TeV dark matter and DAMPE electron excess

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Based on *Phys.Rev.D98 (2018) 035025*, [arXiv:1711.11579]

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August 21, 2018

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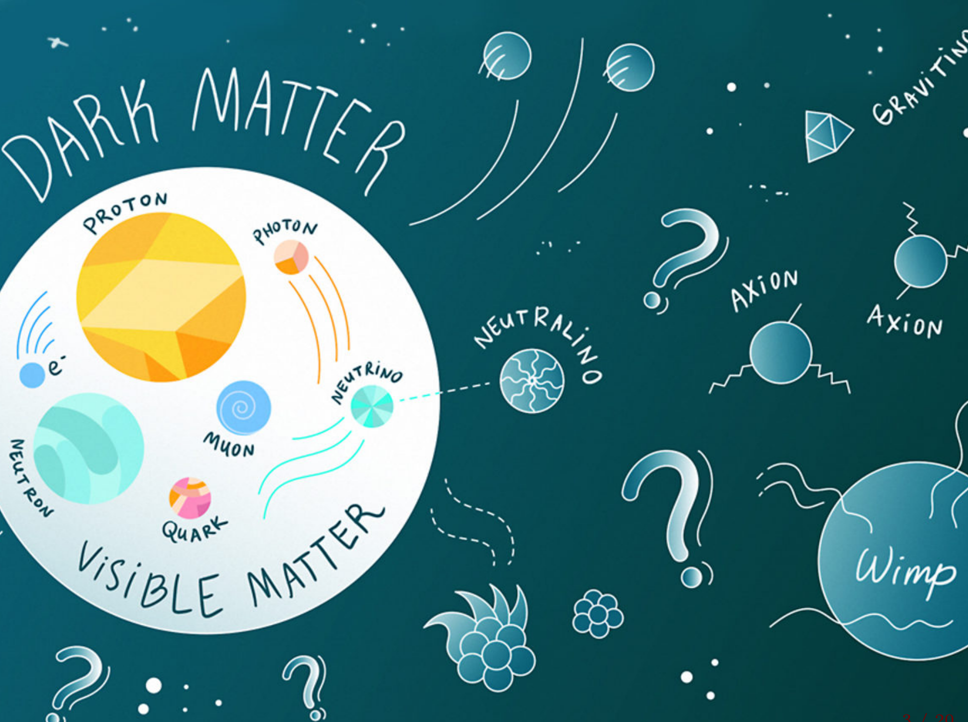
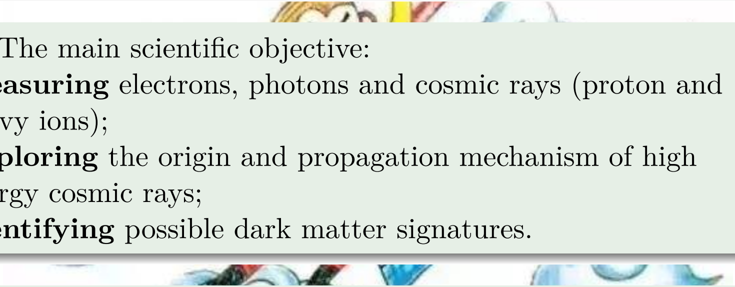
Outline

1. DAMPE experiment: electron excess
2. Electron Propagation
3. DM explanation
4. Constraints and Results
5. Summary


DARK MATTER
PROTON
PHOTON
e-
NEUTRINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
NEUTRALINO
GRAVITIN
AXION
AXION
Wimp


DAMPE

- DAMPE: **DArk Matter Particle Explorer**, a space telescope for high energy cosmic rays detection @ CAS, launched at the 17 December 2015.



- The main scientific objective:

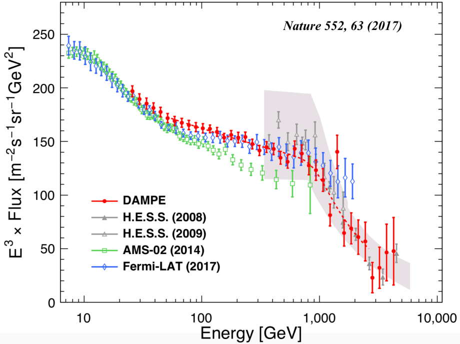
Measuring electrons, photons and cosmic rays (proton and heavy ions);
Exploring the origin and propagation mechanism of high energy cosmic rays;
Identifying possible dark matter signatures.

