VIRGINIA TECH™

Cosmic Rays vs Dark Matter

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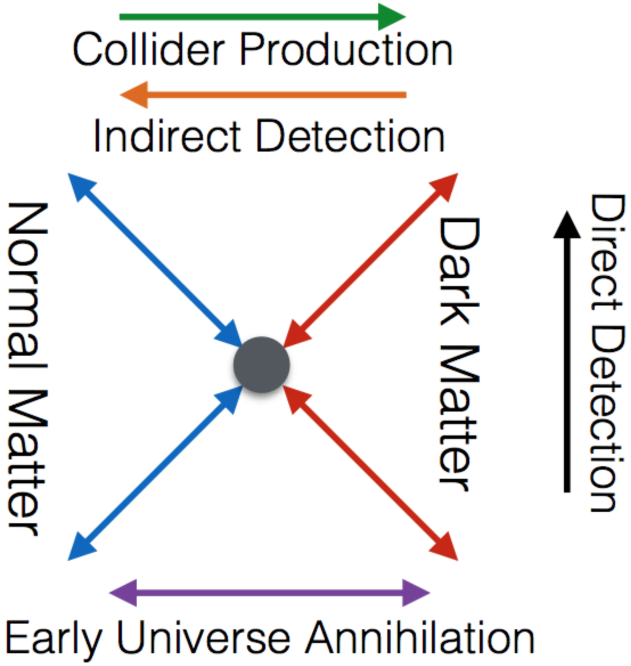
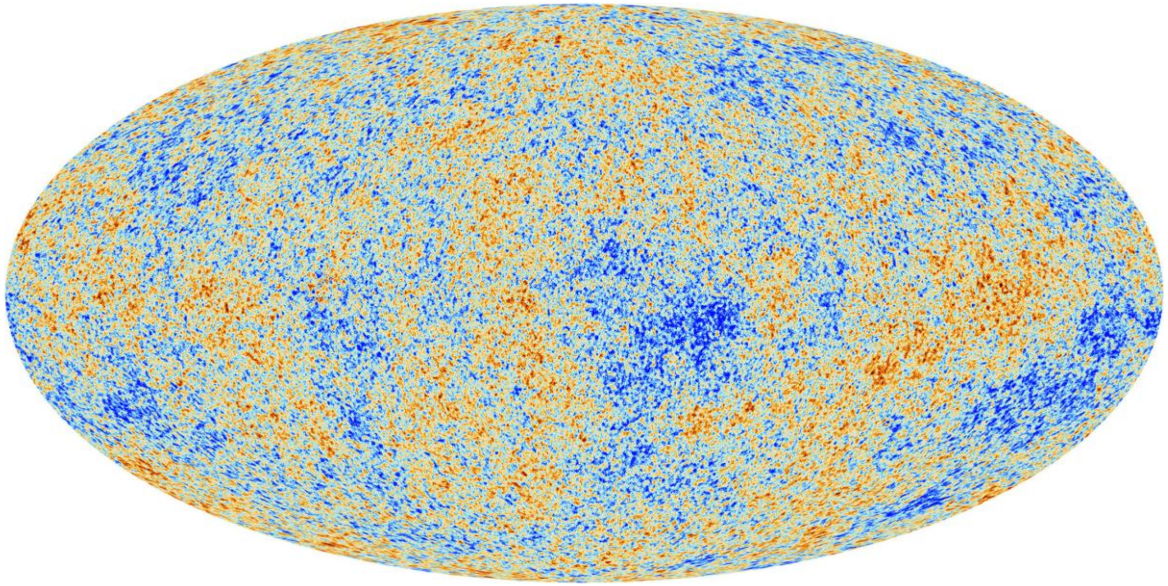
Outline

- How do Cosmic Ray- Dark Matter interactions affect the Cosmic Ray spectrum?
- Can a simple gain loss model for Cosmic Rays test Dark Matter effects?
- Do we need the full treatment of Cosmic Ray propagation- GALPROP?
- Do we need energy dependent cross sections?

Dark Matter

- Most of the matter in the Universe is dark and only interacts weakly with baryonic matter.
- Precision Cosmology requires structure formation to be driven by dark matter. Thermal relic calculation ensured the correct relic density can be achieved by a weak scale interaction with normal matter. This motivated direct detection experiments.

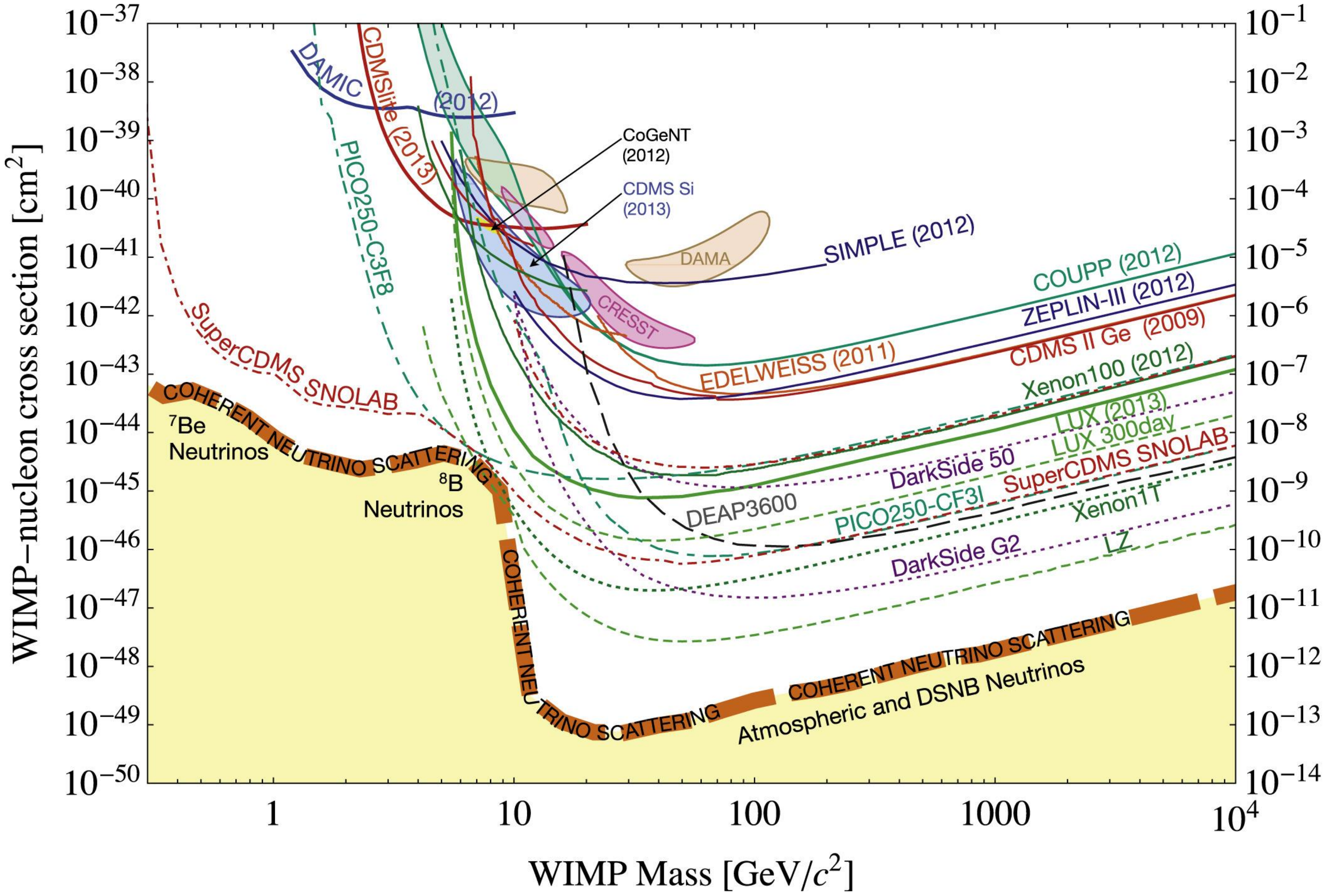




Planck Collaboration, “Planck 2018 results. I. Overview and the cosmological legacy of Planck”, Astronomy and Astrophysics, vol. 641, 2020. doi:10.1051/0004-6361/201833880.

