MILLENNIUM INSTITUTE FOR SUBATOMIC PHYSICS AT HIGH-ENERGY FRONTIER SAPHIR

PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

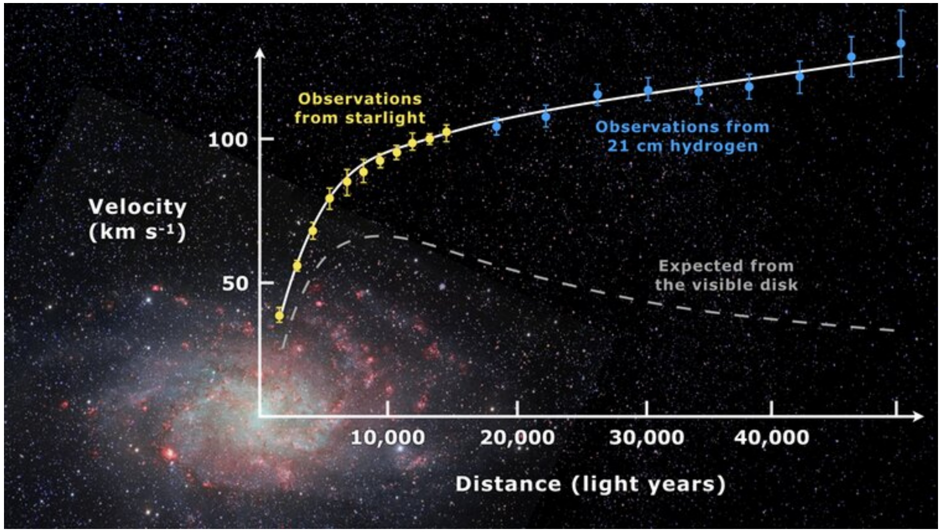
Particles and Space

Marco Aurelio Díaz

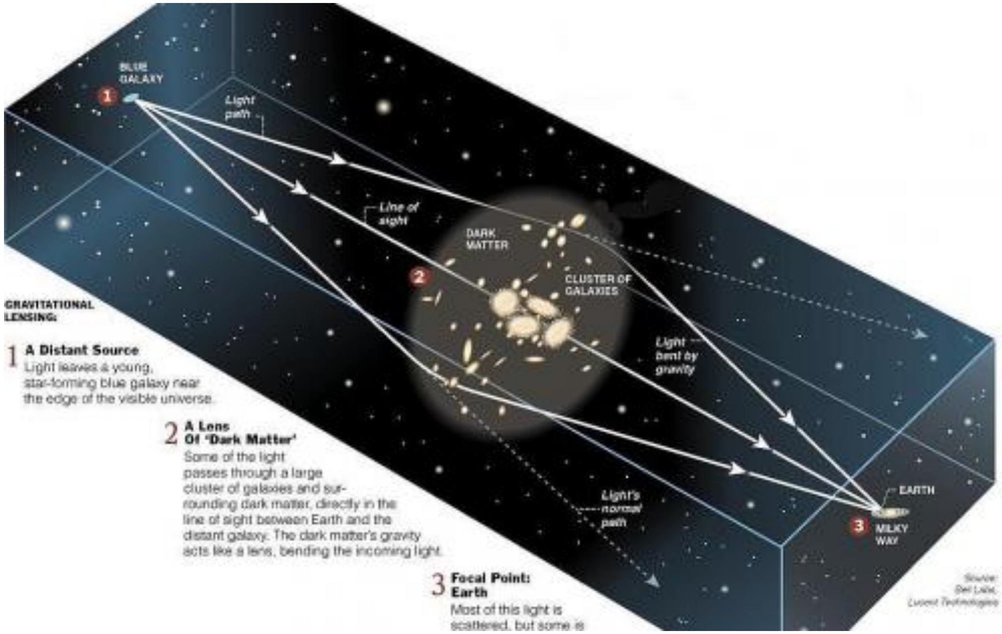
PUC

ATLAS EXPERIMENT

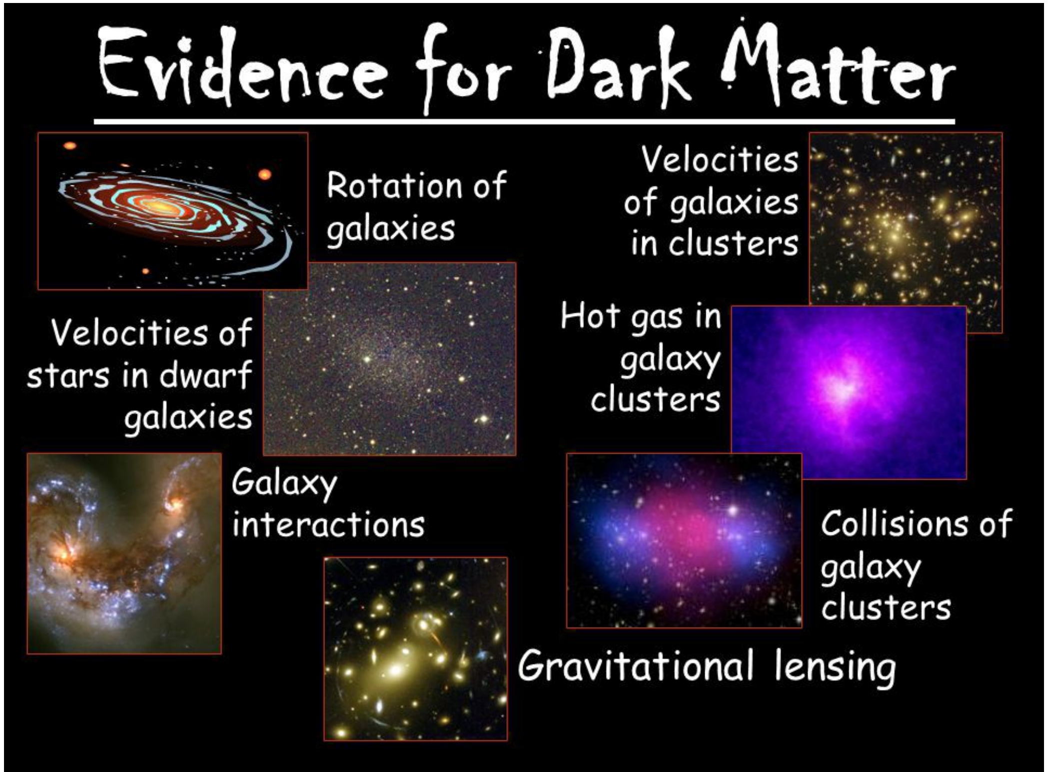
Dark Matter



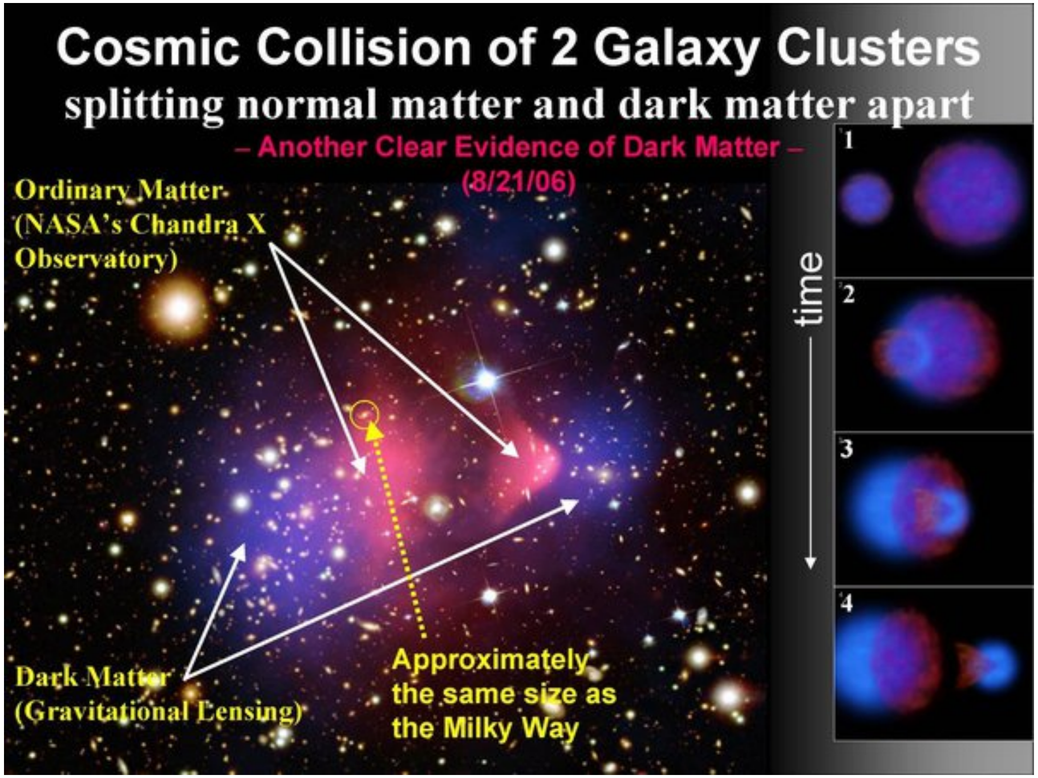
Velocity (km s⁻¹)
100
50
Observations from starlight
Observations from 21 cm hydrogen
Expected from the visible disk
10,000
20,000
30,000
40,000
Distance (light years)



BLUE GALAXY
Light path
Line of sight
DARK MATTER
CLUSTER OF GALAXIES
Light bent by gravity
Light's normal path
EARTH
MILKY WAY
GRAVITATIONAL LENSING:
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.
2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.
3 Focal Point: Earth
Most of this light is scattered, but some is



Evidence for Dark Matter
Rotation of galaxies
Velocities of galaxies in clusters
Velocities of stars in dwarf galaxies
Hot gas in galaxy clusters
Galaxy interactions
Collisions of galaxy clusters
Gravitational lensing



Cosmic Collision of 2 Galaxy Clusters
splitting normal matter and dark matter apart
– Another Clear Evidence of Dark Matter –
(8/21/06)
Ordinary Matter (NASA's Chandra X Observatory)
Dark Matter (Gravitational Lensing)
Approximately the same size as the Milky Way
time
1
2
3
4

