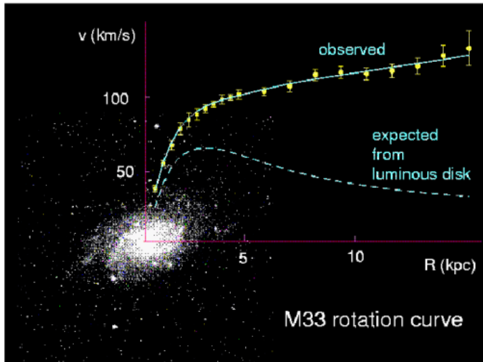
Recent progresses on the astrophysical probe of dark matter

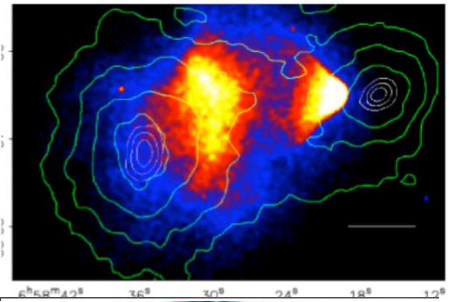
毕效军

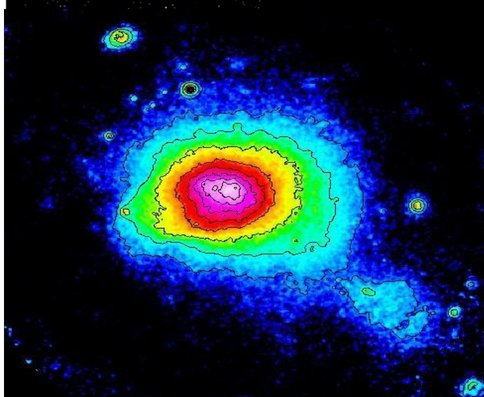
2022/11/18-20

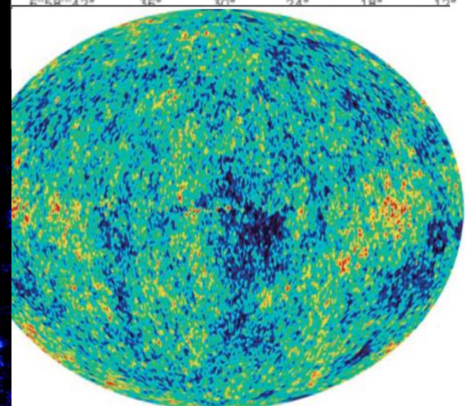
The 2022 Shanghai Particle Physics and Cosmology Symposium:
Neutrino and Dark Matter Physics (SPCS 2022)

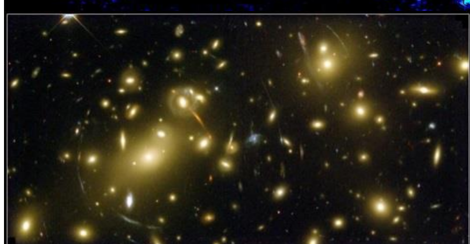
Standard cosmology

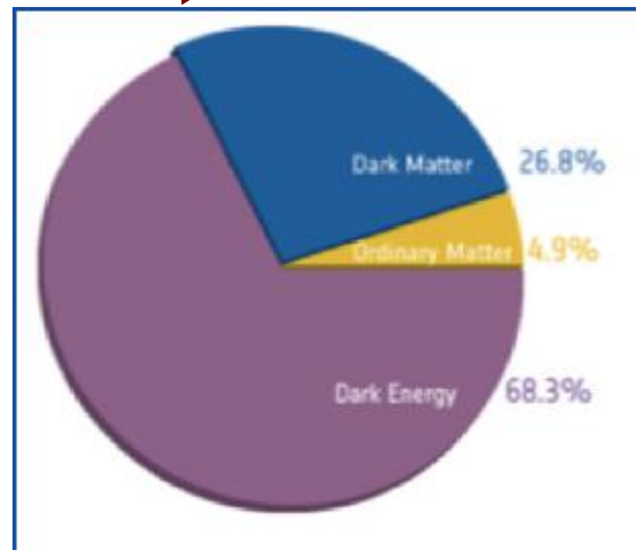












Based on large number of astronomical observations the ΛCDM is established. However, we have to figure out the property of DM particles.

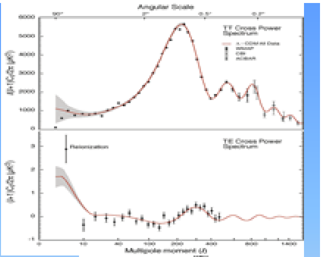
Known properties of dark matter

It is stable, no EM and strong interactions with SM …
Nonbaryonic, Cold – non-relativistic in structure formulation era…
It is generally believed a new particle beyond the SM

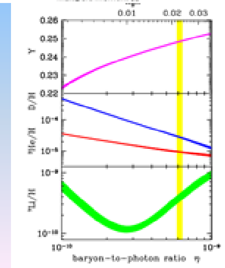
In ΛCDM, dark matter particles are assumed ***collisionless*** and seed the structure formation by a nearly ***scale-invariant*** fluctuation spectrum. All large-scale structure observations are consistent with the picture.

Astrophysical observations today to smaller scales actually set constraints on this standard CDM scenario and probe the propeties of DM particles.