Direct Detection

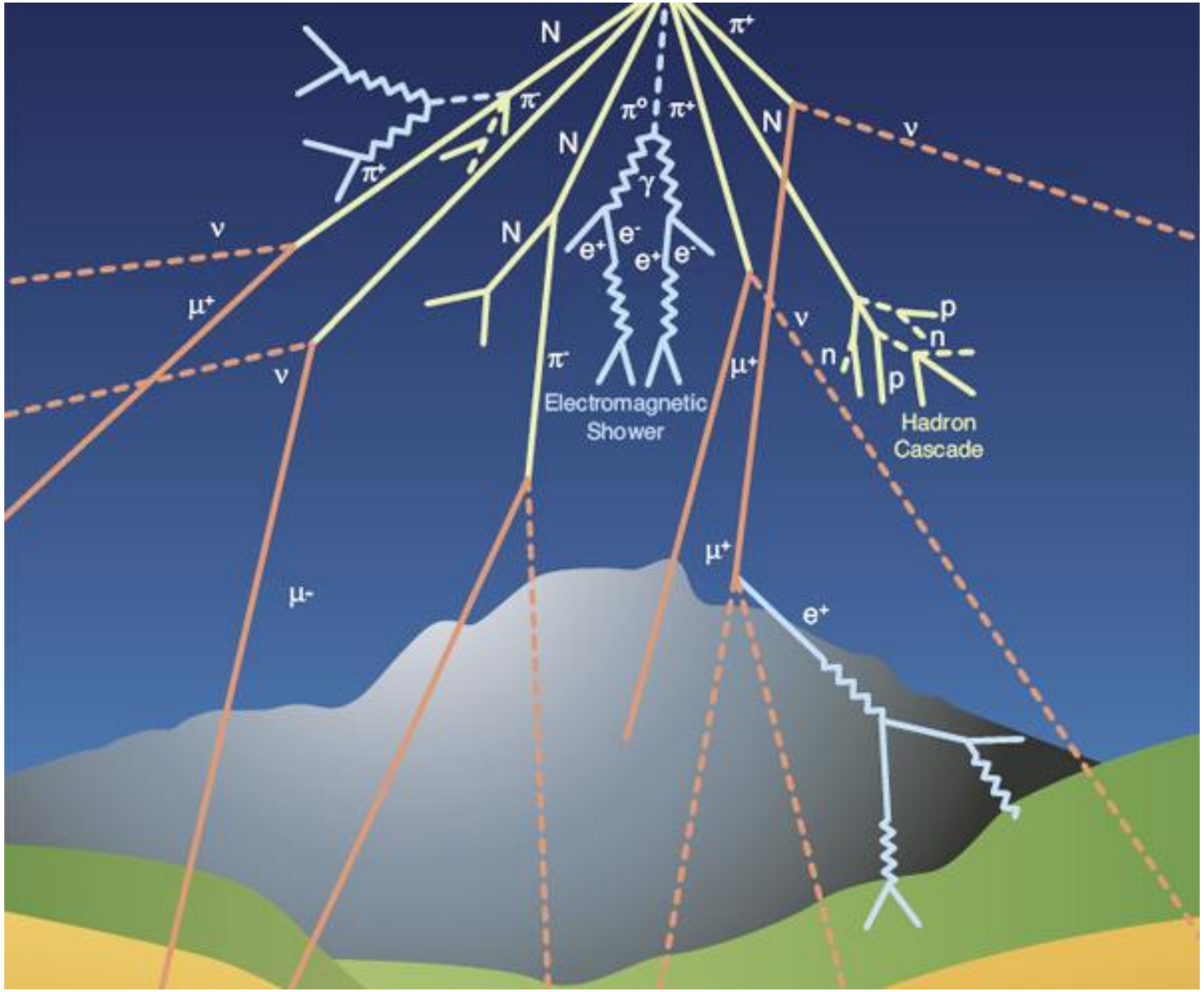
- Direct detection experiments on earth have strongly constrained heavy(GeV) mass dark matter(DM).
- Low mass(<GeV) dark matter(DM) does not have sufficient momentum to produce recoils on Xe and other heavy nuclei in the detectors.
- If there was some mechanism to speed up the low mass DM, then we may improve Direct Detection bounds for low mass DM.



Cooley, J. "Overview of non-liquid noble direct detection dark matter experiments" , Physics of the Dark Universe 2014 https://doi.org/10.1016/j.dark.2014.10.005

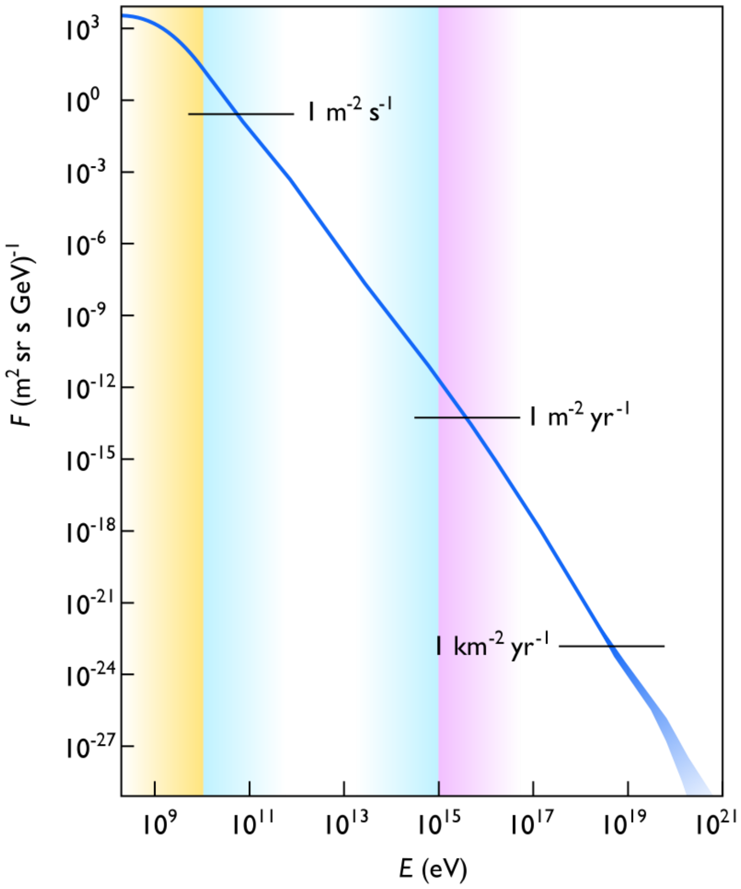
Cosmic Rays

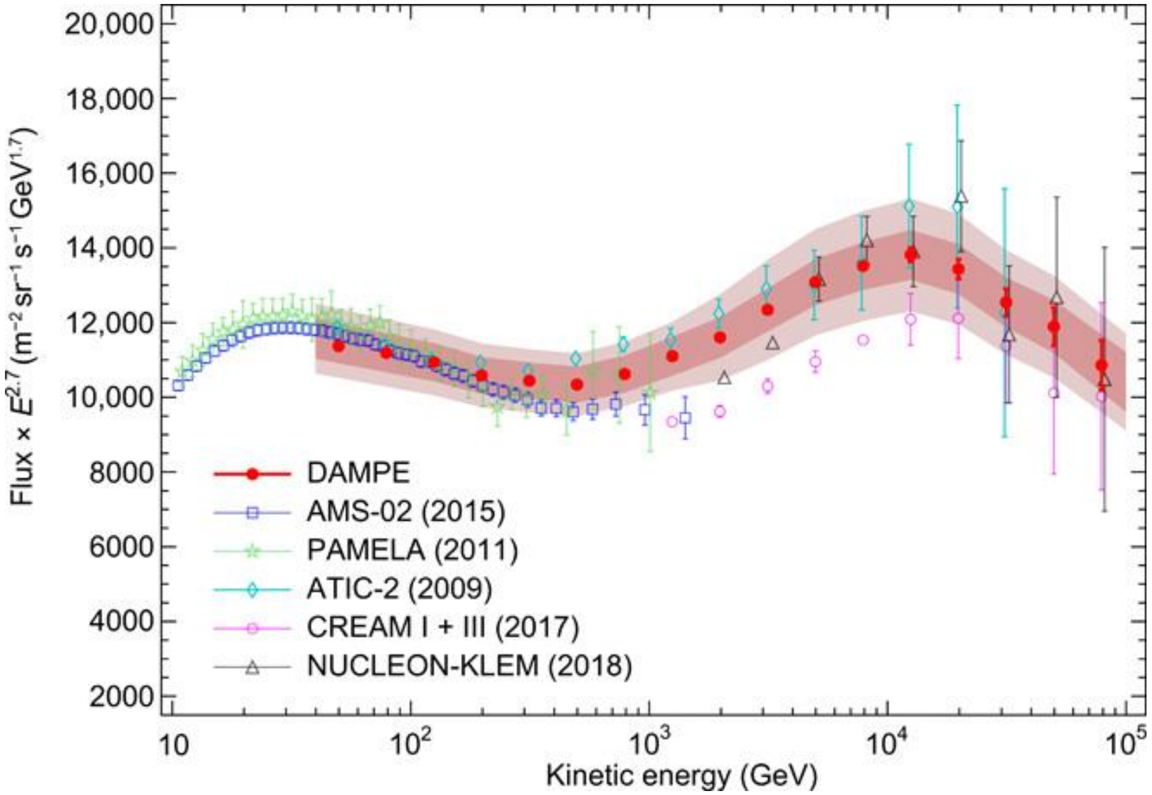
- Cosmic Rays(CR) are high energy charged particles(nuclei) which stream through a galaxy.
- If Dark Matter(DM) can scatter nuclei elastically, then it can also scatter cosmic rays.
- This should have an effect on the spectrum, and also potentially upscatter dark matter to be detected.
- Thus dark matter cosmic ray collision can be used to constrain low mass dark matter.



