮灭或衰变产生的次级粒子, 通常为正负电子、正反质子、光子和中微子. 近些年来, 卫星和空间站实验PAMELA[75], Fermi-

LAT[76], AMS-02[77,78]和DAMPE[79]观测到的正负电子超出被认为可能跟暗物质湮灭有关, 受到了极大的关注. 直接探测则为探测暗物质和地下探测器中核子散射后核子的反冲能量所导致的信号. 1974年, Freedman[80]发现, 中微子与核子可通过中性流发生相互作用, 得益于核子相干效应, 会使得中微子-原子核弹性散射截面增强. 1984年, Drukier和Stodolsky[81]讨论了利用中微子-核子散射来探测中微子的可行性, 阐述了如何确定散射后核子的反冲能量. 随后, Goodman和Witten[82]在1985年指出, 可以利用类似的机制, 探测暗物质-原子核散射的核反冲信号, 从而判断暗物质粒子是否存在. 这样的探测手段现在成为了暗物质直接探测的主流方法, 暗物质粒子的质量、暗物质-核子散射截面大小和暗物质粒子相对于探测器的速度, 均会影响实验的探测率.

为了降低背景干扰, 暗物质直接探测实验装置均位于深地实验室中, 并使用高纯度的探测材料. 目前, 对于暗物质-核子自旋无关散射截面, 当暗物质粒子的质量大于3 GeV时, 最强的限制来自PandaX-4T[83], XENONnT[84]和LZ[85]实验; 在质量低于3 GeV的区间, DarkSide-50[86]和CRESST-III[87]的限制最强. 未来的暗物质直接探测实验的敏感度相较于目前的实验, 有望提高一到两个量级. 有关暗物质直接探测的综述可以参考文献[88, 89].

由于中微子无法被屏蔽, 中微子与靶材料中的核子散射所产生的背景在暗物质直接探测实验中不可忽略[90], 中微子-核相干散射所造成的本底被称为暗物质直接探测实验中的“中微子地板”, 是下一代暗物质直接探测实验需要面对的重要问题[91]. 此外, 中微子可以与靶材料中的电子发生弹性散射, 导致电子反冲[92], 这样的过程会在没有能力区分电子反冲和核反冲的实验中形成显著的背景. 对于中微子相干散射, COHERENT[93,94]实验组于2017年宣布探测到了相应的信号, 随后CONNIE[95,96], NCC-1701[97]和CONUS[98]实验公布了探测结果.

3 中微子和暗物质物理的关联研究

作为超出标准模型的两个重要新物理, 在一个模型框架下解释中微子质量起源和提供暗物质粒子是极具诱惑力的. 实际上, 早在二十世纪六七十年代, 人们就开始探讨标准模型中微子作为暗物质的可能性, 直到八十年代, 通过多粒子模拟, 认识到标准模型中微子作为热暗物质不能成为暗物质的主体[99]. 随着在实验上确定了中微子具有质量, 以及“高精度”天文和宇宙学实验时代的到来, 中微子和暗物质物理的关联研究成为揭示超出标准模型新物理的重要航标, 为此人们做了大量深入的理论探索和唯象研究. 在这一节中, 我们简单总结了一些有代表性的途径, 介绍中微子和暗物质物理的统一和关联研究, 梳理了相关的理论模型. 所涉及的理论模型包括门户暗物质模型、右手惰性中微子暗物质模型、sneutrino暗物质模型以及暗生中微子质量模型.

3.1 门户暗物质模型

一般暗物质模型中, 为保证暗物质的稳定性, 通常暗物质具有特定的对称性. 为区别标准模型粒子, 通常把跟暗物质粒子具有类似特定对称性的粒子称为暗部分(Dark Sector)粒子. 在一类简化模型中, 暗物质粒子通过特定媒介粒子与标准模型粒子耦合, 这样的模型被称为门户(Portal)暗物质模型. 根据媒介粒子类型, 模型又被称为矢量门户模型[100–102]、希格斯粒子门户模型[103–105]和中微子门户模型[106,107]等. 对于门户暗物质模型有效理论的考察可参考文献[108]. 接下来我们将简要介绍单态右手中微子门户模型和三重态希格斯粒子门户模型.

单态右手中微子门户暗物质模型 单态右手中微子门户暗物质模型, 是在标准模型基础上引入了单态右手中微子作为标准模型粒子和暗物质粒子的媒介粒子. 单态右手中微子不携带标准模型规范对称性的量子数, 可以与暗物质粒子耦合, 成为连接标准模型粒子和暗物质粒子的媒介子. 同时, 右手中微子的引入, 可以通过第一类型跷跷板模型来产生中微子的微小质量.

在最初的单态右手中微子门户暗物质模型中[106], 中微子质量通过第一类跷跷板机制来获得, 模型中暗物质粒子湮灭至右手中微子对, 由冻出机制产生合适的暗物质丰度. 而右手中微子作为一个不稳定粒子, 衰变至标准模型粒子. 更多类似和推广的工作见文献[108–119]. 单态右手中微子门户模型中, 除了冻出机制以外, 还有别的机制同样可以生成合适的暗

物质遗迹丰度. 如使用冻入机制[120–125]和非热产生机制[126,127].

右手中微子除了较自然地提供中微子质量外, 还可由轻子生成机制产生宇宙物质正反不对称. 若暗物质跟重子物质类似地存在粒子-反粒子不对称性, 这样的暗物质粒子通称为非对称暗物质. 拓展轻子生成机制, 利用单态右手中微子退耦后衰变同时产生重子物质和暗物质的不对称, 从而可以实现中微子质量、暗物质和宇宙正反物质不对称三者起源的统一[128,129].

右手中微子门户暗物质模型的直接探测截面通常受到大幅度的压低, 对于模型的实验检测研究, 主要集中在间接探测中, 如高能中微子末态[109,126]、电子末态[116]和光子末态[112,115]等, 更多对此类模型探测及限制的讨论可以参考文献[117, 125, 130, 131].

三重态希格斯粒子门户暗物质模型 希格斯粒子门户模型[105], 是指暗部分粒子与标准模型粒子之间的媒介子是希格斯粒子的一类模型. 最早的希格斯粒子门户模型是由Silveira和Zee[103]于1985年提出来的. 模型中暗物质粒子为实标量粒子X, 通过耦合项$X^2H^\dagger H$跟希格斯粒子耦合. 近年来, 希格斯粒子门户暗物质模型受到大量关注和发展, 暗物质粒子类型包括标量粒子[104,132,133]、矢量类型粒子[134–136]和费米子类型暗物质[137,138]. 对模型中相关参数的限制, 主要来自于暗物质直接探测和希格斯粒子不可见衰变[139–144]. 更多关于希格斯粒子门户模型的讨论可以参考综述[145].

如果将媒介粒子替换成三重态的希格斯粒子, 即三重态希格斯粒子门户暗物质模型, 可以很自然地将暗物质与中微子质量起源联系起来. 由于三重态希格斯粒子可直接跟轻子耦合, 利用三重态希格斯粒子来解释暗物质间接探测实验中的电子超出现象是可行且自然的[146–148], 中微子的质量则通过第二类型跷跷板机制产生. 许多工作对三重态希格斯粒子门户暗物质模型进行了讨论, 例如, 文献[149–154]讨论了三重态希格斯粒子门户暗物质模型对Fermi-LAT, AMS-02和DAMPE实验所观测到的电子超出谱的解释.

3.2 右手惰性中微子暗物质

惰性中微子一般指单态中性费米子, 其不直接参与标准模型规范相互作用, 惰性中微子常出现在中微子质量起源机制——跷跷板机制中. 在一般惰性中微子暗物质模型中, 惰性中微子通过与标准模型中微子混合, 可衰变到三个轻中微子. 当其与普通中微子的混合较小且其质量较轻, 如在keV量级时, 其寿命可远大于宇宙的年龄, keV量级的右手惰性中微子满足作为暗物质候选者的基本条件.

Dodelson和Widrow[155]曾提出keV惰性中微子在早期宇宙中可以通过与普通中微子的微小混合来产生, 并且能够充当所有的暗物质, 这样的机制被称为Dodelson-Widrow机制. 在此机制下，轻的普通中微子可以在退耦前通过振荡产生大量的惰性中微子, 这样的机制本质上是一种冻入机制. 另外惰性中微子因为和标准模型中微子的微小混合, 可辐射衰变到普通中微子$\nu_s \to \nu\gamma$. 因此, 若通过Dodelson-Widrow机制来产生合适的暗物质丰度, 则会受到来自X射线观测的强烈限制[156,157]. 为避免这一限制, 挽救惰性中微子作为暗物质候选者的可能, 有许多理论工作提出了其他机制来生成合适的暗物质丰度[158–164], 如其中Shi-Fuller机制[158], 在Dodelson-Widrow机制的基础上, 考虑了惰性中微子和普通中微子之间存在共振效应, 加大了惰性中微子的产生, 从而压低混合参数.

利用跷跷板机制来产生轻的中微子质量, 加入的右手中微子质量一般较重. 若模型除了自然得到小的中微子质量外, 还需容纳keV量级的惰性中微子, 往往在模型构造中, 需要一些压低机制, 使得右手惰性中微子的质量发生分离, 其中最轻的质量被压低至keV量级, 成为合适的暗物质候选者. 文献采用的方式包括使用所谓的Split跷跷板机制[165]、Froggatt-Nielsen机制[166]、添加额外的味对称性[167–169]或更为复杂的跷跷板机制等方法, 可参见综述[170]. 关于keV惰性中微子暗物质的理论、探测手段、早期产生及相关模型建立的完整综述, 可见文献[156, 171, 172].

3.3 Sneutrino暗物质

在超对称理论中, 最轻的超对称粒子可以作为暗物质候选粒子, 常见的候选者为中性伴随子neutralino. 中微子的超对称伴随粒子sneutrino很早就被考虑为冷暗物质候选者[173,174], 但由于左手sneutrino存在和Z玻色子的直接耦合, 使得其与核子的散射截面

超过了直接探测实验给出的上限限制[175], 因此左手sneutrino暗物质模型被排除了. 若加入右手中微子, 左右手sneutrino之间的混合可减弱sneutrino暗物质粒子与Z玻色子的耦合强度, 最轻的混合态作为暗物质可以有合适的遗迹丰度以及压低的散射截面大小[176–178], sneutrino系统的研究综述可见文献[179].

关于sneutrino暗物质的相关研究, 并不仅仅局限于对最小超对称模型(MSSM)的简单扩充. 例如, 文献[180]考虑了在MSSM中加入三重态标量粒子, 该模型下最轻的sneutrino实部可以作为暗物质的候选者; 文献[181]则是考虑在MSSM中引入额外的规范对称性和单态希格斯超场及右手中微子, 使得最轻的CP为偶的sneutrino成为暗物质候选者; 以及在次最小超对称模型(NMSSM)中, 加入Type-I跷跷板机制, 如文献[182–186]; 而在文献[187]中, 作者考虑在NMSSM中引入inverse跷跷板机制, 使sneutrino成为不对称暗物质候选者. 类似的相关工作还有文献[188–196].