Non-baryonic

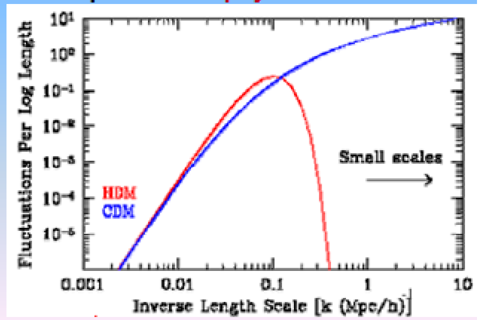


From BBN and CMB, it has $\Omega_B h^2$=0.02+-0.002. Therefore, most dark matter should be non-baryonic. $\Omega_{DM} h^2$=0.113+-0.009

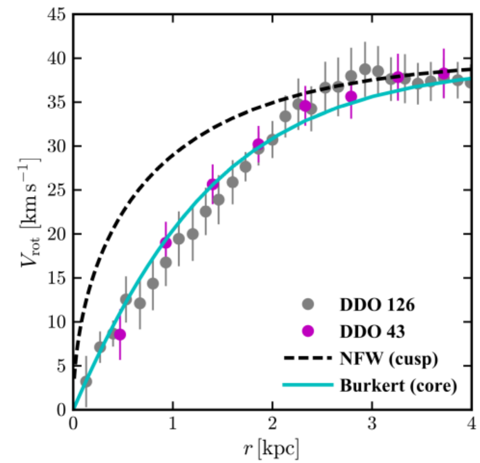


New physics beyond the SM

Non-baryonic cold dark matter dominates the matter contents of the Universe. New particles beyond the standard model are required! New physics!

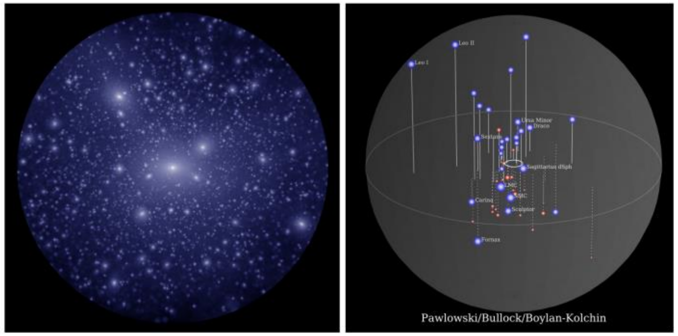


The small scale problems are possible implications on the nature of dark matter particles.

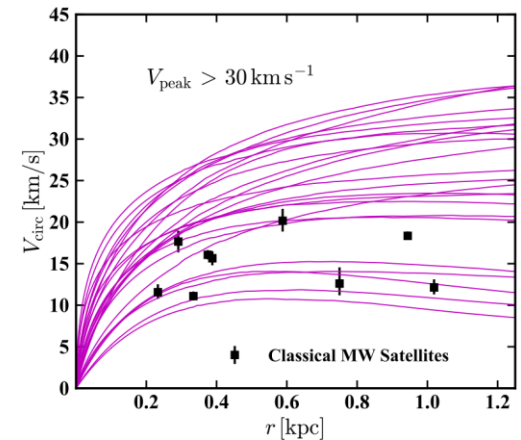


1, core-cusp: The dashed line shows the ΛCDM expectation for a typical rotation curve of a Vmax ≈ 40 km s−1 galaxy. The data points show the measured rotation curves of two example galaxies of this size requiring a constant DM density core. (LITTLE THINGS survey, Oh et al. 2015)

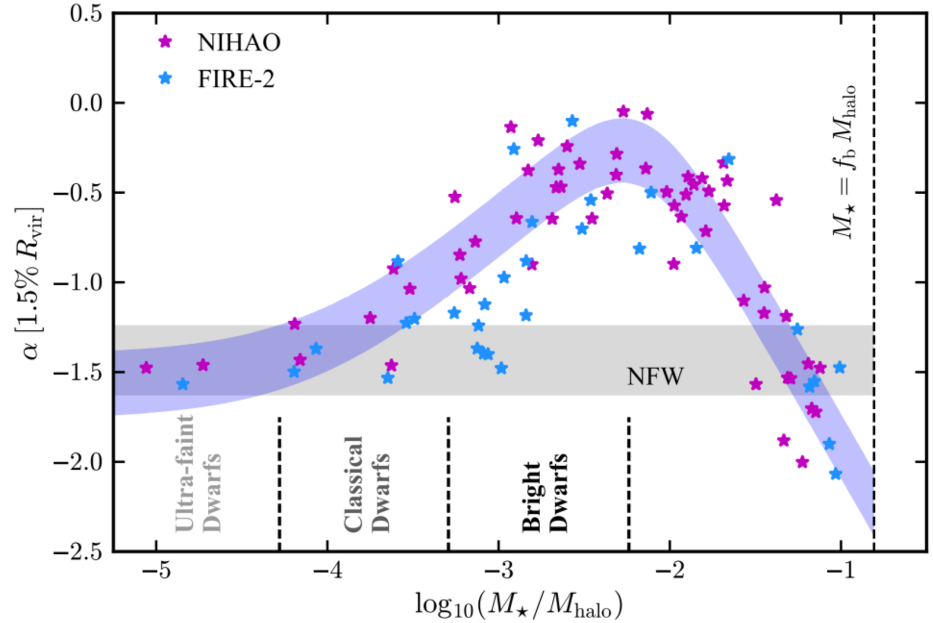
2, missing satellites. Figure show Simulated and observed dwarf galaxies.



3, too-big-too-fail. the central densities of the simulated dwarfs are higher than the central densities observed in the real galaxies. (the circular velocity observed is lower) this is an independent problem to the 1st one.