"Strong New Limits on Light Dark Matter from Neutrino Experiments" Cappiello C.~V., Beacom J.~F., 2019, PhRvD, 100, 103011. doi:10.1103/PhysRevD.100.103011

Cosmic Ray Proton Spectrum





Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite

Leaky Box

- Leaky Box equation assumes an equilibrium between production of Cosmic Rays(CRs) and loss of CRs escaping the galaxy.

$$\frac{N(E)}{T_{\mathrm{esc}}} + \frac{d}{dE}\left[\frac{dE}{dt}N(E)\right] = Q(E)$$

N(E) is the equilibrium spectrum

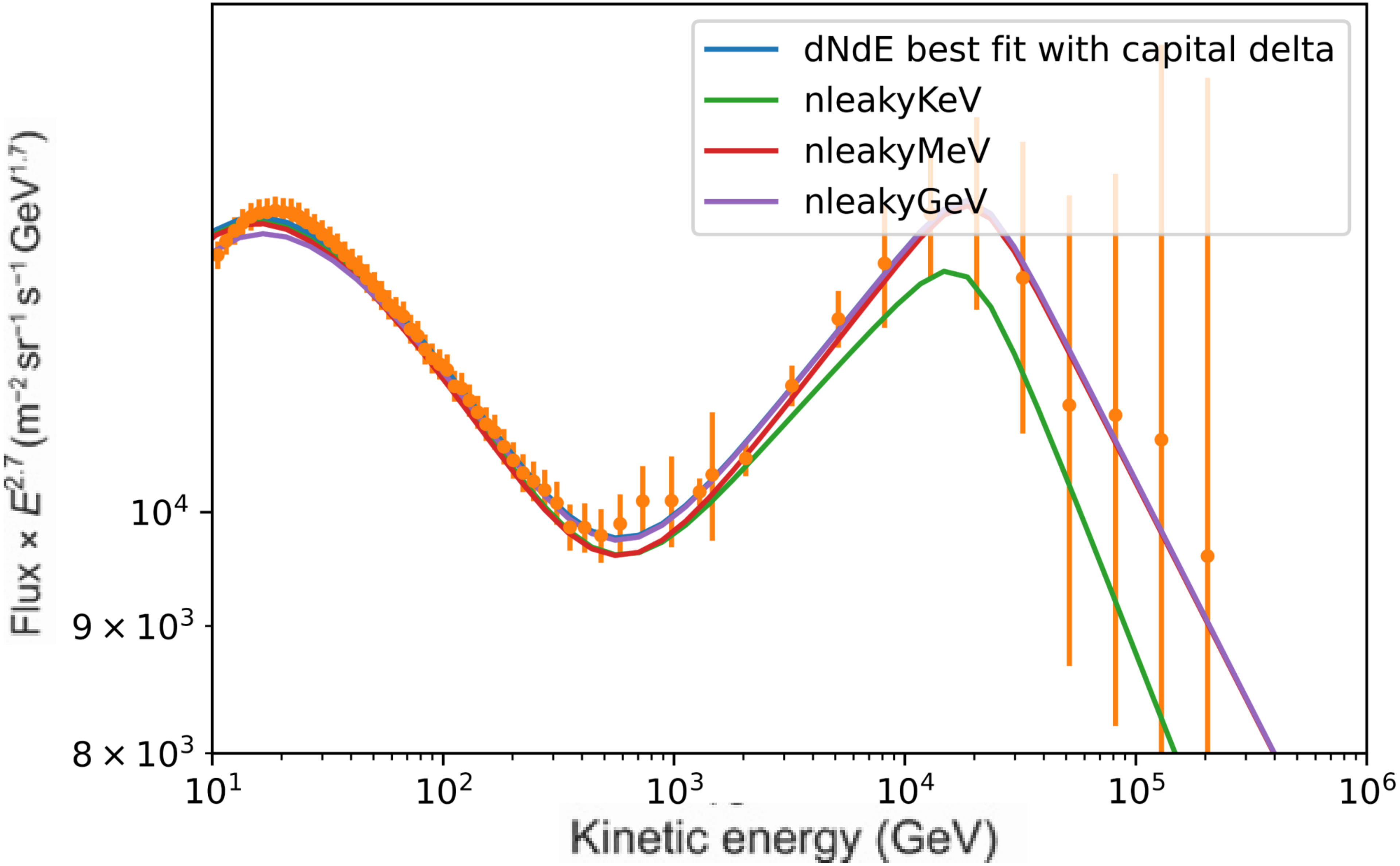
Tesc is the escape time,

$\frac{dE}{dt}$ is energy loss due to dark matter,

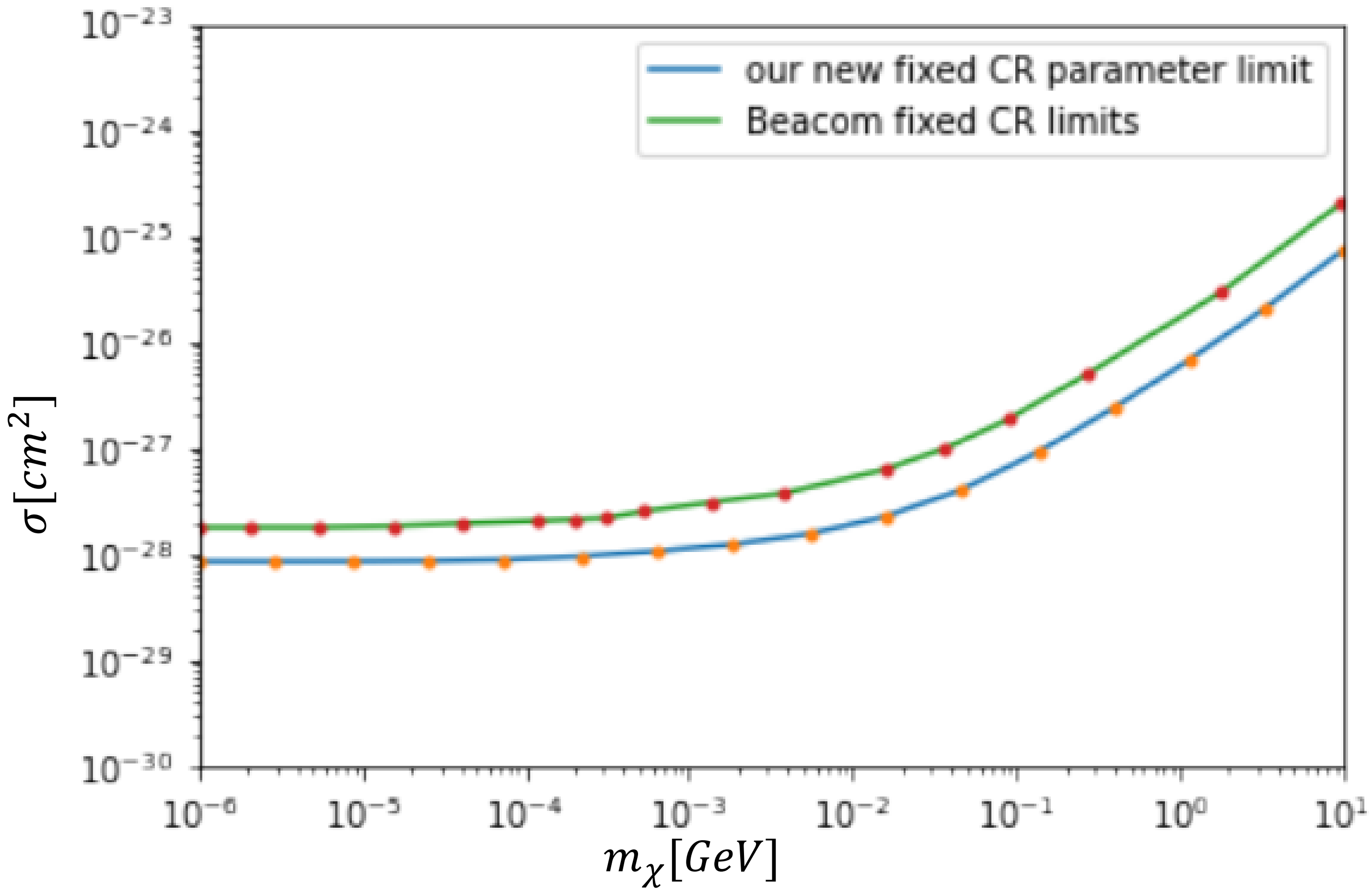
Q(E) is the source spectrum.

