



暗物质理论研究进展

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973项目启动会，2010/03/18-19，北京

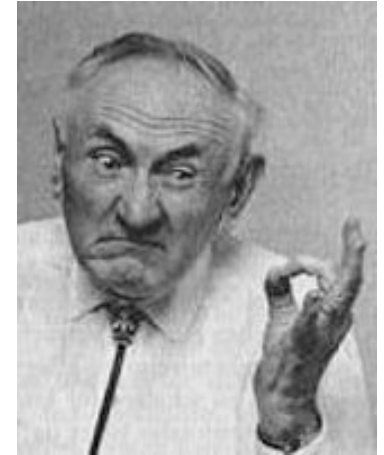
973子课题一

暗物质理论与新物理唯象

- 首席：吴岳良
- 课题负责人：周宇峰
- 学术骨干：罗民兴，何红建，吕才典，刘纯，廖益，毕晓军，郭万磊
- 研究生：数十名博士/硕士研究生

暗物质发现的早期历史

- **1933**, **Zwicky** found a large mass-to-light ratio ~ 400 from velocity dispersion in the Coma cluster. The first indication of dark matter.
- **1936**, **Smith** found unexpected high mass in the Virgo cluster.
- **1939**, **Babcock** found that the outer region of Andromeda galaxy rotates with a high speed.
- **1959**, **Kahn** and **Woltjer** inferred from the relative motion between M31 and our Galaxy that the Local Group is much heavier than expected.
- **1970**, **Rubin** and **Ford** measured the rotation curve in M31 with unprecedented precision and at large distance (24kpc), clearly showed the existence of DM or deviation of Newton's law of gravitation.

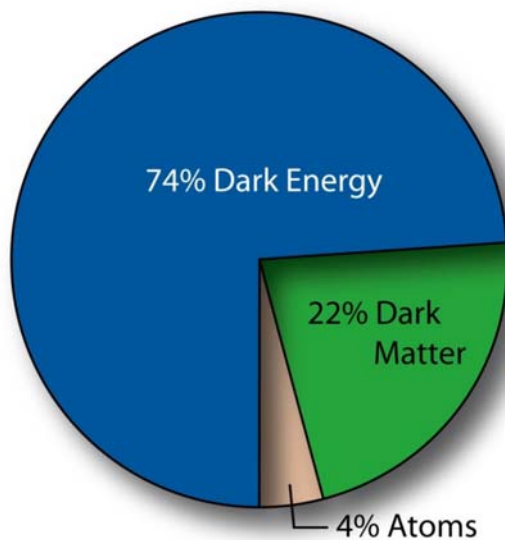
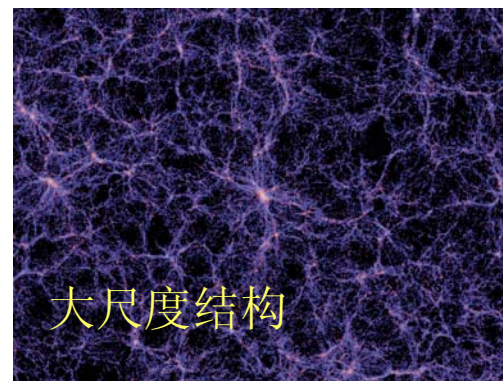
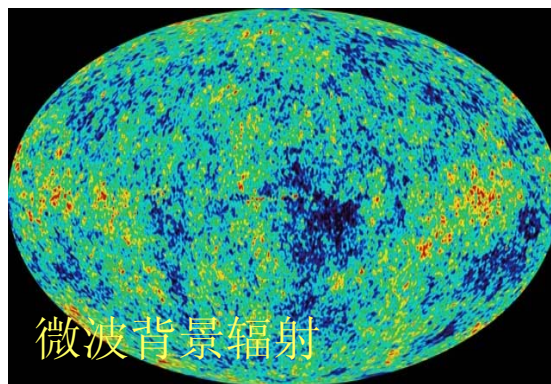
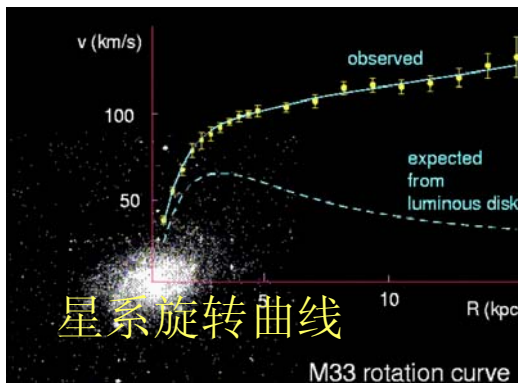


Fritz Zwicky



Vera Rubin

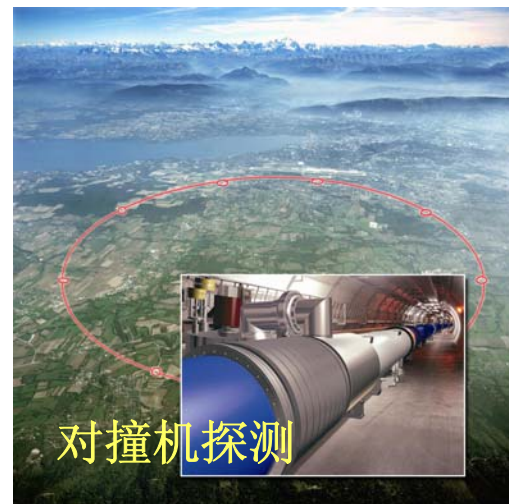
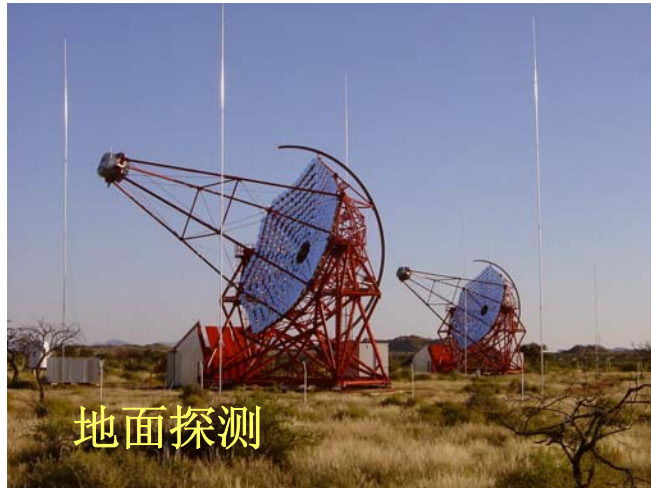
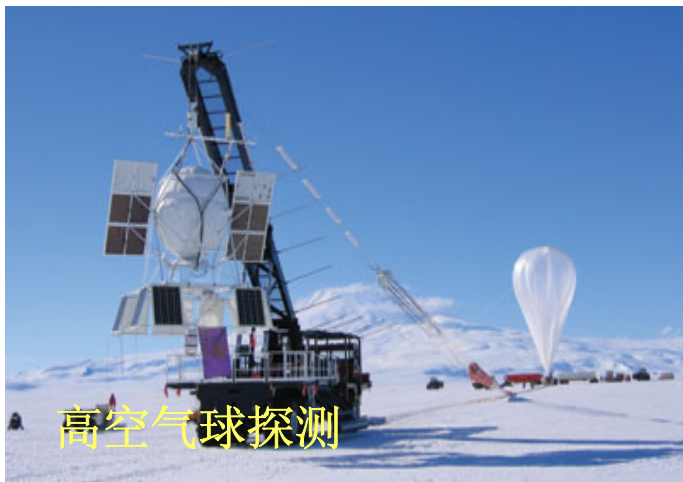
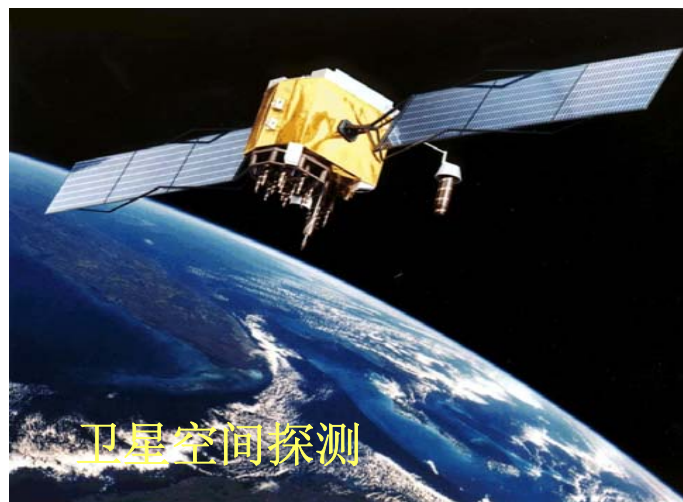
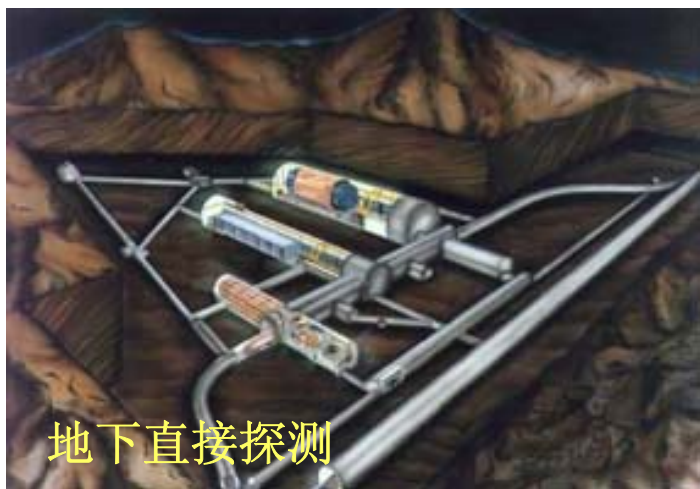
暗物质的存在证据



