3-dimensional modeling of Cosmic Rays electron and positron propagation in the Galaxy with DRAGON

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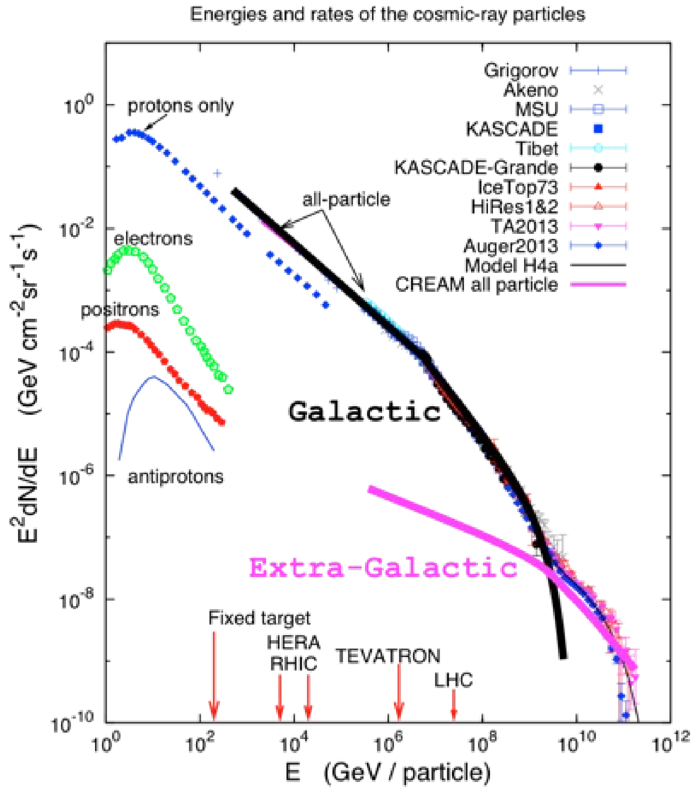
1.Introduction

- ***Cosmic rays**: a flux of massive particles, coming from space and striking the Earth*
- *Origin: Sun, Galactic source, extragalactic ones*
- *They are constituted mainly by protons, with traces of heavy nuclei and relativistic electron and positrons*
- *The spectrum can be fitted by a **power law**:*