- It ignores magnetic fields, size of galaxy and any spatial distributions.
- In the absence of energy loss$\frac{dE}{dt}$, the solution to the leaky box equation is:

$$N(E) = Q(E)T_{esc}(E)$$


dNdE best fit with capital delta
nleakyKeV
nleakyMeV
nleakyGeV
Flux × $E^{2.7}$ (m^{-2} sr^{-1} s^{-1} GeV$^{1.7}$)
10^4
9×10^3
8×10^3
10^1
10^2
10^3
10^4
10^5
10^6
Kinetic energy (GeV)

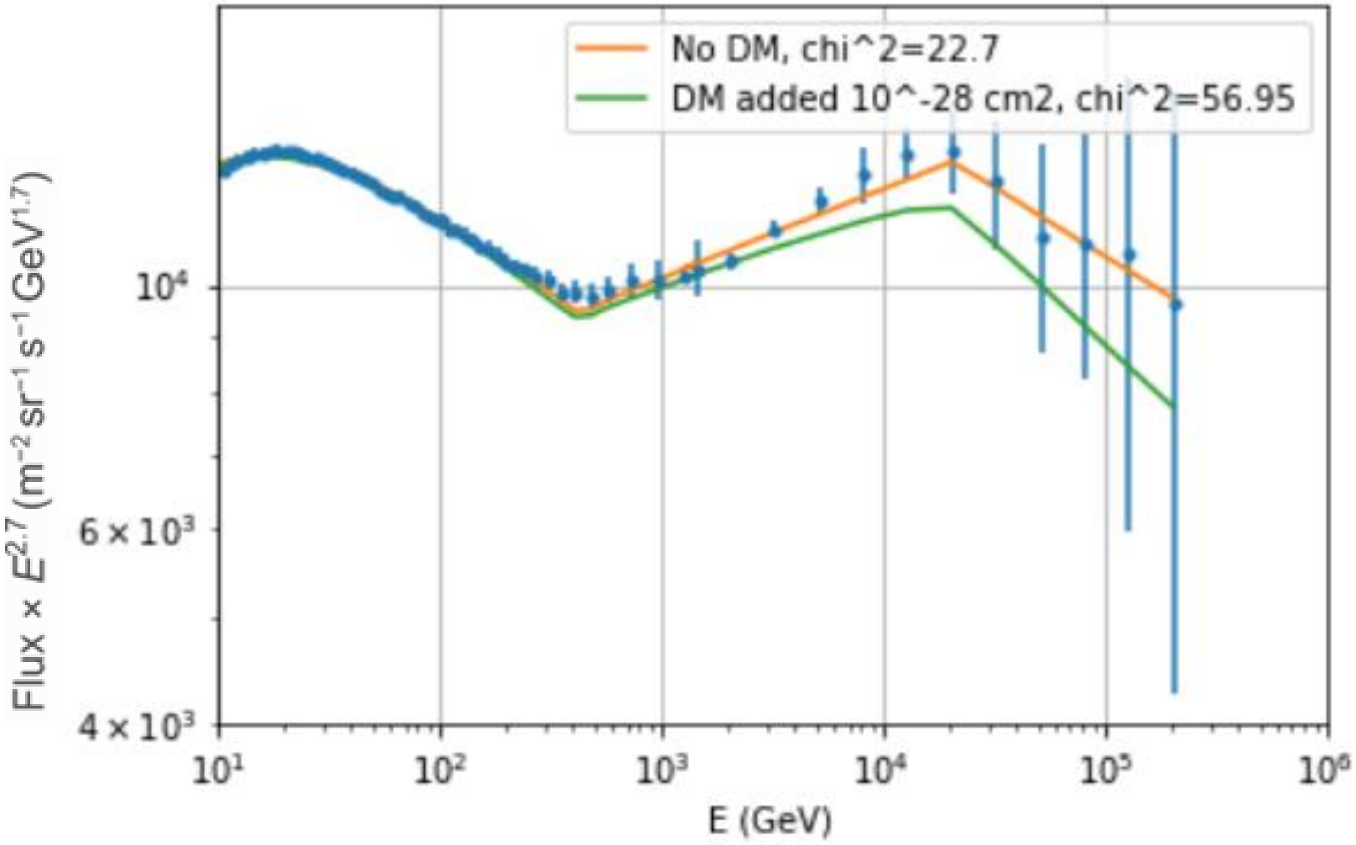
Limits we obtain with fixed CR parameters

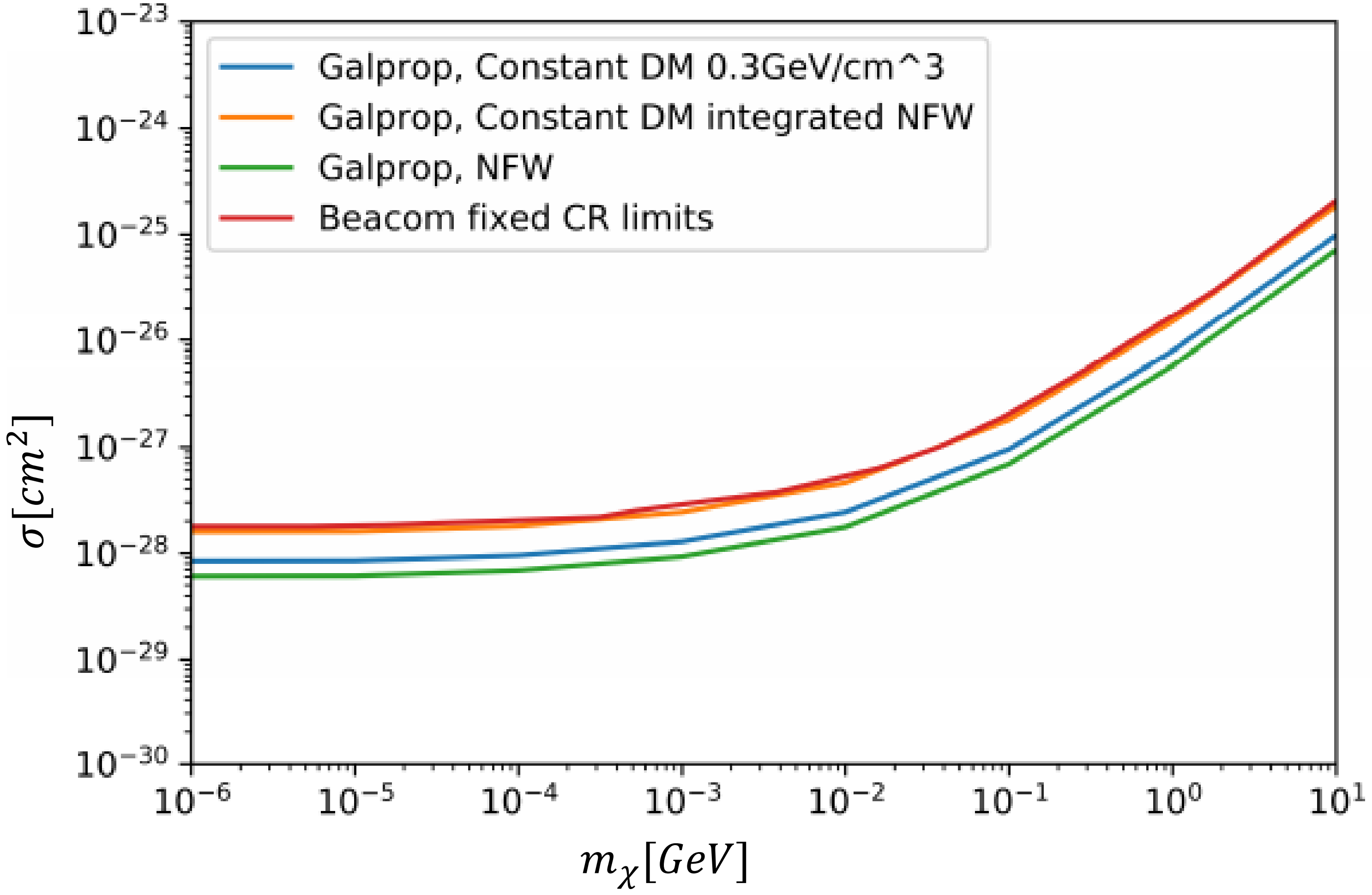


Constant propagation limits with $\chi^2 = 25$

Beyond Leaky Box: GALPROP

- GALPROP is a numerical simulation of propagating CR particles through the galaxy.
- We have modified GALPROP source code to incorporate dark matter energy loss.
- This is a computationally intensive program unlike Leaky Box and requires better algorithms to fit it.
- Note that the breaks are not smoothed.