3.4 辐射中微子质量起源和暗物质模型

在辐射中微子质量模型中, 有一类模型可以提供暗物质粒子候选者, 其中被讨论和研究得最多的被称为暗生中微子质量模型(Scotogenic 模型). Scotogenic模型最早是由Ma[197]于2006年提出, 如图2所示. 该模型中, 除标准模型粒子外, 额外引入了三代重的单态Majorana右手中微子和一个二重态标量粒子η, 并且引入了额外的Z_2对称性. 在Z_2对称性下, 标准模型粒子量子数均为偶, 新物理粒子量子数均为奇, 树图层次的跷跷板机制被禁戒, 并且二重态标量粒子η不具有真空期待值, 中微子没有Dirac质量, 而是通过单圈图生Majorana质量. Z_2对称性为奇的最轻右手中微子或最轻中性标量粒子可以作为合适的暗物质候选者.

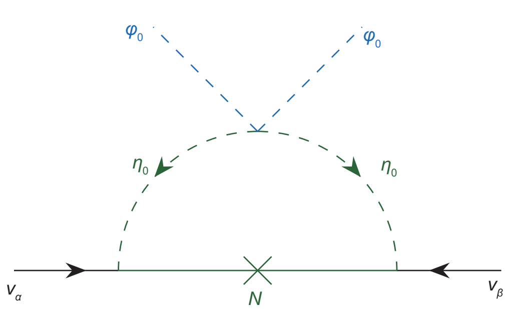

图 2 (网络版彩图)暗生中微子质量模型

Figure 2 (Color online) Neutrino Scotogenic mass model.

在Scotogenic模型的基础上, 有许多工作进行了推广和扩充, 例如引入味对称性, 包括分立对称性A_4[198–200]、$\Delta(27)$[201,202], 连续对称性$U(1)_{L_\mu-L_\tau}$[203–205]、$U(1)_D$[202,206]、$U(1)_{B-L}$[207–210], 或者是模对称性S_3[211]、A_4[212,213]、S_4[214]; 将模型中的右手中微子替换成三重态费米子[215,216], 或是引入额外的粒子, 如单态标量粒子[217–219]、三重态标量粒子[220–222]、带颜色的标量粒子和费米子[223]; 将原有模型中的三代右手中微子和一个二重态标量粒子推广到多个右手中微子和多个二重态标量粒子[224] 等; 对于所有可能的紫外扩充的讨论可见文献[225]. 类似的可以在单圈图层次实现中微子质量和提供暗物质候选者的模型还有许多, 比如文献[226–242], 系统的分析可以参考文献[243, 244].

在两圈或者是三圈层次上, 将辐射Majorana中微子质量模型与暗物质关联考察的相关工作也有很多, 比如, 文献[245]在两圈图Zee-Babu模型的基础上, 引入了Z_2对称性, 并且加入了一个具有真空期待值的单态标量粒子和两个可以作为暗物质候选者的单态费米子; 两圈层次上的系统分析可见文献[45]; 文献[46]是最早在三圈图层次上对中微子质量进行考察的工作, 所提出的模型被称为KNT模型, 在这个模型中, 最轻的右手中微子可以作为暗物质的候选者; 在三圈层次上实现中微子质量且提供暗物质候选者的经典模型还有AKS模型[47]和Cocktail模型[246].

4 暗物质和中微子实验

在这一节中，我们将简要梳理与暗物质探测相关的中微子实验. 对暗物质进行探测, 除了利用直接探测的方式, 还可以通过间接探测的手段. 暗物质间接探测, 是指通过检测暗物质湮灭或者衰变产生的标准模型粒子来寻找暗物质的方法. 这些标准模型粒子可以是电子、质子这样的带电粒子, 也可以是中微子、光子这样的中性粒子. 对于中微子末态, 我们可以借助大型的中微子探测器, 来识别相应的信号, 从而更好地了解暗物质在宇宙中的分布情况. 关于利用中微子实验间接探测暗物质的综述可见文献[247].

暗物质源太阳中微子探测 当太阳系穿越银河系暗物质晕时, 暗物质粒子可能被太阳捕获并聚集在太

阳内部[248–251]. 暗物质粒子在太阳内部湮灭，可产生标准模型粒子, 如$b\bar{b}$, $\tau^+\tau^-$和W^+W^-, 然后衰变产生中微子末态, 也可能暗物质直接湮灭产生中微子对$\nu\bar{\nu}$. 若俘获和湮灭过程达到平衡, 产生的中微子信号束流取决于暗物质与核子的散射截面大小. 通过地球上的中微子探测器探测相应的暗物质湮灭产生的太阳中微子信号, 可探测暗物质和核子之间的散射截面, 这也为地下暗物质直接探测实验提供了一个良好补充. 文献中有大量的研究工作考察了这个过程的相关唯象学, 例如文献[252–264].

目前在实验上, Super-Kamiokande超级神冈探测器[265,266]、IceCube冰立方探测器[267–269]、Antares探测器[270,271]和Baksan探测器[272,273]对暗物质源太阳中微子信号进行了搜寻. 实验所关注的暗物质质量通常在4 GeV以上, 这是因为质量更小的暗物质粒子会在太阳内部受到蒸发的严重影响, 导致湮灭信号会被大幅度压低.

由于太阳主要由较轻的元素构成, 中微子实验对WIMP暗物质自旋无关散射截面的探测能力往往要弱于暗物质直接探测实验. 但对于自旋相关散射截面, 中微子实验则可以提供相当的探测能力. 如图3所示, IceCube实验[268,269]利用暗物质直接湮灭到中微子末态的湮灭道, 对暗物质-质子散射截面给出了很强的限制, 未来的Hyper-Kamiokande顶级神冈探测器[277,278]和IceCube-PINGU探测器[279,280]可以进一步对自旋相关的暗物质-质子散射截面存活区域进行检验.

银河系中心暗物质源中微子信号 由于引力的束缚, 银河系中心会聚集大量的暗物质粒子. 因此, 如果暗物质发生湮灭, 就有可能在地球上发现相应的湮灭末态的信号[281–285]. 相对于对带电粒子末态的探测, 对银河系中心暗物质湮灭产生的中微子进行搜寻具有明显的优势. 中微子在银河系中心产生后可以不受银心区域磁场偏转以及宇宙中其他物质的影响, 几乎沿着直线到达地球, 因此方向的信息往往非常明确.

目前, 依靠暗物质湮灭的中微子信号, 在1 GeV以上的银心暗物质湮灭截面可以被中微子探测器Super-Kamiokande[286], IceCube[287–290]和Antares[291–293]所限制, 这些限制可以受到未来的Hyper-Kamiokande探测器[278,294]、JUNO江门中微子实验[295]、DUNE实验[296]、KM3NeT实验[297]以及IceCube-Gen2[298]探测

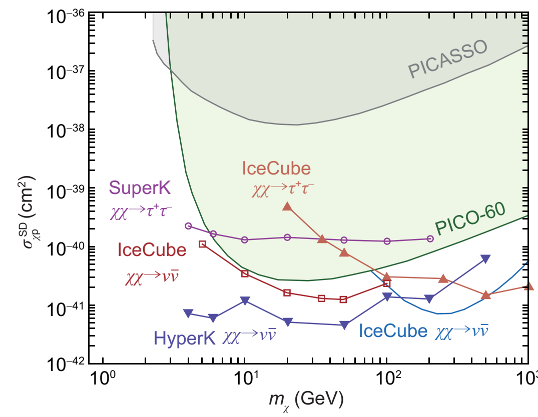

图 3 (网络版彩图)暗物质-质子自旋相关散射截面限制. 这些限制来自PICASSO[274], PICO-60[275], IceCube[268,269,276], Super-Kamiokande[266]和Hyper-Kamiokande[277]

Figure 3 (Color online) Limits on the spin-dependent DM-proton scattering cross section from PICASSO [274], PICO-60 [275], IceCube [268,269,276], Super-Kamiokande [266] and Hyper-Kamiokande [277].

器的进一步检验. 对于暗物质湮灭截面限制的完整总结可见综述[299].

轻暗物质和中微子实验 质量在GeV量级以下的WIMP暗物质常被称为轻暗物质. 加速器中微子振荡实验装置可以满足产生轻暗物质的要求, 并且对于MeV量级的轻暗物质探测具有很高的敏感度[300–305]. 在加速器中微子装置中, 质子束流打到固定靶上时, 有可能会直接产生暗物质粒子以及介子. 介子进一步衰变到暗物质粒子, 随后暗物质传播到附近的探测器中. 当暗物质粒子与探测器中的物质, 如电子或者核子, 发生散射时, 我们就能看到相应的信号.

MiniBooNE实验对于矢量粒子门户的轻暗物质进行了搜寻[306–308], 对于矢量粒子与暗物质粒子质量比m_V/m_χ数值较大的模型, 其参数空间会受到遗迹丰度和MiniBooNE实验的严格限制[308]. 正在运行和升级的长基线加速器中微子实验, T2K[278,309]和NOνA[310], 以及下一代加速器中微子实验, 如DUNE[296], SBND[311], MicroBooNE[312,313], ICARUS[314]和JSNS^2[315]等, 可以对轻暗物质模型进行更为全面的检验.

除加速器中微子实验外, 高能中微子探测器同样具有对轻暗物质模型进行限制和检验的潜力. 如果来自系外的高能中微子在传播到地球的过程中, 在穿越银心的暗物质晕时与暗物质发生了散射并失去一

部分能量, 那么高能中微子的谱线就会发生变化, 银心方向的中微子束流强度会被压低, 也有可能发生味道的改变[316,317]. 这样的过程在门户暗物质模型或暗物质与中微子存在耦合的模型[318,319]中可以被自然地实现. 在实验上, 可以利用河外中微子信号的各向同性性质来搜寻银心暗物质与中微子的相互作用. 当中微子与暗物质耦合强度足够大时, 来自银心的中微子束流会被压低, 在探测器上会观察到明显的信号. 高能中微子实验对于中微子-暗物质散射截面的限制强度依赖于中微子束流的能量大小, IceCube探测器对于质量在GeV能标下的轻暗物质具有较高的敏感度[316,320–324].

重暗物质和高能中微子实验 一般来说, 对于热产生机制的WIMP, 由于幺正性对湮灭截面的限制, 质量一般在GeV到TeV能标之间. 更高质量的暗物质可以通过非热过程产生, 并得到合适的暗物质丰度[325]. 对于重暗物质, 由于其质量可以远大于目前对撞机的能量, 因此通过对撞机对其进行搜寻十分困难, 但是借助其湮灭或者衰变产生的中微子信号, 可以利用高能中微子探测器来进行间接搜寻.