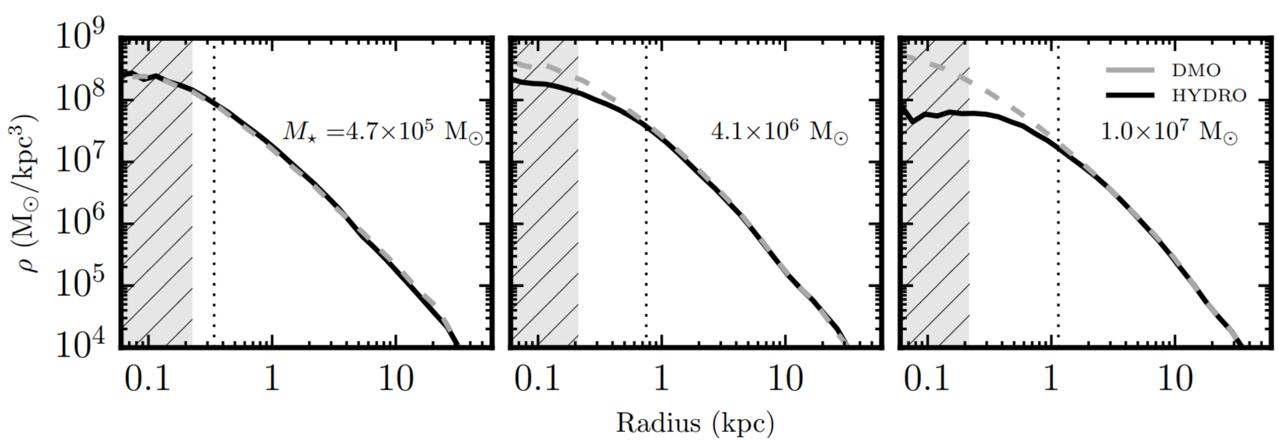


Are these problems due to baryonic effects or non-CDM dark matter ??



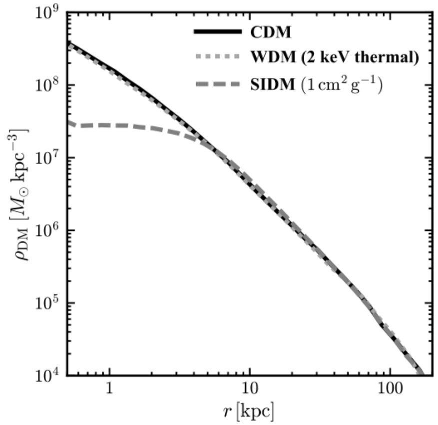
If too many baryons form stars, however, the excess central mass can compensate and drag dark matter back in. At the other extreme, if too few stars are formed, there will not be enough energy in supernovae to change halo density structure and the dark matter distribution will resemble dark-matter-only simulation.

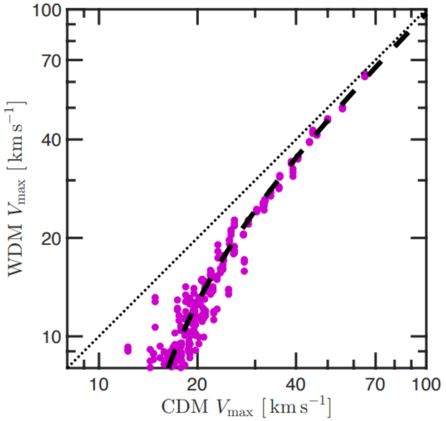
Hydrodynamical simulation results.

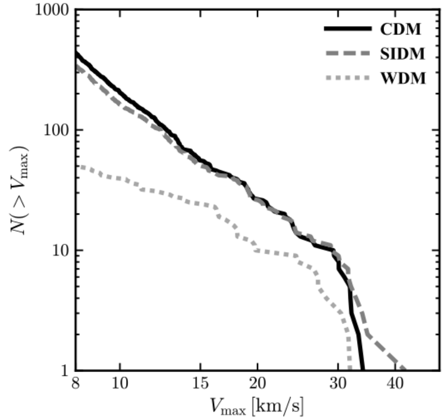


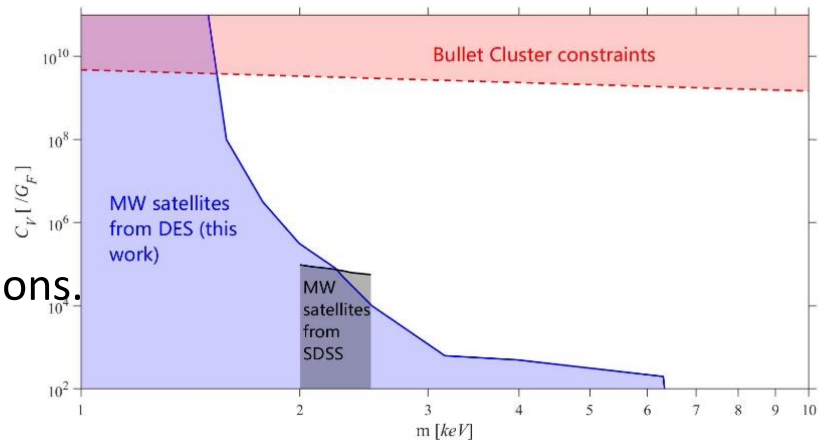
Modifying linear theory predictions ---WDM or modifying the nonlinear prediction --- SIDM

The figures show that the WDM can not generate a core as observed while the SIDM can solve the cusp/core and too-big-to-fail problems but usually does not suppress the small scale structures enough.
Therefore in order to generate truncated power spectra to solve the missing satellites the SIWDM scenario is studied as a benchmark model.









Very preliminary result consider DES observation and satisfy all other observations.

Zhang, BI, Yin 2022.