暗物质基本特点:

- 宇宙学时间尺度上稳定。
- 参与引力作用，电中性。
- 非重子物质
- 非相对论性运动

暗物质实验探测手段



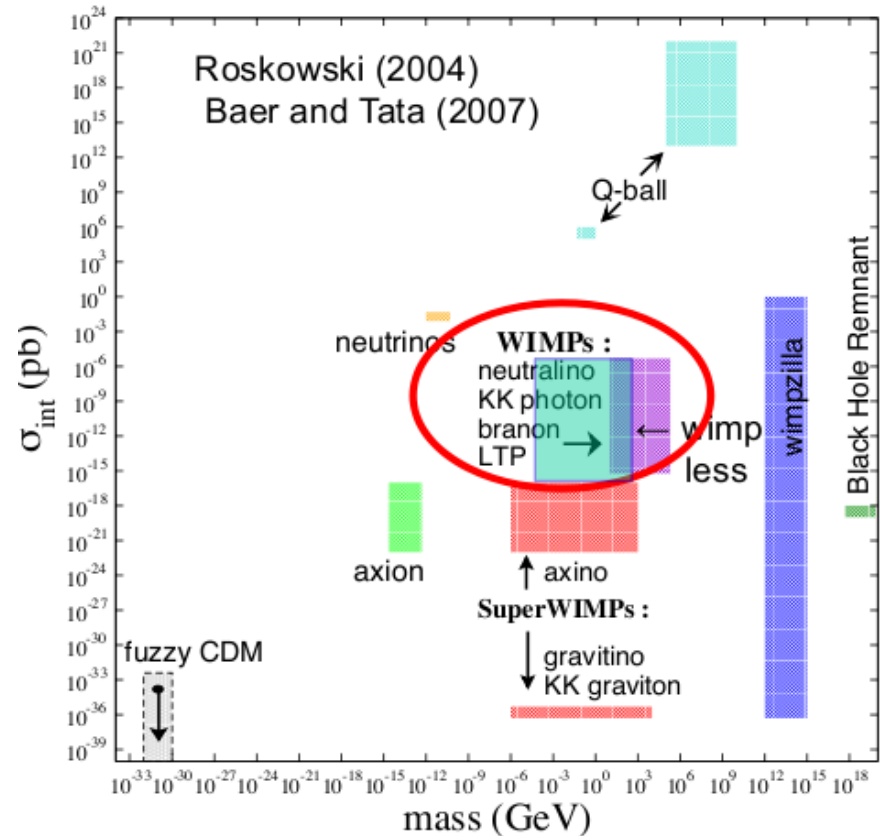
DM candidates from particle physics

WIMP 类型

- LSP: neutrinos, sneutrinos, gravitinos, axinos
- LKP: $B^{(1)}$
- Little Higgs models: A_h

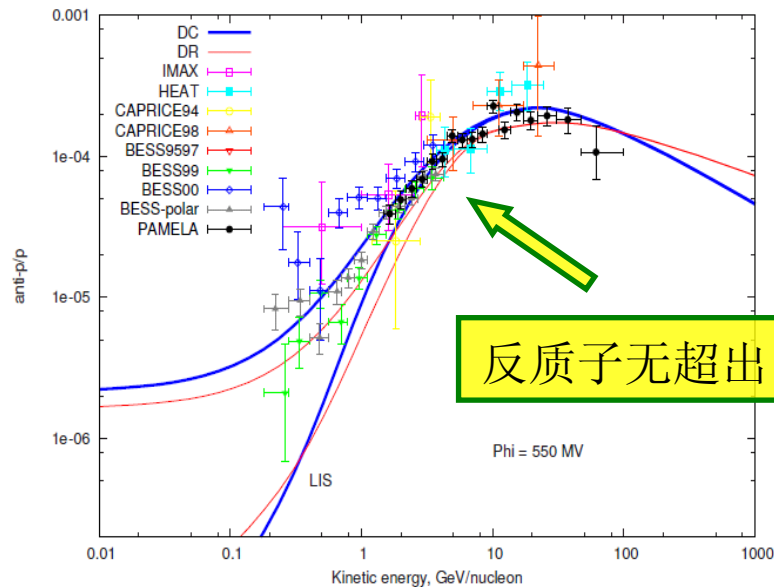
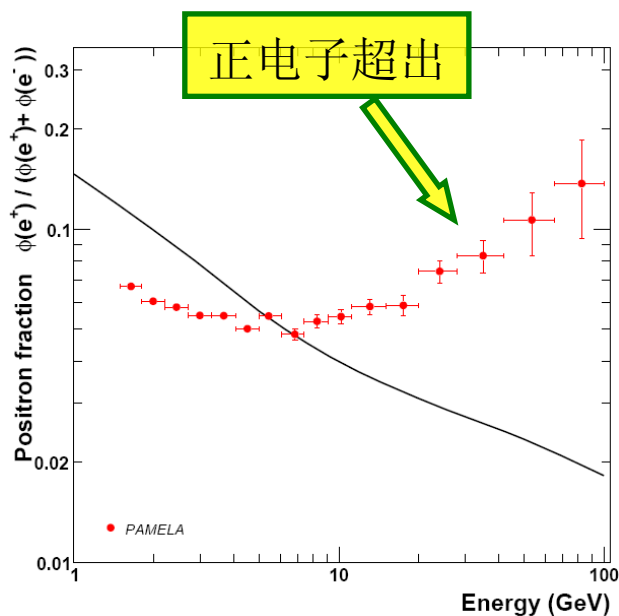
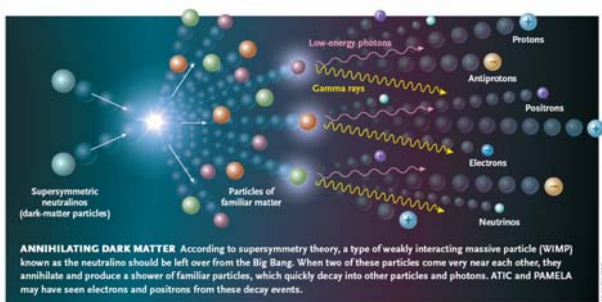
非WIMP 类型