暗物质通常被认为是稳定的粒子, 但是严格上来说, 暗物质粒子不需要完全稳定, 只需要寿命比宇宙年龄长即可. 如果暗物质以足够高的速率衰变, 其衰变产物就可能被检测到. 在一些理论模型中, 如大统一模型[326–328]和R宇称破坏的超对称模型[146,329–332], 暗物质候选粒子可以发生两体或多体衰变, 从而解释早期Fermi-LAT[76], HESS[333], PAMELA[75]和ATIC[334]等实验中电子超出的反常现象[327,335]. 在这些模型中, 暗物质通常是亲轻子(Leptophilic)衰变的, 伴随有中微子末态, 也就是说, 通过中微子末态去考察暗物质衰变也是自然且可行的[336–338]. 在2013年, IceCube实验组宣布测量到了PeV量级的高能中微子[339,340], 有一系列的探测数据分析证实了其结果的可靠性[341–343]. 随后, 有许多理论工作将高能中微子事例与重暗物质的衰变联系起来, 如文献[344–358], 这些研究工作考查了高能中微子信号对于不同模型中的重暗物质寿命及相关参数的限制.

现有的高能中微子实验, 如IceCube[290,321,359,360]和Antares[291–293], 对质量在1 TeV–10 PeV范围内的暗物质湮灭和衰变所产生的中微子信号具有较高的敏感度, 可以很好地限制重暗物质的湮灭截面和寿命. 当位于银河系中心、系晕以及银河系外的暗物质发生湮灭或者衰变时, 有可能直接或者间接产生高能中微子. 这些中微子往往有特定的方向分布及能谱, 因此探测器可以从天文事例产生的高能中微子中分析并识别出相应的信号, 信号的背景主要来源于高能宇宙射线撞击大气层时所产生的缪子和大气中微子.

未来的中微子实验对于探测重暗物质的湮灭和衰变到中微子的能力会有极大的提高, 目前正在升级或是建设中的高能中微子及超高能中微子实验有P-ONE[361,362], KM3NeT[297], TAMBO[361], IceCube-Gen2[361], RNO-G[361]和GRAND[361]等. 关于高能中微子实验对于重暗物质湮灭截面和寿命限制的总结可见文献[299, 363], 实验现状及未来发展的详细介绍可见文献[364].

5 总结

中微子和暗物质物理是极其丰富的前沿领域, 中微子质量和混合起源机制和暗物质本质是亟待解决的重大科学问题, 也是探索超出标准模型新物理的重要途径. 我们简单介绍了中微子混合与质量机制、主流的暗物质粒子模型, 以及中微子物理与暗物质物理在理论模型和实验探测的关联研究. 可以预见, 随着更多国内和国际中微子和暗物质实验的投入运行, 以及理论研究工作的持续推动, 人们对中微子质量起源机制、暗物质的本质和超出标准模型新物理将有更深入的认识.

参考文献

1 Pauli W. Dear radioactive ladies and gentlemen. Phys Today, 1978, 31N9: 27
2 Zwicky F. Die rotverschiebung von extragalaktischen Nebeln. Helv Phys Acta, 1933, 6: 110–127
3 Gribov V, Pontecorvo B. Neutrino astronomy and lepton charge. Phys Lett B, 1969, 28: 493–496
4 Davis R, Harmer D S, Hoffman K C. Search for neutrinos from the Sun. Phys Rev Lett, 1968, 20: 1205–1209

5 Fukuda Y, Hayakawa T, Ichihara E, et al. Evidence for oscillation of atmospheric neutrinos. Phys Rev Lett, 1998, 81: 1562–1567

6 Esteban I, Gonzalez-Garcia M C, Maltoni M, et al. The fate of hints: Updated global analysis of three-flavor neutrino oscillations. J High Energ Phys, 2020, 2020(9): 178

7 Esteban I, Gonzalez-Garcia M C, Maltoni M, et al. Three-neutrino fit based on data available in november 2022. Nufit5.2(2022) at nufit webpage, 2022, http://www.nu-fit.org

8 Aker M, Beglarian A, Behrens J, et al. Direct neutrino-mass measurement with sub-electronvolt sensitivity. Nat Phys, 2022, 18: 160–166

9 Alam S, Aubert M, Avila S, et al. Completed SDSS-IV extended baryon oscillation spectroscopic survey: Cosmological implications from two decades of spectroscopic surveys at the Apache Point Observatory. Phys Rev D, 2021, 103: 083533

10 Palanque-Delabrouille N, Yèche C, Schöneberg N, et al. Hints, neutrino bounds, and WDM constraints from SDSS DR14 Lyman-α and Planck full-survey data. J Cosmol Astropart Phys, 2020, 2020(4): 038

11 Abbott T M C, et al. (DES Collaboration). Dark energy survey year 3 results: Cosmological constraints from galaxy clustering and weak lensing. Phys Rev D, 2022, 105: 023520

12 An F, Balantekin A, Band H, et al. Search for a light sterile neutrino at Daya Bay. Phys Rev Lett, 2014, 113: 141802

13 Adamson P, An F, Anghel I, et al. Limits on active to sterile neutrino oscillations from disappearance searches in the MINOS, Daya Bay, and Bugey-3 experiments. Phys Rev Lett, 2016, 117: 151801 [Addendum: Phys Rev Lett, 2016, 117: 209901]

14 Ko Y, Kim B, Kim J, et al. Sterile neutrino search at the NEOS experiment. Phys Rev Lett, 2017, 118: 121802

15 Atif Z, Choi J, Han B, et al. Search for sterile neutrino oscillations using RENO and NEOS data. Phys Rev D, 2022, 105: L111101

16 Minkowski P. $\mu \to e\gamma$ at a rate of one out of 10^9 muon decays? Phys Lett B, 1977, 67: 421–428

17 Mohapatra R N, Senjanović G. Neutrino mass and spontaneous parity nonconservation. Phys Rev Lett, 1980, 44: 912–915

18 Gell-Mann M, Ramond P, Slansky R. Complex spinors and unified theories. Conf Proc C, 1979, 790927: 315–321

19 Glashow S L. The future of elementary particle physics. In: Proceedings of Quarks and Leptons. Boston, 1980

20 Weinberg S. Baryon- and lepton-nonconserving processes. Phys Rev Lett, 1979, 43: 1566–1570

21 Ma E. Pathways to naturally small neutrino masses. Phys Rev Lett, 1998, 81: 1171–1174

22 Konetschny W, Kummer W. Nonconservation of total lepton number with scalar bosons. Phys Lett B, 1977, 70: 433–435

23 Cheng T P, Li L F. Neutrino masses, mixings, and oscillations in SU(2) × U(1) models of electroweak interactions. Phys Rev D, 1980, 22: 2860–2868

24 Lazarides G, Shafi Q, Wetterich C. Proton lifetime and fermion masses in an SO(10) model. Nucl Phys B, 1981, 181: 287–300

25 Schechter J, Valle J W F. Neutrino masses in SU(2) × U(1) theories. Phys Rev D, 1980, 22: 2227–2235

26 Mohapatra R N, Senjanović G. Neutrino masses and mixings in gauge models with spontaneous parity violation. Phys Rev D, 1981, 23: 165–180

27 Foot R, Lew H, He X G, et al. See-saw neutrino masses induced by a triplet of leptons. Z Phys C-Part Fields, 1989, 44: 441–444

28 Wetterich C. Natural maximal $\nu\mu$-$\nu\tau$ mixing . Phys Lett B, 1999, 451: 397–405

29 Rodejohann W, Xing Z Z. Flavor democracy and type-II seesaw realization of bilarge neutrino mixing. Phys Lett B, 2004, 601: 176–183

30 Antusch S, King S F. From hierarchical to partially degenerate neutrinos via type II upgrade of type I see-saw models. Nucl Phys B, 2005, 705: 239–268

31 Chen S L, Frigerio M, Ma E. Hybrid seesaw neutrino masses with family symmetry. Nucl Phys B, 2005, 724: 423–431

32 Barr S M. New type of seesaw mechanism for neutrino masses. Phys Rev Lett, 2004, 92: 101601

33 Mohapatra R N, Valle J W F. Neutrino mass and baryon-number nonconservation in superstring models. Phys Rev D, 1986, 34: 1642–1645

34 Gonzalez-Garcia M C, Valle J W F. Fast decaying neutrinos and observable flavour violation in a new class of majoron models. Phys Lett B, 1989, 216: 360–366

35 Mohapatra R N. Mechanism for understanding small neutrino mass in superstring theories. Phys Rev Lett, 1986, 56: 561–563

36 Zee A. A theory of lepton number violation and neutrino Majorana masses. Phys Lett B, 1980, 93: 389–393 [Erratum: Phys Lett B, 1980, 95: 461]

37 Bonnet F, Hirsch M, Ota T, et al. Systematic study of the $d = 5$ Weinberg operator at one-loop order. J High Energ Phys, 2012, 2012(7): 153

38 Zee A. Quantum numbers of Majorana neutrino masses. Nucl Phys B, 1986, 264: 99–110

39 Babu K S. Model of "calculable" Majorana neutrino masses. Phys Lett B, 1988, 203: 132–136

40 Ma E. Z(3) dark matter and two-loop neutrino mass. Phys Lett B, 2008, 662: 49–52

41 Guo G, He X G, Li G N. Radiative two loop inverse seesaw and dark matter. J High Energ Phys, 2012, 2012(10): 044

42 Farzan Y. Two-loop snail diagrams: Relating neutrino masses to dark matter. J High Energ Phys, 2015, 2015(5): 29

43 Cao Q H, Chen S L, Ma E, et al. New class of two-loop neutrino mass models with distinguishable phenomenology. Phys Lett B, 2018, 779:

430–435
44 Aristizabal Sierra D, Degee A, Dorame L, et al. Systematic classification of two-loop realizations of the Weinberg operator. J High Energ Phys, 2015, 2015(3): 040
45 Simoes C, Wegman D. Radiative two-loop neutrino masses with dark matter. J High Energ Phys, 2017, 2017(4): 148
46 Krauss L M, Nasri S, Trodden M. Model for neutrino masses and dark matter. Phys Rev D, 2003, 67: 085002
47 Aoki M, Kanemura S, Seto O. Neutrino mass, dark matter, and baryon asymmetry via TeV-scale physics without fine-tuning. Phys Rev Lett, 2009, 102: 051805
48 Farzan Y, Pascoli S, Schmidt M A. Recipes and ingredients for neutrino mass at loop level. J High Energ Phys, 2013, 2013(3): 107
49 Cepedello R, Fonseca R M, Hirsch M. Systematic classification of three-loop realizations of the Weinberg operator. J High Energ Phys, 2018, 2018(10): 197 [Erratum: J High Energ Phys, 2019, 2019(06): 034]
50 Cai Y, Herrero García J, Schmidt M A, et al. From the trees to the forest: A review of radiative neutrino mass models. Front Phys, 2017, 5: 63
51 Liao Y. Unique neutrino mass operator at any mass dimension. Phys Lett B, 2011, 694: 346–348
52 Liao Y. Cascade seesaw for tiny neutrino mass. J High Energ Phys, 2011, 2011(6): 98
53 Cepedello R, Hirsch M, Helo J C. Loop neutrino masses from $d = 7$ operator. J High Energ Phys, 2017, 2017(7): 079
54 Roncadelli M, Wyler D. Naturally light Dirac neutrinos in gauge theories. Phys Lett B, 1983, 133: 325–329
55 Ma E, Srivastava R. Dirac or inverse seesaw neutrino masses from gauged B-L symmetry. Mod Phys Lett A, 2015, 30: 1530020
56 Centelles Chuliá S, Ma E, Srivastava R, et al. Dirac neutrinos and dark matter stability from lepton quarticity. Phys Lett B, 2017, 767: 209–213
57 Gu P H, He H J. Neutrino mass and baryon asymmetry from Dirac seesaw. J Cosmol Astropart Phys, 2006, 2006(12): 010
58 Valle J W F, Vaquera-Araujo C A. Dynamical seesaw mechanism for Dirac neutrinos. Phys Lett B, 2016, 755: 363–366
59 Gu P H. Peccei-Quinn symmetry for Dirac seesaw and leptogenesis. J Cosmol Astropart Phys, 2016, 2016(7): 004
60 Yao C Y, Ding G J. Systematic analysis of Dirac neutrino masses from a dimension five operator. Phys Rev D, 2018, 97: 095042
61 Chuliá S C, Cepedello R, Peinado E, et al. Systematic classification of two-loop $d = 4$ Dirac neutrino mass models and the Diracness-dark matter stability connection. J High Energ Phys, 2019, 2019(10): 93
62 Mohapatra R N. Left-right symmetry and finite one-loop Dirac neutrino mass. Phys Lett B, 1988, 201: 517–524
63 Ma E, Popov O. Pathways to naturally small Dirac neutrino masses. Phys Lett B, 2017, 764: 142–144
64 Bonilla C, Ma E, Peinado E, et al. Two-loop Dirac neutrino mass and WIMP dark matter. Phys Lett B, 2016, 762: 214–218
65 Ma E, Sarkar U. Radiative left-right Dirac neutrino mass. Phys Lett B, 2018, 776: 54–57
66 Yao C Y, Ding G J. Systematic study of one-loop Dirac neutrino masses and viable dark matter candidates. Phys Rev D, 2017, 96: 095004 [Erratum: Phys Rev D, 2018, 98: 039901]
67 Kim J E, Carosi G. Axions and the strong CP problem. Rev Mod Phys, 2010, 82: 557–601 [Erratum: Rev Mod Phys, 2019, 91: 049902]
68 Hook A. TASI Lectures on the strong CP problem and Axions. PoS, 2019, TASI2018: 004
69 Adams C B, Aggarwal N, Agrawal A, et al. Axion dark matter. In: Proceedings of the 2021 US Community Study on the Future of Particle Physics (Snowmass2021). Seattle, 2022
70 Carr B, Kühnel F. Primordial black holes as dark matter: Recent developments. Annu Rev Nucl Part Sci, 2020, 70: 355–394
71 Green A M, Kavanagh B J. Primordial black holes as a dark matter candidate. J Phys G-Nucl Part Phys, 2021, 48: 043001
72 Carr B, Kohri K, Sendouda Y, et al. Constraints on primordial black holes. Rep Prog Phys, 2021, 84: 116902
73 Bertone G, Hooper D, Silk J. Particle dark matter: evidence, candidates and constraints. Phys Rep, 2005, 405: 279–390
74 Bauer M, Plehn T. Yet another introduction to dark matter: The particle physics approach. In: Lecture Notes in Physics. Cham: Springer, 2019. 959
75 Adriani O, Barbarino G C, Bazilevskaya G A, et al. An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV. Nature, 2009, 458: 607–609
76 Abdo A A, Ackermann M, Ajello M, et al. Measurement of the cosmic ray e^+ plus e^- spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope. Phys Rev Lett, 2009, 102: 181101
77 Aguilar M, Alberti G, Alpat B, et al. First result from the alpha magnetic spectrometer on the international space station: Precision measurement of the positron fraction in primary cosmic rays of 0.5–350 GeV. Phys Rev Lett, 2013, 110: 141102
78 Accardo L, Aguilar M, Aisa D, et al. high statistics measurement of the positron fraction in primary cosmic rays of 0.5–500 GeV with the alpha magnetic spectrometer on the international space station. Phys Rev Lett, 2014, 113: 121101
79 Ambrosi G, et al. (DAMPE Collaboration). Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons. Nature, 2017, 552: 63–66

80 Freedman D Z. Coherent effects of a weak neutral current. Phys Rev D, 1974, 9: 1389–1392
81 Drukier A, Stodolsky L. Principles and applications of a neutral-current detector for neutrino physics and astronomy. Phys Rev D, 1984, 30: 2295–2309
82 Goodman M W, Witten E. Detectability of certain dark-matter candidates. Phys Rev D, 1985, 31: 3059–3063
83 Meng Y, Wang Z, Tao Y, et al. Dark matter search results from the PandaX-4T commissioning run. Phys Rev Lett, 2021, 127: 261802
84 Aprile E, Abe K, Agostini F, et al. First dark matter search with nuclear recoils from the XENONnT experiment. Phys Rev Lett, 2023, 131: 041003
85 Aalbers J, Akerib D, Akerlof C, et al. First dark matter search results from the LUX-ZEPLIN (LZ) experiment. Phys Rev Lett, 2023, 131: 041002
86 Agnes P, Albuquerque I, Alexander T, et al. Search for low-mass dark matter WIMPs with 12 ton-day exposure of DarkSide-50. Phys Rev D, 2023, 107: 063001
87 Abdelhameed A, Angloher G, Bauer P, et al. First results from the CRESST-III low-mass dark matter program. Phys Rev D, 2019, 100: 102002
88 Billard J, Boulay M, Cebrián S, et al. Direct detection of dark matter—APPEC committee report. Rep Prog Phys, 2022, 85: 056201
89 Essig R, Giovanetti G K, Kurinsky N, et al. Snowmass 2021 cosmic frontier: The landscape of low-threshold dark matter direct detection in the next decade. In: Proceedings of the 2021 US Community Study on the Future of Particle Physics (Snowmass2021). Seattle, 2022
90 Strigari L E. Neutrino coherent scattering rates at direct dark matter detectors. New J Phys, 2009, 11: 105011
91 Billard J, Figueroa-Feliciano E, Strigari L. Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments. Phys Rev D, 2014, 89: 023524
92 Cabrera B, Krauss L M, Wilczek F. Bolometric detection of neutrinos. Phys Rev Lett, 1985, 55: 25–28
93 Akimov D, Albert J B, An P, et al. Observation of coherent elastic neutrino-nucleus scattering. Science, 2017, 357: 1123–1126
94 Akimov D, Albert J, An P, et al. First measurement of coherent elastic neutrino-nucleus scattering on argon. Phys Rev Lett, 2021, 126: 012002
95 Aguilar-Arevalo A, Bertou X, Bonifazi C, et al. The CONNIE experiment. J Phys-Conf Ser, 2016, 761: 012057
96 Aguilar-Arevalo A, Bertou X, Bonifazi C, et al. Exploring low-energy neutrino physics with the coherent neutrino nucleus interaction experiment. Phys Rev D, 2019, 100: 092005
97 Colaresi J, Collar J, Hossbach T, et al. Measurement of coherent elastic neutrino-nucleus scattering from reactor antineutrinos. Phys Rev Lett, 2022, 129: 211802
98 Bonet H, Bonhomme A, Buck C, et al. Constraints on elastic neutrino nucleus scattering in the fully coherent regime from the CONUS experiment. Phys Rev Lett, 2021, 126: 041804
99 White S D M, Frenk C S, Davis M. Clustering in a neutrino-dominated universe. Astrophys J, 1983, 274: L1
100 Okun L B. Limits of electrodynamics: Paraphotons? Sov Phys JETP, 1982, 56: 502
101 Holdom B. Two U(1)'s and ε charge shifts. Phys Lett B, 1986, 166: 196–198
102 Alexander J, Battaglieri M, Echenard B, et al. Dark sectors 2016 Workshop: Community report. In: Proceedings of Dark Sectors Workshop. Menlo Park, 2016
103 Silveira V, Zee A. Scalar phantoms. Phys Lett B, 1985, 161: 136–140
104 McDonald J. Gauge singlet scalars as cold dark matter. Phys Rev D, 1994, 50: 3637–3649
105 Patt B, Wilczek F. Higgs-field portal into hidden sectors. arXiv: hep-ph/0605188
106 Pospelov M, Ritz A, Voloshin M. Secluded WIMP dark matter. Phys Lett B, 2008, 662: 53–61
107 Falkowski A, Juknevich J, Shelton J. Dark matter through the neutrino portal. arXiv: 0908.1790
108 Macías V G, Wudka J. Effective theories for dark matter interactions and the neutrino portal paradigm. J High Energ Phys, 2015, 2015(7): 161
109 Cherry J F, Friedland A, Shoemaker I M. Neutrino portal dark matter: From dwarf galaxies to IceCube. arXiv: 1411.1071
110 Tang Y L, Zhu S. Dark matter annihilation into right-handed neutrinos and the galactic center gamma-ray excess. J High Energ Phys, 2016, 2016(3): 43
111 Macías V G, Illana J I, Wudka J. A realistic model for dark matter interactions in the neutrino portal paradigm. J High Energ Phys, 2016, 2016(5): 171
112 Escudero M, Rius N, Sanz V. Sterile neutrino portal to dark matter I: the U(1) B-L case. J High Energ Phys, 2017, 2017(2): 045
113 Escudero M, Rius N, Sanz V. Sterile neutrino portal to dark matter II: Exact dark symmetry. Eur Phys J C, 2017, 77: 397
114 Bandyopadhyay P, Chun E J, Mandal R. Implications of right-handed neutrinos in B-L extended standard model with scalar dark matter. Phys Rev D, 2018, 97: 015001
115 Batell B, Han T, Shams Es Haghi B. Indirect detection of neutrino portal dark matter. Phys Rev D, 2018, 97: 095020