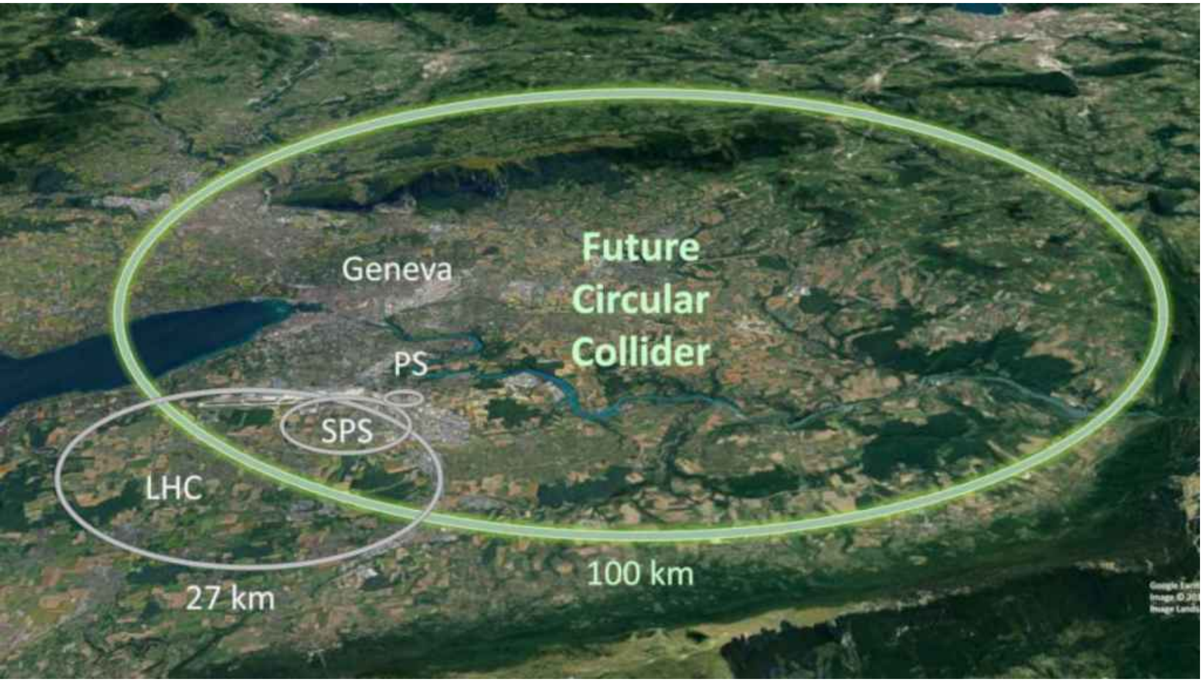
Neutrinos

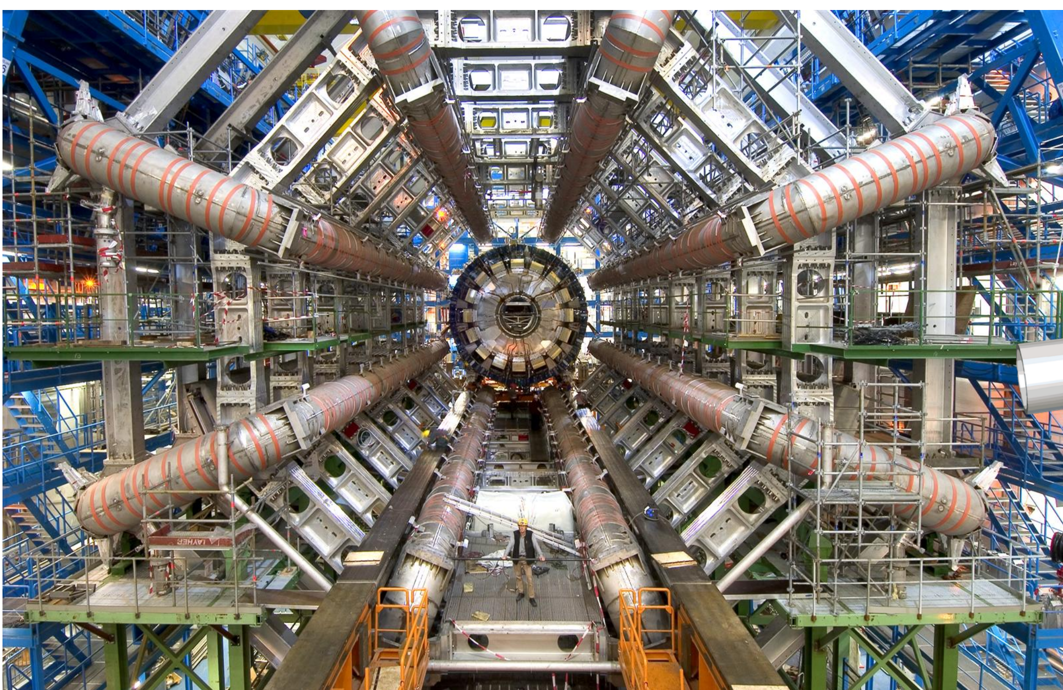
parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21} [10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert [10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert [10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

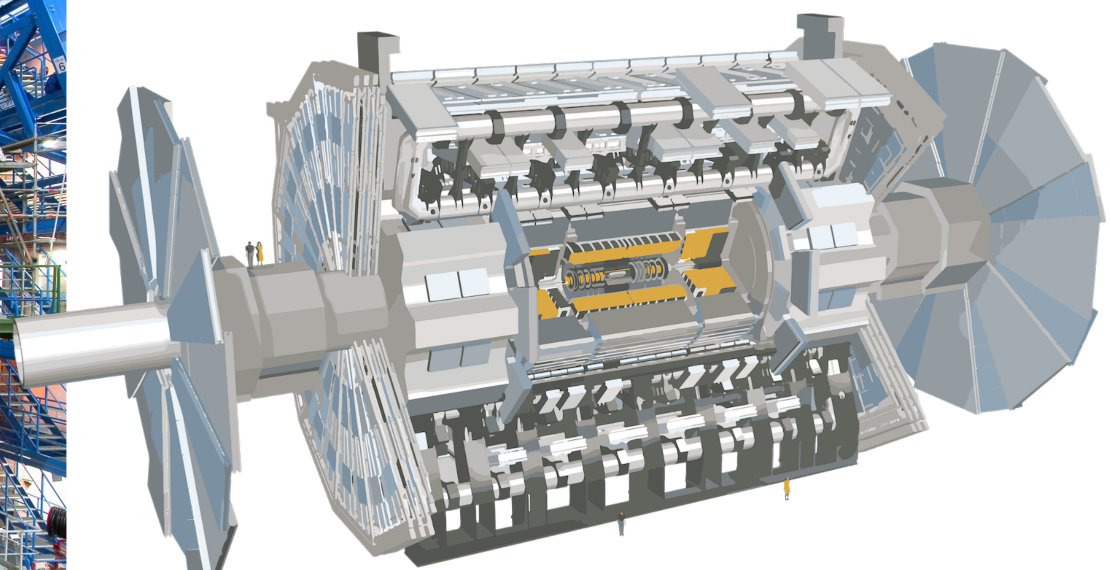
From:

JHEP **02**, 071 (2021),
P.F. de Salas, D.V. Forero,
S. Gariazzo,
P. Martínez-Miravé,
O. Mena, C.A. Ternes,
M. Tórtola, J.W.F. Valle.

Colliders







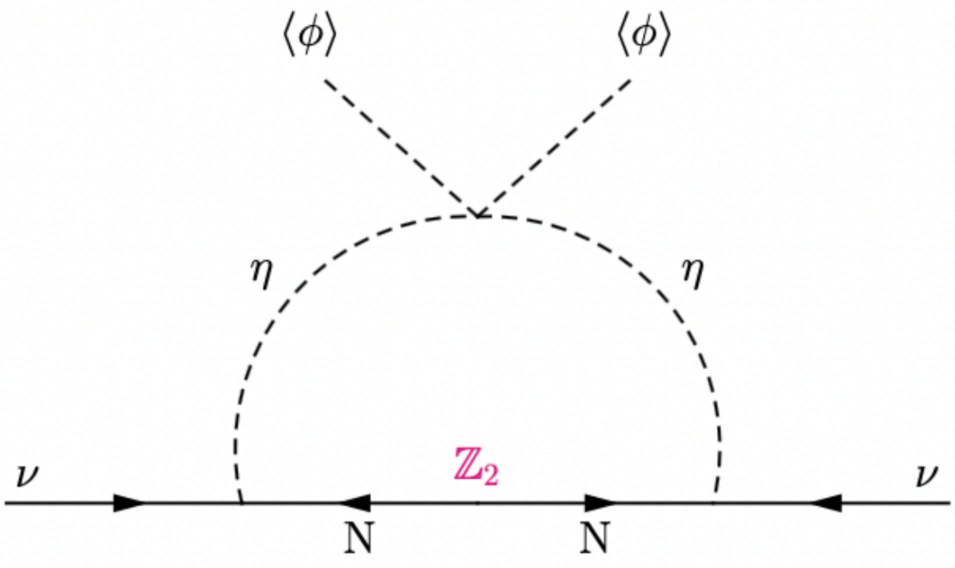
Particles from Space

Scotogenic Model

Due to E. Ma, *Phys. Rev D* **73**, 077301 (2006).

1.- Neutrino Masses (1 loop ⇒ small)
2.- Dark Matter (DM)

	Standard Model			Fermions	Scalar
	L	e	ϕ	N	η
$SU(2)_L$	2	1	2	1	2
Y	-1	-2	1	0	1
$\mathbb{Z}_2$	+	+	+	−	−
l	1	1	0	1	0



$$\mathscr{L} = -\,Y_N^{\alpha\beta}\overline{N}_\alpha\eta^\dagger L_\beta - \frac{1}{2}\overline{N}^\alpha M_{\alpha\beta}N^{\beta\,c} + \ldots$$

- DM: Real part of η (scalar DM)
- Look for long lived particles

$$m_\phi^2 = 2\lambda_1 v^2$$

$$m_{\eta^\pm}^2 = m_\eta^2 + \lambda_3\frac{v^2}{2}$$

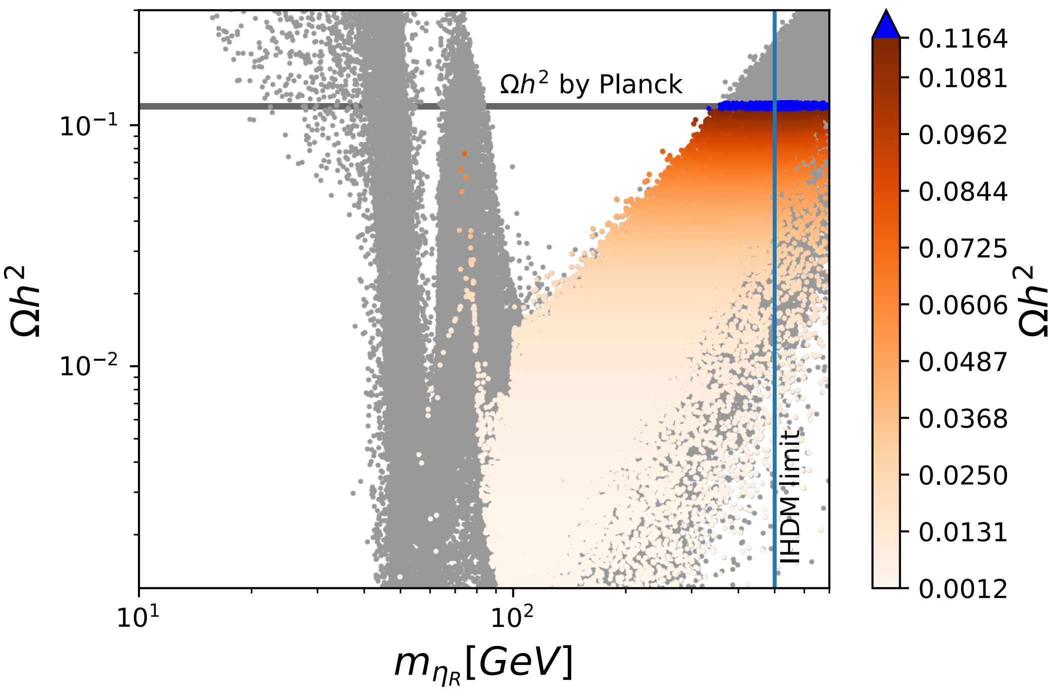
$$m_{\eta_R}^2 = m_\eta^2 + (\lambda_3+\lambda_4+\lambda_5)\frac{v^2}{2}$$

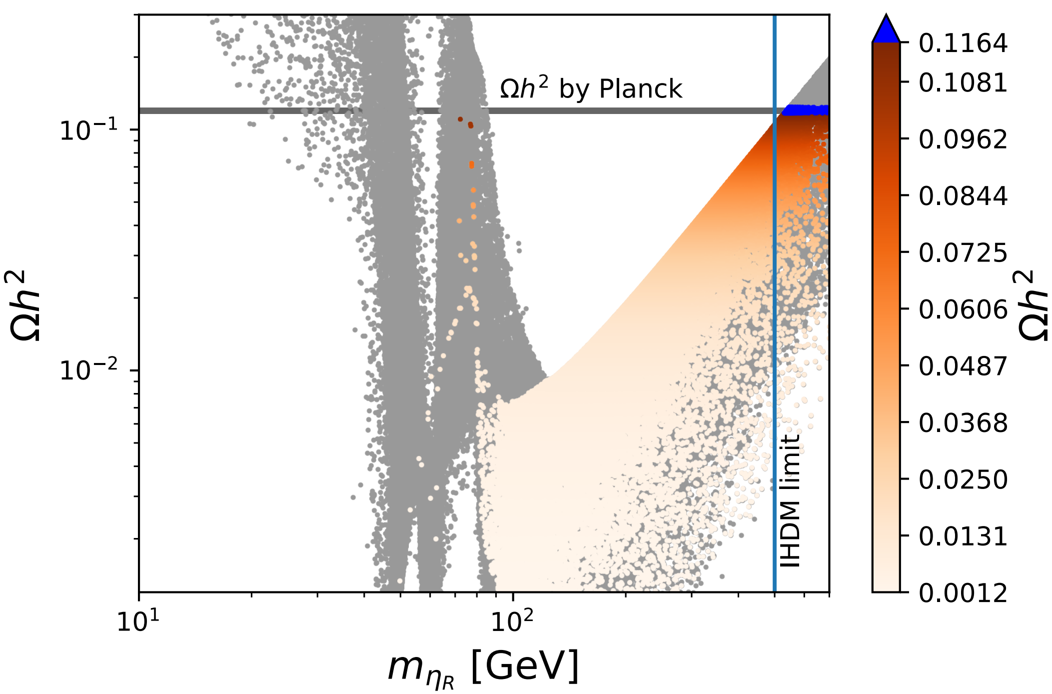
$$m_{\eta_I}^2 = m_\eta^2 + (\lambda_3+\lambda_4-\lambda_5)\frac{v^2}{2}$$

$$V = m_\phi^2\phi^\dagger\phi + m_\eta^2\eta^\dagger\eta + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\eta^\dagger\eta)^2$$
$$+\lambda_3(\phi^\dagger\phi)(\eta^\dagger\eta) + \lambda_4(\phi^\dagger\eta)(\eta^\dagger\phi)$$
$$+\frac{\lambda_5}{2}\left((\phi^\dagger\eta)+(\eta^\dagger\phi)\right)^2$$

Based on *J. Phys. G* **49**, 6, 065001 (2022), in collaboration with Ivania Maturana-Avila and Giovanna Cottin.