- Axions
- SuperWIMP, Wimpzilla, Q-ball,



WIMP: 来源于热力学退耦剩余丰度，质量及相互作用强度在电弱能标附近

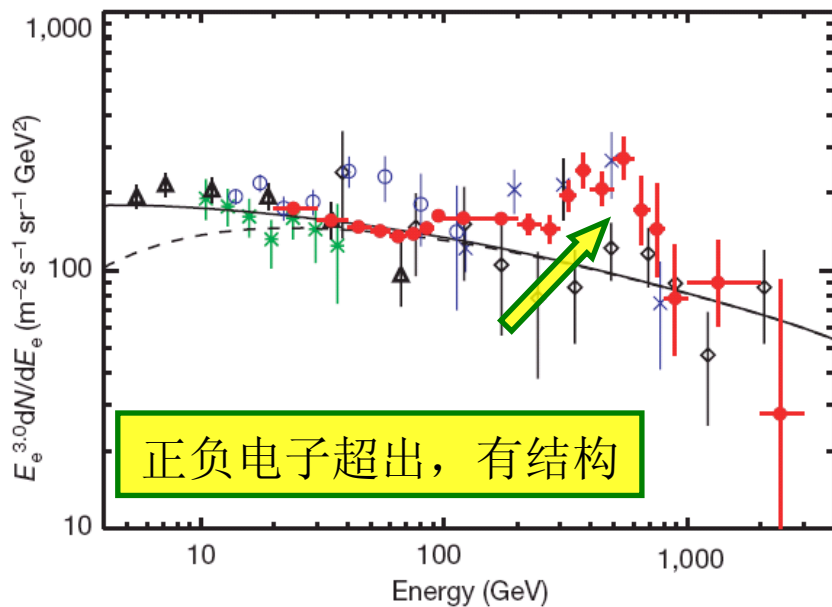
近期实验进展回顾：空间间接探测



Nature 458, 607 (2009)