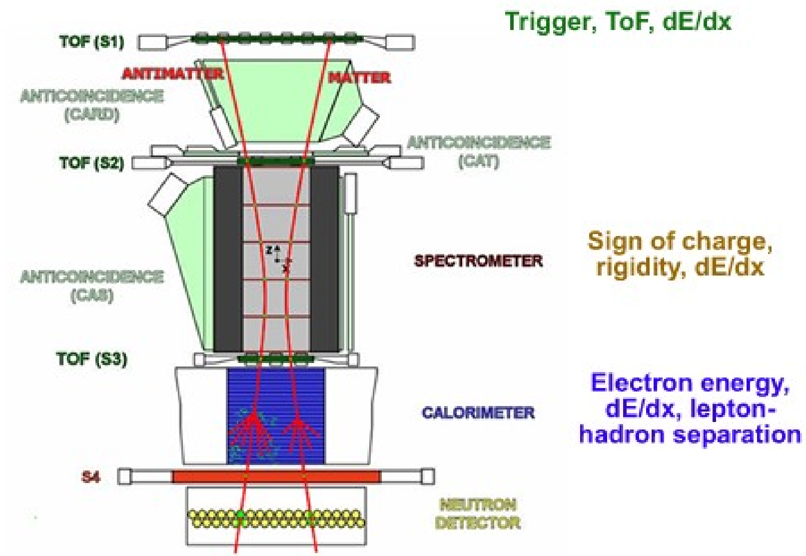
$$N(E) \sim E^{\alpha}$$

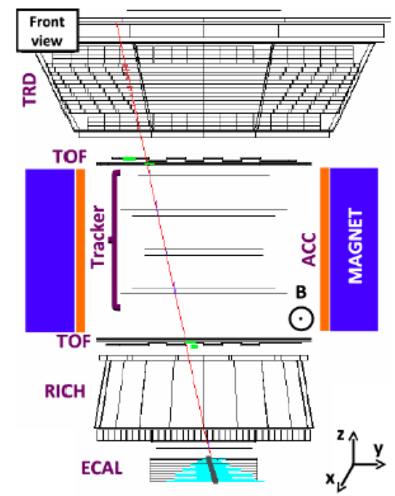
where $\alpha \sim -2.7$

- *They can reach extremely high energies!*



1.1 PAMELA and AMS-02 space observatories





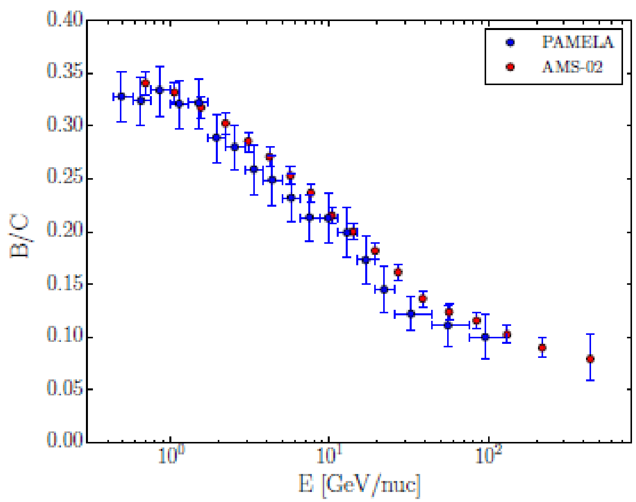
PAMELA

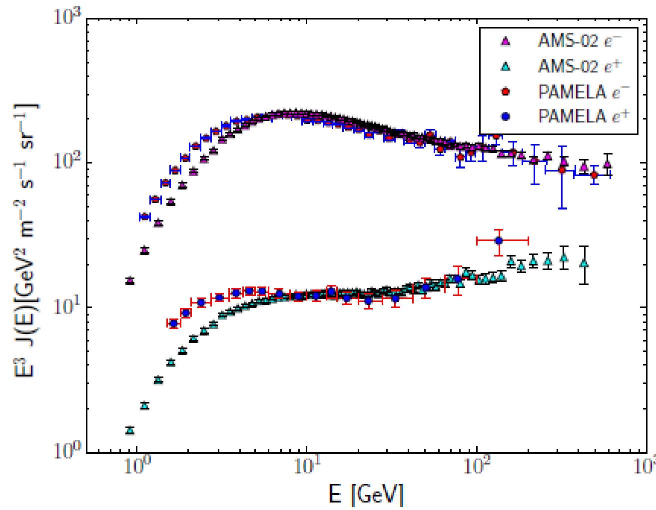
- *Launched in 2006*
- *Magnetic spectrometer → it can distinguish between e⁻ and e⁺*

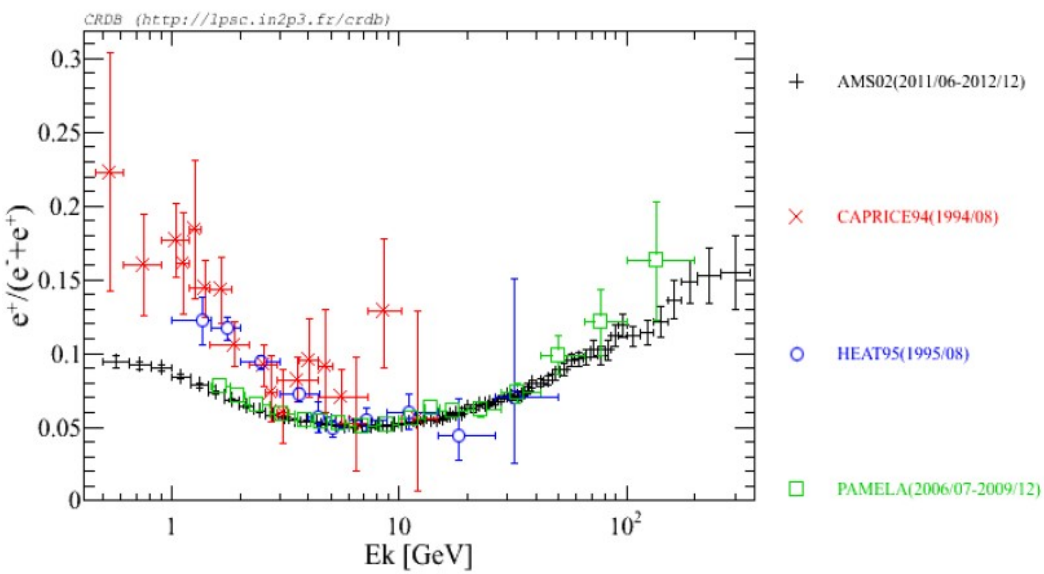
AMS-02

- *Launched in 2011*
- *It can distinguish between e⁻ and e⁺*
- *Monte Carlo simulations → very good efficiency in particle identification!*

1.2 Latest Results on CR







We expected the positron fraction to be a quantity decreasing in energy. But…

← *the* ***"Positron anomaly":*** *a monotonic increase in positron fraction from 10 to 100 GeV*

1.3 The Positron Anomaly: an interpretation

- *Hypothesis: positrons are pure secondaries, i.e. produced in particle reaction between CR nuclei and ISM,*

$$p_{CR}+p_{ISM} \rightarrow p + n\ (p) + a\pi \text{ and then}$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + e^{\pm}$$

we then should have for the spectral indices: proton index + diffusion + energy losses

$$\rightarrow\ \gamma_{e+} \sim \gamma_p + \delta/2 + 0.5$$

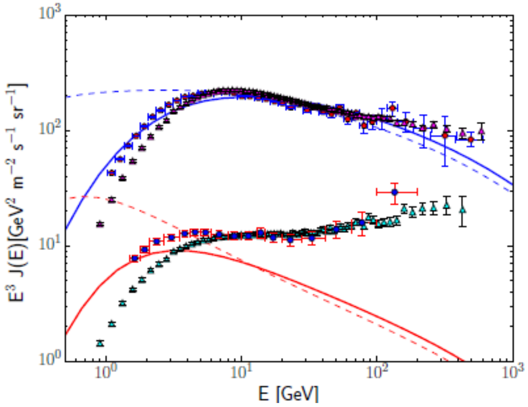
but observation gives us $\gamma_{e+} \sim 2.8$ *and* $\gamma_p \sim 2.7 - 2.8$

- ***Need of an e+ extra component*** $N(e^+) \rightarrow$ $\mathbf{N(e^+) \sim E^{-\gamma_{extra}}\, e^{-E/E_{extra}}}$