- DAMPE will have unprecedented **sensitivity** and **energy reach** for the cosmic rays:

For electrons and photons, the detection range is 5 GeV –10 TeV, with an energy resolution of about 1.5% at 1TeV .

[http://dpnc.unige.ch/dampe]

DAMPE electron spectrum

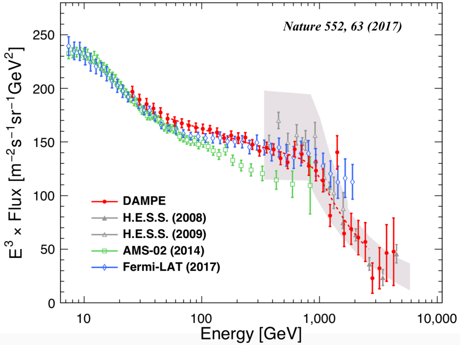


◆ DATA: G. Ambrosi *et al.* [DAMPE Collaboration], *Nature* **552**, *63 (2017).*

◆ Direct detection of a spectral break at ~ 1 TeV with 6.6 σ confidence level.

◆ Evidence for excess electron and positron events near 1.4 TeV.

DAMPE electron spectrum



Explanations for the tentative peak around 1.4 TeV:

◆ CREs come from a nearby area;

◆ Astrophysical explanation;

◆ DM explanation.

DAMPE papers

C. Jin et al., arXiv:1611.08384
Q. Yuan et al., arXiv:1711.10989
Y.-Z. Fan et al., arXiv:1711.10995
K. Fang et al., arXiv:1711.10996
P.-H. Gu, arXiv:1711.11000
G.-H. Duan et al., arXiv:1711.11012
L. Zu et al., arXiv:1711.11052
Y.-L. Tang et al., arXiv:1711.11058
W. Chao, Q. Yuan, arXiv:1711.11182
P.-H. Gu, arXiv:1711.11333
P. Athron et al., arXiv:1711.11376
J. Cao et al., arXiv:1711.11452
G.-H. Duan et al., arXiv:1711.11563
X. Liu, Z. Liu, arXiv:1711.11579
X.-J. Huang et al., arXiv:1712.00005
W. Chao et al., arXiv:1712.00037
H.-B. Jin et al., arXiv:1712.00362
Y. Gao, Y.-Z. Ma, arXiv:1712.00370
J.-S. Niu et al., arXiv:1712.00372
C.-H. Chen et al., arXiv:1712.00793
T. Li et al., arXiv:1712.00869
P.-H. Gu, arXiv:1712.00922
T. Nomura, H. Okada, arXiv:1712.00941
R. Zhu, Y. Zhang, arXiv:1712.01143
K. Ghorbani, P. Ghorbani, arXiv:1712.01239
J. Cao et al., arXiv:1712.01244
F. Yang, M. Su, arXiv:1712.01724
R. Ding et al., arXiv:1712.02021
G.-L. Liu et al., arXiv:1712.02381
S.-F. Ge, H.-J. He., arXiv:1712.02744
Y. Zhao et al., arXiv:1712.03210
Y. Sui, Y. Zhang, arXiv:1712.03642
N. Okada, O. Seto, arXiv:1712.03652
A. Fowlie, arXiv:1712.05089
J. Cao et al., arXiv:1712.05351
Z.-L. Han et al., arXiv:1712.05722
W. Zhu et al., arXiv:1712.07868
J.S.Niu, T.Li, F. Z. Xu, arXiv:1712.09586
T. Nomura et al., arXiv:1801.04729
...

Electron flux from a local DM subhalo

- We study the possibility of attributing the excess of the TeV electrons and positrons to the DM annihilations.

- The localized feature in the energy spectrum of the excess events hints a nearby source.
  Consider a DM subhalo $d_s \lesssim 1$ kpc away from us.

- NFW density profile: $\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$,
  with $(\gamma, \rho_s, r_s, d_s) = (0.5, 100\ \mathrm{GeV/cm}^3, 0.1\mathrm{kpc}, 0.3\mathrm{kpc})$
  [Choquette, 1705.09676], [Walker, et. al, 0811.0118], [Simon, Geha, 0706.0516]

Electrons Propagation

The "diffusion-loss" equation

$$\partial_t f - D(E)\nabla^2 f - \partial_E(b(E)f) = Q$$

- $f = dN/(dE\,dV)$ is the electron number density per unit energy
- $b(E) = -dE/dt$ is the energy loss coefficient
- $D(E)$ is the diffusion coefficient
- DM source term $Q(\mathbf{x}, E) = \frac{1}{4}\frac{\rho_\chi^2(\mathbf{x})}{m_\chi^2}\langle\sigma v\rangle\frac{dN}{dE}$
- $\frac{dN}{dE}$ is the energy spectrum of electrons and positrons per annihilation
- For the steady-state case: $\partial_t f = 0$