Relic Density





Comparison of the relic density of DM in the Scotogenic model (top), with the Inert Higgs Doublet model (bottom).

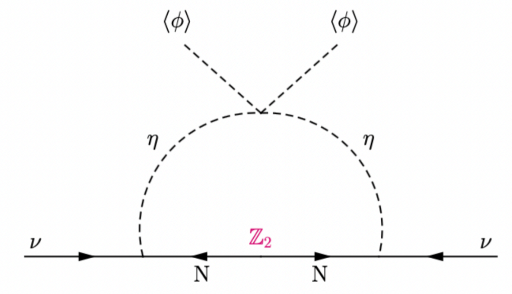
The IHDM limit of about 500 GeV is reduced to about 300 GeV.

Parameter	Scanned range
λ_1	$[10^{-8}\ ,\ 1]$
λ_2	$[10^{-8}\ ,\ 1]$
λ_3	$\pm[10^{-8}\ ,\ 1]$
λ_4	$\pm[10^{-8}\ ,\ 1]$
λ_5	$\pm[10^{-8}\ ,\ 1]$
m_η [GeV]	$[10\ ,\ 1000]$
M_{N_1} [GeV]	$[50\ ,\ 5000]$
M_{N_2} [GeV]	$[5 \times 10^3\ ,\ 2 \times 10^6]$
M_{N_3} [GeV]	$[5 \times 10^3\ ,\ 3.5 \times 10^6]$

Constraints.

- Theoretical: η_R is the lightest (at tree level), potential bounded from below, perturbativity.
- Experimental: Neutrino masses and oscillations, electroweak precision, LFV, colliders, DM.

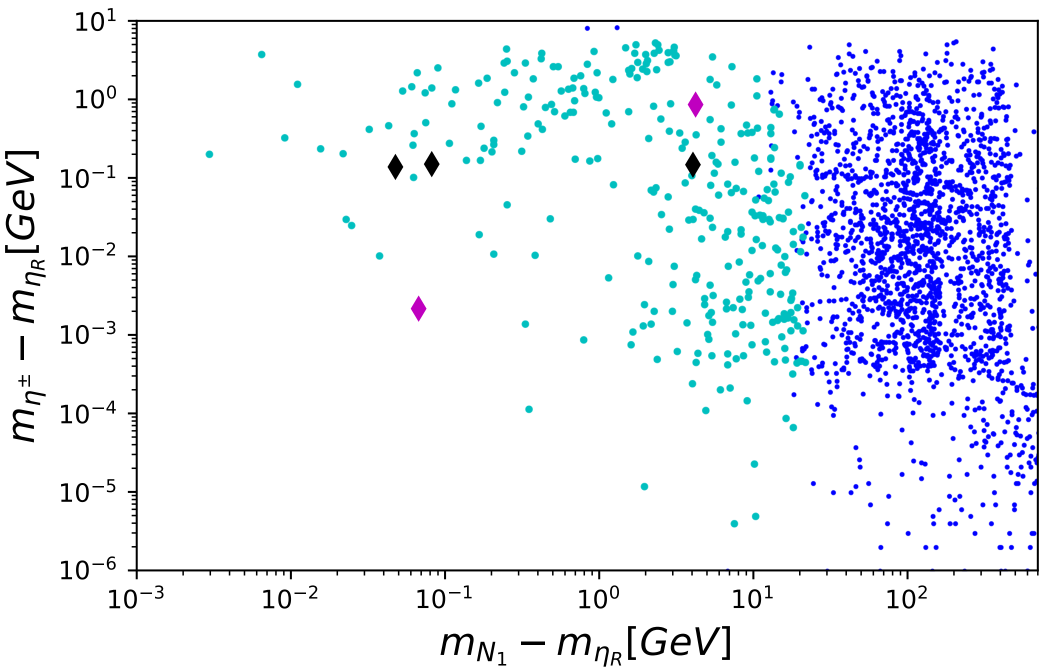
Neutrinos



Benchmark Points

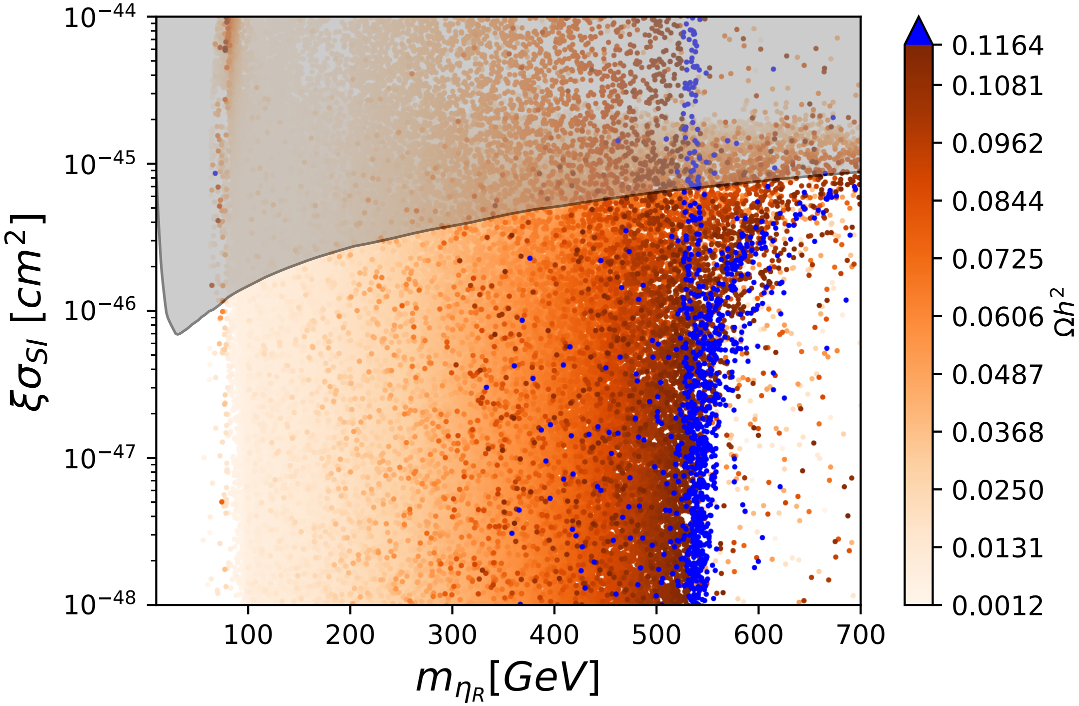
$$\mathscr{M}^{\nu}_{\alpha\beta} = \frac{m_{N_i}}{32\pi^2} Y_N^{\alpha i} Y_N^{\beta i} \left[\frac{m^2_{\eta_R}}{m^2_{\eta_R} - m^2_{N_i}} \ln\left(\frac{m^2_{\eta_R}}{m^2_{N_i}}\right) - \frac{m^2_{\eta_I}}{m^2_{\eta_I} - m^2_{N_i}} \ln\left(\frac{m^2_{\eta_I}}{m^2_{N_i}}\right) \right]$$

Parameter	B1	B2
λ_3	-2.809×10^{-4}	2.322×10^{-8}
λ_4	1.16×10^{-5}	-1.538×10^{-5}
λ_5	-2.511×10^{-2}	-2.878×10^{-5}
m^2_η [GeV]	1.966×10^5	9.608×10^4
m_{η_R} [GeV]	442.535	309.961
m_{η_I} [GeV]	444.252	309.964
$m_{\eta^\pm}$ [GeV]	443.394	309.964
m_{N_1} [GeV]	446.754	310.028
$c\tau_{N_1}$ [mm]	0.467	0.149
$\sigma(e^+e^- \to N_1 N_1)$ [fb]	9.89×10^{-20}	1.68×10^{-11}
Ωh^2	0.122	0.092



Parameter	B3	B4	B5
λ_3	-2.392×10^{-5}	3.305×10^{-6}	4.447×10^{-5}
λ_4	-6.923×10^{-7}	-1.46×10^{-3}	-3.293×10^{-6}
λ_5	-4.177×10^{-3}	-2.07×10^{-3}	-3.191×10^{-3}
m^2_η [GeV]	1.851×10^5	1.276×10^5	1.234×10^5
m_{η_R} [GeV]	430.141	357.093	351.087
m_{η_I} [GeV]	430.435	357.269	351.362
$m_{\eta^\pm}$ [GeV]	430.288	357.243	351.224
m_{N_1} [GeV]	434.197	357.175	351.134
$c\tau_{\eta^\mp}$ [mm]	16.859	14.587	28.412
$\sigma(pp \to \eta\eta j)$ [fb]	2.525	5.44	5.81
$N = \sigma \times BR \times \mathcal{L} \times \epsilon$	19.392	33.474	77.811
Ωh^2	0.121	0.121	0.119

Direct and Indirect Detection



-) Direct searches.

-) η_R−nucleon spin independent elastic scattering cross section.

-) Grey: XENON1T.

-) Blue points: satisfy the totality of the relic density (300 to 700 GeV).

-) Orange points satisfy it partially.

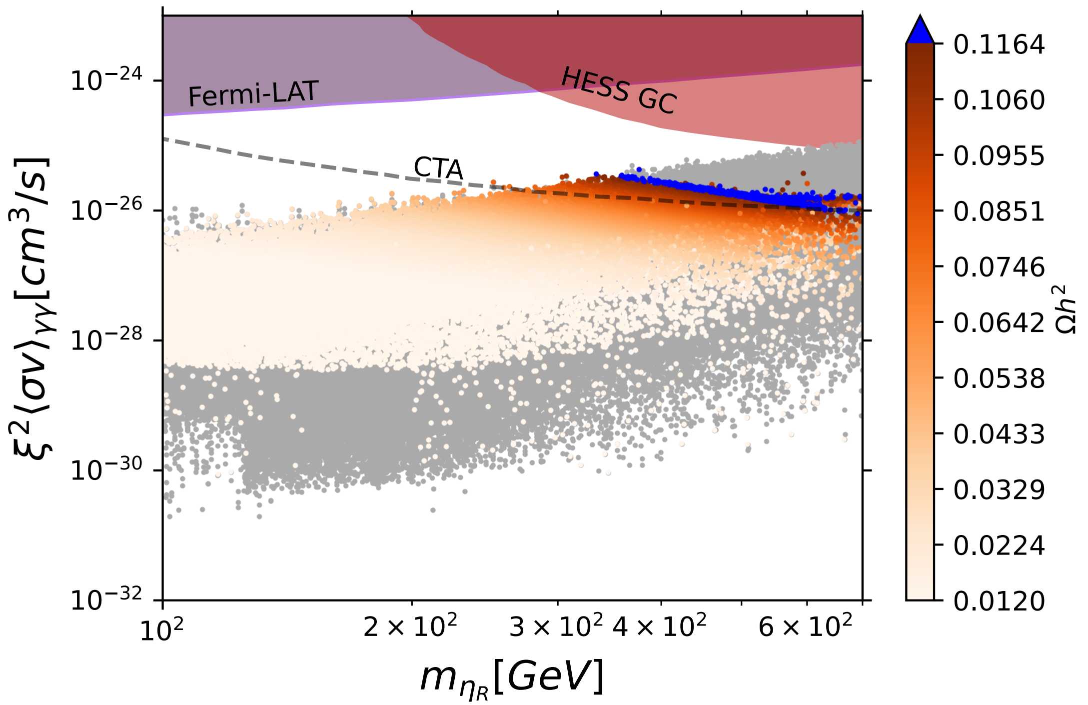
-) Indirect searches.