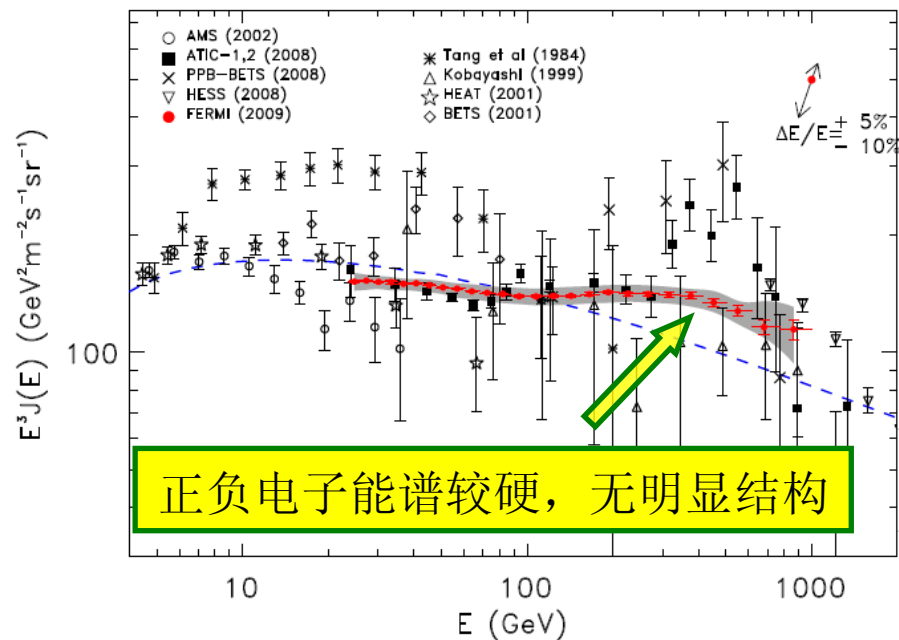
正负电子总流强

ATIC



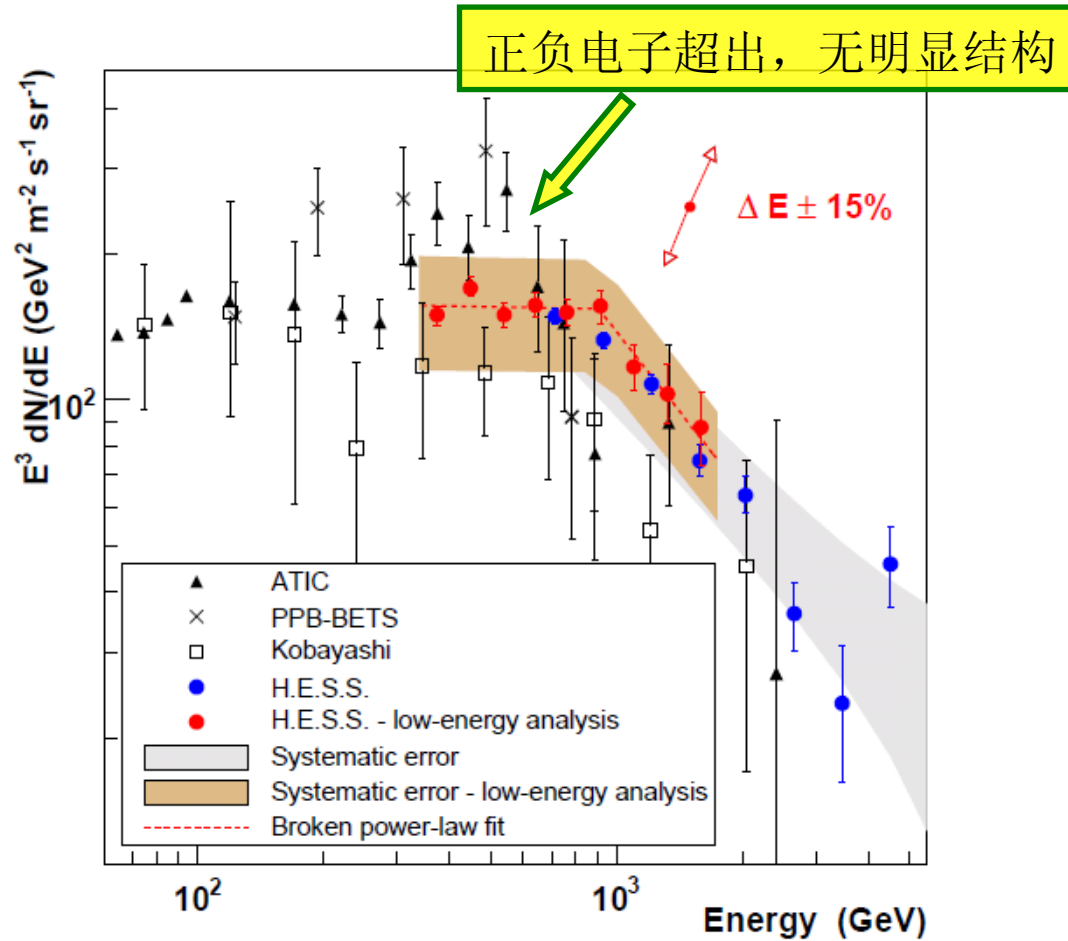
Nature, 456, 2008,362-365

Fermi LAT



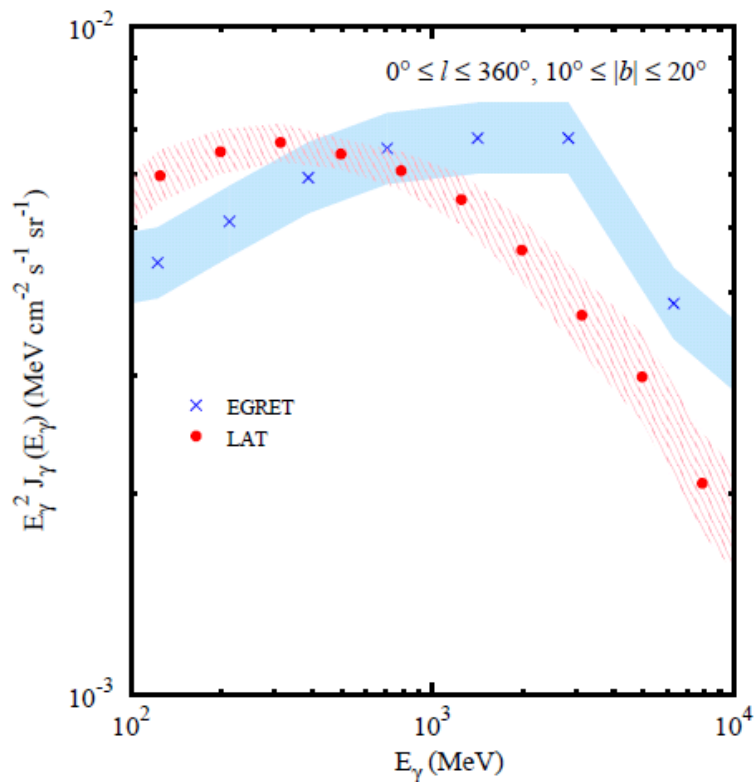
Phys.Rev.Lett.102:181101,2009

HESS

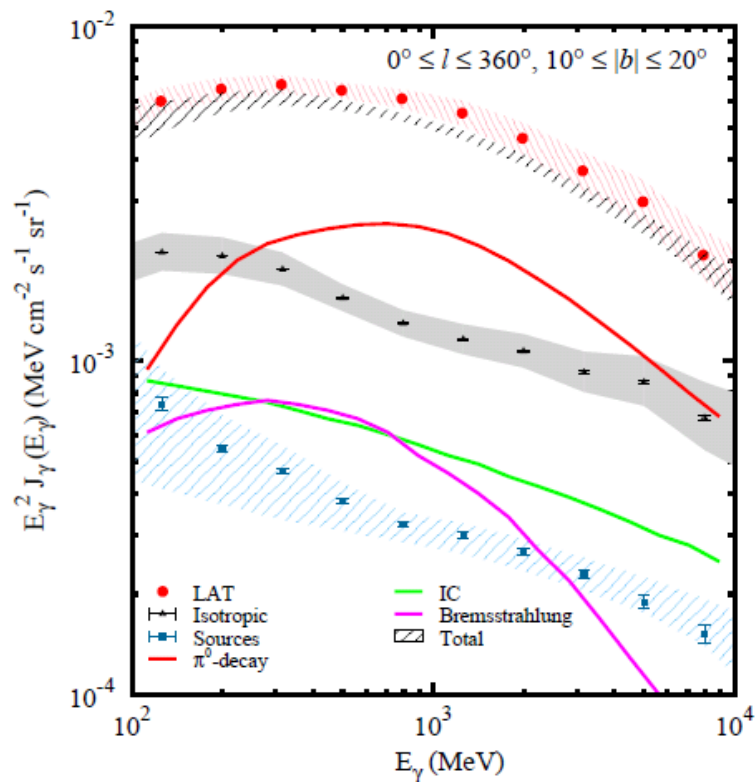


Fermi LAT 弥散光子

Phys.Rev.Lett.103:251101, 2009



未证实EGRET结果

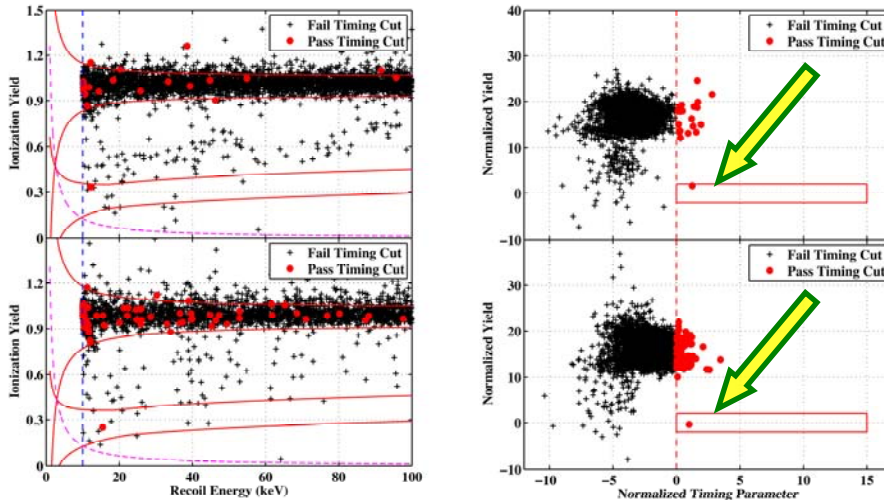


低能区结果与预期符合

近期结果包括银河系中心区和各向同性弥散光子能谱，未观察到明显结构

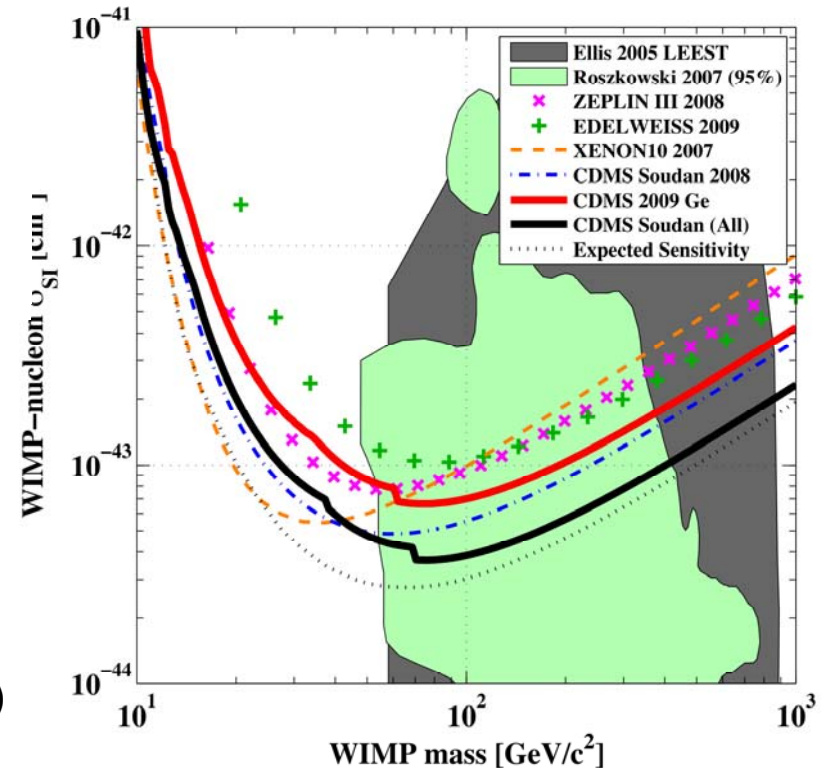
近期实验进展回顾：地下直接探测

CMDS-II



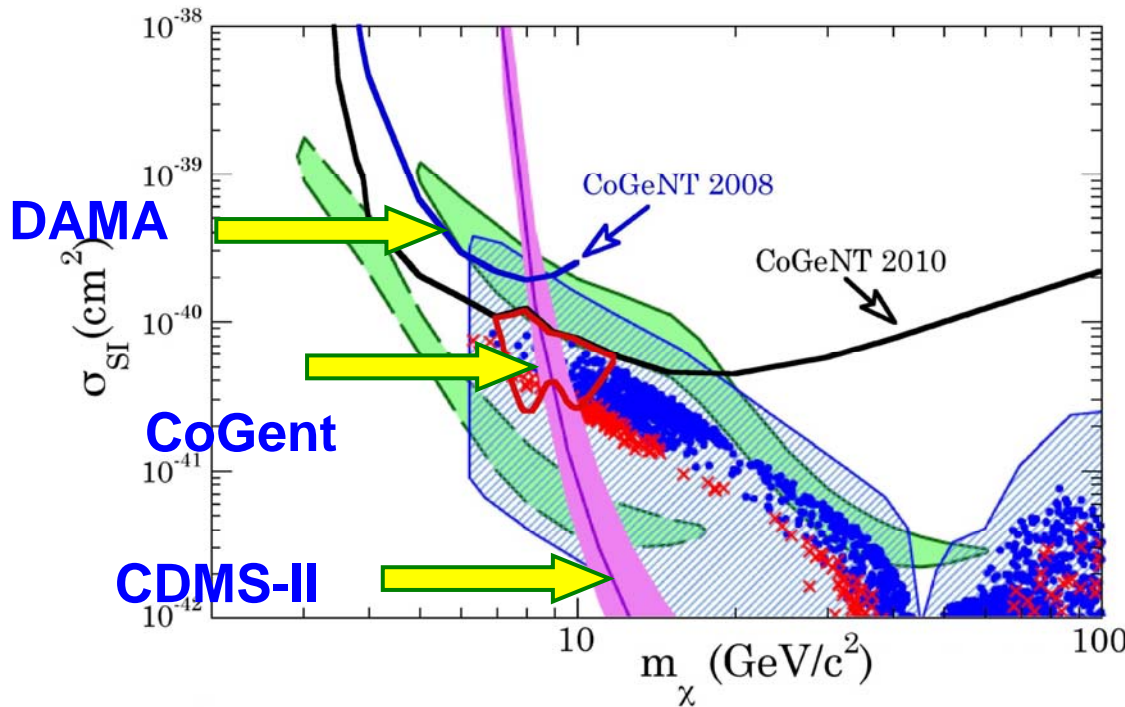
- Occur during a time of nearly ideal detector performance. Separated in time by several months and occur on detectors in different towers (T1Z5, T3Z4)
- Occur on inner detectors where we have a stronger handle of our background estimate
- Recoil energy: 12.3keV(T1Z5), 15.5keV(T3Z4)
- Confidence level ~77%, favor light DM <100GeV

Minimum cross section: $7.7 \cdot 10^{-44}$
 ($3.8 \cdot 10^{-44}$ when combined with previous analyzed exposure) @ 70GeV



CoGeNT 实验结果

arXiv:1002.4703



- Germanium based 440g p-type point contact (PPC) detector
 - Low threshold energy 0.4 KeV
 - Favor DM mass 7-11 GeV
- With confidence level ~90%
Incompatible with zero.