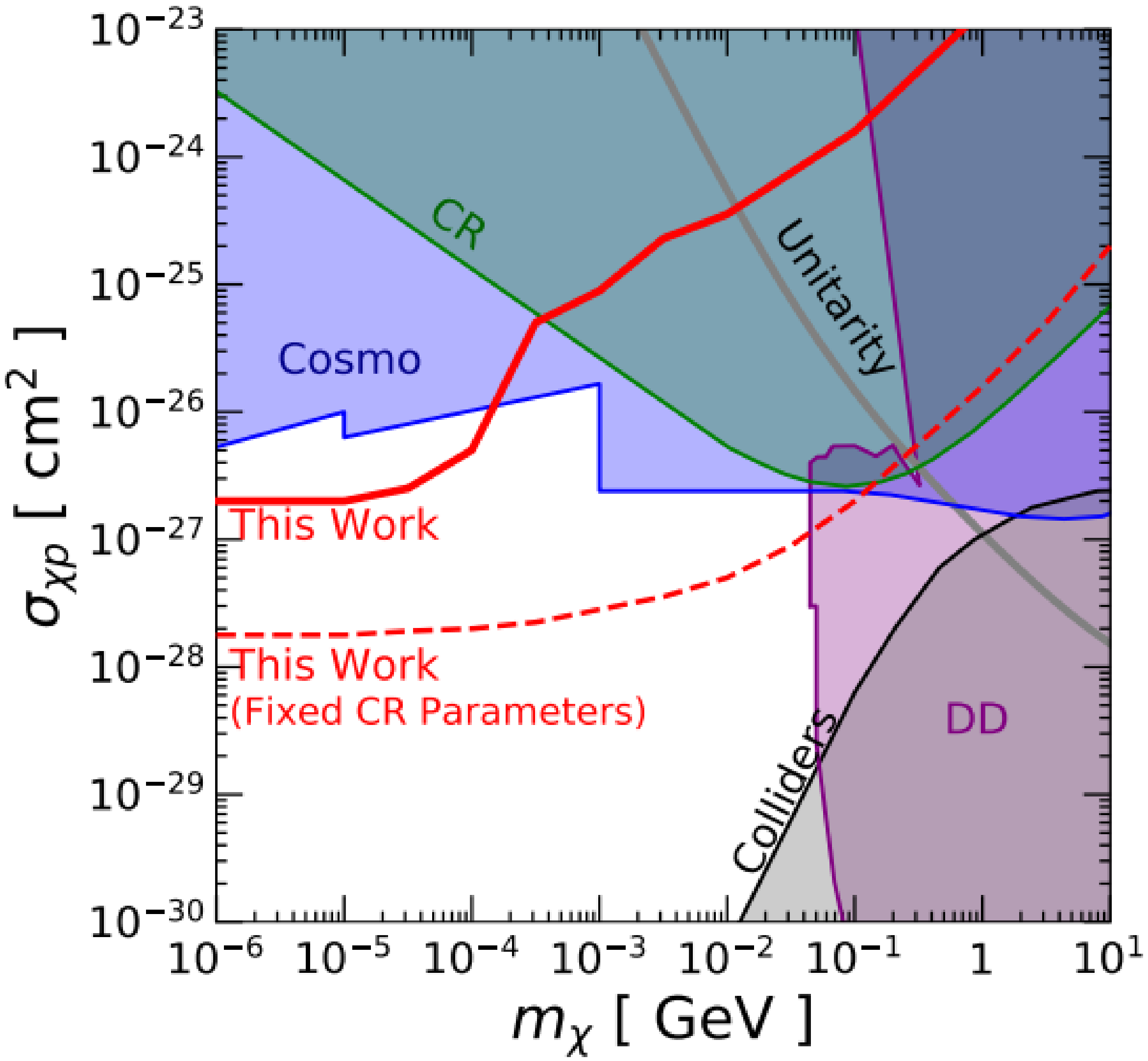




Limits with fixed CR parameters with GALPROP

Cappiello 2019 limits on CRs

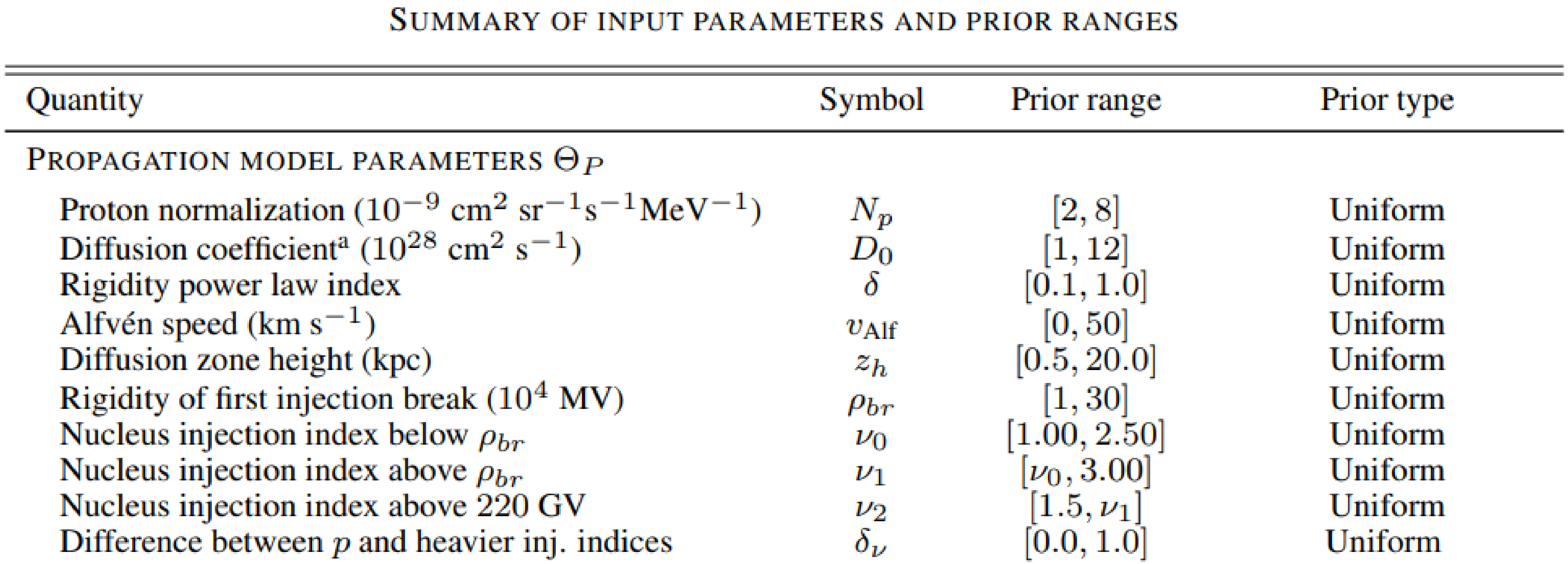
- We don’t know the CR source and propagation parameters.
- Solid red curve shows the limit on dark matter cross sections by allowing CR parameters to vary.
- They(Cappiello et al) fit the CR parameters for a given mass, increasing the cross section until no reasonable CR parameters can fit the data.
- Can we do this with GALPROP?



Cappiello, C. V., Ng, K. C. Y., and Beacom, J. F., “Reverse direct detection: Cosmic ray scattering with light dark matter”, Physical Review D, vol. 99, no. 6, 2019. doi:10.1103/PhysRevD.99.063004.

Fitting GALPROP to data

- Johannesson 2016 performed a scan over GALPROP input parameter space using MultiNest.
- They assume uniform priors and obtain a posterior distribution on relevant GALPROP parameters .
- We fit GALPROP with dark matter energy loss using the same method.