Where γ_{extra}~1.5 *and* $E_{extra} \sim$ 1TeV – 10 TeV

So the spectrum of our positron component becomes

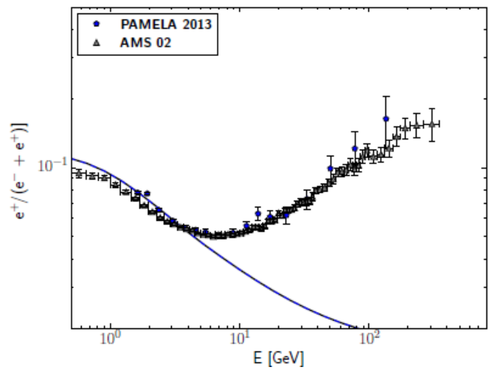
$$N(e^+) = N(e^+)_{secondary\ prod} * N(e^+)_{extra}$$



Astrophysical or DM sources

without extra component positrons are NOT reproduced; electrons are reproduced only with unphysical parameters

charge symmetric extra component



2. The transport equation

Once produced, CRs undergo diffusive propagation. The interaction with turbulent galactic plasma also yields diffusion in momentum space, and the interaction with interstellar gas, magnetic fields, etc, causes energy losses. The combination of all these processes, can be described by:

$$\nabla \cdot (\vec{J} - \vec{v}_w N) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N\right] = Q - \frac{N}{\tau_r}$$

Where $Q = Q(r,p)$ is the source distribution, v_w is the Galactic wind velocity (advection), $\dot{p}$ accounts for energy losses and τ_r is the radioactive exponential decay constant.

The CRs macroscopic current $\vec{J}(\vec{r}, p)$ is related to the spatial diffusion tensor D_{ij} as $J_{ij} = - D_{ij} \nabla_j N$

3. Numerical Codes

DRAGON* open code (Diffusion of cosmic* ***RA****ys in* ***G****alaxy modelizatio***N** *, www.dragonproject.org) for CRs propagation :*

1. *It can* ***solve the diffusion equation*** *that describe CRs propagation for different species*

2. *It can* ***operate in a 3D setup***

3. *A* ***generic electron and positron extra component*** *can be implemented*

4. *It can propagate CRs originated by* ***Dark Matter*** *sources.*

5. ***Different models*** *for gas distribution, galactic fields, ISRF, etc. are implemented in the code. The choice of model is up to the user*

3. Numerical Codes

- *DRAGON works with xml interface: a sample xml is provided with the code, containing reference to all the models among which the user can choose. A typical line of the xml in which the user can specify the model he desire to use is the following:*

```
<MagneticField type="Pshirkov"> <!-- Model for the magnetic field. Options: Pshirkov, Farrar, Uniform, Toymodel -->
   <B0disk value="2.e-06" /> <!-- Useful for Pshirkov field: halo regular field normalization in Gauss -->
   <B0halo value="4.e-06" /> <!-- Useful for Pshirkov field: turbulent regular field normalization in Gauss -->
   <B0turb value="12.e-06" />
</MagneticField>
```

- *For this work, DRAGON operated on 64 CPU of the parallel cluster "Zefiro" of INFN section in Pisa*

- *Each 3D run lasted between 4 and 20 hours, depending on propagation parameters (in particular Galaxy dimensions and number of species propagated)*

4. *Propagation Models*

- *An important propagation parameter in DRAGON is the* ***Diffusion coefficient***

$$D \sim D_0 R^{\delta}$$

where R is the particle rigidity and δ is the diffusion coefficient index.

- *We identify three propagation models corresponding to astrophysically acceptable turbulence models. These models are characterized by different δ:*

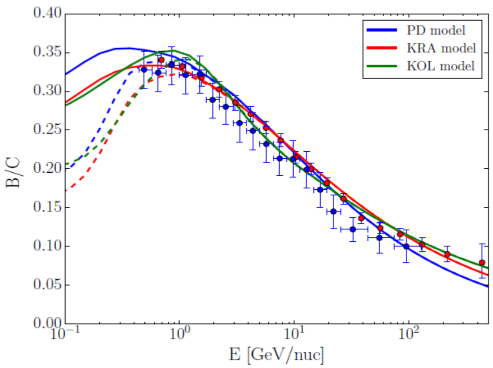
    1. ***KOL model***: $\delta = 0.33$

    2. ***KRA-like model***: $\delta \sim 0.5$

    3. ***PD model*** *(Plain Diffusion)*: $\delta = 0.6$

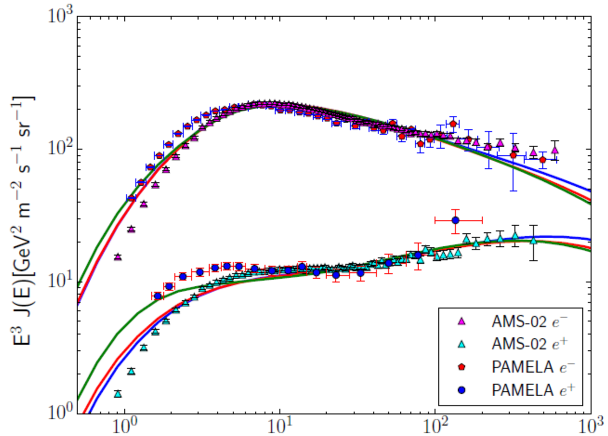
    All this models need to be tested against some experimental data set, to determinate their agreement with observations $\rightarrow$ ***Boron-to-Carbon ratio and leptonic spectra.***

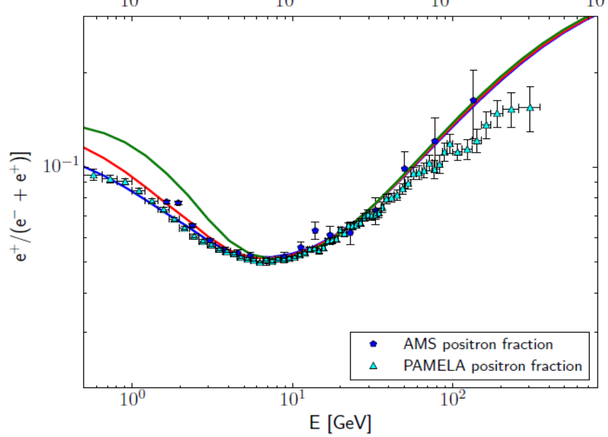
4.1 Testing Models against data



Model	δ	D_0 ($\times 10^{28} cm^2/s$)
KOL	0.33	4.7
KRA-like	0.42	3.2
PD	0.60	2.8

KOL model (green) PD model (blue) and KRA-like model (red).