Future prospects – disentangle the baryonic and DM effects

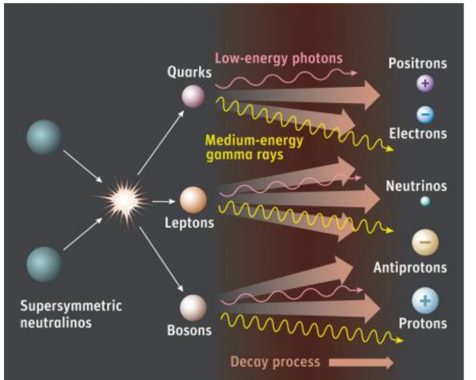
LSST, planed to operate soon, has the ability to detect galaxies that are one hundred times fainter than SDSS.

More fainter dwarfs should be observed.

One unique feature of LSST is able to explore the properties of low-mass, isolated dark matter halos, thereby separating the effects of baryonic feedback and dark matter physics.

To achieve such a goal, $M \sim 10^6 M_*$ at $\sim$ 1 Mpc from the Milky Way and M31 will be attractive targets. At this distance, spectrographs on 10m-class telescopes is not sufficient to measure kinematics of resolved stars; planned 30m-class telescopes are suitable to this task.

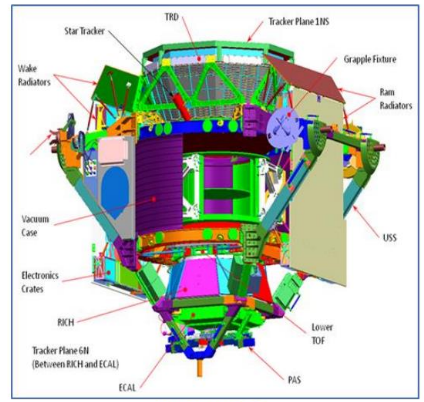
Another important way for probing the properties of dark matter ***is indirect detection*** of the annihilation products.