-) DM annihilation cross section.

-) Grey points are excluded.

-) Blue points satisfy the total relic density.

-) Orange points satisfy it partially.

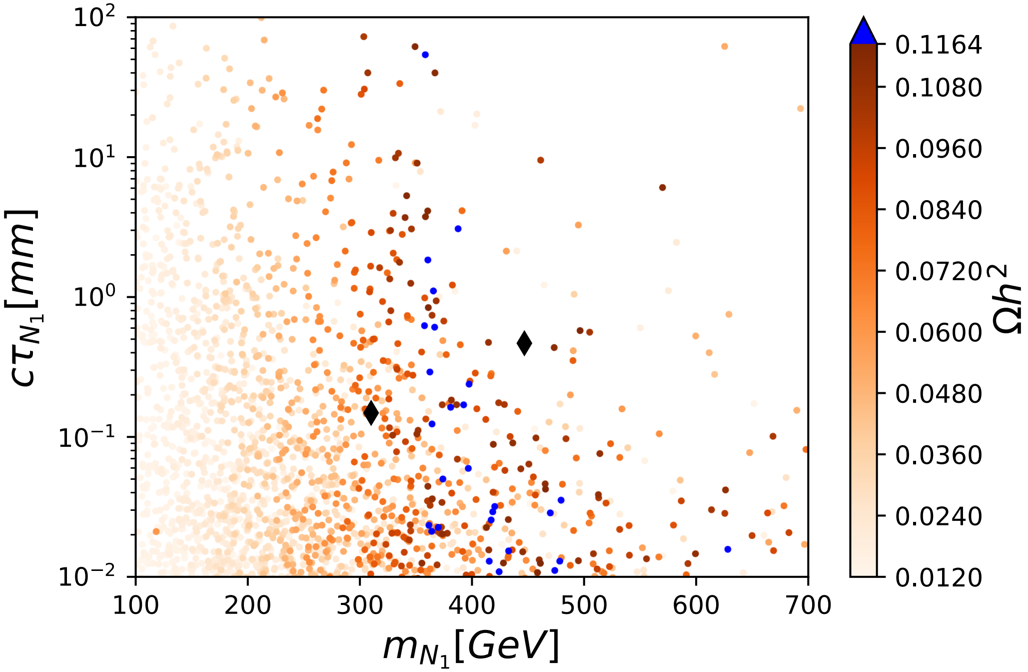


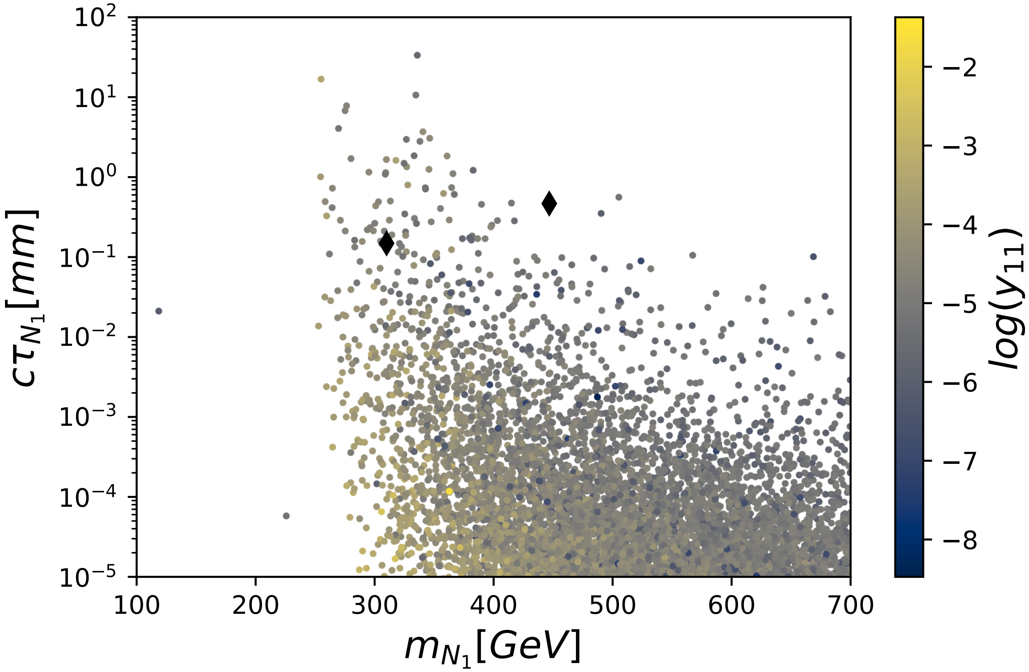
Long Lived N_1

$$\Gamma(N_k \to \ell_j^{\pm}\eta^{\mp}) = \frac{|Y_{jk}|^2}{32\pi}\frac{m_{N_k}^2 + m_{\ell_j}^2 - m_{\eta^\pm}^2}{m_{N_k}^3}\sqrt{(m_{N_k}^2 - m_{\ell_j}^2 - m_{\eta^\pm}^2)^2 - 4m_{\ell_j}^2 m_{\eta^\pm}^2}$$

$$\Gamma(N_k \to \nu\eta_\alpha) = \sum_j \frac{|Y_{jk}|^2}{32\pi}\frac{(m_{N_k}^2 - m_{\eta_\alpha}^2)^2}{m_{N_k}^3}$$

N_1 can be long-lived, but its production cross section is small.



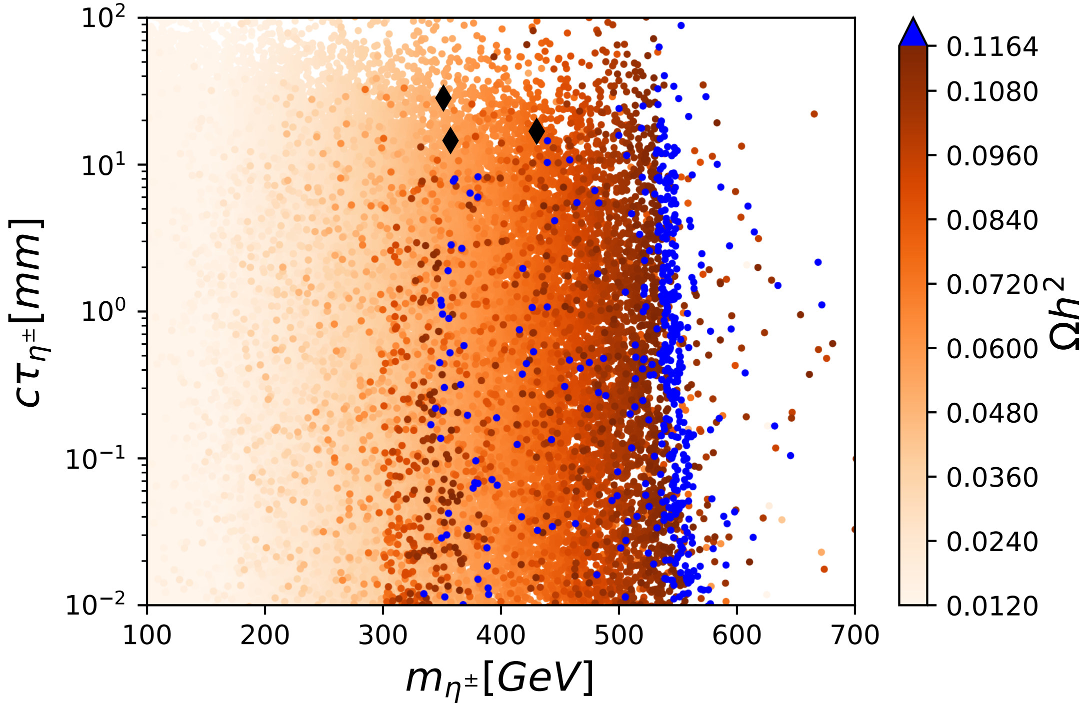


Long Lived $\eta^{\pm}$

$$\Gamma(\eta^{\pm} \to N_1 \ell^{\pm}) = \frac{Y_{\ell 1}^2 (m_{\eta^{\pm}}^2 - (m_{N_1} + m_\ell)^2)}{8\pi m_{\eta^{\pm}}} \sqrt{1 - \left(\frac{m_{N_1} - m_\ell}{m_{\eta^{\pm}}}\right)^2} \sqrt{1 - \left(\frac{m_{N_1} + m_\ell}{m_{\eta^{\pm}}}\right)^2}$$

$$\Gamma(\eta^{\pm} \to \eta_R \pi^{\pm}) = \frac{f_\pi^2 g^4 (m_{\eta^{\pm}}^2 - m_{\eta_R}^2)}{512\pi m_W^4 m_{\eta^{\pm}}} \sqrt{1 - \left(\frac{m_{\eta_R} - m_\pi}{m_{\eta^{\pm}}}\right)^2} \sqrt{1 - \left(\frac{m_{\eta_R} + m_\pi}{m_{\eta^{\pm}}}\right)^2}$$

$\eta^{\pm}$ can be long-lived, and its production cross section is large.