SUMMARY OF INPUT PARAMETERS AND PRIOR RANGES

Quantity	Symbol	Prior range	Prior type
PROPAGATION MODEL PARAMETERS Θ_P			
Proton normalization (10^{-9} cm^2 sr^{-1}s^{-1}MeV^{-1})	N_p	$[2, 8]$	Uniform
Diffusion coefficient[a] (10^{28} cm^2 s^{-1})	D_0	$[1, 12]$	Uniform
Rigidity power law index	δ	$[0.1, 1.0]$	Uniform
Alfvén speed (km s^{-1})	$v_{\rm Alf}$	$[0, 50]$	Uniform
Diffusion zone height (kpc)	z_h	$[0.5, 20.0]$	Uniform
Rigidity of first injection break (10^4 MV)	ρ_{br}	$[1, 30]$	Uniform
Nucleus injection index below ρ_{br}	ν_0	$[1.00, 2.50]$	Uniform
Nucleus injection index above ρ_{br}	ν_1	$[\nu_0, 3.00]$	Uniform
Nucleus injection index above 220 GV	ν_2	$[1.5, \nu_1]$	Uniform
Difference between p and heavier inj. indices	δ_ν	$[0.0, 1.0]$	Uniform

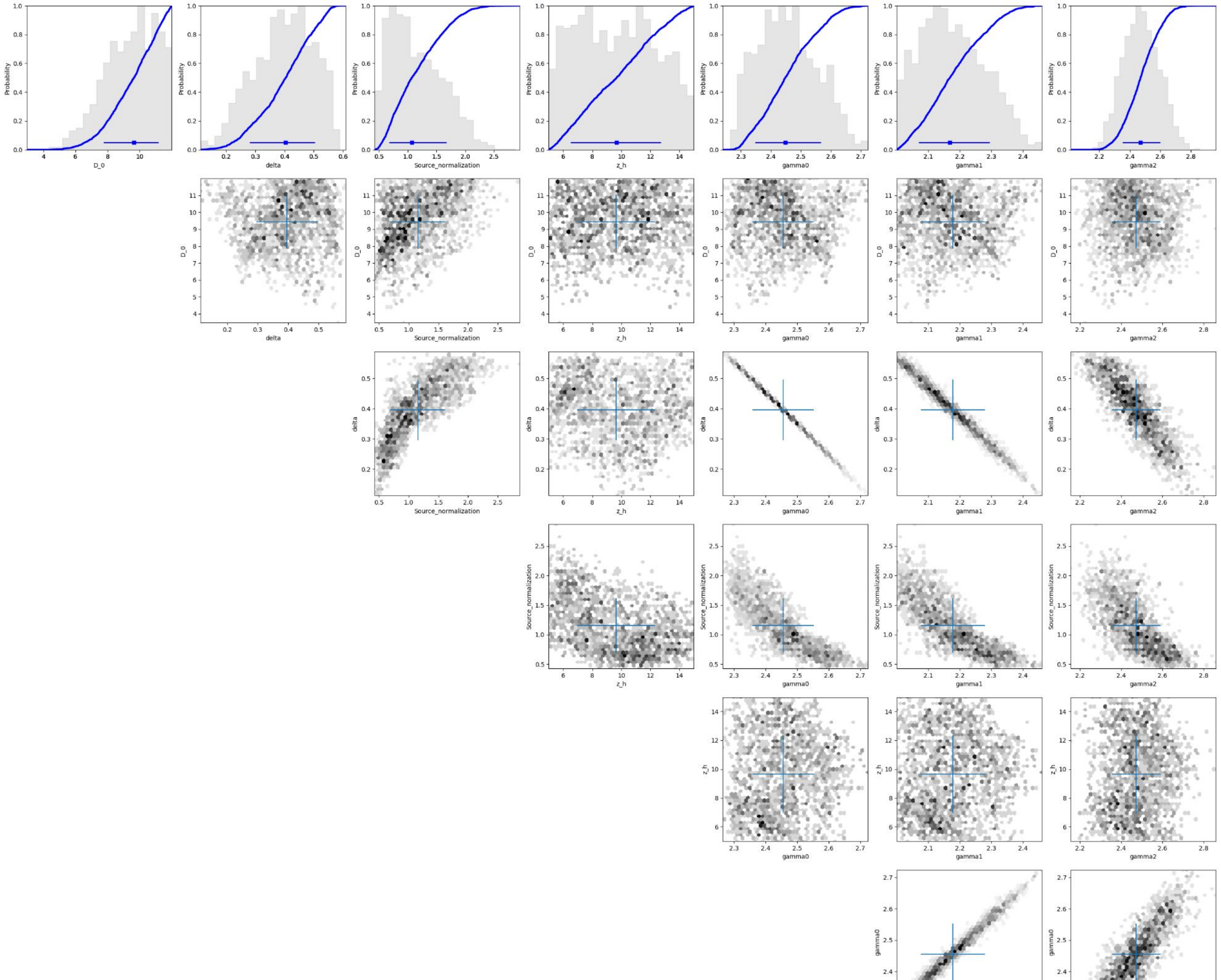
Jóhannesson, G., "Bayesian Analysis of Cosmic Ray Propagation: Evidence against Homogeneous Diffusion", <i>The Astrophysical Journal</i>, vol. 824, no. 1, 2016. doi:10.3847/0004-637X/824/1/16.

Conclusion and Future Prospects

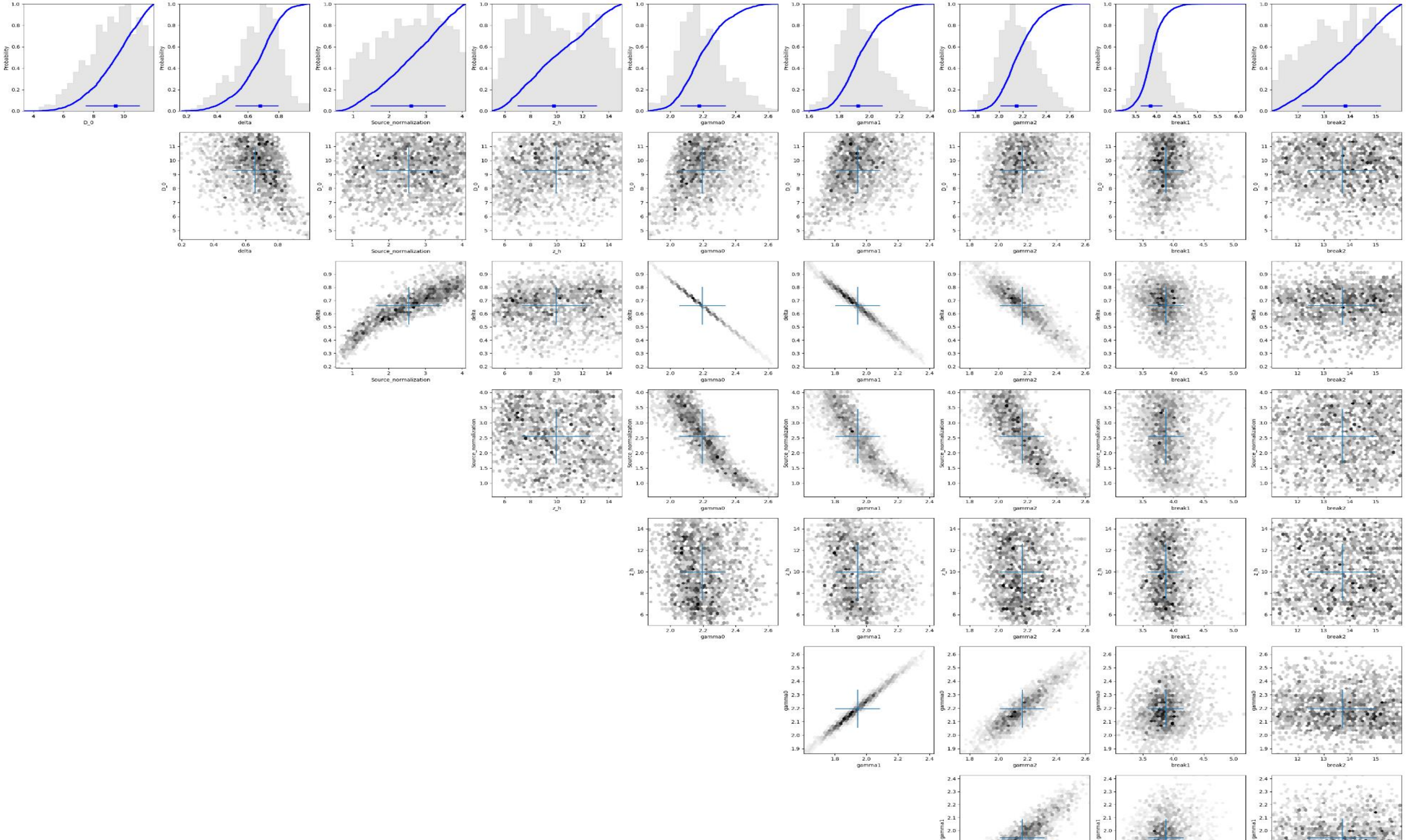
- Fixing Cosmic Ray parameters and finding the limiting cross section of DM allowed yields little difference between GALPROP and Leaky Box.
- Due to the much wider possibilities that GALPROP incorporated in the propagation of CRs, we expect a much weaker set of constraints if we vary GALPROP parameters.
- Varying cosmic ray parameters with GALPROP is computationally challenging and forces us to use Bayesian statistical methods which are being debated.
- Does GALPROP with weak assumptions result in DM bounds so weak that they are phenomenologically uninteresting?
- We are also considering CR-electron scattering and energy dependent cross sections