116 Bandyopadhyay P, Chun E J, Mandal R, et al. Scrutinizing right-handed neutrino portal dark matter with Yukawa effect. Phys Lett B, 2019, 788: 530–534
117 Berlin A, Blinov N. Thermal neutrino portal to sub-MeV dark matter. Phys Rev D, 2019, 99: 095030
118 Chao W. Neutrino portal via loops. arXiv: 2009.12002
119 Biswas A, Borah D, Nanda D. Light Dirac neutrino portal dark matter with observable $\Delta N_{\rm eff}$. J Cosmol Astropart Phys, 2021, 2021(10): 002
120 Becker M. Dark matter from freeze-in via the neutrino portal. Eur Phys J C, 2019, 79: 611
121 Bian L, Tang Y L. Thermally modified sterile neutrino portal dark matter and gravitational waves from phase transition: The freeze-in case. J High Energ Phys, 2018, 2018(12): 6
122 Chianese M, King S F. The dark side of the Littlest Seesaw: Freeze-in, the two right-handed neutrino portal and leptogenesis-friendly fimpzillas. J Cosmol Astropart Phys, 2018, 2018(9): 027
123 Chianese M, Fu B, King S F. Minimal seesaw extension for neutrino mass and mixing, leptogenesis and dark matter: FIMPzillas through the right-handed neutrino portal. J Cosmol Astropart Phys, 2020, 2020(3): 030
124 Cosme C, Dutra M, Ma T, et al. Neutrino portal to FIMP dark matter with an early matter era. J High Energ Phys, 2021, 2021(3): 026
125 Barman B, Bhupal Dev P S, Ghoshal A. Probing freeze-in dark matter via heavy neutrino portal. arXiv: 2210.07739
126 Ko P, Tang Y. IceCube events from heavy DM decays through the right-handed neutrino portal. Phys Lett B, 2015, 751: 81–88
127 Falkowski A, Kuflik E, Levi N, et al. Light dark matter from leptogenesis. Phys Rev D, 2019, 99: 015022
128 An H, Chen S L, Mohapatra R N, et al. Leptogenesis as a common origin for matter and dark matter. J High Energ Phys, 2010, 2010(3): 124
129 Falkowski A, Ruderman J T, Volansky T. Asymmetric dark matter from leptogenesis. J High Energ Phys, 2011, 2011(5): 106
130 Patel H H, Profumo S, Shakya B. Loop dominated signals from neutrino portal dark matter. Phys Rev D, 2020, 101: 095001
131 Kelly K J, Kling F, Tuckler D, et al. Probing neutrino-portal dark matter at the forward physics facility. Phys Rev D, 2022, 105: 075026
132 Burgess C P, Pospelov M, ter Veldhuis T. The minimal model of nonbaryonic dark matter: A singlet scalar. Nucl Phys B, 2001, 619: 709–728
133 Barger V, Langacker P, McCaskey M, et al. Complex singlet extension of the standard model. Phys Rev D, 2009, 79: 015018
134 Hambye T. Hidden vector dark matter. J High Energ Phys, 2009, 2009(01): 028
135 Lebedev O, Lee H M, Mambrini Y. Vector Higgs portal dark matter and the invisible Higgs. Phys Lett B, 2012, 707: 570–576
136 Gross C, Lebedev O, Mambrini Y. Non-Abelian gauge fields as dark matter. J High Energ Phys, 2015, 2015(8): 158
137 Baek S, Ko P, Park W I. Search for the Higgs portal to a singlet fermionic dark matter at the LHC. J High Energ Phys, 2012, 2012(2): 047
138 Lopez-Honorez L, Schwetz T, Zupan J. Higgs portal, fermionic dark matter, and a standard model like Higgs at 125 GeV. Phys Lett B, 2012, 716: 179–185
139 Cai Y, He X G, Ren B. Low mass dark matter and invisible Higgs width in darkon models. Phys Rev D, 2011, 83: 083524
140 Djouadi A, Lebedev O, Mambrini Y, et al. Implications of LHC searches for Higgs-portal dark matter. Phys Lett B, 2012, 709: 65–69
141 Djouadi A, Falkowski A, Mambrini Y, et al. Direct detection of Higgs-portal dark matter at the LHC. Eur Phys J C, 2013, 73: 2455
142 Athron P, Cornell J M, Kahlhoefer F, et al. Impact of vacuum stability, perturbativity and XENON1T on global fits of $\mathbb{Z}_2$ and $\mathbb{Z}_3$ scalar singlet dark matter. Eur Phys J C, 2018, 78: 830
143 Arcadi G, Djouadi A, Raidal M. Dark matter through the Higgs portal. Phys Rep, 2020, 842: 1–180
144 Arcadi G, Djouadi A, Kado M. The Higgs-portal for dark matter: Effective field theories versus concrete realizations. Eur Phys J C, 2021, 81: 653
145 Lebedev O. The Higgs portal to cosmology. Prog Particle Nucl Phys, 2021, 120: 103881
146 Chen S L, Mohapatra R N, Nussinov S, et al. R-parity breaking via type II seesaw, decaying gravitino dark matter and PAMELA positron excess. Phys Lett B, 2009, 677: 311–317
147 Gogoladze I, Okada N, Shafi Q. Type II seesaw and the PAMELA/ATIC signals. Phys Lett B, 2009, 679: 237–241
148 Gu P H, He H J, Sarkar U, et al. Double type-II seesaw scenario, baryon asymmetry, and dark matter for cosmic $e^{\pm}$ excesses. Phys Rev D, 2009, 80: 053004
149 Dev P S B, Ghosh D K, Okada N, et al. Neutrino mass and dark matter in light of recent AMS-02 results. Phys Rev D, 2014, 89: 095001
150 Sui Y, Zhang Y. Prospects of type-II seesaw models at future colliders in light of the DAMPE e^+e^- excess. Phys Rev D, 2018, 97: 095002
151 Li T, Okada N, Shafi Q. Scalar dark matter, type II seesaw and the DAMPE cosmic ray e^++e^- excess. Phys Lett B, 2018, 779: 130–135
152 Ding R, Han Z L, Feng L, et al. Confronting the DAMPE excess with the scotogenic type-II seesaw model. Chin Phys C, 2018, 42: 083104
153 Li T, Okada N, Shafi Q. Type II seesaw mechanism with scalar dark matter in light of AMS-02, DAMPE, and Fermi-LAT data. Phys Rev D, 2018, 98: 055002
154 Chen S L, Banik A D, Liu Z K. Confronting cosmic ray electron and positron excesses with hybrid triplet Higgs portal dark matter. Chin Phys

C, 2022, 46: 063101
155 Dodelson S, Widrow L M. Sterile neutrinos as dark matter. Phys Rev Lett, 1994, 72: 17–20
156 Adhikari R, Agostini M, Ky N A, et al. A white paper on keV sterile neutrino dark matter. J Cosmol Astropart Phys, 2017, 2017(1): 025
157 Abazajian K N. Sterile neutrinos in cosmology. Phys Rep, 2017, 711-712: 1–28
158 Shi X, Fuller G M. New dark matter candidate: Nonthermal sterile neutrinos. Phys Rev Lett, 1999, 82: 2832–2835
159 Asaka T, Shaposhnikov M. The νMSM, dark matter and baryon asymmetry of the universe. Phys Lett B, 2005, 620: 17–26
160 Shaposhnikov M, Tkachev I. The νMSM, inflation, and dark matter. Phys Lett B, 2006, 639: 414–417
161 Laine M, Shaposhnikov M. Sterile neutrino dark matter as a consequence of νMSM-induced lepton asymmetry. J Cosmol Astropart Phys, 2008, 2008(6): 031
162 Merle A, Niro V, Schmidt D. New production mechanism for keV sterile neutrino dark matter by decays of frozen-in scalars. J Cosmol Astropart Phys, 2014, 2014(3): 028
163 Merle A, Totzauer M. keV sterile neutrino dark matter from singlet scalar decays: Basic concepts and subtle features. J Cosmol Astropart Phys, 2015, 2015(6): 011
164 Chao W, Jiang S, Wang Z Y, et al. Pseudo-Dirac sterile neutrino dark matter. arXiv: 2112.14527
165 Kusenko A, Takahashi F, Yanagida T T. Dark matter from split seesaw. Phys Lett B, 2010, 693: 144–148
166 Merle A, Niro V. Deriving models for keV sterile neutrino dark matter with the Froggatt-Nielsen mechanism. J Cosmol Astropart Phys, 2011, 2011(7): 023
167 Shaposhnikov M. A possible symmetry of the νMSM. Nucl Phys B, 2007, 763: 49–59
168 Lindner M, Merle A, Niro V. Soft L_e-L_μ-L_τ flavour symmetry breaking and sterile neutrino keV dark matter. J Cosmol Astropart Phys, 2011, 2011(1): 034 [Erratum: J Cosmol Astropart Phys, 2014, 07: E01]
169 Araki T, Li Y F. Q_6 flavor symmetry model for the extension of the minimal standard model by three right-handed sterile neutrinos. Phys Rev D, 2012, 85: 065016
170 Merle A. keV neutrino model building. Int J Mod Phys D, 2013, 22: 1330020
171 Kusenko A. Sterile neutrinos: The dark side of the light fermions. Phys Rep, 2009, 481: 1–28
172 Boyarsky A, Drewes M, Lasserre T, et al. Sterile neutrino dark matter. Prog Particle Nucl Phys, 2019, 104: 1–45
173 Ibáñez L E. The scalar neutrinos as the lightest supersymmetric particles and cosmology. Phys Lett B, 1984, 137: 160–164
174 Hagelin J S, Kane G L, Raby S. Perhaps scalar neutrinos are the lightest supersymmetric partners. Nucl Phys B, 1984, 241: 638–652
175 Falk T, Olive K A, Srednicki M. Heavy sneutrinos as dark matter. Phys Lett B, 1994, 339: 248–251
176 Hall L J, Moroi T, Murayama H. Sneutrino cold dark matter with lepton-number violation. Phys Lett B, 1998, 424: 305–312
177 Arkani-Hamed N, Hall L, Murayama H, et al. Small neutrino masses from supersymmetry breaking. Phys Rev D, 2001, 64: 115011
178 Hooper D, March-Russell J, West S M. Asymmetric sneutrino dark matter and the Ω(b)/Ω(DM) puzzle. Phys Lett B, 2005, 605: 228–236
179 Arina C, Fornengo N. Sneutrino cold dark matter, a new analysis: Relic abundance and detection rates. J High Energ Phys, 2007, 2007(11): 029
180 Ma E, Sarkar U. Scalar neutrino as asymmetric dark matter: Radiative neutrino mass and leptogenesis. Phys Rev D, 2012, 85: 075015
181 Zhao S M, Feng T F, Zhang M J, et al. Scalar neutrino dark matter in U(1)XSSM. J High Energ Phys, 2020, 2020(2): 130
182 Kitano R, Oda K. Neutrino masses in the supersymmetric standard model with right-handed neutrinos and spontaneous R-parity violation. Phys Rev D, 2000, 61: 113001
183 Cerdeño D G, Muñoz C, Seto O. Right-handed sneutrino as thermal dark matter. Phys Rev D, 2009, 79: 023510
184 Cerdeño D G, Seto O. Right-handed sneutrino dark matter in the NMSSM. J Cosmol Astropart Phys, 2009, 2009(8): 032
185 Chatterjee A, Das D, Mukhopadhyaya B, et al. Right sneutrino dark matter and a monochromatic photon line. J Cosmol Astropart Phys, 2014, 2014(7): 023
186 Cao J, Li J, Pan Y, et al. Bayesian analysis of sneutrino dark matter in the NMSSM with a type-I seesaw mechanism. Phys Rev D, 2019, 99: 115033
187 Kang Z, Li J, Li T, et al. The maximal $U(1)_L$ inverse seesaw from d=5 operator and oscillating asymmetric Sneutrino dark matter. Eur Phys J C, 2016, 76: 270
188 Page V. Non-thermal right-handed sneutrino dark matter and the Ω(DM)/Ω(b) problem. J High Energ Phys, 2007, 2007(04): 021
189 An H, Dev P S B, Cai Y, et al. Sneutrino dark matter in gauged inverse seesaw models for neutrinos. Phys Rev Lett, 2012, 108: 081806
190 Dev P S B, Mondal S, Mukhopadhyaya B, et al. Phenomenology of light sneutrino dark matter in cMSSM/mSUGRA with inverse seesaw. J High Energ Phys, 2012, 2012(9): 110
191 Jocher G R, Bondy D A, Dobbs B M, et al. Theoretical antineutrino detection, direction and ranging at long distances. Phys Rep, 2013, 527:

131–204
192 Choi K Y, Seto O. Light Dirac right-handed sneutrino dark matter. Phys Rev D, 2013, 88: 035005
193 Guo J, Kang Z, Li T, et al. Higgs boson mass and complex sneutrino dark matter in the supersymmetric inverse seesaw models. J High Energ Phys, 2014, 2014(2): 080
194 Chen S L, Kang Z. Oscillating asymmetric sneutrino dark matter from the maximally $U(1)_L$ supersymmetric inverse seesaw. Phys Lett B, 2016, 761: 296–302
195 Cao J, Guo X, He Y, et al. Sneutrino DM in the NMSSM with inverse seesaw mechanism. J High Energ Phys, 2017, 2017(10): 044
196 Zhang M J, Zhao S M, Dong X X, et al. Scalar neutrino dark matter in the BLMSSM. Chin Phys C, 2021, 45: 093106
197 Ma E. Verifiable radiative seesaw mechanism of neutrino mass and dark matter. Phys Rev D, 2006, 73: 077301
198 Ma E. Dark scalar doublets and neutrino tribimaximal mixing from A(4) symmetry. Phys Lett B, 2009, 671: 366–368
199 Ahn Y H, Chen C S. Nonzero Ue3 and TeV leptogenesis through A4 symmetry breaking. Phys Rev D, 2010, 81: 105013
200 Ma E, Natale A, Rashed A. Scotogenic A_4 neutrino model for nonzero θ_{13} and large δ_{CP}. Int J Mod Phys A, 2012, 27: 1250134
201 Ma E. Neutrino mixing and geometric CP violation with Δ(27) symmetry. Phys Lett B, 2013, 723: 161–163
202 Ma E, Natale A. Scotogenic Z2 or $U(1)_D$ model of neutrino mass with Δ(27) symmetry. Phys Lett B, 2014, 734: 403–405
203 Baek S, Okada H, Yagyu K. Flavour dependent gauged radiative neutrino mass model. J High Energ Phys, 2015, 2015(4): 049
204 Han Z L, Ding R, Lin S J, et al. Gauged $U(1)_{L_\mu-L_\tau}$ scotogenic model in light of $R_{K^{(*)}}$ anomaly and AMS-02 positron excess. Eur Phys J C, 2019, 79: 1007
205 Borah D, Dutta M, Mahapatra S, et al. Lepton anomalous magnetic moment with singlet-doublet fermion dark matter in a scotogenic $U(1)_{L_\mu\text{-}L_\tau}$ model. Phys Rev D, 2022, 105: 015029
206 Ma E, Picek I, Radovčić B. New scotogenic model of neutrino mass with $U(1)_D$ gauge interaction. Phys Lett B, 2013, 726: 744–746
207 Kanemura S, Seto O, Shimomura T. Masses of dark matter and neutrino from TeV-scale spontaneous $U(1)_{B\text{-}L}$ breaking. Phys Rev D, 2011, 84: 016004
208 Okada H, Orikasa Y. Classically conformal radiative neutrino model with gauged B-L symmetry. Phys Lett B, 2016, 760: 558–564
209 Seto O, Shimomura T. Atomki anomaly and dark matter in a radiative seesaw model with gauged B-L symmetry. Phys Rev D, 2017, 95: 095032
210 Borah D, Nanda D, Narendra N, et al. Right-handed neutrino dark matter with radiative neutrino mass in gauged B-L model. Nucl Phys B, 2020, 950: 114841
211 Okada H, Orikasa Y. Modular S_3 symmetric radiative seesaw model. Phys Rev D, 2019, 100: 115037
212 Nomura T, Okada H, Popov O. A modular A_4 symmetric scotogenic model. Phys Lett B, 2020, 803: 135294
213 Behera M K, Singirala S, Mishra S, et al. A modular A_4 symmetric scotogenic model for neutrino mass and dark matter. J Phys G, 2022, 49: 035002
214 Okada H, Orikasa Y. Neutrino mass model with a modular S_4 symmetry. arXiv: 1908.08409
215 Ma E, Suematsu D. Fermion triplet dark matter and radiative neutrino mass. Mod Phys Lett A, 2009, 24: 583–589
216 Chao W. Dark matter, LFV and neutrino magnetic moment in the radiative seesaw model with fermion triplet. Int J Mod Phys A, 2015, 30: 1550007
217 Farzan Y. Minimal model linking two great mysteries: Neutrino mass and dark matter. Phys Rev D, 2009, 80: 073009
218 De Romeri V, Nava J, Puerta M, et al. Dark matter in the Scotogenic model with spontaneous lepton number violation. Nucl Phys B, 2017, 924: 279–311
219 Dcruz R, Thapa A. W boson mass shift, dark matter, and (g-2)ℓ in a scotogenic-Zee model. Phys Rev D, 2023, 107: 015002
220 Lu W B, Gu P H. Mixed Inert scalar triplet dark matter, radiative neutrino masses and leptogenesis. Nucl Phys B, 2017, 924: 279–311
221 Brdar V, Picek I, Radovčić B. Radiative neutrino mass with scotogenic scalar triplet. Phys Lett B, 2014, 728: 198–201
222 Batra A, ShivaSankar K A, Mandal S, et al. W boson mass in Singlet-Triplet Scotogenic dark matter model. arXiv: 2204.09376
223 Liao Y, Liu J Y. Radiative and flavor-violating transitions of leptons from interactions with color-octet particles. Phys Rev D, 2010, 81: 013004
224 Escribano P, Reig M, Vicente A. Generalizing the Scotogenic model. J High Energ Phys, 2020, 2020(7): 097
225 Portillo-Sánchez D, Escribano P, Vicente A. Ultraviolet extensions of the Scotogenic model. J High Energ Phys, 2023, 2020(08): 023
226 Okada H, Toma T. Fermionic dark matter in radiative inverse seesaw model with $U(1)_{B\text{-}L}$. Phys Rev D, 2012, 86: 033011
227 Hirsch M, Lineros R A, Morisi S, et al. WIMP dark matter as radiative neutrino mass messenger. J High Energ Phys, 2013, 2013(10): 149
228 Fraser S, Ma E, Popov O. Scotogenic inverse seesaw model of neutrino mass. Phys Lett B, 2014, 737: 280–282
229 Wang W, Han Z L. Radiative linear seesaw model, dark matter, and $U(1)_{B\text{-}L}$. Phys Rev D, 2015, 92: 095001
230 Arhrib A, Bœhm C, Ma E, et al. Radiative model of neutrino mass with neutrino interacting MeV dark matter. J Cosmol Astropart Phys, 2016,