• Fit details:

$$\chi^2/dof = 20.4/20 \text{ (without DM)}$$
$$\chi^2/dof = 20.1/18$$
$$(m_\chi = 9\text{GeV}, \sigma = 6.7 \times 10^{-41}\text{cm}^2)$$

地下直接探测实验显示有轻的暗物质的可能迹象，但有待确认

宇宙线粒子能谱超出的可能解释

天体物理解释?

- Pulsar, SNR, ...
- CR interactions

Hu, Yuan, Zhang, Wang, Fan, Bi, 0901.1520

暗物质解释?

- 较大的暗物质作用截面
- 主要末态为轻子, 夸克末态必需被压低

Yin, Yuan, Liu, Zhang, Bi, Zhu, Zhang,
arXiv:0811.0176
Liu, Yuan, Bi, Li, Zhang, 0906.3858

暗物质湮灭

暗物质衰变

WIMP

Boost factor ?

Constraints?

Fine tuning?

DM分布局部不均匀性

Sommerfeld效应

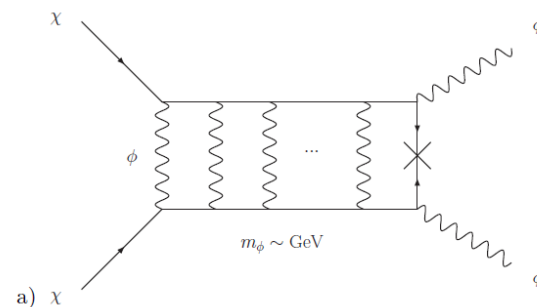
共振态效应

Guo, Wu, PRD09

- Galactic diff. gamma-ray
- Subhalo structure
- CMB

Luo, Wang, Wu, Zhu, 0911.3235
Guo, Wu, Zhou, in preparation

Boost factor 来源: 量子索末菲效应



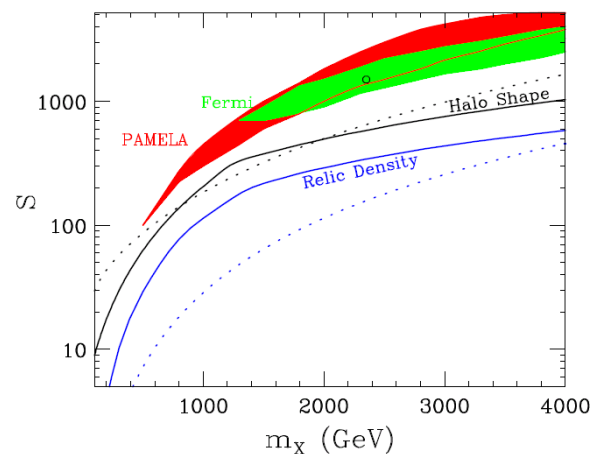
暗物质之间的长程吸引相互作用可导致低温时暗物质湮灭截面提高

$$S = \frac{|\psi_k(0)|^2}{|\psi_k^0(0)|^2} = \frac{2n\pi}{e^{2n\pi} - 1} = \frac{-\alpha\pi/v}{e^{-\alpha\pi/v} - 1} \quad (\text{零质量极限})$$

存在的限制

- 长程力可导致暗物质分布结构变化
- 影响暗物质剩余丰度
- 产生大的增强因子需要一定的 fine tuning

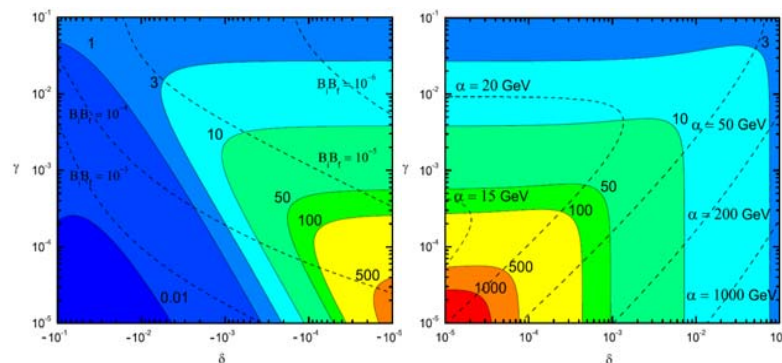
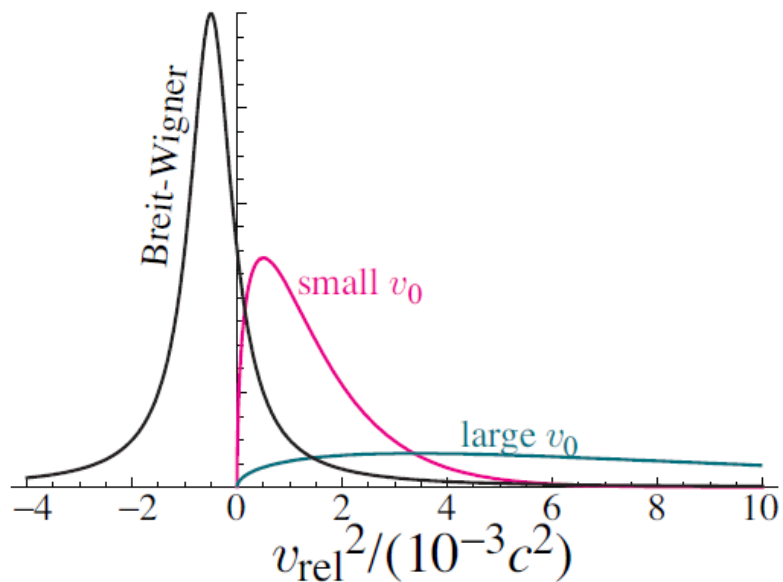
Yuan, Bi, Liu, Yin, Zhang and Zhu,
Astro-ph/0905.2736



J.L.Feng, et.al, arXiv:0911.0422

Boost factor 来源: 共振态增强效应

Guo, Wu, PRD79,055012



$$\sigma = \frac{16\pi}{E_{\text{cm}}^2 \beta_i \beta_f} \frac{M^2 \Gamma^2}{(E_{\text{cm}}^2 - M^2)^2 + M^2 \Gamma^2} B_i B_f,$$

Ibe, Murayama, Yanagida, PRD79,095009,2009

存在问题

- 模型实现有一定难度
- 对共振态粒子质量存在较大的fine tuning

Bi, He, Yuan, Astro-ph/0903.0122

暗物质模型构造

如何实现暗物质的稳定性？

1. 引入额外分立对称性

1. 最小超对称，额外维度，little Higgs 等
2. Z_2 对称性

2. 利用量子场论基本对称性

- 利用宇称 (P)，粒子-反粒子变换对称性 (C)
- 规范场custodial对称性等

P 和**C**等场论基本对称性及破缺与宇宙中重子物质的起源联系密切，有可能也联系到暗物质的起源。

一类最简单的暗物质模型

Minimal models for DM (C, P 对称性明显破缺)

Silveira, Zee, 1985

McDondald, 1994,

Burgess, Pospelov & Veldhuis, 2001

Barger, Langacker, KcCaskey, 2007

Shafi, Okada, 2009

He, Li, Tsai, 2007, 2009

e.g.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{m_0^2}{2} D^2 - \frac{\lambda_D}{4} D^4 - \lambda D^2 H^\dagger H$$

SM

ν SM

2HDM



Scalar DM

Stability set by hand

Z_2 type: $D \rightarrow -D$

Left-right models with scalar DM (C, P 对称性自发破缺)

e.g.