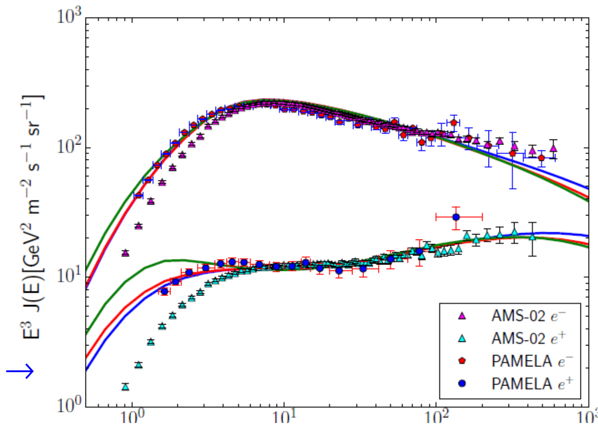


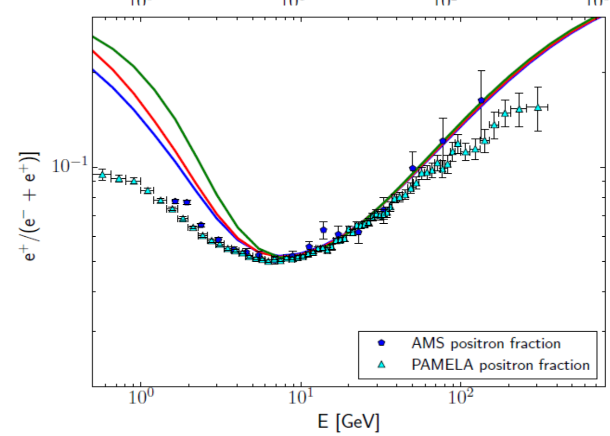


← AMS-02 and PAMELA →

relative modulations.

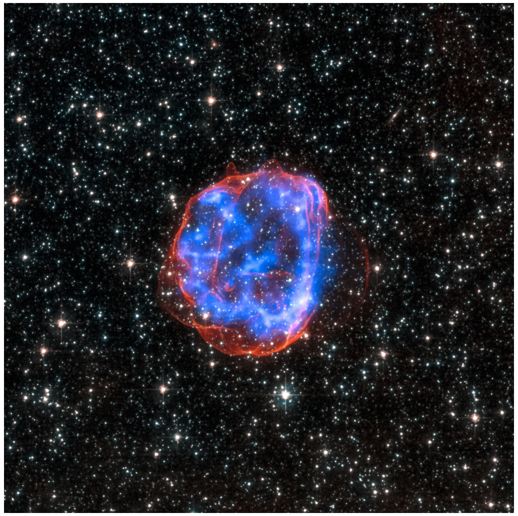
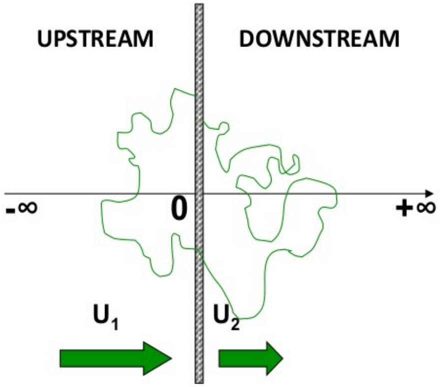
We choose KRA model





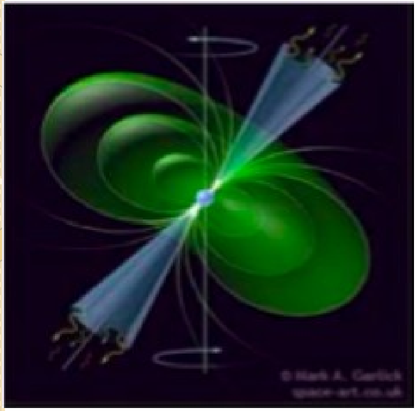
5. Sources candidates: SuperNova Remnants (SNRs)

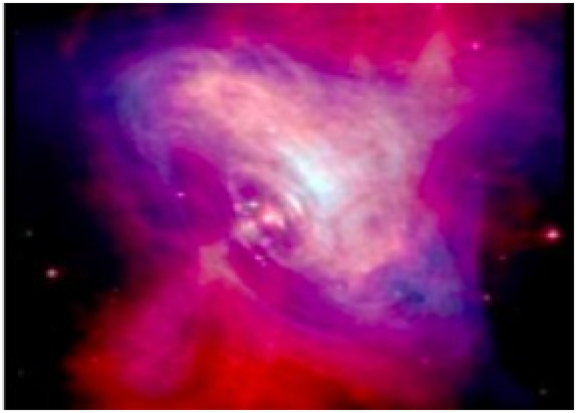
- *SNRs can be a suitable source of accelerated e^-: particles get accelerated through shocks.*