2016(4): 049
231 Yu J H. Hidden gauged U(1) model: Unifying scotogenic neutrino and flavor dark matter. Phys Rev D, 2016, 93: 113007
232 Lu W B, Gu P H. Leptogenesis, radiative neutrino masses and inert Higgs triplet dark matter. J Cosmol Astropart Phys, 2016, 2016(5): 040
233 Ahriche A, McDonald K L, Nasri S. The scale-invariant scotogenic model. J High Energ Phys, 2016, 2016(6): 182
234 Ahriche A, Jueid A, Nasri S. Radiative neutrino mass and Majorana dark matter within an inert Higgs doublet model. Phys Rev D, 2018, 97: 095012
235 Fiaschi J, Klasen M, May S. Singlet-doublet fermion and triplet scalar dark matter with radiative neutrino masses. J High Energ Phys, 2019, 2019(5): 015
236 Esch S, Klasen M, Yaguna C E. A singlet doublet dark matter model with radiative neutrino masses. J High Energ Phys, 2018, 2018(10): 055
237 Ma E. Leptonic source of dark matter and radiative Majorana or Dirac neutrino mass. Phys Lett B, 2020, 809: 135736
238 Chen S L, Dutta Banik A, Liu Z K. Common origin of radiative neutrino mass, dark matter and leptogenesis in scotogenic Georgi-Machacek model. Nucl Phys B, 2021, 966: 115394
239 Jana S, Vishnu P K, Rodejohann W, et al. Dark matter assisted lepton anomalous magnetic moments and neutrino masses. Phys Rev D, 2020, 102: 075003
240 Lineros R A, Pierre M. Dark matter candidates in a type-II radiative neutrino mass model. J High Energ Phys, 2020, 2020(21): 072
241 Soualah R, Ahriche A. Scale invariant scotogenic model: Dark matter and the scalar sector. Phys Rev D, 2022, 105: 055017
242 De Romeri V, Puerta M, Vicente A. Dark matter in a charged variant of the Scotogenic model. Eur Phys J C, 2022, 82: 623
243 Restrepo D, Zapata O, Yaguna C E. Models with radiative neutrino masses and viable dark matter candidates. J High Energ Phys, 2013, 2013(11): 011
244 Law S S C, McDonald K L. A class of inert N-tuplet models with radiative neutrino mass and dark matter. J High Energ Phys, 2013, 2013(09): 092
245 Lindner M, Schmidt D, Schwetz T. Dark matter and neutrino masses from global $U(1)_{BL}$ symmetry breaking. Phys Lett B, 2011, 705: 324–330
246 Gustafsson M, No J M, Rivera M A. Predictive model for radiatively induced neutrino masses and mixings with dark matter. Phys Rev Lett, 2013, 110: 211802 [Erratum: Phys Rev Lett, 2014, 112: 259902]
247 Argüelles C A, Aurisano A J, Batell B, et al. New opportunities at the next-generation neutrino experiments I: BSM neutrino physics and dark matter. Rep Prog Phys, 2020, 83: 124201
248 Press W H, Spergel D N. Capture by the sun of a galactic population of weakly interacting, massive particles. Astrophys J, 1985, 296: 679–684
249 Silk J, Olive K, Srednicki M. The photino, the sun, and high-energy neutrinos. Phys Rev Lett, 1985, 55: 257–259
250 Gaisser T K, Steigman G, Tilav S. Limits on cold-dark-matter candidates from deep underground detectors. Phys Rev D, 1986, 34: 2206–2222
251 Gould A. Direct and indirect capture of weakly interacting massive particles by the earth. Astrophys J, 1988, 328: 919–939
252 Kamionkowski M. Energetic neutrinos from heavy-neutralino annihilation in the Sun. Phys Rev D, 1991, 44: 3021–3042
253 Bottino A, Fornengo N, Mignola G, et al. Signals of neutralino dark matter from Earth and Sun. Astroparticle Phys, 1995, 3: 65–75
254 Barger V, Keung W Y, Shaughnessy G, et al. High energy neutrinos from neutralino annihilations in the Sun. Phys Rev D, 2007, 76: 095008
255 Liu J, Yin P, Zhu S. Neutrino signals from solar neutralino annihilations in anomaly mediated supersymmetry breaking model. Phys Rev D, 2008, 77: 115014
256 Nussinov S, Wang L T, Yavin I. Capture of inelastic dark matter in the sun. J Cosmol Astropart Phys, 2009, 2009(8): 037
257 Zentner A R. High-energy neutrinos from dark matter particle self-capture within the Sun. Phys Rev D, 2009, 80: 063501
258 Chen S L, Zhang Y. Isospin-violating dark matter and neutrinos from the Sun. Phys Rev D, 2011, 84: 031301
259 Rott C, Tanaka T, Itow Y. Enhanced sensitivity to dark matter self-annihilations in the Sun using neutrino spectral information. J Cosmol Astropart Phys, 2011, 2011(9): 029
260 Bernal N, Martín-Albo J, Palomares-Ruiz S. A novel way of constraining WIMPs annihilations in the Sun: MeV neutrinos. J Cosmol Astropart Phys, 2013, 2013(8): 011
261 Ibarra A, Totzauer M, Wild S. Higher order dark matter annihilations in the Sun and implications for IceCube. J Cosmol Astropart Phys, 2014, 2014(4): 012
262 Chen J, Liang Z L, Wu Y L, et al. Long-range self-interacting dark matter in the Sun. J Cosmol Astropart Phys, 2015, 2015(12): 021
263 Murase K, Shoemaker I M. Detecting asymmetric dark matter in the Sun with neutrinos. Phys Rev D, 2016, 94: 063512
264 Fornengo N, Masiero A, Queiroz F S, et al. On the role of neutrinos telescopes in the search for dark matter annihilations in the Sun. J Cosmol Astropart Phys, 2017, 2017(12): 012
265 Fukuda S, Fukuda Y, Hayakawa T, et al. The Super-Kamiokande detector. Nucl Instrum Methods Phys Res Sect A, 2003, 501: 418–462

266 Choi K, Abe K, Haga Y, et al. Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by Super-Kamiokande. Phys Rev Lett, 2015, 114: 141301
267 Aartsen M G, Abbasi R, Abdou Y, et al. Search for dark matter annihilations in the Sun with the 79-String IceCube detector. Phys Rev Lett, 2013, 110: 131302
268 Aartsen M G, Abraham K, Ackermann M, et al. Improved limits on dark matter annihilation in the Sun with the 79-string IceCube detector and implications for supersymmetry. J Cosmol Astropart Phys, 2016, 2016(4): 022
269 Aartsen M G, Ackermann M, Adams J, et al. Search for annihilating dark matter in the Sun with 3 years of IceCube data. Eur Phys J C, 2017, 77: 146 [Erratum: Eur Phys J C, 2019, 79: 214]
270 Ageron M, Aguilar J A, Al Samarai I, et al. ANTARES: The first undersea neutrino telescope. Nucl Instruments Methods Phys Res Sect A, 2011, 656: 11–38
271 Adrián-Martínez S, Albert A, André M, et al. Limits on dark matter annihilation in the sun using the ANTARES neutrino telescope. Phys Lett B, 2016, 759: 69–74
272 Pomanskii A A. The Baksan Neutrino Observatory of the nuclear research institute of the academy of sciences of the USSR. At Energy, 1978, 44: 433–437
273 Boliev M M, Demidov S V, Mikheyev S P, et al. Search for muon signal from dark matter annihilations in the Sun with the Baksan Underground Scintillator Telescope for 24.12 years. J Cosmol Astropart Phys, 2013, 2013(9): 019
274 Behnke E, Besnier M, Bhattacharjee P, et al. Final results of the PICASSO dark matter search experiment. Astroparticle Phys, 2017, 90: 85–92
275 Amole C, Ardid M, Arnquist I, et al. Dark matter search results from the complete exposure of the PICO-60 C_3F_8 bubble chamber. Phys Rev D, 2019, 100: 022001
276 Abbasi R, Ackermann M, Adams J, et al. Search for GeV-scale dark matter annihilation in the Sun with IceCube DeepCore. Phys Rev D, 2022, 105: 062004
277 Bell N F, Dolan M J, Robles S. Searching for dark matter in the Sun using Hyper-Kamiokande. J Cosmol Astropart Phys, 2021, 2021(11): 004
278 Abe K, Aihara H, Aimi A, et al. Hyper-Kamiokande design report. arXiv: 1805.04163
279 Aartsen M G, Abbasi R, Ackermann M, et al. Letter of intent: The precision IceCube next generation upgrade (PINGU). arXiv: 1401.2046
280 Aartsen M G, et al. (IceCube Collaboration). The IceCube neutrino observatory. In: Proceedings of 35th International Cosmic Ray Conference (ICRC2017). Busan, 2017
281 Berezinsky V S, Gurevich A V, Zybin K P. Distribution of dark matter in the galaxy and the lower limits for the masses of supersymmetric particles. Phys Lett B, 1992, 294: 221–228
282 Bergström L, Ullio P, Buckley J H. Observability of γ rays from dark matter neutralino annihilations in the Milky Way halo. Astroparticle Phys, 1998, 9: 137–162
283 Gondolo P, Silk J. Dark matter annihilation at the galactic center. Phys Rev Lett, 1999, 83: 1719–1722
284 Hooper D, Goodenough L. Dark matter annihilation in the galactic center as seen by the Fermi Gamma Ray Space Telescope. Phys Lett B, 2011, 697: 412–428
285 Abramowski A, Acero F, Aharonian F, et al. Search for a dark matter annihilation signal from the galactic center halo with H.E.S.S.. Phys Rev Lett, 2011, 106: 161301
286 Frankiewicz K. Searching for dark matter annihilation into neutrinos with Super-Kamiokande. In: Proceedings of Meeting of the APS Division of Particles and Fields (DPF2015), Ann Arbor, 2015
287 Aartsen M G, Abraham K, Ackermann M, et al. Search for dark matter annihilation in the galactic center with IceCube-79. Eur Phys J C, 2015, 75: 492
288 Aartsen M G, Abraham K, Ackermann M, et al. All-flavour search for neutrinos from dark matter annihilations in the Milky Way with IceCube/DeepCore. Eur Phys J C, 2016, 76: 531
289 Aartsen M G, Ackermann M, Adams J, et al. Search for neutrinos from dark matter self-annihilations in the center of the Milky Way with 3 years of IceCube/DeepCore. Eur Phys J C, 2017, 77: 627
290 Abbasi R, Ackermann M, Athanasiadou S, et al. Search for neutrino lines from dark matter annihilation and decay with IceCube. arXiv: 2303.13663
291 Adrian-Martinez S, et al. (ANTARES Collaboration). Search of dark matter annihilation in the galactic centre using the ANTARES neutrino telescope. J Cosmol Astrop Phys, 2015, 2015(10): 068
292 Albert A, André M, Anghinolfi M, et al. Results from the search for dark matter in the Milky Way with 9 years of data of the ANTARES neutrino telescope. Phys Lett B, 2017, 769: 249–254 [Erratum: Phys Lett B, 2019, 796: 253–255]

293 Albert A, André M, Anghinolfi M, et al. Combined search for neutrinos from dark matter self-annihilation in the galactic center with ANTARES and IceCube. Phys Rev D, 2020, 102: 082002

294 Bell N F, Dolan M J, Robles S. Searching for Sub-GeV dark matter in the galactic centre using Hyper-Kamiokande. J Cosmol Astropart Phys, 2020, 2020(9): 019

295 An F, An G, An Q, et al. Neutrino physics with JUNO. J Phys G-Nucl Part Phys, 2016, 43: 030401

296 Acciarri R, Patzak T, Tonazzo A, et al. Long-baseline neutrino facility (LBNF) and deep underground neutrino experiment (DUNE): Conceptual design report, Volume 2: The Physics Program for DUNE at LBNF. arXiv: 1512.06148

297 Adrián-Martínez S, Ageron M, Aharonian F, et al. Letter of intent for KM3NeT 2.0. J Phys G-Nucl Part Phys, 2016, 43: 084001

298 Aartsen M G, Ackermann M, Adams J, et al. IceCube-Gen2: A vision for the future of neutrino astronomy in antarctica. arXiv: 1412.5106

299 Argüelles C A, Diaz A, Kheirandish A, et al. Dark matter annihilation to neutrinos. Rev Mod Phys, 2021, 93: 035007

300 Batell B, Pospelov M, Ritz A. Exploring portals to a hidden sector through fixed targets. Phys Rev D, 2009, 80: 095024

301 deNiverville P, Pospelov M, Ritz A. Observing a light dark matter beam with neutrino experiments. Phys Rev D, 2011, 84: 075020

302 deNiverville P, McKeen D, Ritz A. Signatures of sub-GeV dark matter beams at neutrino experiments. Phys Rev D, 2012, 86: 035022

303 Kahn Y, Krnjaic G, Thaler J, et al. DAEδALUS and dark matter detection. Phys Rev D, 2015, 91: 055006

304 deNiverville P, Pospelov M, Ritz A. Light new physics in coherent neutrino-nucleus scattering experiments. Phys Rev D, 2015, 92: 095005