LRM



Scalar DM

Stability protected by CP

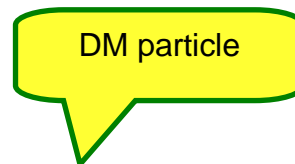
Guo, Wang, Wu, YFZ, Zhuang, PRD79, 055015(2009);

左右对称模型中暗物质的稳定性

Wang, Guo, Wu, Zhou, Zhuang, PRD79, 055015

规范对称群: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$.

粒子内容 (标量部分)



$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \chi = \begin{pmatrix} \chi_1^0 & \chi_1^+ \\ \chi_2^- & \chi_2^0 \end{pmatrix}, \Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}, S = \frac{1}{\sqrt{2}}(S_\sigma + iS_D). \quad (1)$$

P 和 CP 变换性质

	P	CP
ϕ	ϕ^\dagger	ϕ^*
χ	χ^\dagger	χ^*
$\Delta_{L(R)}$	$\Delta_{R(L)}$	$\Delta_{L(R)}^*$
S	S	S^*

对称性禁戒的相互作用-> 暗物质粒子稳定

	P	CP
$(S - S^*)^{1,3}$	✓	×
$(S - S^*)Tr(\phi^\dagger\phi)$	✓	×
$(S - S^*)Tr(\phi^\dagger\tilde{\phi} + \tilde{\phi}^\dagger\phi)$	✓	×
$(S - S^*)Tr(\Delta_L^\dagger\Delta_L + \Delta_R^\dagger\Delta_R)$	✓	×

模型中粒子间相互作用

Before symmetry breaking

dominant part: C- and P-even

$$\mathcal{V} = \mathcal{V}_0 + \mathcal{V}_1.$$

tiny part: C-odd

$$\begin{aligned} -\mathcal{V}_0 = & \frac{1}{\sqrt{2}}\tilde{\mu}_0^3(S + S^*) - \tilde{\mu}_S^2 SS^* - \frac{1}{4}\tilde{\mu}_\sigma^2(S + S^*)^2 + \sqrt{2}\tilde{\mu}_{\sigma S}(S + S^*)SS^* \\ & + \frac{1}{6\sqrt{2}}\tilde{\mu}_{3\sigma}(S + S^*)^3 + \tilde{\lambda}_S(SS^*)^2 - \frac{1}{4}\tilde{\lambda}_{\sigma S}(S + S^*)^2SS^* - \frac{1}{16}\tilde{\lambda}_\sigma(S + S^*)^4 \\ & + \sum_{i=1}^5 \left[-\frac{1}{\sqrt{2}}\tilde{\mu}_{i,\sigma}(S + S^*) + \tilde{\lambda}_{i,S}SS^* - \frac{1}{4}\tilde{\lambda}_{i,\sigma}(S + S^*)^2 \right] O_i, \end{aligned}$$

Guo, Wu, YFZ, arXiv:1001.0307

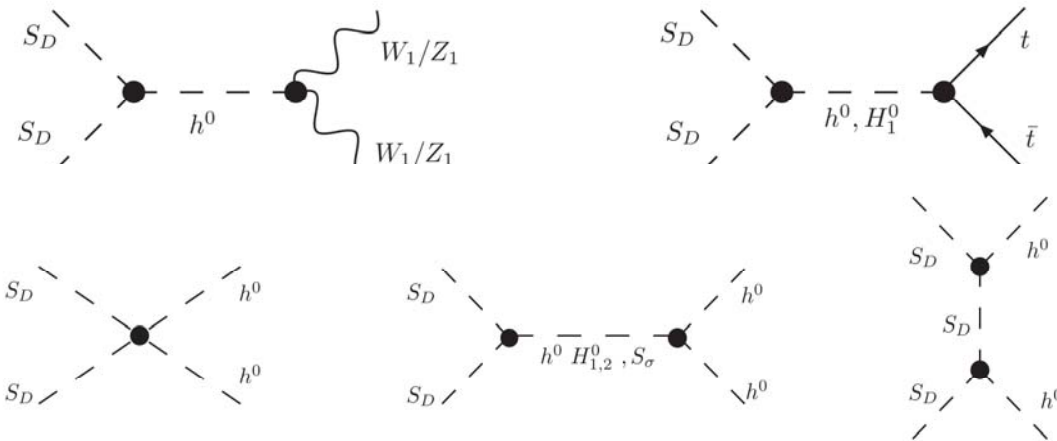
$$\begin{aligned} O_1 &= \text{Tr}(\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R), \\ O_2 &= \text{Tr}(\phi^\dagger \phi), O_3 = \text{Tr}(\phi^\dagger \tilde{\phi} + \tilde{\phi}^\dagger \phi) \\ O_4 &= \text{Tr}(\chi^\dagger \chi), O_5 = \text{Tr}(\chi^\dagger \tilde{\chi} + \tilde{\chi}^\dagger \chi). \end{aligned}$$

After symmetry breaking

- Require that S_D obtain no VEV
- S_D is still stable due to the gauge singlet nature

暗物质粒子湮灭与热力学剩余丰度

Main annihilation channels



Thermally averaged cross section & relic density

$$\langle \sigma v \rangle = \sigma_0 x^{-n} = \frac{1}{m_D^2} \left[\omega - \frac{3}{2} (2\omega - \omega') x^{-1} + \dots \right]_{s/4m_D^2=1},$$

$$\Omega_{DM} h^2 = 1.07 \times 10^9 \frac{(n+1) x_f^{n+1}}{g_*^{1/2} M_{Pl} \sigma_0} \text{GeV}^{-1}$$

对直接探测截面的预言

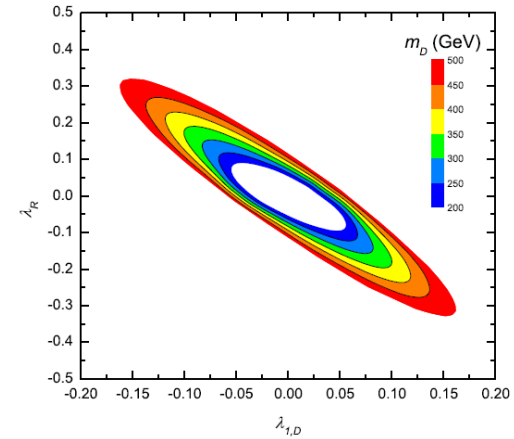
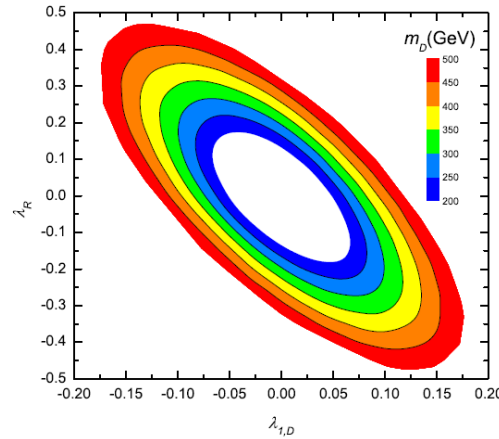
$$0.105 \leq \Omega_{DM} h^2 \leq 0.117$$