Ongoing experiments in space

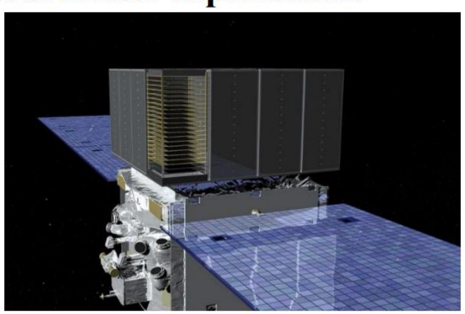
Magnetic spectrometer experiments

PAMELA

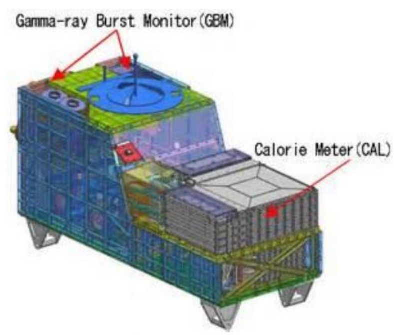


AMS-02

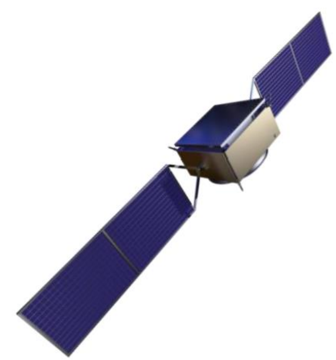
Calorimeter experiments



Fermi-LAT

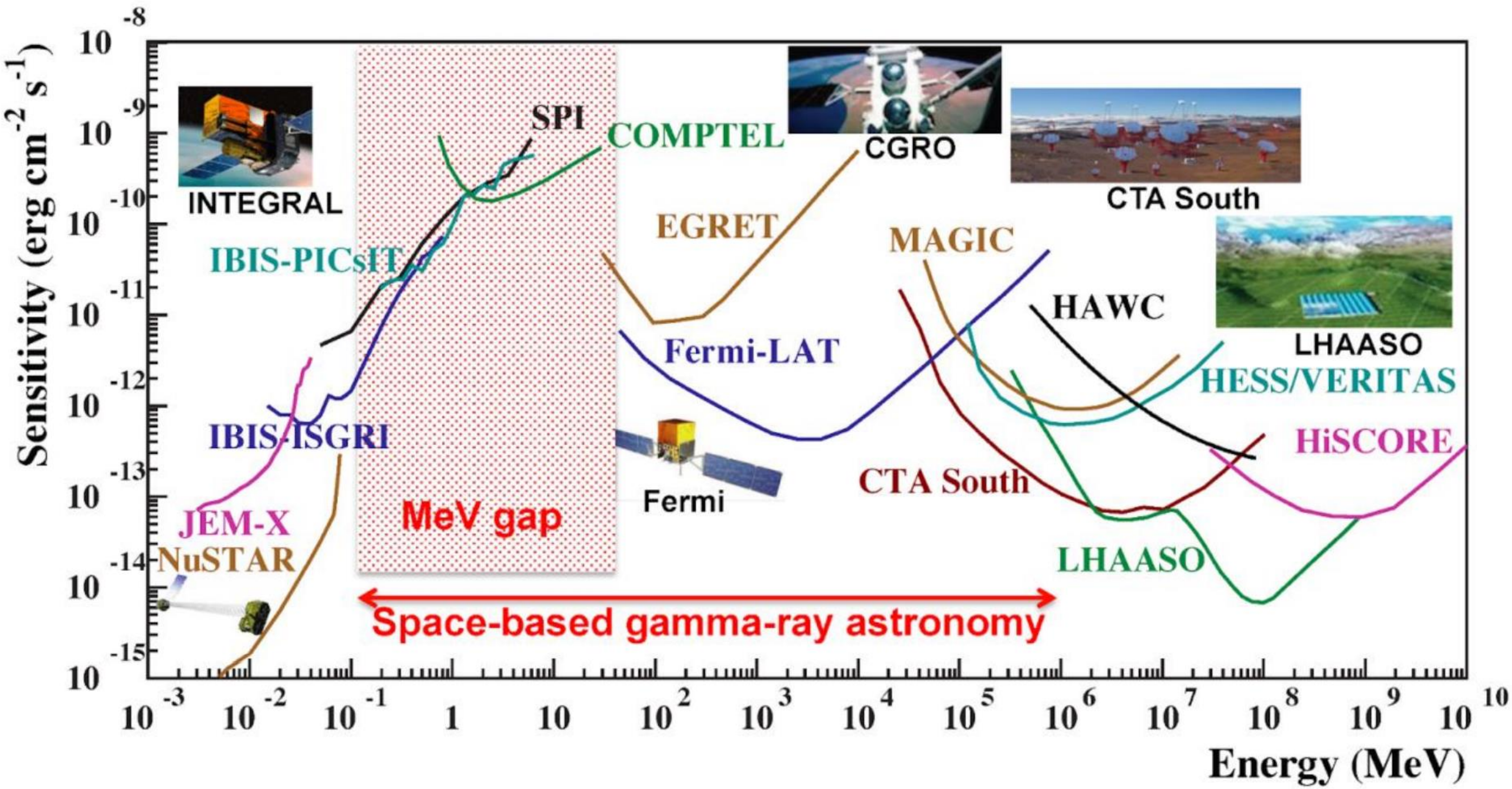


CALET



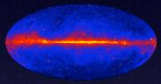
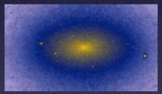
DAMPE

Sensitivity of X-ray and gamma ray detectors



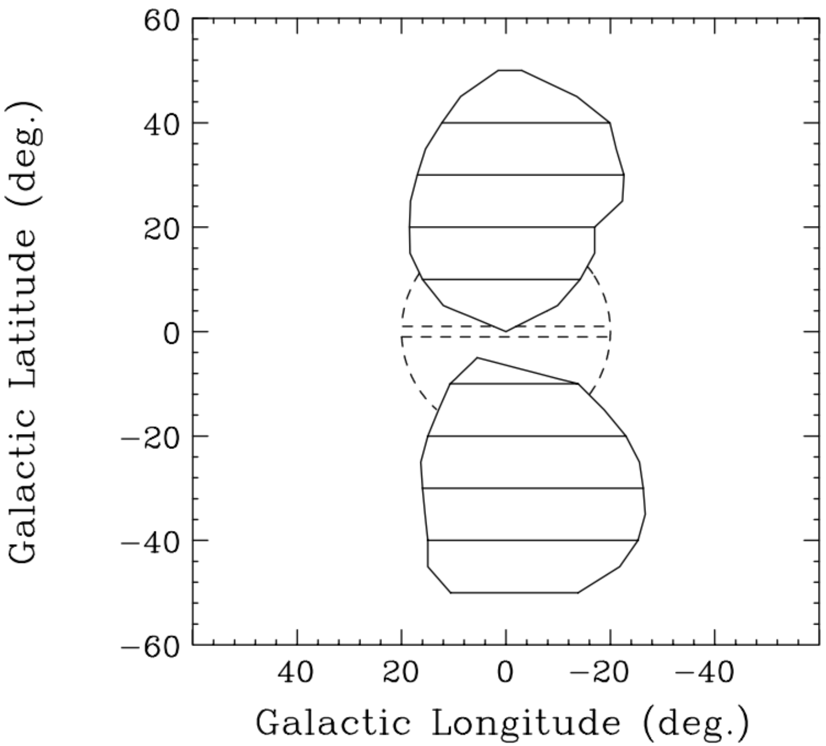
Caputo, TAUP2021

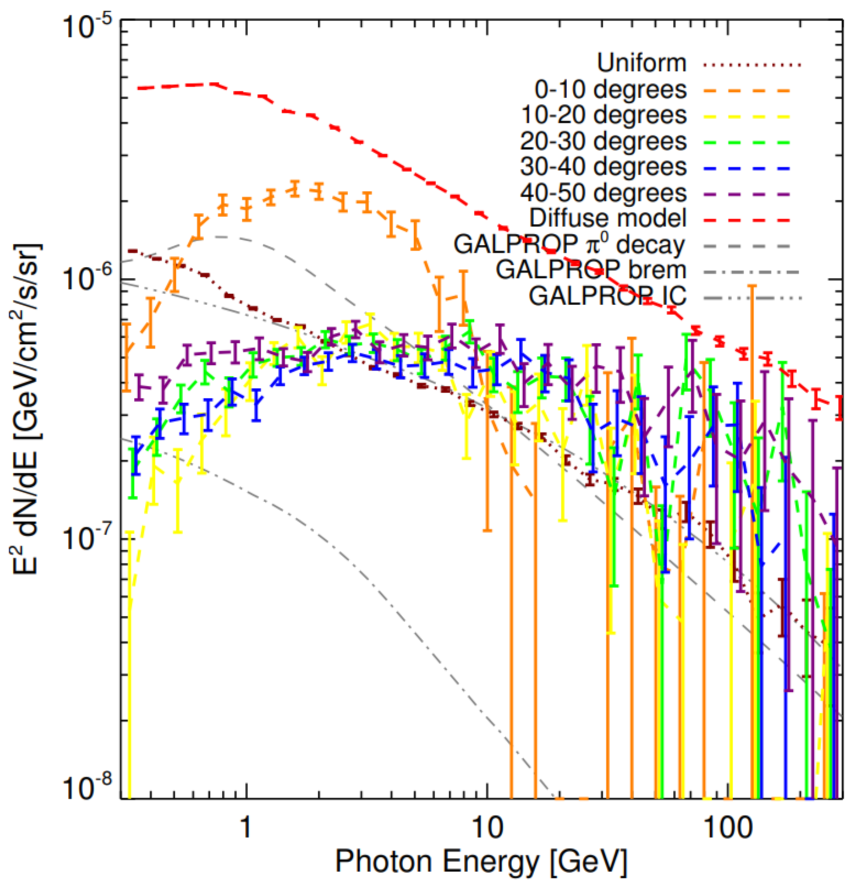
Where to look for the gamma ray signals?