305 Izaguirre E, Kahn Y, Krnjaic G, et al. Testing light dark matter coannihilation with fixed-target experiments. Phys Rev D, 2017, 96: 055007

306 Dharmapalan R, Habib S, Jiang C, et al. Light mass WIMP searches with a neutrino experiment: A proposal for further MiniBooNE running. arXiv: 1211.2258

307 Aguilar-Arevalo A, Backfish M, Bashyal A, et al. Dark matter search in a proton beam dump with MiniBooNE. Phys Rev Lett, 2017, 118: 221803

308 Aguilar-Arevalo A, Backfish M, Bashyal A, et al. Dark matter search in nucleon, pion, and electron channels from a proton beam dump with MiniBooNE. Phys Rev D, 2018, 98: 112004

309 Abe K, Abgrall N, Aihara H, et al. The T2K experiment. Nucl Instrum Methods Phys Res Sect A, 2011, 659: 106–135

310 Ayres D S, Dawson J, Drake G, et al. NOvA: Proposal to build a 30 kiloton off-axis detector to study $\nu_\mu \to \nu_e$ oscillations in the NuMI Beamline. arXiv: hep-ex/0503053

311 Brailsford D. Physics program of the short-baseline near detector. J Phys-Conf Ser, 2017, 888: 012186

312 Antonello M, Adams C, An R, et al. A proposal for a three detector short-baseline neutrino oscillation program in the fermilab booster neutrino beam. arXiv: 1503.01520

313 Acciarri R, Adams C, An R, et al. Design and construction of the MicroBooNE detector. J Inst, 2017, 12: P02017

314 Varanini F. ICARUS detector: Present and future. EPJ Web Conf, 2017, 164: 07017

315 Ajimura S, Cheoun M, Choi J, et al. Technical design report (TDR): Searching for a sterile neutrino at J-PARC MLF (E56, JSNS2). arXiv: 1705.08629

316 Argüelles C A, Kheirandish A, Vincent A C. Imaging galactic dark matter with high-energy cosmic neutrinos. Phys Rev Lett, 2017, 119: 201801

317 Capozzi F, Shoemaker I M, Vecchi L. Neutrino oscillations in dark backgrounds. J Cosmol Astropart Phys, 2018, 2018(7): 004

318 Olivares-Del Campo A, Bæhm C, Palomares-Ruiz S, et al. Dark matter-neutrino interactions through the lens of their cosmological implications. Phys Rev D, 2018, 97: 075039

319 Blennow M, Fernandez-Martinez E, Olivares-Del Campo A, et al. Neutrino portals to dark matter. Eur Phys J C, 2019, 79: 555

320 Choi K Y, Kim J, Rott C. Constraining dark matter-neutrino interactions with IceCube-170922A. Phys Rev D, 2019, 99: 083018

321 Abbasi R, Ackermann M, Adams J, et al. Searches for connections between dark matter and high-energy neutrinos with IceCube. arXiv: 2205.12950

322 Cline J M, Gao S, Guo F, et al. Blazar constraints on neutrino-dark matter scattering. Phys Rev Lett, 2023, 130: 091402

323 Ferrer F, Herrera G, and Ibarra A. New constraints on the dark matter-neutrino and dark matter-photon scattering cross sections from TXS 0506+056. J Cosmol Astropart Phys, 2023, 2023(05): 057

324 Cline J M, Puel M. NGC 1068 constraints on neutrino-dark matter scattering. arXiv: 2301.08756

325 Chung D J H, Kolb E W, Riotto A. Superheavy dark matter. Phys Rev D, 1998, 59: 023501

326 Arvanitaki A, Dimopoulos S, Dubovsky S, et al. Astrophysical probes of unification. Phys Rev D, 2009, 79: 105022

327 Nardi E, Sannino F, Strumia A. Decaying dark matter can explain the $e^\pm$ excesses. J Cosmol Astropart Phys, 2009, 2009(1): 043

328 Hamaguchi K, Shirai S, Yanagida T T. Cosmic ray positron and electron excess from hidden-fermion dark matter decays. Phys Lett B, 2009, 673: 247–250

329 Buchmüller W, Covi L, Hamaguchi K, et al. Gravitino dark matter in R-parity breaking vacua. J High Energ Phys, 2007, 2007(3): 037
330 Yin P, Yuan Q, Liu J, et al. PAMELA data and leptonically decaying dark matter. Phys Rev D, 2009, 79: 023512
331 Shirai S, Takahashi F, Yanagida T T. R-violating decay of Wino dark matter and electron/positron excesses in the PAMELA/Fermi experiments. Phys Lett B, 2009, 680: 485–488
332 Chen C H, Geng C Q, Zhuridov D V. Resolving Fermi, PAMELA and ATIC anomalies in split supersymmetry without R-parity. Eur Phys J C, 2010, 67: 479–487
333 Aharonian F, Akhperjanian A G, Barres de Almeida U, et al. Energy spectrum of cosmic-ray electrons at TeV energies. Phys Rev Lett, 2008, 101: 261104
334 Torii S, Yamagami T, Tamura T, et al. High-energy electron observations by PPB-BETS flight in Antarctica. arXiv: 0809.0760
335 Ibarra A, Tran D. Decaying dark matter and the PAMELA anomaly. J Cosmol Astropart Phys, 2009, 2009(2): 021
336 Buckley M R, Spolyar D, Freese K, et al. High-energy neutrino signatures of dark matter. Phys Rev D, 2010, 81: 016006
337 Covi L, Grefe M, Ibarra A, et al. Neutrino signals from dark matter decay. J Cosmol Astropart Phys, 2010, 2010(4): 017
338 Esmaili A, Ibarra A, Peres O L G. Probing the stability of superheavy dark matter particles with high-energy neutrinos. J Cosmol Astropart Phys, 2012, 2012(11): 034
339 Aartsen M G, Abbasi R, Abdou Y, et al. First observation of PeV-energy neutrinos with IceCube. Phys Rev Lett, 2013, 111: 021103
340 Aartsen M G, et al. (IceCube Collaboration). Evidence for high-energy extraterrestrial neutrinos at the IceCube detector. Science, 2013, 342: 1242856
341 Aartsen M, Ackermann M, Adams J, et al. Observation of high-energy astrophysical neutrinos in three years of IceCube data. Phys Rev Lett, 2014, 113: 101101
342 Aartsen M, Abraham K, Ackermann M, et al. Evidence for astrophysical muon neutrinos from the northern sky with IceCube. Phys Rev Lett, 2015, 115: 081102
343 Aartsen M G, Abraham K, Ackermann M, et al. Observation and characterization of a cosmic muon neutrino flux from the northern hemisphere using six years of IceCube data. Astrophys J, 2016, 833: 3
344 Feldstein B, Kusenko A, Matsumoto S, et al. Neutrinos at IceCube from heavy decaying dark matter. Phys Rev D, 2013, 88: 015004
345 Esmaili A, Serpico P D. Are IceCube neutrinos unveiling PeV-scale decaying dark matter? J Cosmol Astropart Phys, 2013, 2013(11): 054
346 Bai Y, Lu R, Salvado J. Geometric compatibility of IceCube TeV-PeV neutrino excess and its galactic dark matter origin. J High Energ Phys, 2016, 2016(1): 161
347 Rott C, Kohri K, Park S C. Superheavy dark matter and IceCube neutrino signals: Bounds on decaying dark matter. Phys Rev D, 2015, 92: 023529
348 Bhattacharya A, Reno M H, Sarcevic I. Reconciling neutrino flux from heavy dark matter decay and recent events at IceCube. J High Energ Phys, 2014, 2014(6): 110
349 Esmaili A, Kang S K, Serpico P D. IceCube events and decaying dark matter: Hints and constraints. J Cosmol Astropart Phys, 2014, 2014(12): 054
350 Higaki T, Kitano R, Sato R. Neutrinoful universe. J High Energ Phys, 2014, 2014(7): 044
351 Dudas E, Mambrini Y, Olive K A. Monochromatic neutrinos generated by dark matter and the seesaw mechanism. Phys Rev D, 2015, 91: 075001
352 Fong C S, Minakata H, Panes B, et al. Possible interpretations of IceCube high-energy neutrino events. J High Energ Phys, 2015, 2015(2): 189
353 Boucenna S M, Chianese M, Mangano G, et al. Decaying leptophilic dark matter at IceCube. J Cosmol Astropart Phys, 2015, 2015(12): 055
354 Dev P S B, Kazanas D, Mohapatra R N, et al. Heavy right-handed neutrino dark matter and PeV neutrinos at IceCube. J Cosmol Astropart Phys, 2016, 2016(8): 034
355 Chianese M, Miele G, Morisi S. Interpreting IceCube 6-year HESE data as an evidence for hundred TeV decaying dark matter. Phys Lett B, 2017, 773: 591–595
356 Hiroshima N, Kitano R, Kohri K, et al. High-energy neutrinos from multibody decaying dark matter. Phys Rev D, 2018, 97: 023006
357 Sui Y, Dev P S B. A combined astrophysical and dark matter interpretation of the IceCube HESE and throughgoing muon events. J Cosmol Astropart Phys, 2018, 2018(7): 020
358 Dudas E, Heurtier L, Mambrini Y, et al. Model of metastable EeV dark matter. Phys Rev D, 2020, 101: 115029
359 Aartsen M G, Ackermann M, Adams J, et al. Search for neutrinos from decaying dark matter with IceCube. Eur Phys J C, 2018, 78: 831
360 Bhattacharya A, Esmaili A, Palomares-Ruiz S, et al. Update on decaying and annihilating heavy dark matter with the 6-year IceCube HESE data. J Cosmol Astropart Phys, 2019, 2019(5): 051

361 Agostini M, Böhmer M, Bosma J, et al. The Pacific ocean neutrino experiment. Nat Astron, 2020, 4: 913–915
362 Desai K, Li R, Meighen-Berger S. Searching for dark matter annihilation with IceCube and P-ONE. arXiv: 2302.10542
363 Argüelles C A, Delgado D, Friedlander A, et al. Dark matter decay to neutrinos. arXiv: 2210.01303
364 Ackermann M, Bustamante M, Lu L, et al. High-energy and ultra-high-energy neutrinos: A snowmass white paper. J High Energy Astrophys, 2022, 36: 55–110

A note on the interplay of neutrino and dark matter physics

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The origin of neutrino masses and the identity of dark matter are both significant scientific problems in particle physics and cosmology. They play crucial roles in the searching for the new physics beyond the Standard Model. This paper briefly reviews the recent progress in theoretical studies and experimental research on neutrino and dark matter physics, particularly on the interplay of them.

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