Backup slides

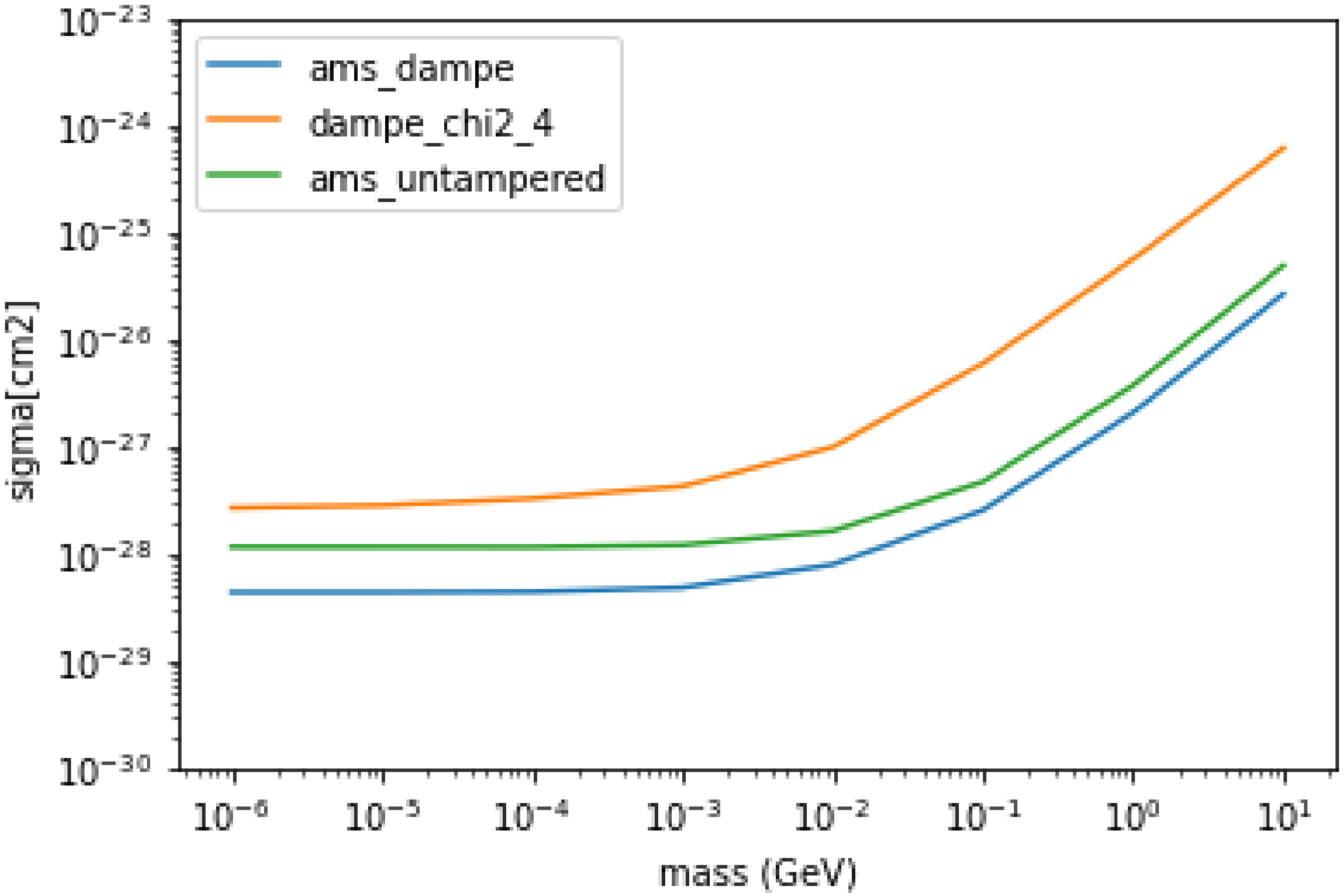
Posterior



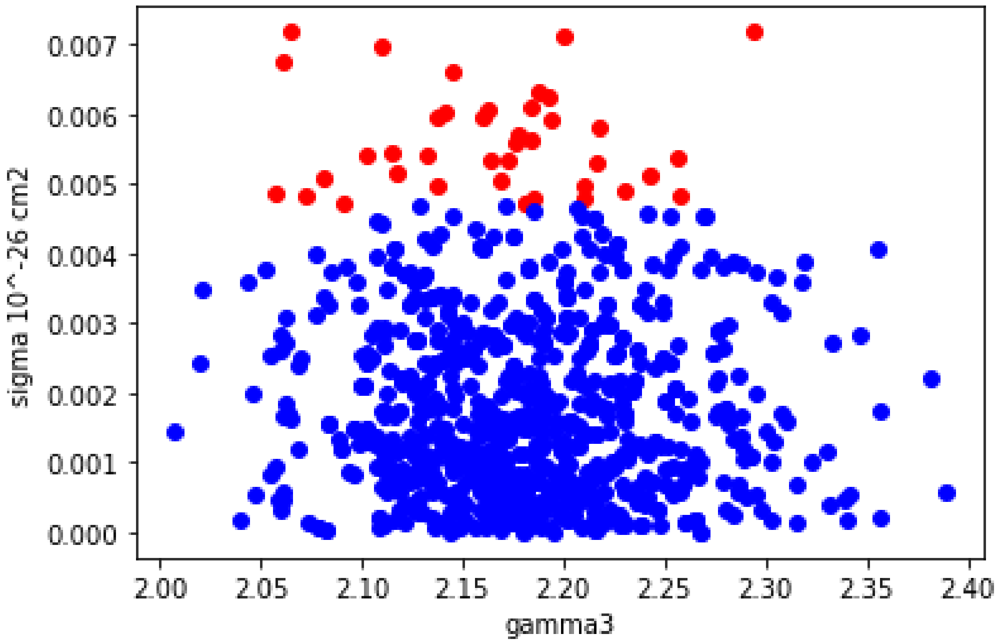
Probability
D_0
delta
Source_normalization
z_h
gamma0
gamma1
gamma2


Probability
D_0
delta
Source_normalization
z_h
gamma0
gamma1
gamma2
break1
break2