Electrons Propagation: Green's function method

Green's function method

$$G(\mathbf{x}, E; \mathbf{x}_s, E_s) = \frac{\exp\left[-(\mathbf{x}-\mathbf{x}_s)^2/\lambda^2\right]}{b(E)(\pi\lambda^2)^{3/2}}, \quad \lambda^2 = 4\int_E^{E_s} dE'\,\frac{D(E')}{b(E')}$$

♦ λ: the effective propagation length of CREs within the cooling time

The general solution

$$f(\mathbf{x}, E) = \int d^3x_s \int dE_s\, G(\mathbf{x}, E; \mathbf{x}_s, E_s)\, Q(\mathbf{x}_s, E_s)$$

Flux: $\Phi(\mathbf{x}, E) = v f(\mathbf{x}, E)/(4\pi)$

Electrons background

- Broken power-law forms [Huang, Tsai, Yuan, 1603.07119]
- 3 components: $$\begin{aligned}\phi_{\text{primary}} &= CE^{-\alpha}/(1+(E/E_b)^{\beta}).\\ \phi_{\text{secondary}} &= CE^{-\alpha}/(1+(E/E_b)^{\beta}).\\ \phi_{\text{source}} &= CE^{-\gamma}\exp(-E/E_c).\end{aligned}$$
- The total flux : $$\begin{aligned}\Phi_{e^+} &= \phi_{\text{secondary}} + \phi_{\text{source}},\\ \Phi_{e^-} &= \phi_{\text{primary}} + \phi_{\text{secondary}} + \phi_{\text{source}} .\end{aligned}$$

Working in a $U(1)_X$ extended model

$U(1)_X$ extension model

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}M_X^2 X_\mu X^\mu + X_\mu J^\mu$$

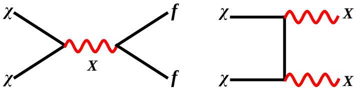
- X_μ is the new gauge boson, $X_{\mu\nu}$ is the field strength.
- Consider a vector current form: $J_\mu = g_f \bar{f}\gamma_\mu f + g_\chi \bar{\chi}\gamma_\mu \chi$,
- χ as the Dirac DM particle .

Three scenarios

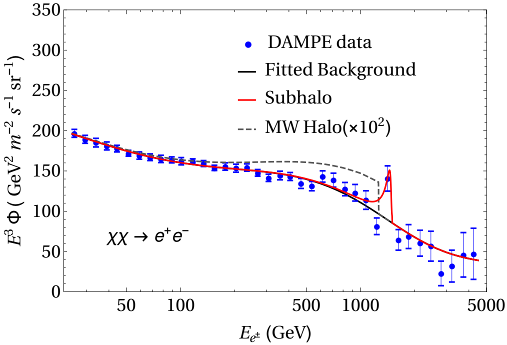
(A) : $\chi\chi \to X \to e^- e^+$ (only $g_e \neq 0$)

(B) : $\chi\chi \to XX \to 2e^+ 2e^-$

(C) : $\chi\chi \to X \to \bar{f}f$ (universally)



DAMPE data fitting



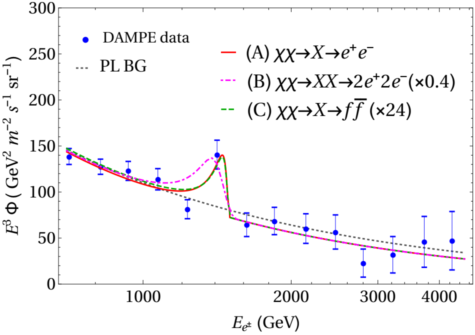
♦ DM mass $m_\chi = 1.5$ TeV.

♦ The DM annihilation cross section: $\sigma v = 3 \times 10^{-26}$ cm^3/s,

♦ The DAMPE excess events are well fitted !

♦ Spectrum from MW DM annihilation is soft, checked !

DAMPE data fitting



Case A:
$\sigma v = 1$ pb; $\chi^2 = 9.0$,
improved by $\Delta\chi^2 = 11.4$

Case B:
DM mass: 3 TeV;
Box-shaped distribution [J. Mardon et al., 0901.2926] [A. Ibarra et al., 1205.0007];
$\Delta m = m_\chi - M_X = 2$ GeV, small!
$\Delta\chi^2 = 5.1$

Case C:
$\Delta\chi^2 = 11$;
Electron channel is the dominant mode.