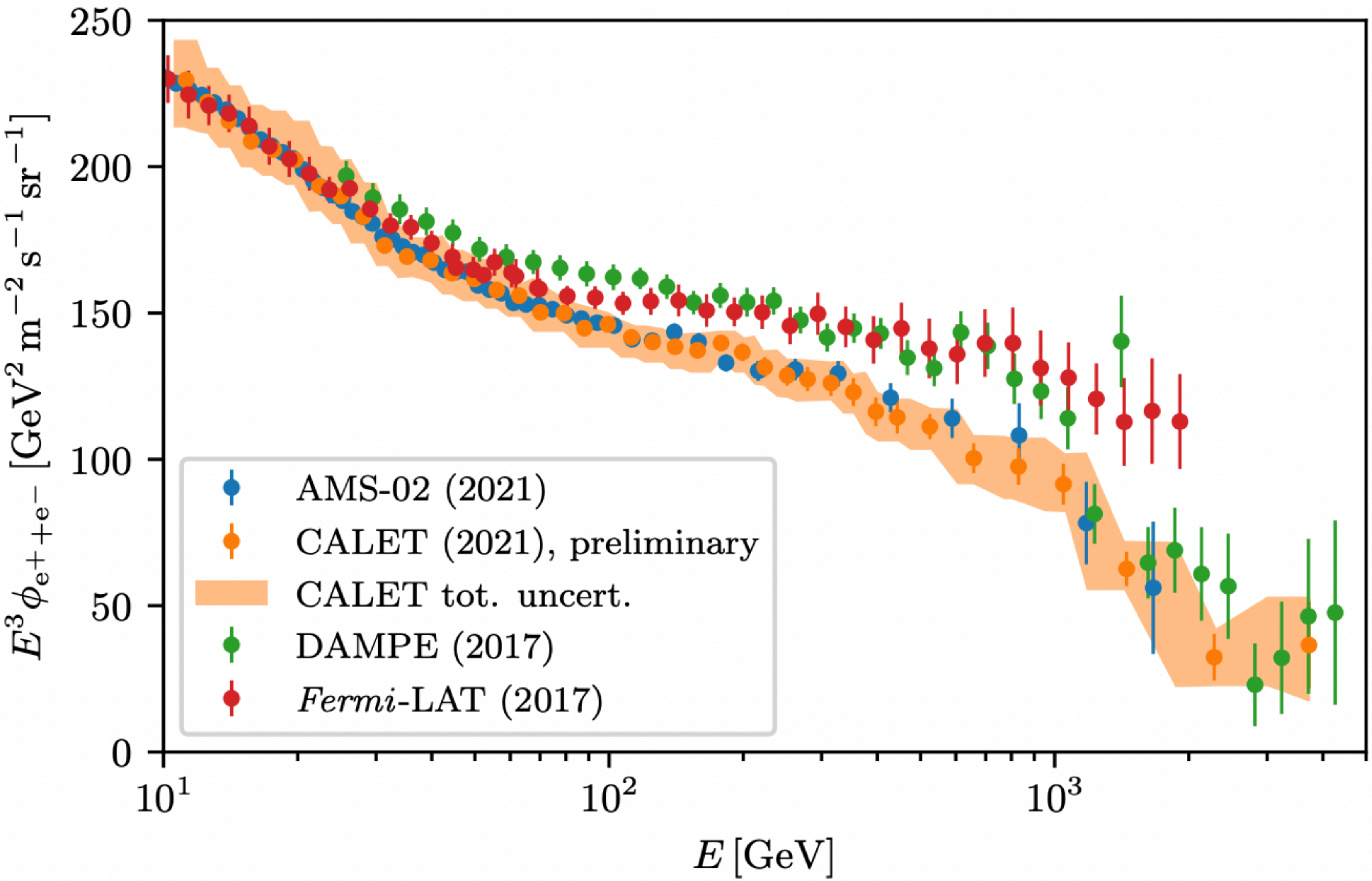
Particles from Space

All-electron Flux

Between 10 and 30 GeV: $E^{-3.25}$

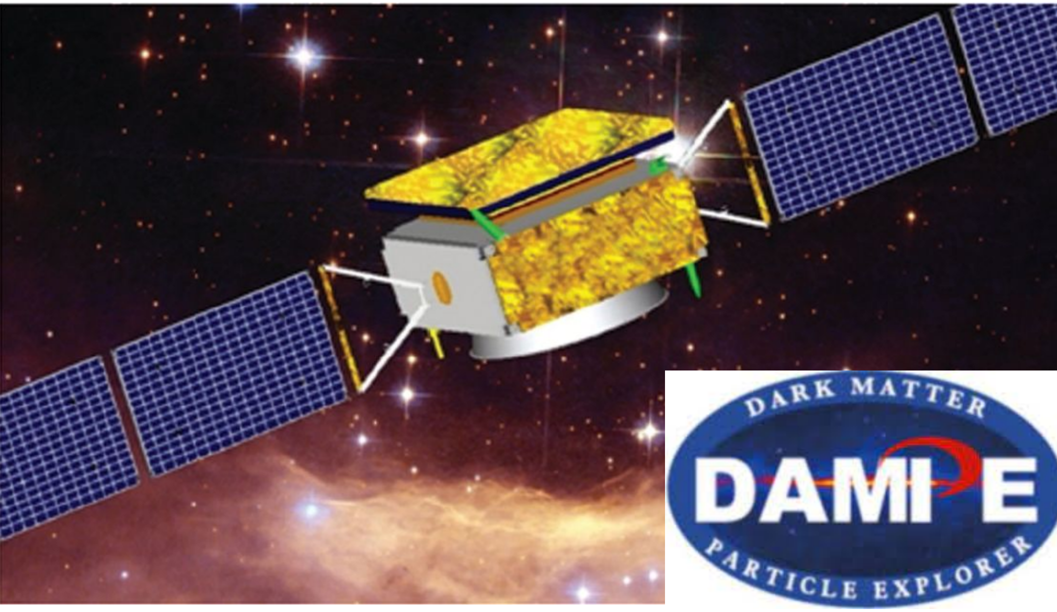
Between 30 GeV and cutoff: $E^{-3.1}$ (DAMPE, Fermi-LAT)

$E^{-3.15}$ (AMS-02, CALET)



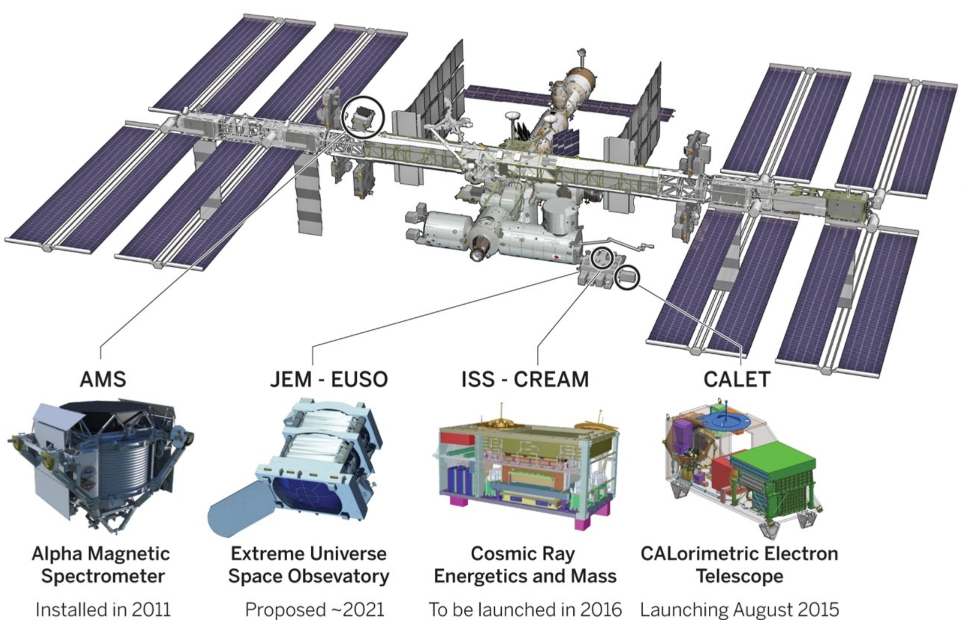
From P. Mertsch, arXiv:2211.14930

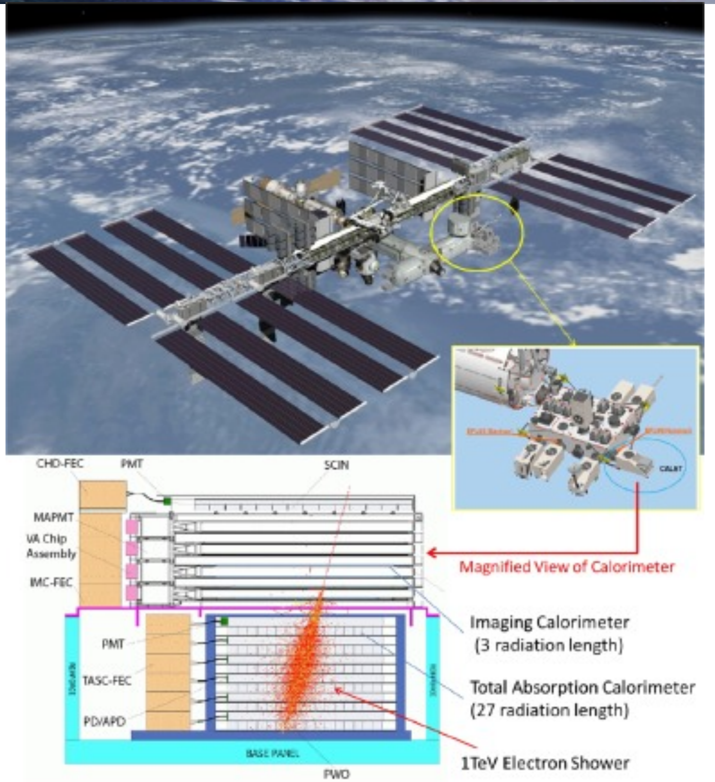
Satellites



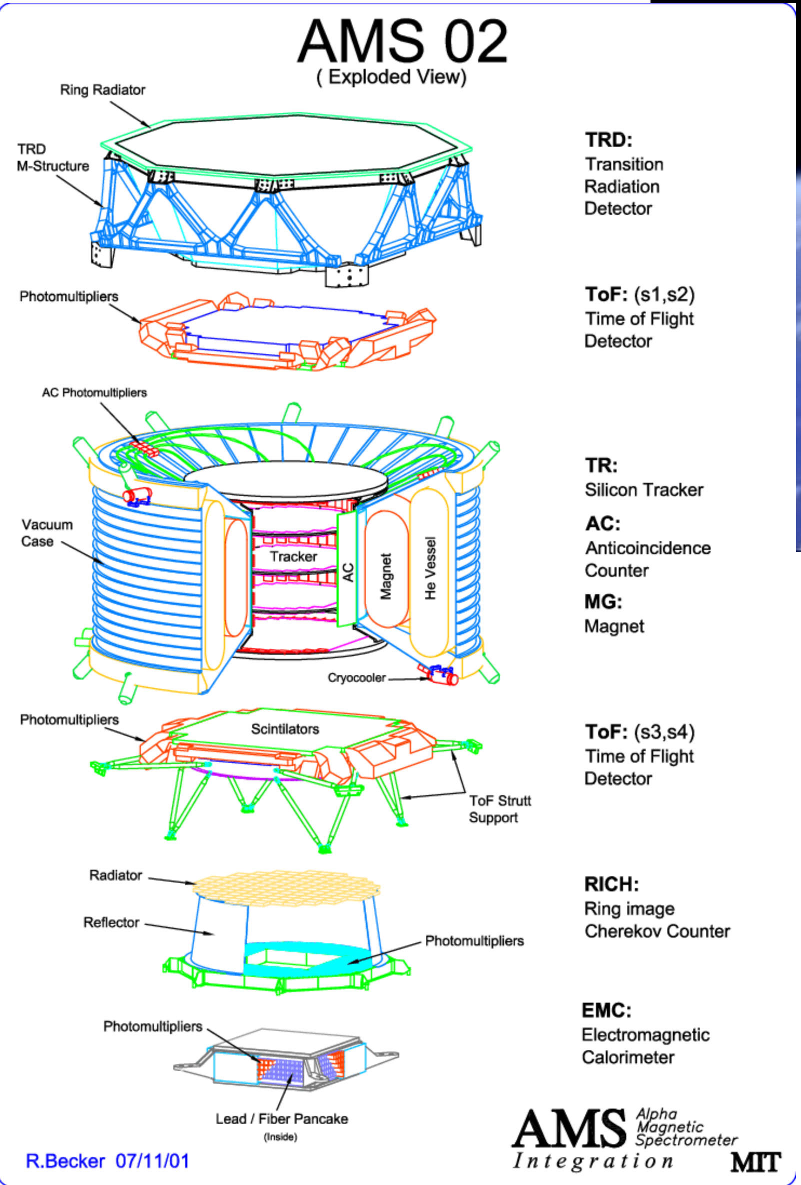
Cosmic ray detectors on the ISS

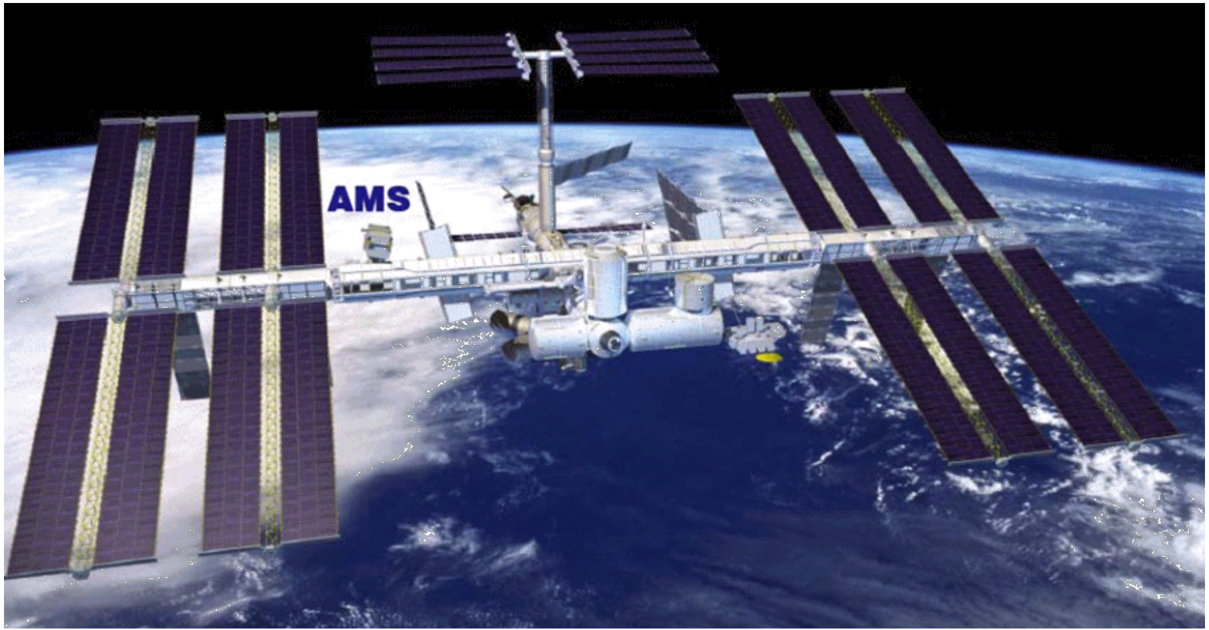
New experiments, perched outside Earth's atmosphere, promise to turn the International Space Station into a well-rounded platform for unlocking the secrets of supernovae and even dark matter.