- Parameter space from relic density

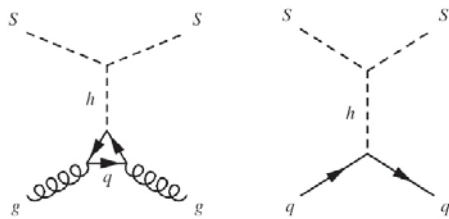
$$-1 \leq \lambda_R \leq 1,$$

$$-1 \leq \lambda_{1,D} \leq 1,$$

$$200 \text{ GeV} \leq m_D \leq 500 \text{ GeV}.$$



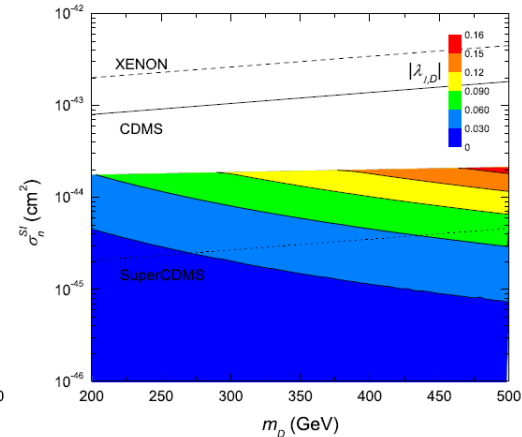
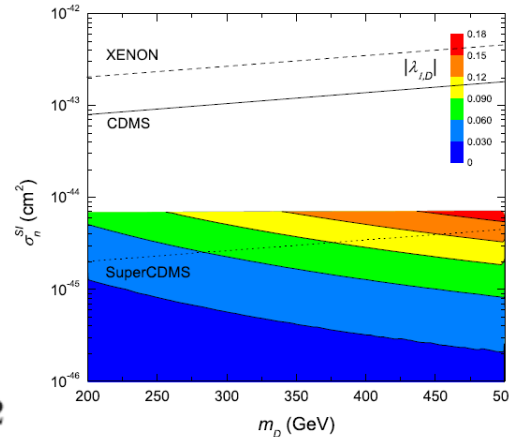
- Prediction for direct detection rate



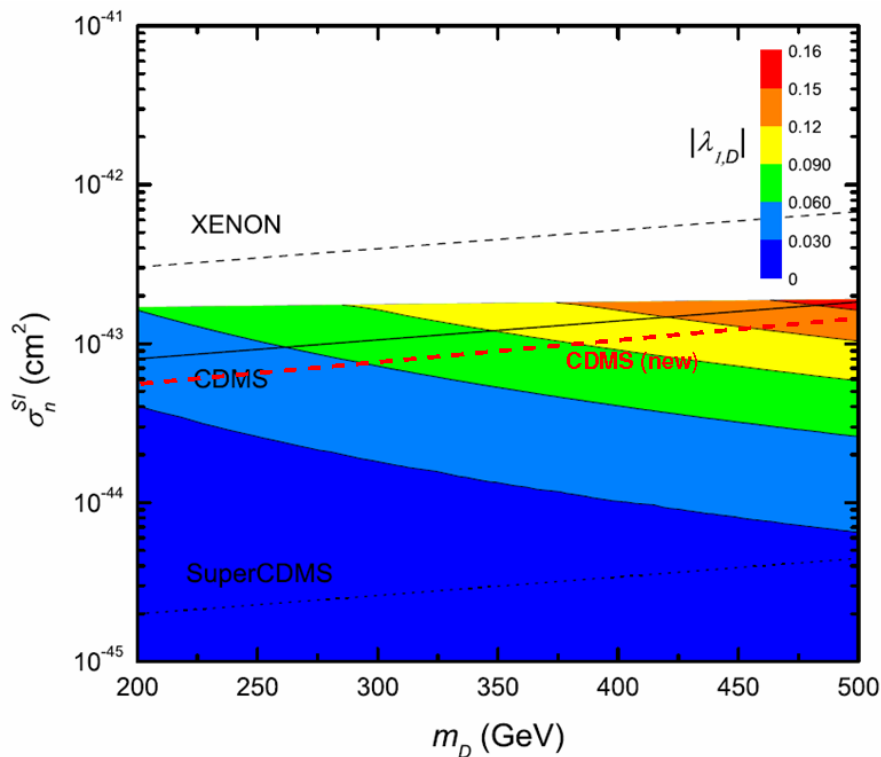
$$\sigma_{\mathcal{N}} = \frac{4M^2(\mathcal{N})}{\pi} (Zf_p + (A-Z)f_n)^2,$$

one bi-doublet case

two bi-doublet case



大的轻夸克 Yukawa coupling 情况



- 模型中第二个bidoublet 与轻夸克的耦合可以较大
- 由此预言的弹性散射截面可以达到目前**CDMS-II**的上限

对称性软破缺可导致暗物质粒子微小衰变

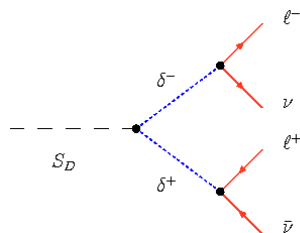
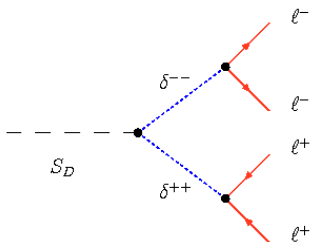
■ Generic soft C-breaking term

Guo, Wu, YFZ, arXiv:1001.0307

$$-\mathcal{V}_1 = \mu_\epsilon (S - S^*) \left[\sum_{i=1}^5 \zeta_i O_i + \zeta_6 (S + S^*)^2 + \zeta_7 (S - S^*)^2 \right].$$

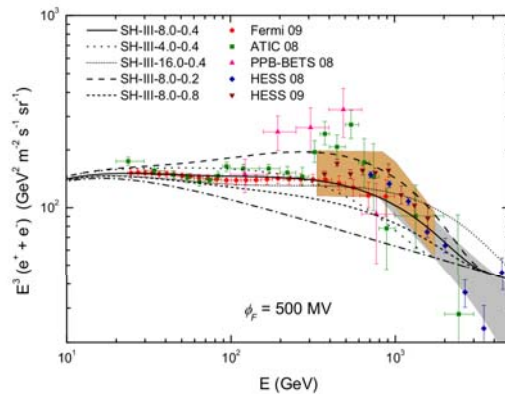
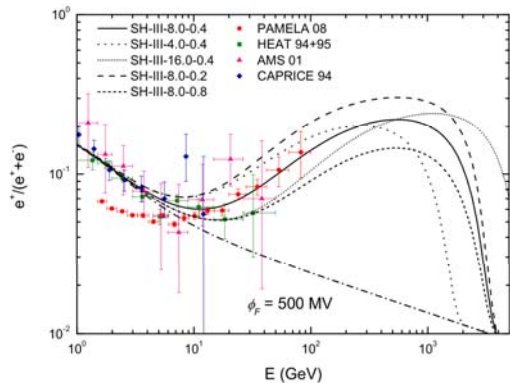
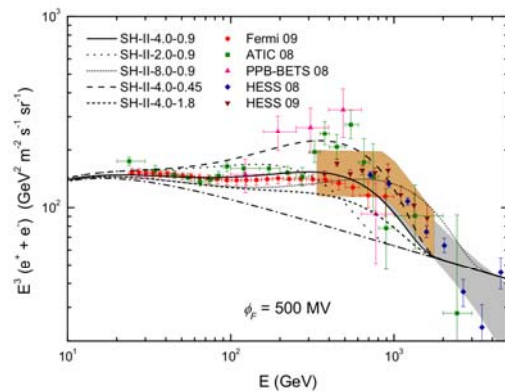
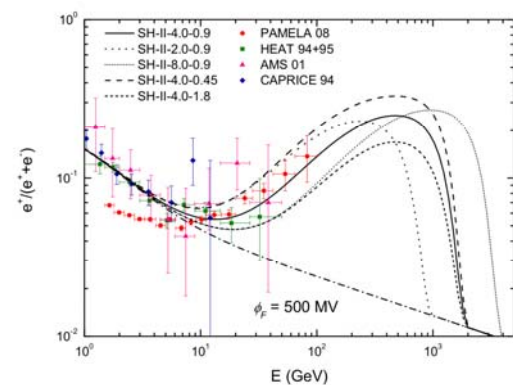
$$O_1 = \text{Tr}(\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R), O_2 = \text{Tr}(\phi^\dagger \phi), O_3 = \text{Tr}(\phi^\dagger \tilde{\phi} + \tilde{\phi}^\dagger \phi)$$

$$O_4 = \text{Tr}(\chi^\dagger \chi), O_5 = \text{Tr}(\chi^\dagger \tilde{\chi} + \tilde{\chi}^\dagger \chi).$$



- 暗物质通过三重态 (Triplet) 衰变
- Triplet通过Yukawa作用只耦合到轻子。
- Triplet与规范粒子和希格斯粒子作用被压低。
- 对中微子和弥散光子流强有新贡献，有可以被实验检验的新预言