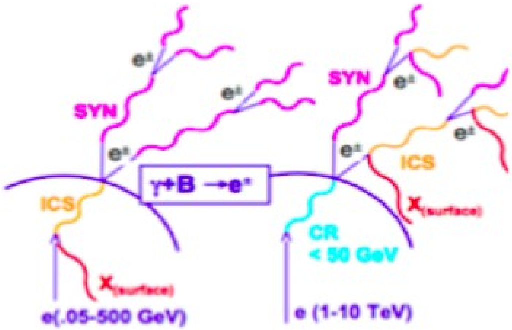



- *We would expect that SNRs do not accelerate e^+: (SNRs should be made of "conventional matter"). However, when the shocks interact with interstellar clouds secondaries can be produced and accelerated*

5.1 Source candidates: Pulsars







1. *Rotational energy + strong B field*

2. *Induced E field → electron extraction*

3. *Pair production in the strong magnetic field*

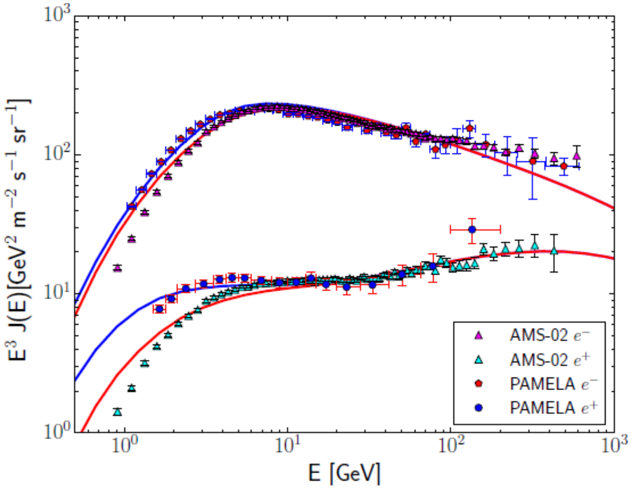
4. *Particles generated in these processes remain in the pulsar nebula until the pulsar sweeps them away*

Pulsars can be sources for electron-positron pairs

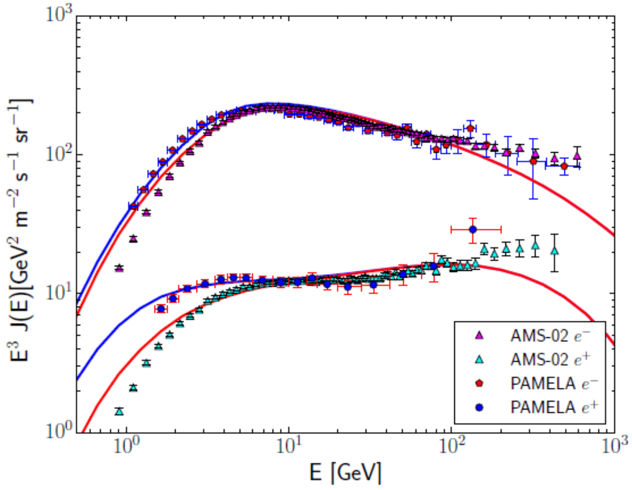
6. Nearby Sources

- *Remind now that we had for the extra component:* $N(e^+) \propto E^{-\gamma_{extra}} e^{-\frac{E}{E_{extra}}}$

  with two different scenarios for the cutoff energy: $E_{extra} = 10$ *TeV and* $E_{extra} = 1$ *TeV*



$E_{extra} = 10$ *TeV*



$E_{extra} = 1$ *TeV*

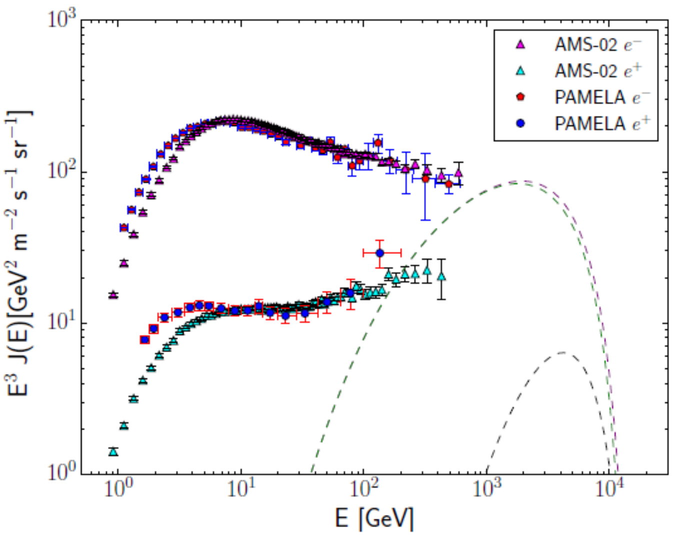
- ***E_{extra} = 10 TeV:*** *positrons are reproduced, need of an electron contribution →* ***Nearby SNRs***

- ***E_{extra} = 1 TeV:*** *both positrons and electrons need a contribution from nearby sources →* ***Nearby SNRs and Pulsars***

6.1 High Energy Cutoff: Nearby SNRs

Contribution from SNRs nearer than 1Kpc:

Vela *(green),* ***Cygnus*** *Loop (black)*
and overall contribution (purple)