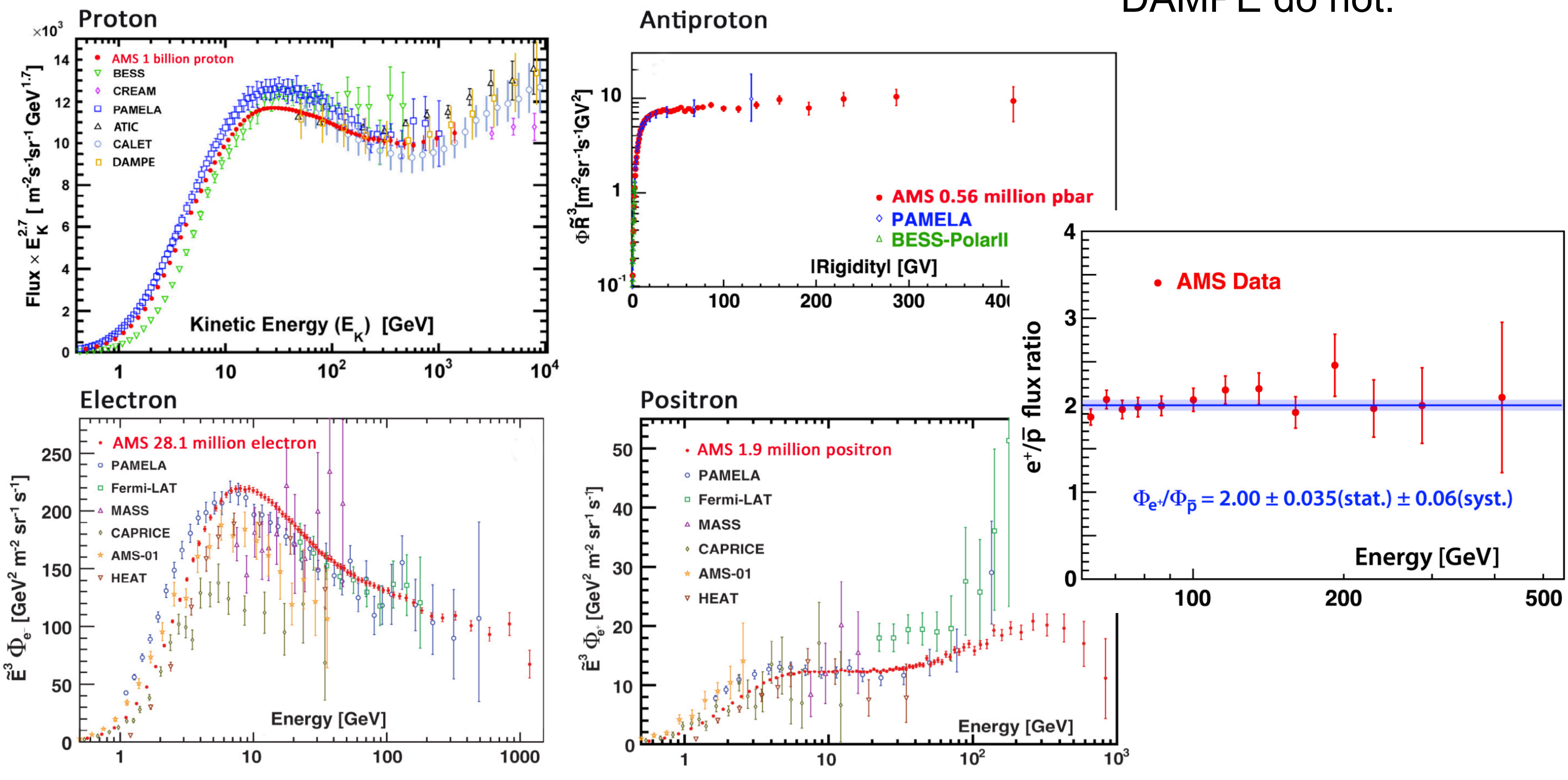
Alpha Magnetic Spectrometer (AMS-02)





Latest results from AMS-02

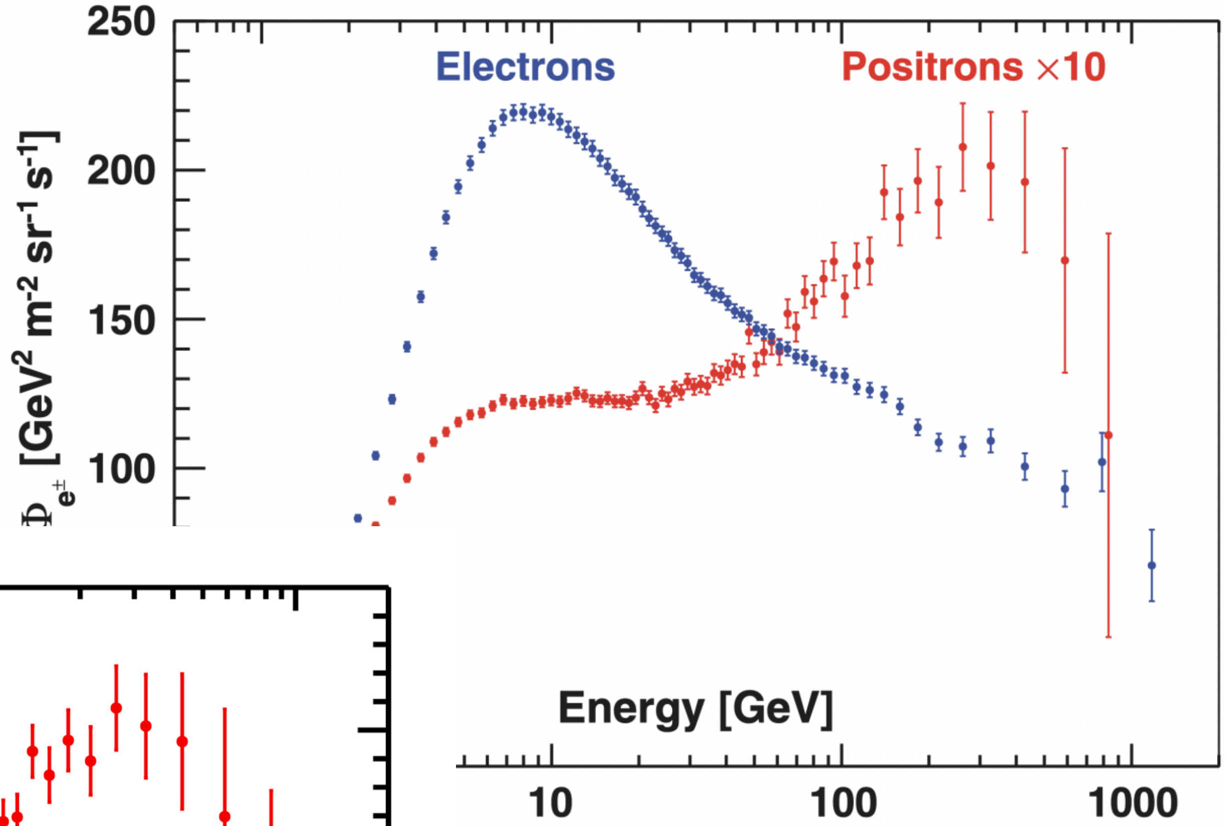
AMS-02 can differentiate between electrons and positrons, but CALET and DAMPE do not.

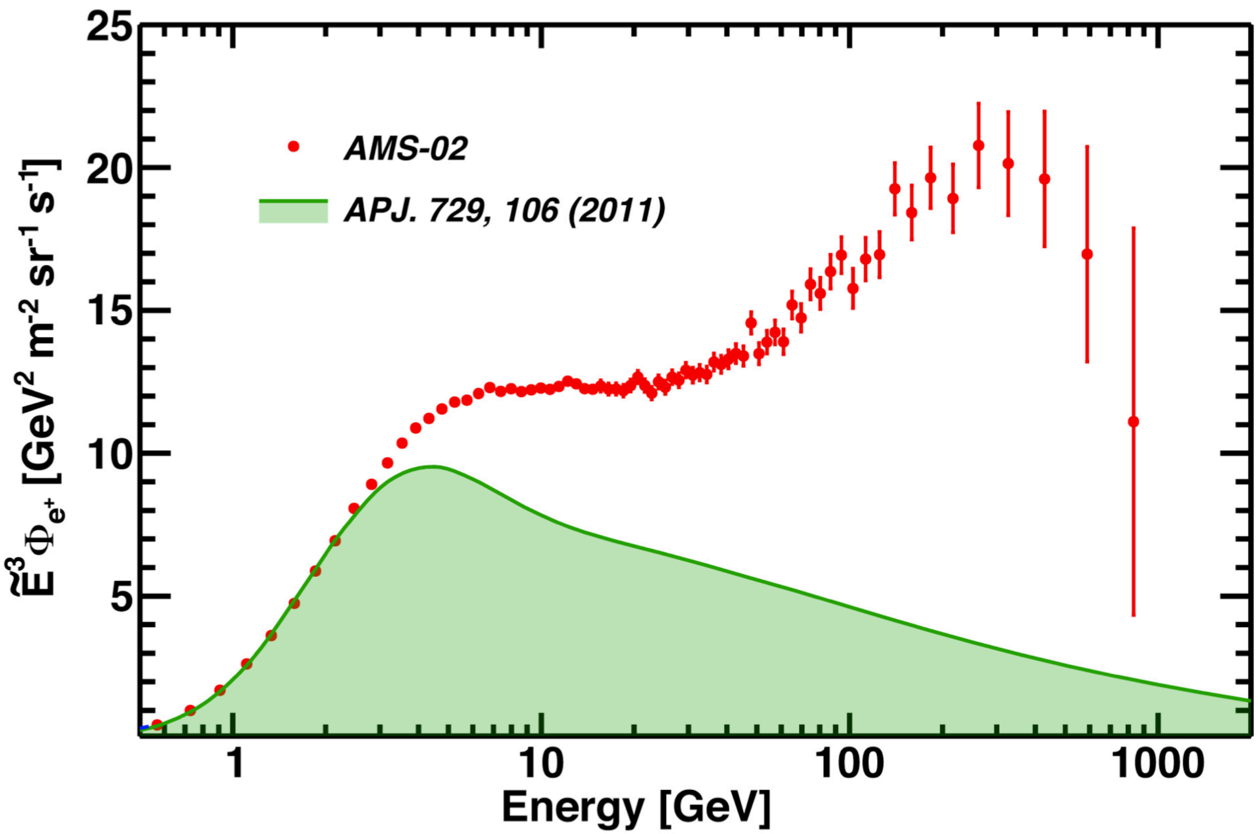


Significant excess starting from 25.2±1.8 GeV, with a sharp drop above 284^{+91}_{-64} GeV [Z. Weng, PoS 045, ICHEP2020 (2020)]. Antiproton flux has a similar behavior.

Latest Results on Electrons and Positrons from AMS

Rise on positron flux persists withtime [Z. Weng, PoS 045, ICHEP2020 (2020)].





Positron flux measured by AMS-02 [J. Bedugo, PoS 016, ICRC2021 (2021)] compared to GALPROP prediction for cosmic rays.