- Dwarf galaxies  low background, nearby
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos potentially numerous, probe small-scale structure
- Extragalactic background radiation holds redshift information, probes halos at all scales

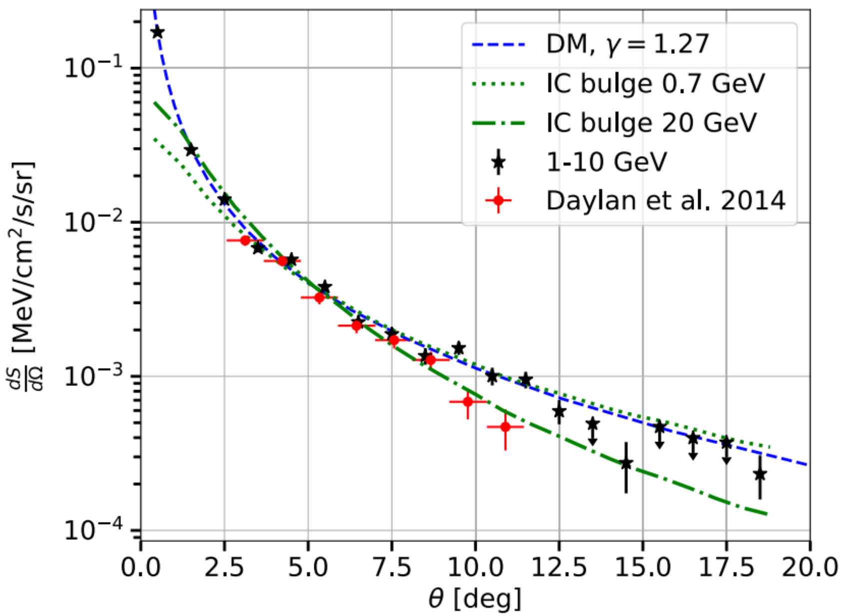
The present anomaly – GeV gamma ray excess at the Galactic center

The gamma ray data by Fermi-LAT is modeled as a linear combination of spatial "templates", including the disk, the bubble. An excess around the GC (low latitude) is detected.
The underlying physical processes for these backgrounds are largely well-understood, but the three-dimensional distributions of gas, starlight and cosmic rays are not well-measured, making precise prediction difficult.





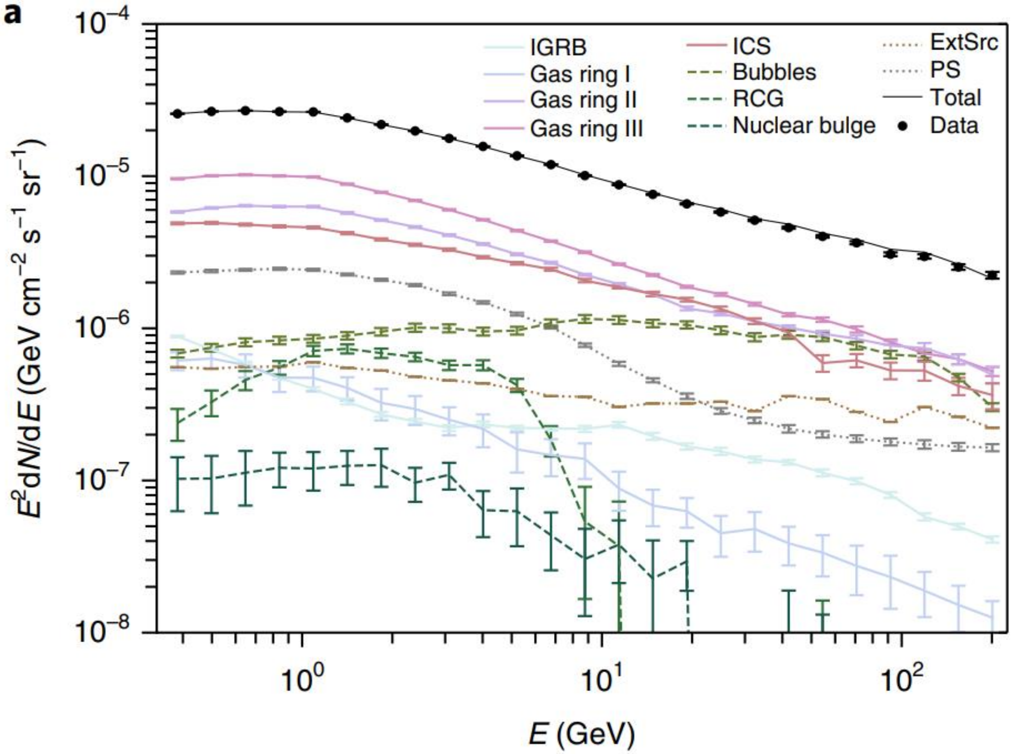
Possible origins include: DM or millisecond pulsars in the bulge



Mattia Di Mauro
Phys. Rev. D **103**, 063029 (2021)

Angular distribution for GCE is well consistent with DM annihilation.