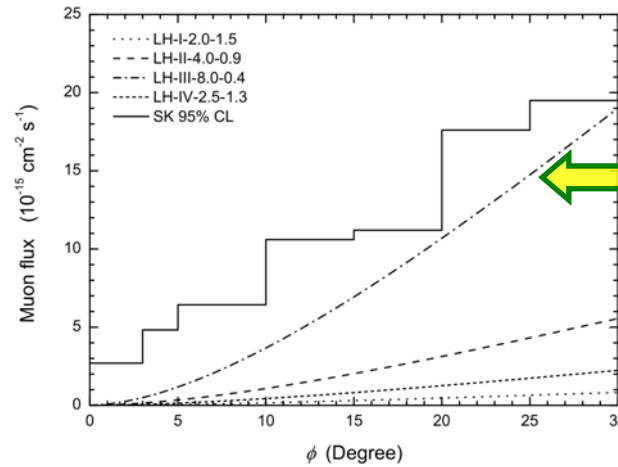
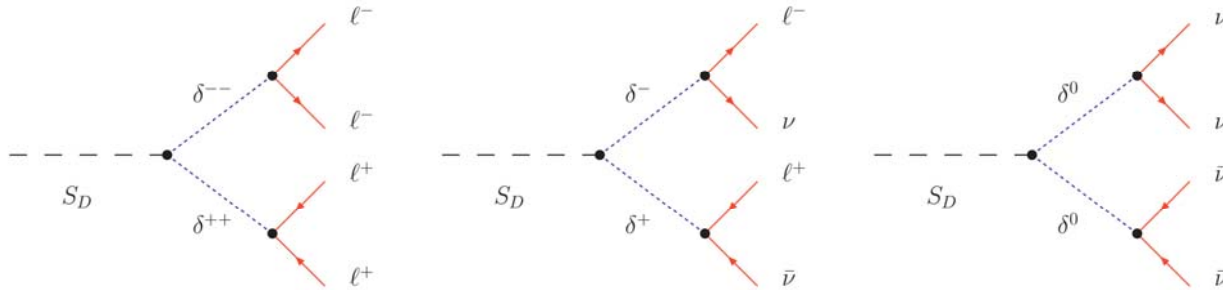
解释正负电子超出



- DM 质量主要影响“峰”的位置。
- DM 寿命主要影响“峰”的高度。
- 末态为 μ, τ 轻子时能谱较平滑，接近 Fermi 结果。
- 电子末态谱的结构较突出，接近 ATIC 结果。

预言新的宇宙线中微子源

Triplet 与同样强度耦合到轻子和中微子



τ - type final states

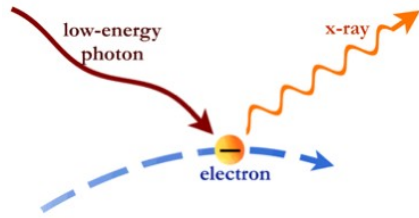
μ - type final states

中微子引起的up-going muon flux 可接近目前实验限

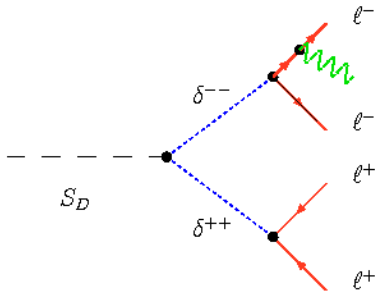
预言新的弥散伽玛射线源

依赖于质量差 $m_D - m_\delta$

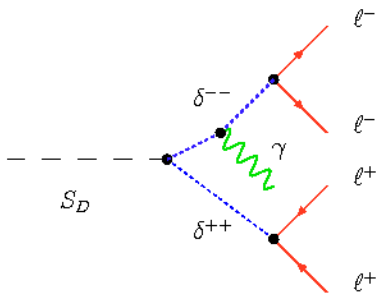
Inverse Compton scattering (ICS)



Final state radiation (FSI)

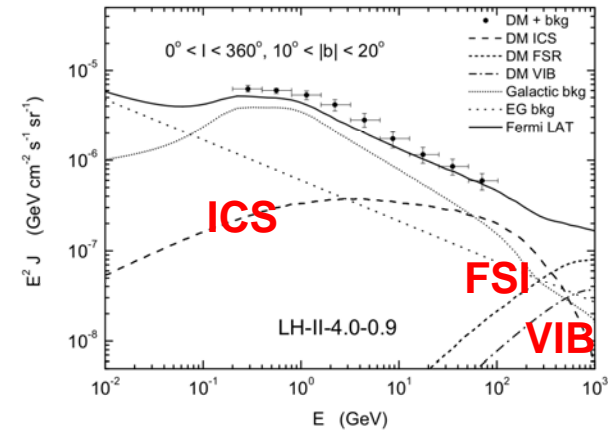
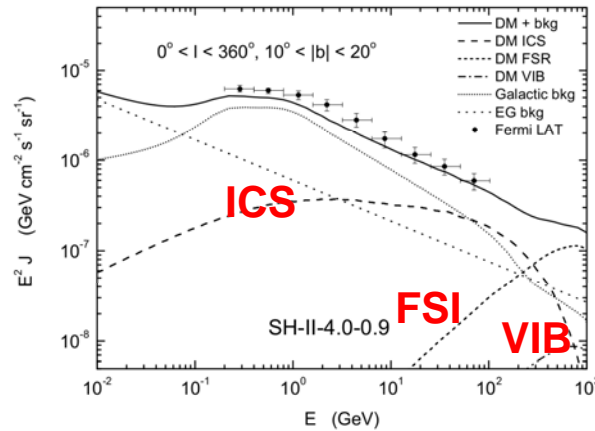


Virtual internal bremsstrahlung (VIB)

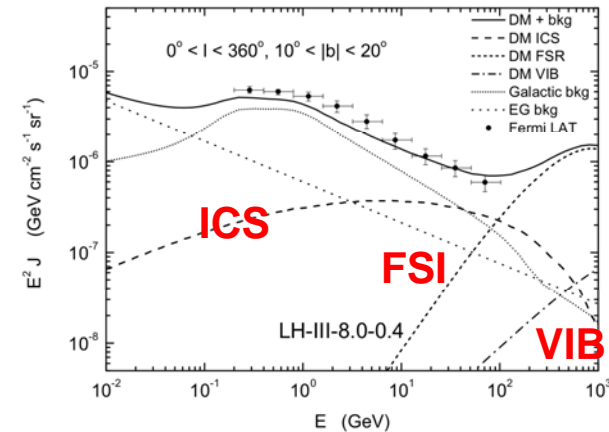
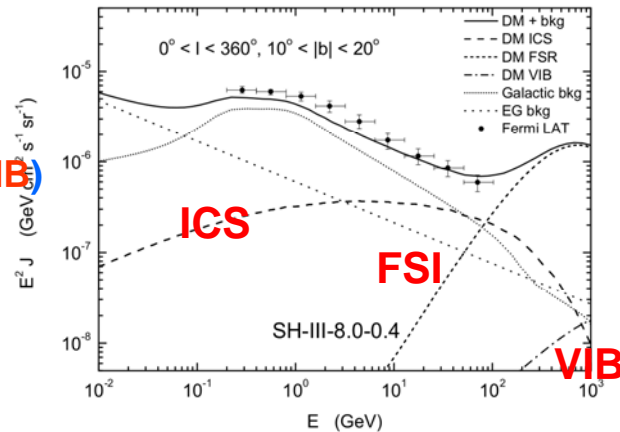


小质量差情况

大质量差情况



$\mu-$ type final states



$\tau-$ type final states

总结和展望

- 近期空间及地下暗物质实验和LHC的重新启动推动当前国内外暗物质的理论研究处于非常活跃的状态。
- 国内已经在暗物质模型湮灭/衰变模型构造（如左右对称模型，超对称SU(5)，扩展的最小超对称）；暗物质的湮灭机制（如 Sommerfeld 效应，Breit-Wigner 共振态增强效应）实验结果的唯象分析（模型无关暗物质的轻子衰变分析及整体拟合，弥散光子信号，高能中微子信号）等方面开展了研究工作，取得了一批成果。
- 研究发现暗物质的稳定性可以来自量子场论的基本对称性，可在左右对称模型中实现。该模型可解释PAMALA, Fermi/ATIC 等结果并对中微子及光子信号给出预言。
- 将进一步在暗物质起源，暗物质探测，和相关新物理唯象，LHC上的暗物质产生及探测等当面开展工作，并推动我国的暗物质地下及空间探测实验研究。



谢谢！