Supersymmetry

1.- R-Parity (Rp) Conserving:

a.- Dark Matter (DM) candidate: neutralino

b.- Superpotential:

$$W_{MSSM} = (\mu \hat{H}_u^a \hat{H}_d^b + h_{ij}^e \hat{H}_d^a \hat{H}_u^b + h_{ij}^d \hat{H}_d^a \hat{Q}_i^b \hat{D}_j - h_{ij}^u \hat{H}_u^a \hat{Q}_i^b \hat{U}_j)\varepsilon_{ab}$$

2.- R-Parity Violating:

a.- Dark Matter candidate: gravitino

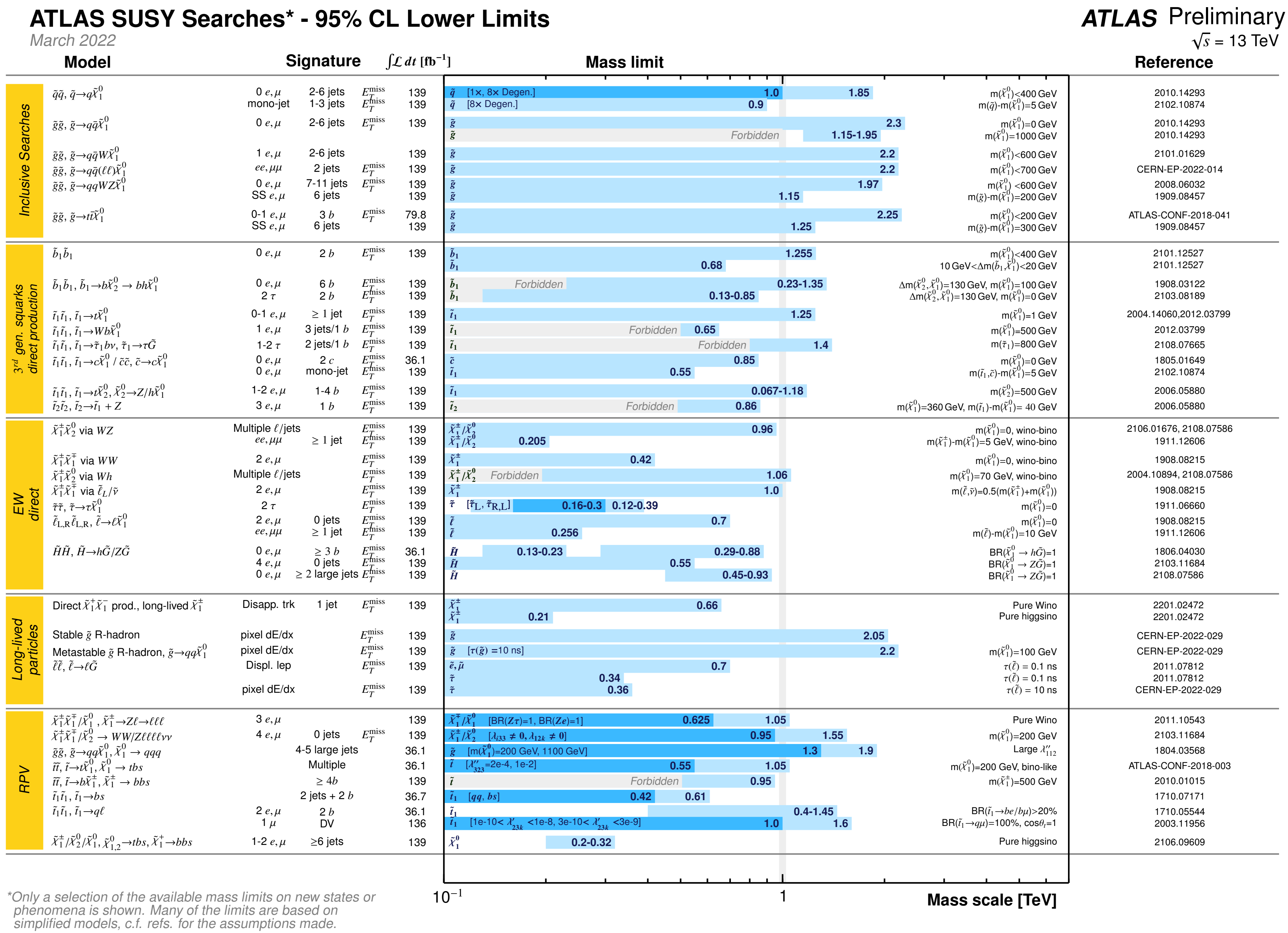
b.- Superpotential:

$$W_{MSSM+RpV} = W_{MSSM} + (\epsilon_i \hat{H}_u^a \hat{L}_i^b + \frac{1}{2}\lambda_{ijk} \hat{L}_i^a \hat{L}_j^b \hat{R}_k + \lambda'_{ijk} \hat{L}_i^a \hat{Q}_j^b \hat{D}_k)\varepsilon_{ab} + \frac{1}{2}\lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}_k$$

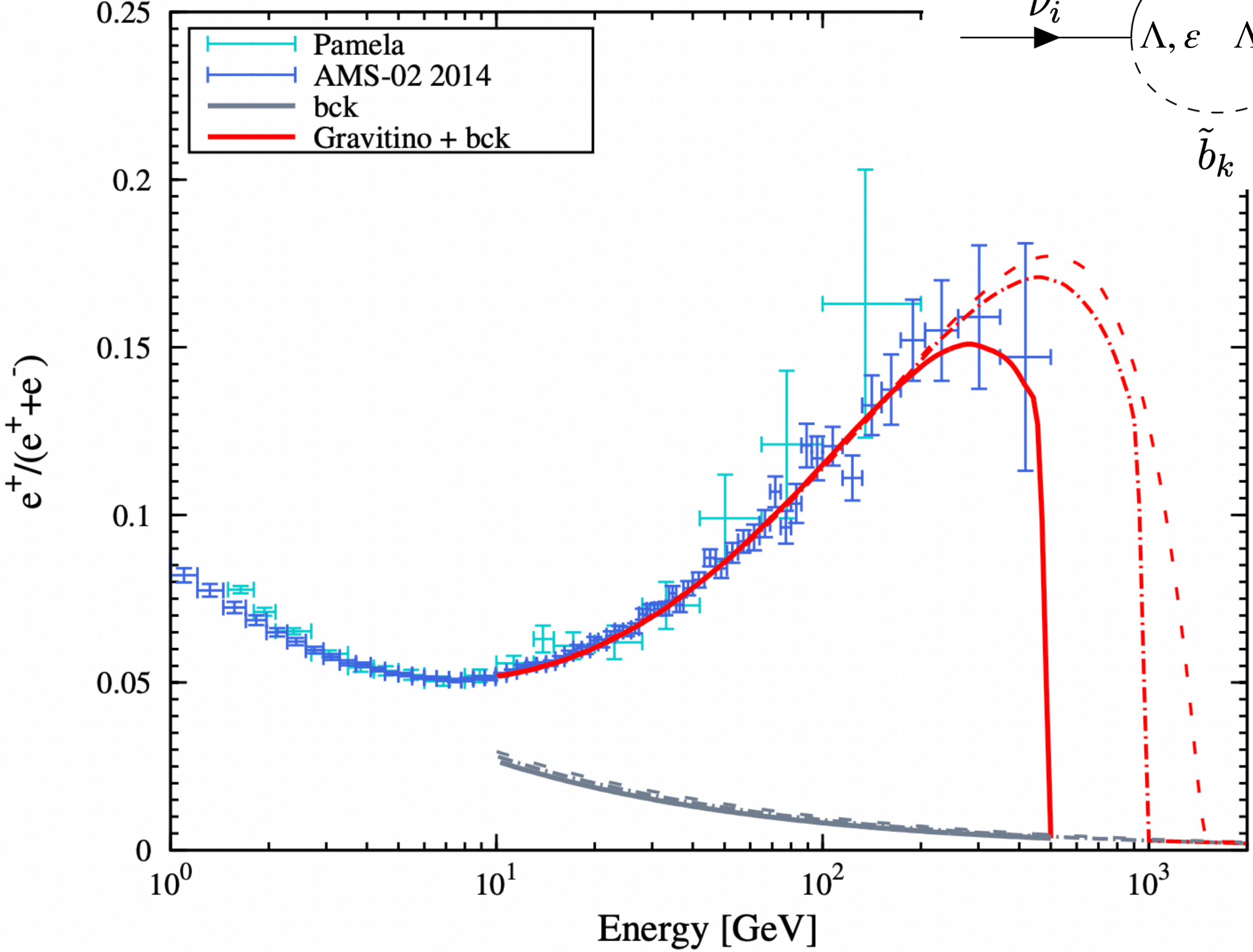
3.- The gravitino interaction is governed by:

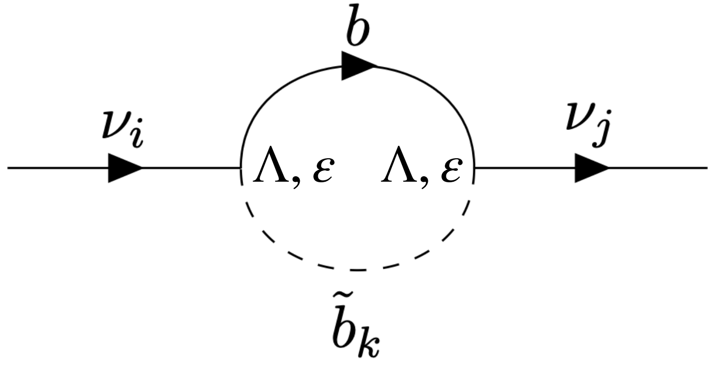
$$\mathscr{L} = -\frac{1}{\sqrt{2}M_P}\overline{F}\gamma^\mu \gamma^\nu \partial_\nu \tilde{F}\tilde{G}_\mu$$

Latest Results for ATLAS Susy Searches



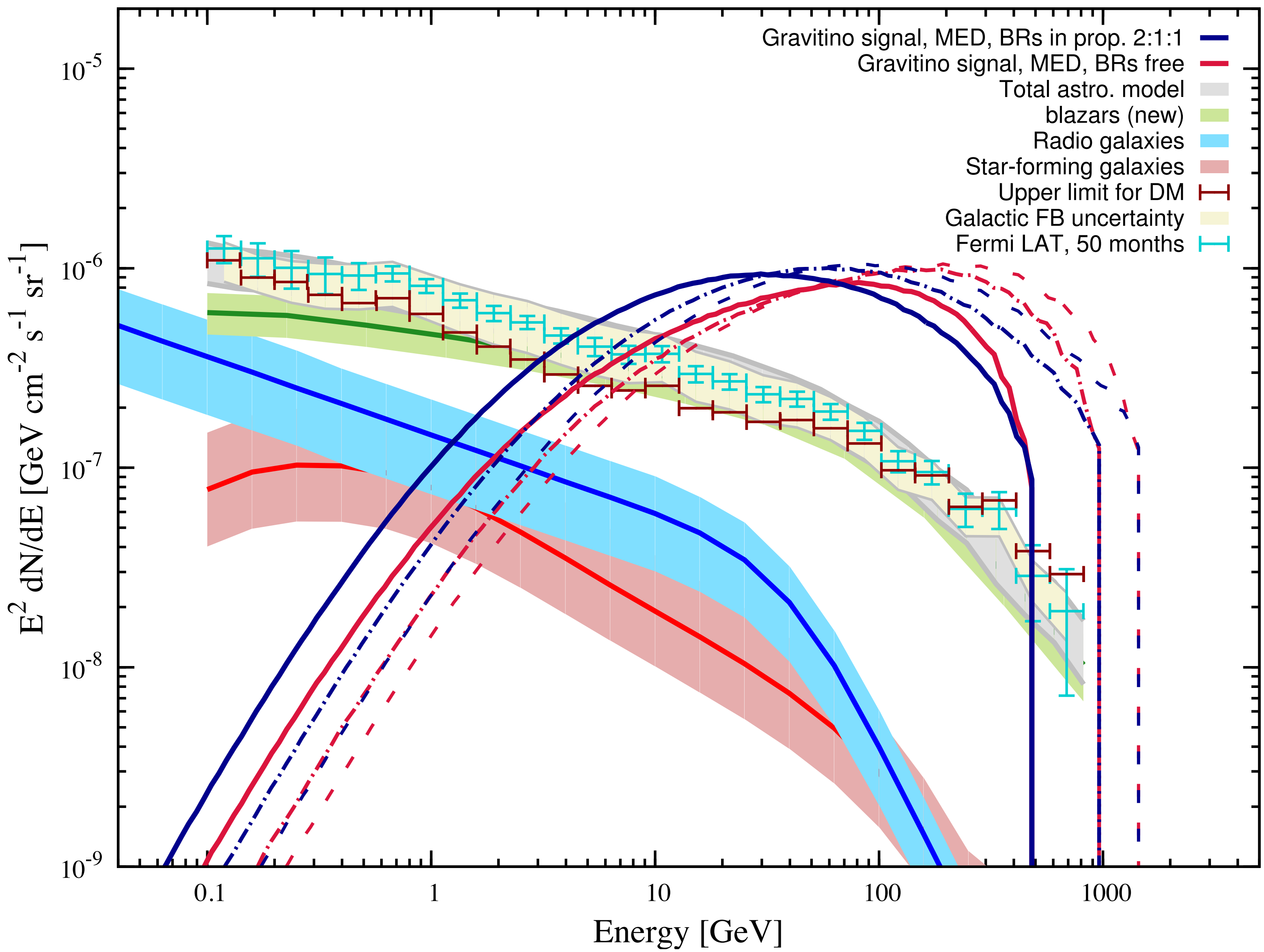
BRpV Only



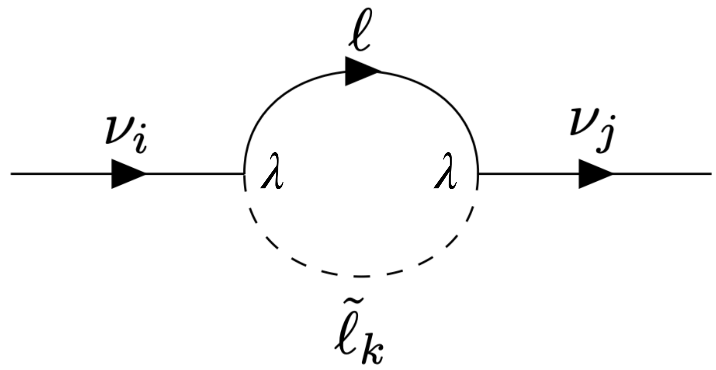


Based on *Phys. Dark Univ.* **11**, 1 (2016), in collaboration with E. Carquin, G. Gómez-Vargas, B. Panes, and N. Viaux.