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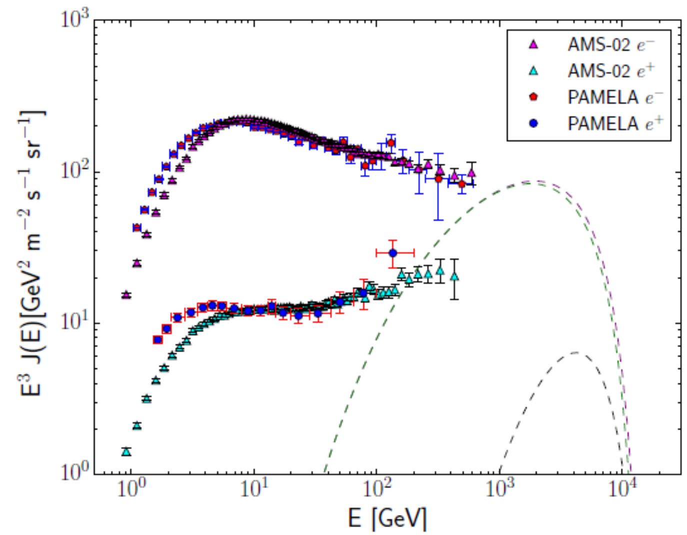
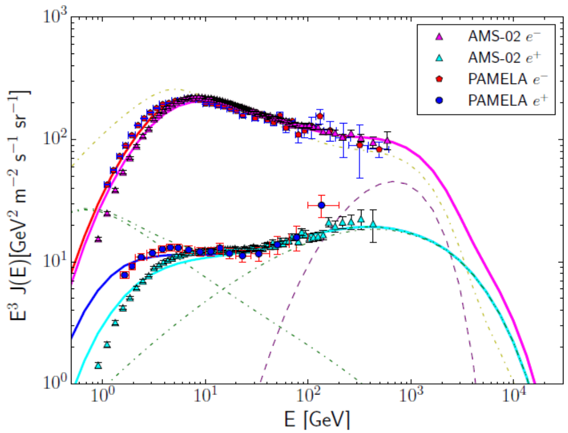
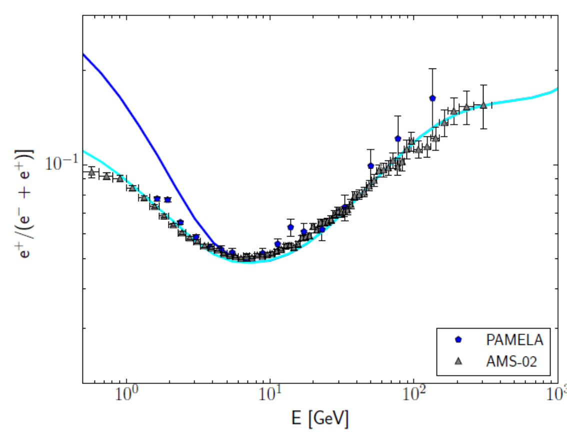
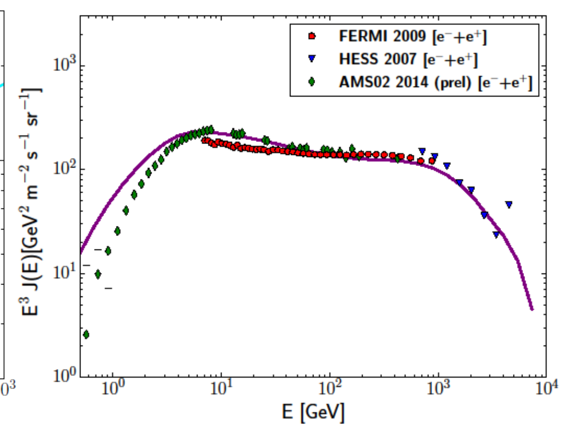




(a) Leptons spectra



(b) Positron Fraction



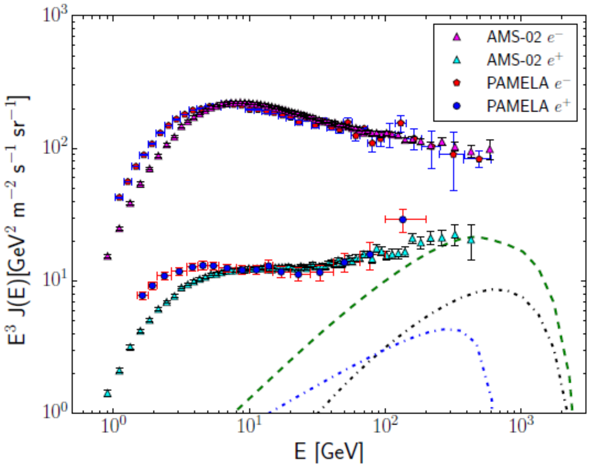
Data are very well reproduced!