Constraints and Results: (A) $\chi\chi \to X \to e^- e^+$

- Constraints: Search of the $e^- e^+ \to e^- e^+$ process @ LEPII.

- Set constraint on $\Lambda > 15.9$ TeV at 95 % C.L. [hep-ex/0312023] [ALEPH Collaboration, hep-ex/0609051].

- In our model: $\Lambda = \sqrt{\pi} M_X / g_e$.

- $\Longrightarrow g_e \lesssim 0.11 (M_X/\text{TeV})$.

- Benchmark model: $(\delta m, g_e, g_\chi) = (100 \text{ GeV}, 0.1, 0.4)$

- $\delta m \equiv 2 m_\chi - M_X$.

- The DM annihilation cross section:

$$\sigma v \simeq 1.3 \text{ pb}$$

- This can explain both the DAMPE excess & the relic density.

Constraints and Results: (B) $\chi\chi \to XX \to 2e^+2e^-$

- Constraint comes from the indirect detection limits $\Longleftarrow g_e$ small.

- $\Delta m = m_\chi - M_X$ should be sufficiently small!

- H.E.S.S. data: the most stringent constraint [S. Profumo, 1711.03133]

  For $\chi\chi \to 4e$ channel is $\langle \sigma v \rangle < 4.6 \times 10^{-25}$ cm$^3/s$ in the $m_\chi \sim M_X$ case, for the 3 TeV DM.

- The required DM annihilation cross section for the DAMPE excess consistent with the H.E.S.S. constraint.

[Fermi-LAT Collaboration, 1503.02641][T. Slatyer, 1506.03811, 1506.03812].

Constraints and Results: (C) $\chi\chi \to X \to \bar{f}f$

- PandaX experiment: $\sigma_{\chi p}^{\rm SI} \lesssim 1.7 \times 10^{-45}\ {\rm cm}^2$

[PandaX-II Collaboration, 1708.06917]

- Constraint: $\sqrt{|g_\chi g_p|} \lesssim 6 \times 10^{-2}(M_X/{\rm TeV})$

- ATLAS@LHC results on dilepton signals search

[ATLAS Collaboration, 1707.02424]

$$\mathcal{L} = \frac{4\pi}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma^\mu q_i)(\bar{\ell}_j\gamma_\mu\ell_j)$$

$\Longrightarrow \sqrt{|g_q g_\ell|} < 0.09(\frac{M_X}{\rm TeV})$ when $\Lambda > 40$ TeV

- Benchmark: near the resonance

$(\delta m, g_f, g_\chi) = (10\ {\rm GeV}, 4 \times 10^{-3}, 1)$.

- Annihilation at the halo is $\sigma v \simeq 30$ pb;

- Fine with taking into account the thermal average at the freeze-out $\Longleftarrow$ Breit-Wigner enhancement.

[D. Feldman, Z. Liu, P. Nath, 0810.5762],
[M. Ibe et al., 0812.0072],
[W-L Guo, Y-L. Wu , 0901.1450]

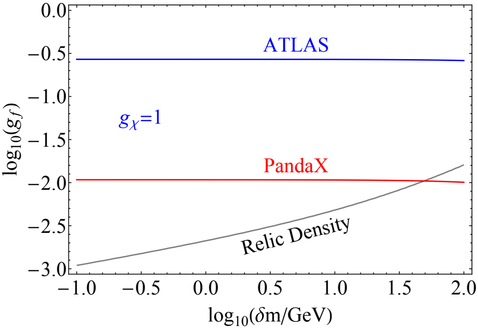
Constraints and Results: (C) $\chi\chi \to X \to \bar{f}f$

Near the resonance region:

the ATLAS constraint;

the PandaX constraint;

the relic density line.



Summary

- Explaining the DAMPE electron excess: DM annihilations in a local subhalo which is 0.3 kpc away from us.

- Three scenarios in the $U(1)_X$ extended model were investigated:

  (A) : $\chi\chi \to X \to e^- e^+$: provides a good fitting to the excess while satisfying the various constraints.

  (B) : $\chi\chi \to XX \to 2e^+ 2e^-$: the mass gap between the DM and the X boson has to be in the GeV range.

  (C) : $\chi\chi \to X \to \bar{f}f$: DM has to annihilate near the X boson resonance to generate a much larger annihilation cross section to explain the excess.

- Need more data for conformation!

Thanks for your attention!