the spatial morphology of the GCE do not change significantly between 0.7 and 20 GeV. Therefore the variation of the galactic bulge emission as a function of energy is problematic for the interpretation of the GCE with this mechanism.



nature astronomy ARTICLES
https://doi.org/10.1038/s41550-018-0531-z

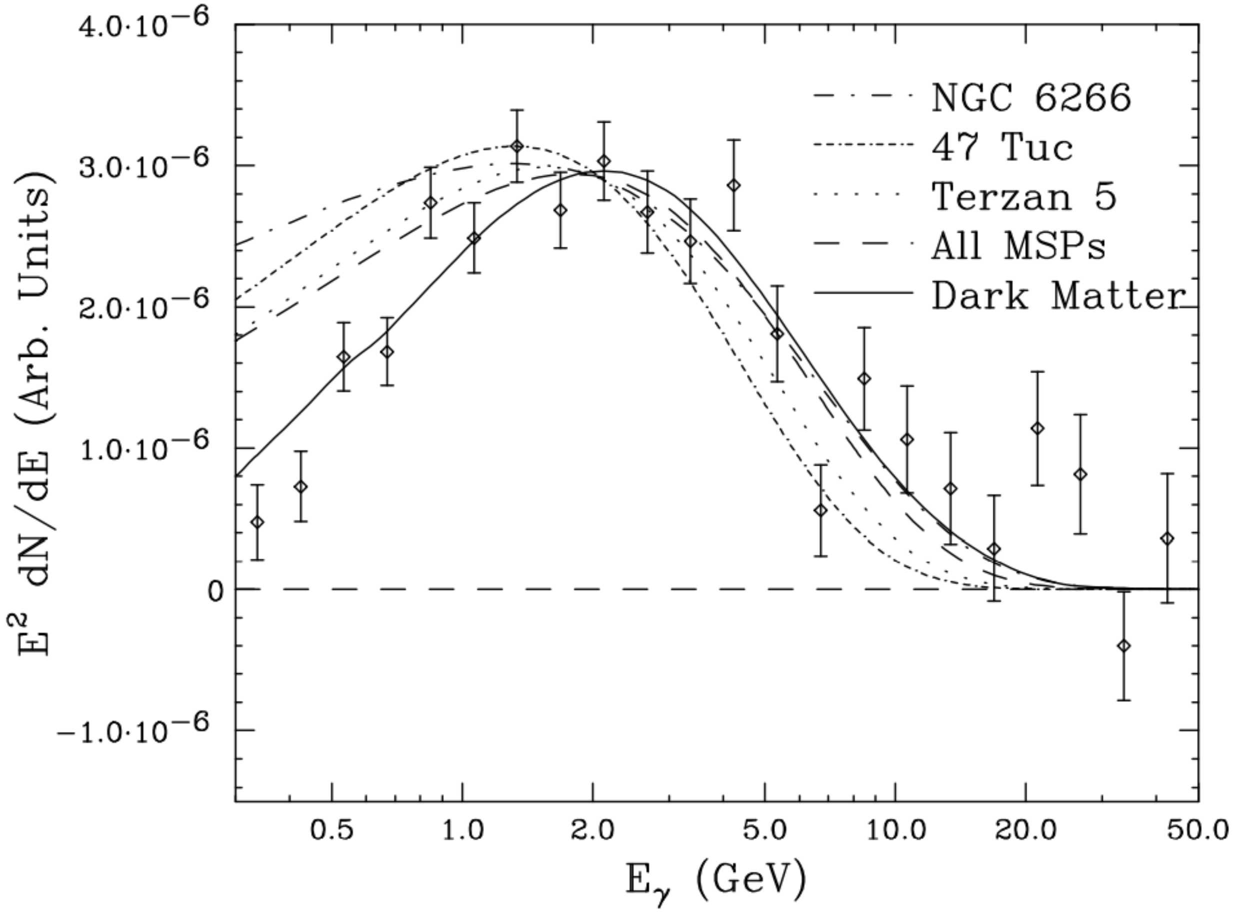
The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

nature astronomy LETTERS
https://doi.org/10.1038/s41550-018-0414-3

Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess

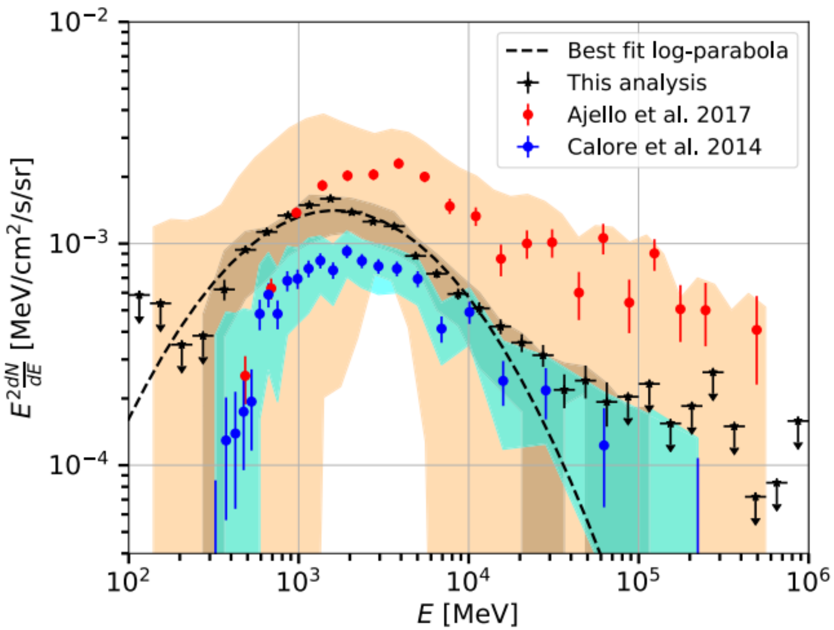
However, two analyses in NA adopting different diffuse gamma rays, (slightly different gas distribution) found GCE favors bulge morphology. A bulge-like morphology would be a strong hint for the origin in the Milky Way's stellar bulge, instead of DM.