AMS and DAMPE

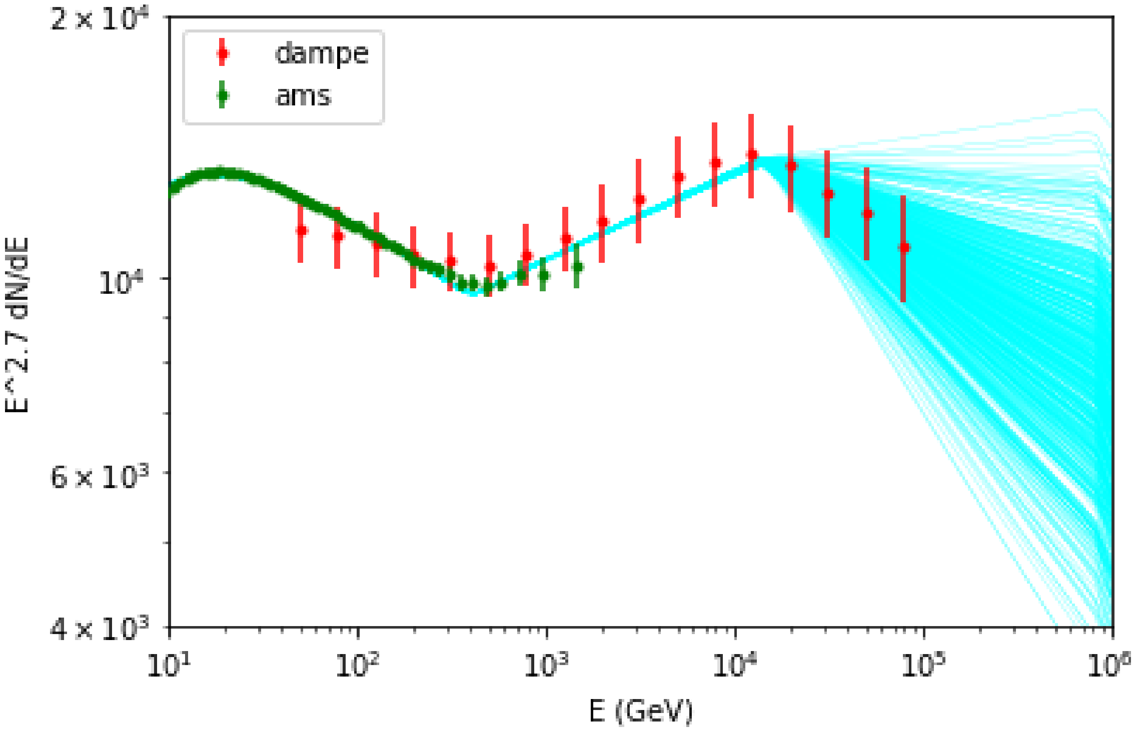


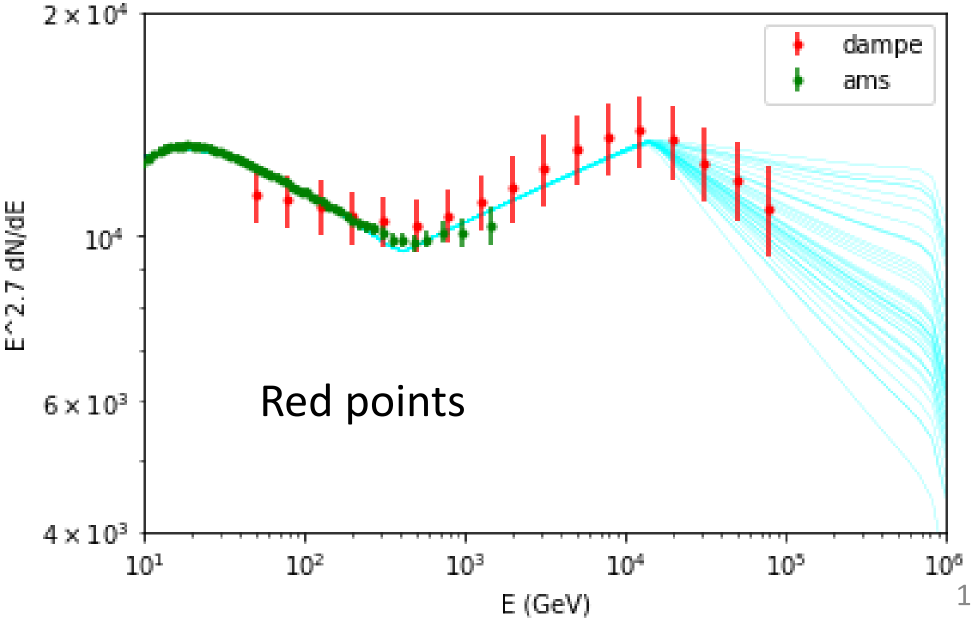
Gamma3



Total points=800, Limit=4.7e-29 cm2

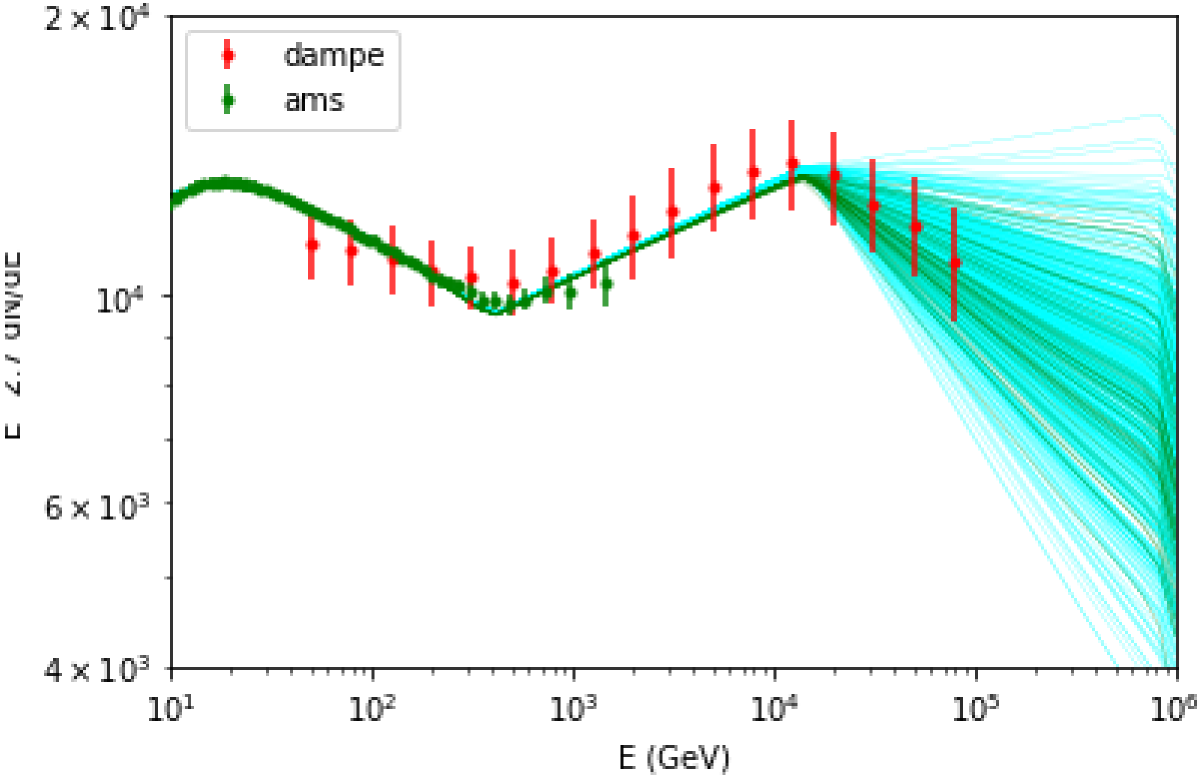
Blue points:

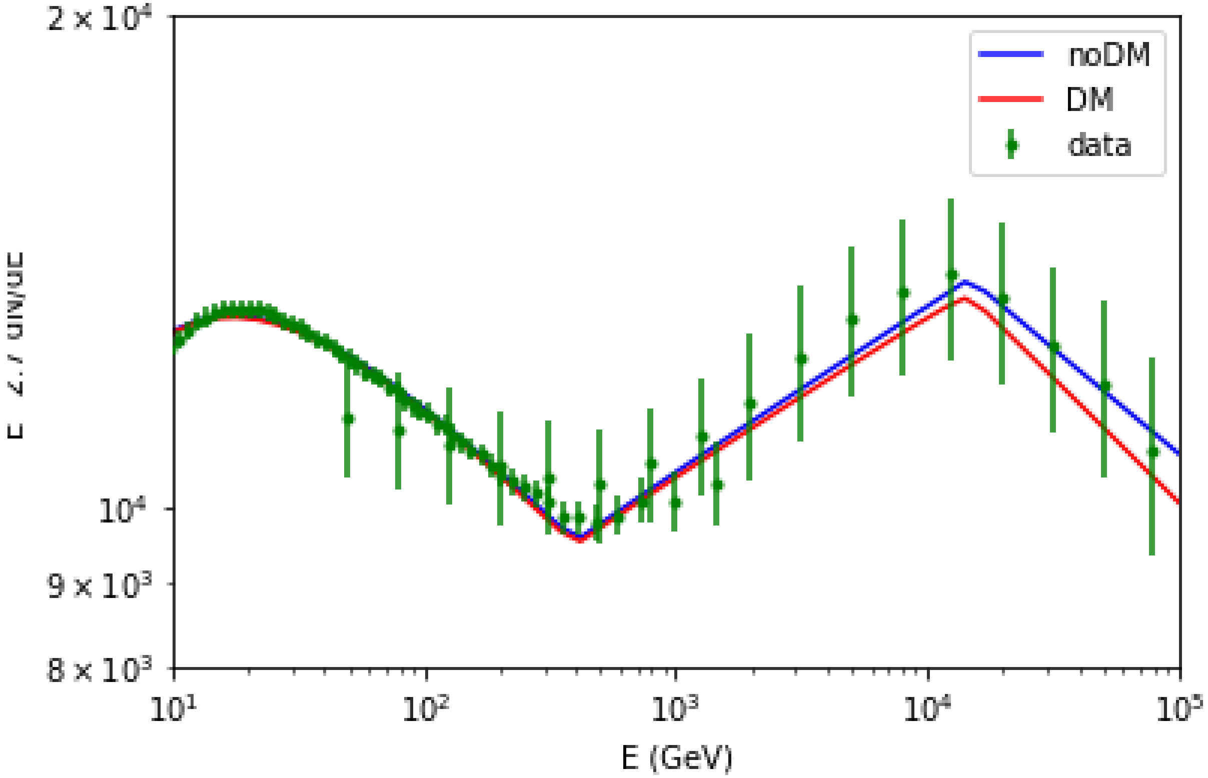




Red points

Green(high DM sigma-red) and Cyan(low sigma-blue)





Cosmic Ray diffusion equation for Galprop

$$\frac{dN(E)}{dt} - \nabla \cdot [D(E)\nabla N(E) + \mathbf{V} N(E)] + \frac{d}{dE}\left[\frac{dE}{dt} N(E)\right]$$
$$= Q(E) - \frac{c\rho\sigma}{\lambda} + \sum_k \int_E^\infty dE' \frac{d\sigma_k(E', E)}{dE} n_k(E').$$