Explains the rise and drop of the positrons flux, but emits too many photons. That is, the galaxy would be too bright.



TRpV Only



$$\Phi_{e^-} = C_e \left(\frac{E}{1\,\mathrm{GeV}} \right)^{-\gamma_e}$$

$$\Phi_{e^+} = C_p \left(\frac{E}{1\,\mathrm{GeV}} \right)^{-\gamma_p}$$

$$\alpha_1 = B(\tilde{G} \to e^- e^+ \nu) + B(\tilde{G} \to e^- \mu^+ \nu) + B(\tilde{G} \to e^- \tau^+ \nu)$$

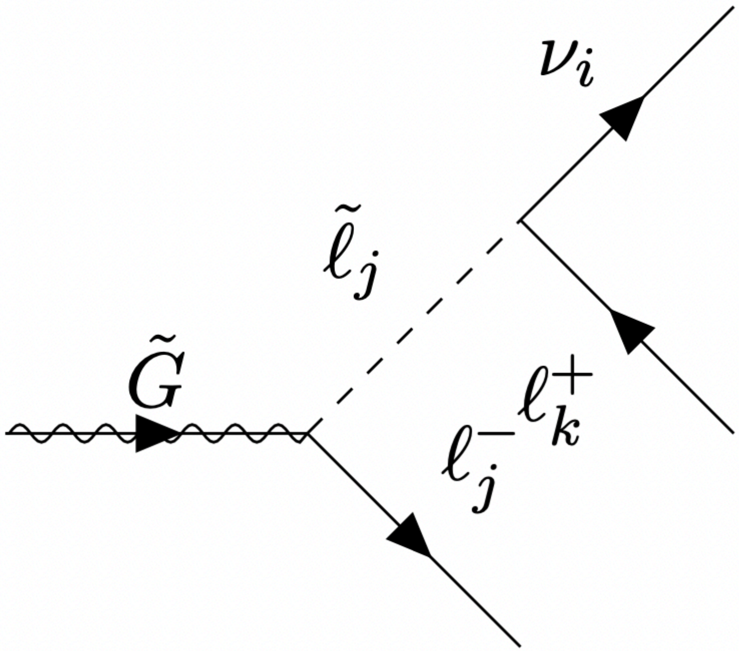
$$\alpha_2 = B(\tilde{G} \to \mu^- e^+ \nu) + B(\tilde{G} \to \mu^- \mu^+ \nu) + B(\tilde{G} \to \mu^- \tau^+ \nu)$$

$$\alpha_3 = B(\tilde{G} \to \tau^- e^+ \nu) + B(\tilde{G} \to \tau^- \mu^+ \nu) + B(\tilde{G} \to \tau^- \tau^+ \nu)$$

Parameter	Case 1	Case 2	Case 3	Case 4
C_p [1/GeV cm^2 s str]	14.90	14.74	14.93	14.37
γ_p	3.11	3.10	3.11	3.09
C_e [1/GeV cm^2 s str]	426.10	421.77	422.08	422.67
γ_e	3.27	3.27	3.27	3.27
m_G [GeV]	1281	2274	3604	3751
τ_G [10^{26} s]	4.61	3.59	2.27	2.29
$\alpha_1 : e^- l^+ \nu$	0.43	0.06	0.03	0.32
$\alpha_2 : \mu^- l^+ \nu$	0.03	0.36	0.15	0
$\alpha_3 : \tau^- l^+ \nu$	0.54	0.58	0.82	0.68

Based on *e-Print 2011.09344*, in collaboration with J. Buchner, E. Carquin, G. Gómez-Vargas, B. Panes, and N. Viaux.

Gravitino decay



$$\tilde{m} \equiv m_{\tilde{\nu}_i} = m_{\tilde{\ell}_{i,1}} = m_{\tilde{\ell}_{i,2}}$$

$$\Gamma(\tilde{G} \to \nu_i e_j \bar{e}_k) \approx \frac{\lambda_{ijk}^2}{3\pi^3 2^{11}} \frac{m_{\tilde{G}}^7}{M_P^2 \tilde{m}^4}$$

$$\tau_{\tilde{G}} = 4 \times 10^{26}\,\mathrm{s} \left(\frac{1}{\lambda_{ijk}\lambda_{ijk}}\right)\left(\frac{\tilde{m}}{10^8\,\mathrm{GeV}}\right)^4 \left(\frac{2\,\mathrm{TeV}}{m_{\tilde{G}}}\right)^7$$

Neutrinos

$$M_{ij}^{\nu(1)} \approx \frac{1}{16\pi^2} \sum_{gr} s_{\tilde{\ell}} c_{\tilde{\ell}} (\lambda_{igr}\lambda_{jrg} + \lambda_{jgr}\lambda_{irg}) m_g \ln \frac{m^2_{\tilde{\ell}_{r,2}}}{m^2_{\tilde{\ell}_{r,1}}}$$

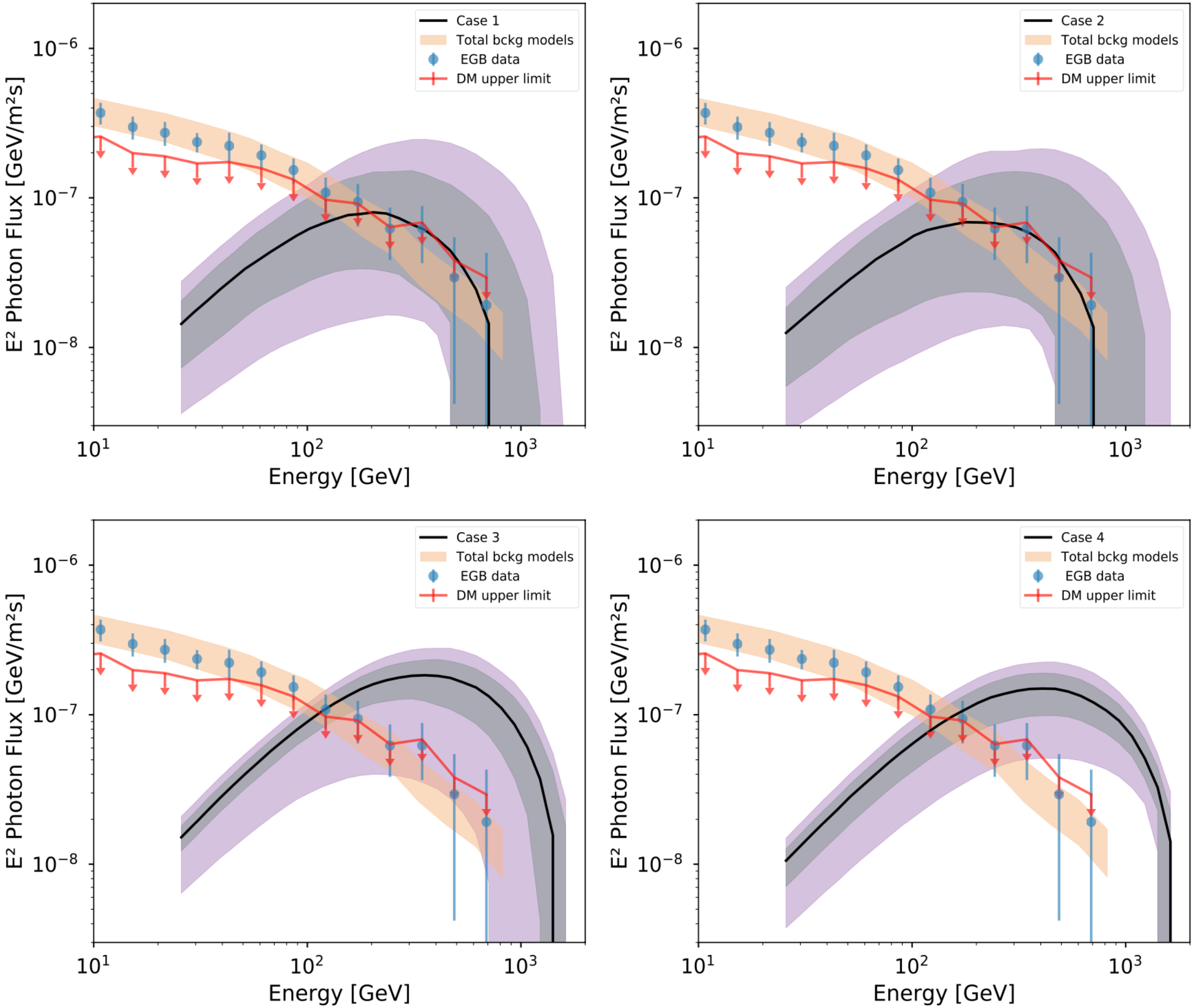
$$M_{ij}^{\nu(1)} \approx \frac{1}{8\pi^2} \lambda_{i23}\lambda_{j32} \frac{m_\mu m_\tau A_\tau}{\tilde{m}^2}$$

$$\approx 2 \times 10^{-2}\mathrm{eV}\, \lambda_{i23}\lambda_{j32} \left(\frac{10^8\,\mathrm{GeV}}{\tilde{m}}\right)$$

$$\approx 2 \times 10^{-2}\mathrm{eV}\, (\lambda_{i23}\lambda_{j32})^{3/4} \left(\frac{4 \times 10^{26}\mathrm{s}}{\tau_{\tilde{G}}}\right)^{1/4} \left(\frac{2\,\mathrm{TeV}}{m_{\tilde{G}}}\right)^{7/4}$$

Photon Flux

Pure TRpV can explain AMS-02



Another effect: DAMPE and CALET can measure all electron flux to higher energies.

There is tension be-tween this explanation and the photon flux when we add CALET and/or DAMPE.

Conclusions

1.- In the original Scotogenic model masses of dark matter can be smaller than 500 GeV, as noticed before (in contrast in the IHDM it cannot).

2.- In this model, charged and neutral new particles can be long lived.

3.- The positron fraction in cosmic rays rises with energy. A decaying Gravitino with mass of a few TeV can explain it. In this case, pure BRpV produce in too many photons.

4.- Pure TRpV produce less photons than pure BRpV, and can explain the rise of positron fraction measured by AMS-02. But there is tension between the measurement of different satellites. In addition, neutrino masses and mixing angles should be evaluated.

5.- Cosmic rays provide complementary information, thus satellites are an important tool. Particles can reach higher energies, although we loose control.

6.- To establish a model beyond the SM we should use a combination of results from different experiments: neutrino, colliders, and satellites.

7.- Any possible discrepancy between measurements coming from different satellites might be important and should be resolved.