6.2 Low Energy Cutoff: All Nearby Sources

- *Need of nearby SNRs + Pulsar in order to reproduce data*

- *Contribution from Pulsar nearer than 1Kpc:*

  ***Monogem** (black), **Geminga** (blue) and overall contribution (green)*



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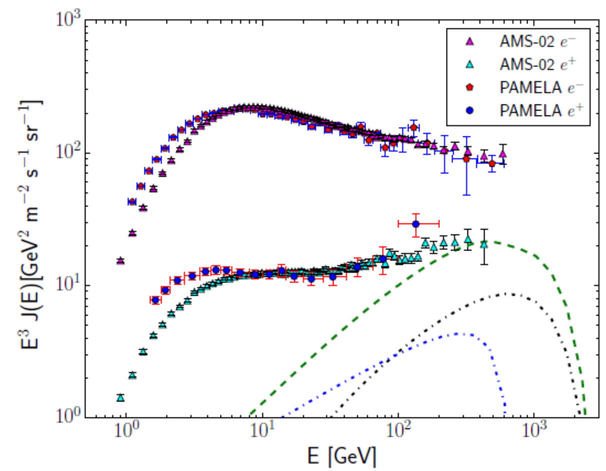
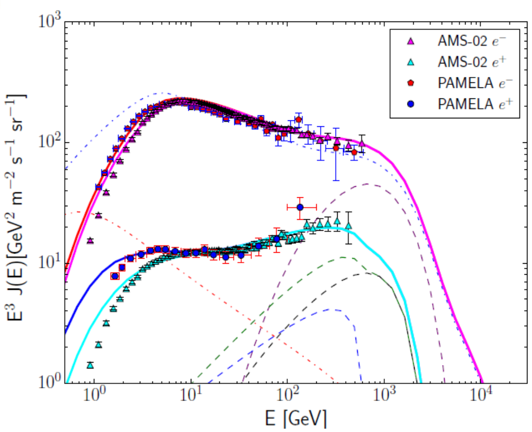
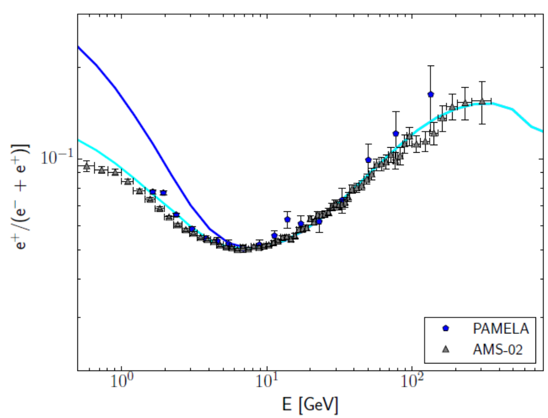
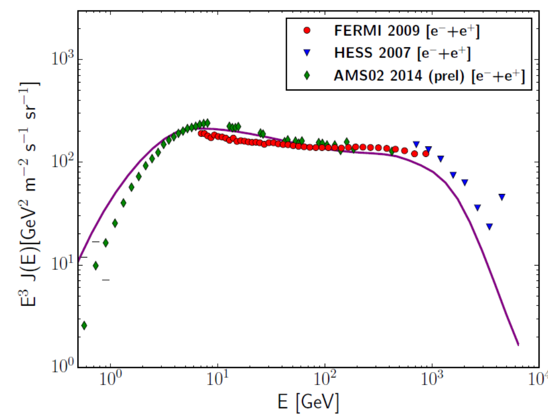




(a) Leptons spectra



(b) Positron Fraction



An astrophysical contribution seems to be enough to reproduce electron and positrons spectra

7. Dark Matter Scenario: DM annihilation

- *To reproduce leptonic data we need an* ***annihilation rate*** ***$\sigma v \sim 10^{-22}$-10^{-23} $cm^3\ s^{-1}$****, while cosmological considerations lead to $\sigma v \sim 10^{-26}\ cm^3\ s^{-1} \rightarrow$ need for an enhancement mechanism*

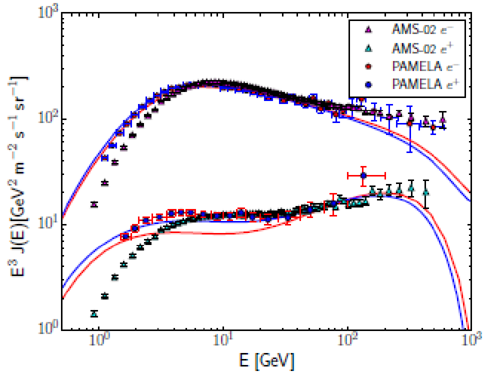
- *We chose two annihilation channels:* ***$VV \rightarrow 4\mu$*** *(annihilation products: 4 muons) and* ***$VV \rightarrow 4\tau$*** *(annihilation products: 4 tauons), where V is a light, hypothetical new pseudoscalar which does not decays into hadrons.*

- *Secondaries production cross sections: Kamae and GalProp*

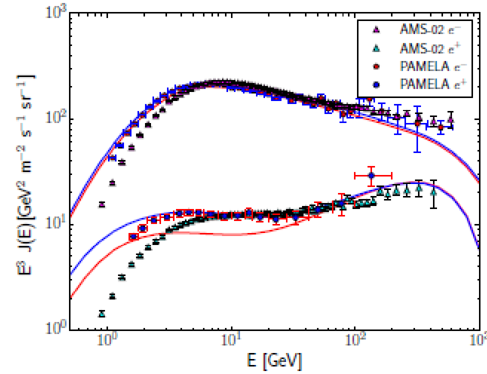
- *Four different DM masses: 1, 1.5, 2, 2.5 TeV*

7.2 4μ Channel

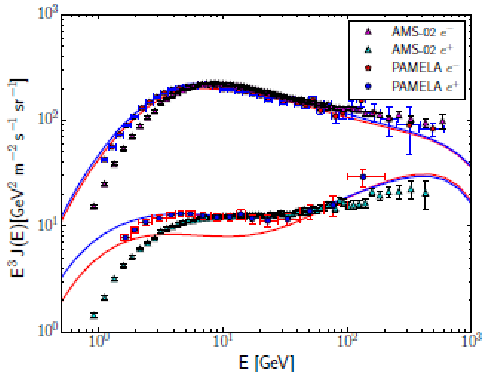
- ***Muons*** *mostly decay in* $e^{\pm} + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$ *hence produce electrons (positrons)*



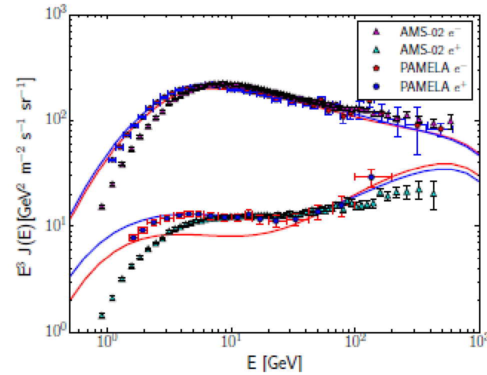
(a) M_{DM} = 1.0 TeV



(b) M_{DM} = 1.5 TeV



(c) M_{DM} = 2.0 TeV



(d) M_{DM} = 2.5 TeV

DM mass (TeV)	σv $(cm^3 sec^{-1})$
1.0	1.00×10^{-23}
1.5	2.00×10^{-23}
2.0	3.30×10^{-23}
2.5	5.50×10^{-22}

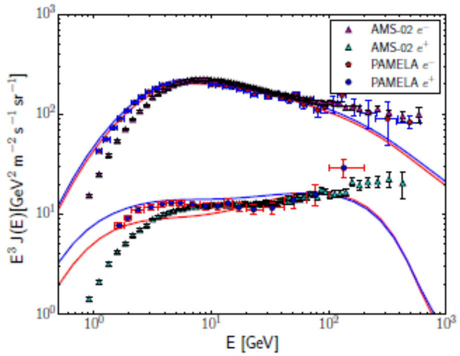
GalProp

DM mass (TeV)	σv $(cm^3 sec^{-1})$
1.0	1.00×10^{-23}
1.5	2.00×10^{-23}
2.0	3.50×10^{-23}
2.5	6.00×10^{-23}

Kamae

7.3 4τ Channel

- ***Tauons*** *can decay in μ or in $\pi \to \mu$, hence they too produce electrons (positrons).*



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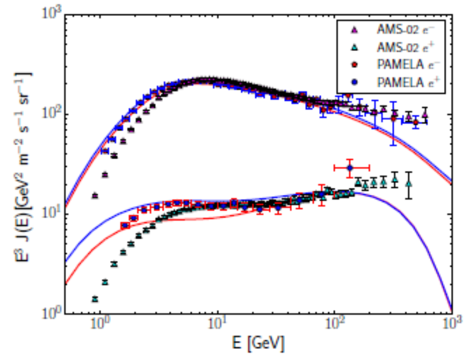

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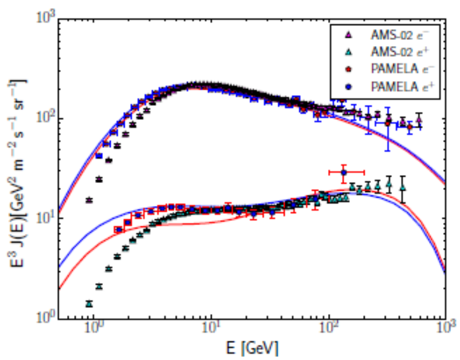

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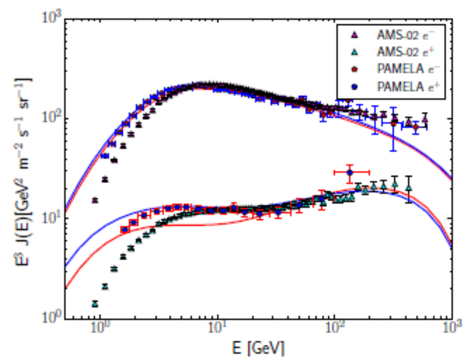

(d) M_{DM} = 2.5 TeV

DM mass (TeV)	σv $(cm^3 sec^{-1})$
1.0	2.00×10^{-23}
1.5	3.00×10^{-23}
2.0	5.50×10^{-23}
2.5	7.50×10^{-23}

GalProp

DM mass (TeV)	σv $(cm^3 sec^{-1})$
1.0	2.00×10^{-23}
1.5	3.00×10^{-23}
2.0	6.00×10^{-23}
2.5	7.00×10^{-23}

Kamae

8. The New DRAGON project

- *Started in early 2015, with the aim of producing a lighter, more accurate version of the code*
- *We surveyed the most endorsed models for gas distribution, galactic fields, etc. and implemented them anew in the code*
- *We implemented second order discretization for energy losses: this should allow us to model these process with more accuracy*
- *Testing in progress: we isolated the solver of the code and produced a stand-alone simplified version of DRAGON, called DRAGONCELLO, with which we are testing convergence and accuracy of our solutions.*
- *Paper in preparation:* "Cosmic-ray propagation in the Galaxy with the DRAGON code: I. Primary nuclei and leptons", *C. Evoli, D. Gaggero, G. Di Bernardo, M. Di Mauro, D. Grasso, A. Ligorini, A.Vittino*
- *DRAGON manual, which will explain in deep detail the processes and models implemented in DRAGON, soon to be uploaded on the website www.dragonproject.org*

9. Summary

- *The high energy part of e^+ and e^- spectra and positron fraction can be reproduced only assuming the presence of an* ***extra component****. We looked for a* ***source*** *for this extra component*

- *We introduced an extra component generated by* ***astrophysical*** *sources situated in the Galactic arms, with the contribution of nearby sources:*

A pure astrophysical scenario is able to reproduce data under natural assumption

- ***DM scenario****: → Different models for secondaries production cross section gives us fairly different description of leptons spectra.*

Peculiars models with high DM masses and very large annihilation σv can marginally reproduce experimental data: however, uncertainties still play a role.

- *Hopefully, in the upcoming years a better knowledge for the secondary production cross section will be achieved: this will allow to use positrons data to provide constraint on DM*

- *We will also hope that the new DRAGON code will soon allow us to test again these scenarios*

Thanks