It will be very challenging to exclude a stellar-bulge-shaped GCE with current data, even if such a GCE morphology appears to be disfavored in a GALPROP-based model. The apparent exclusion could simply be due to not fully accounting for uncertainties in the gas distribution

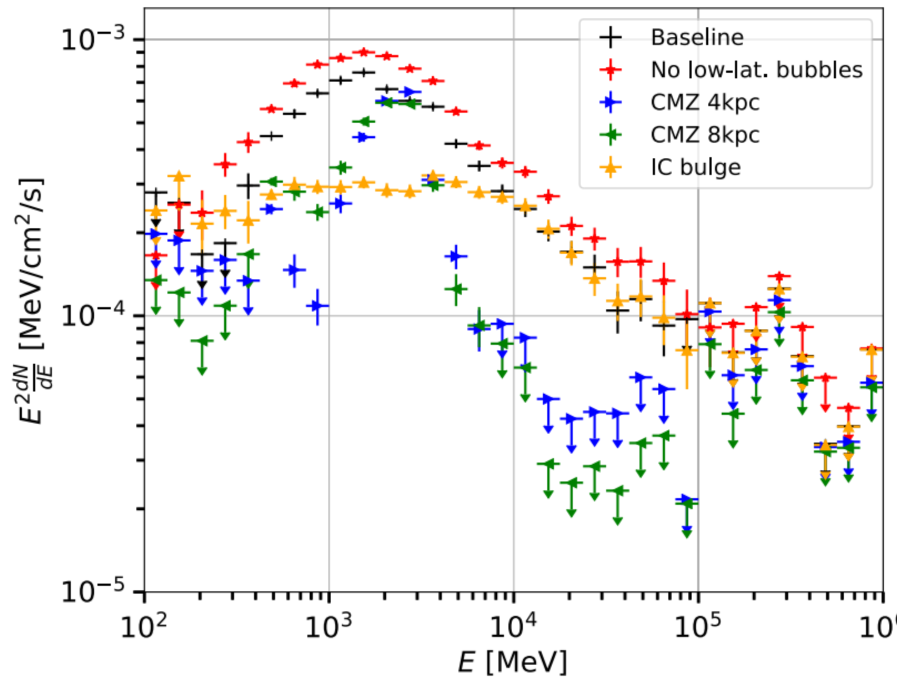


GCE energy spectrum seems favor DM scenario.

Similarly, the GCE energy spectrum is also bkg dependent. No consensus is achieved.



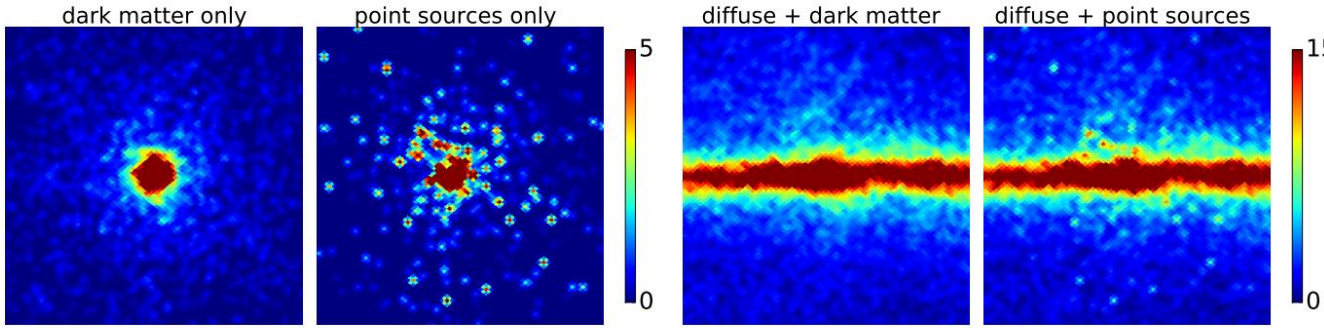
The spectrum of GC from different analysis for adopting slightly different bkg models



For different bkg assumptions on IEMs

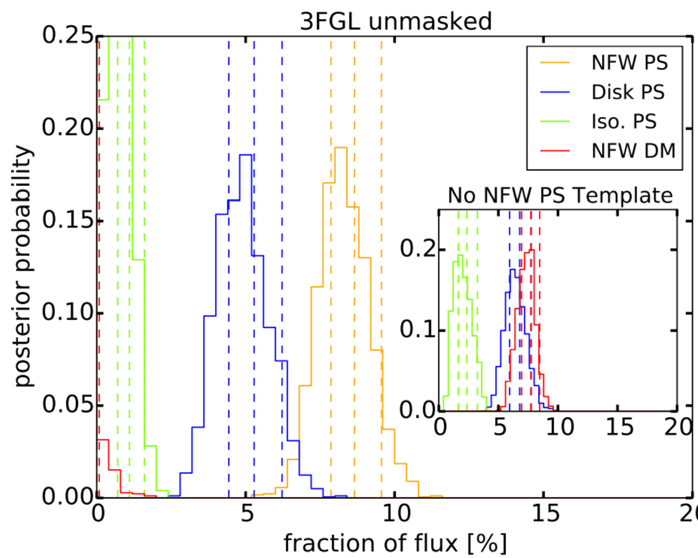
Hint from photon statistics

Distinguish between the various hypotheses is to examine the clumpiness of the photons.

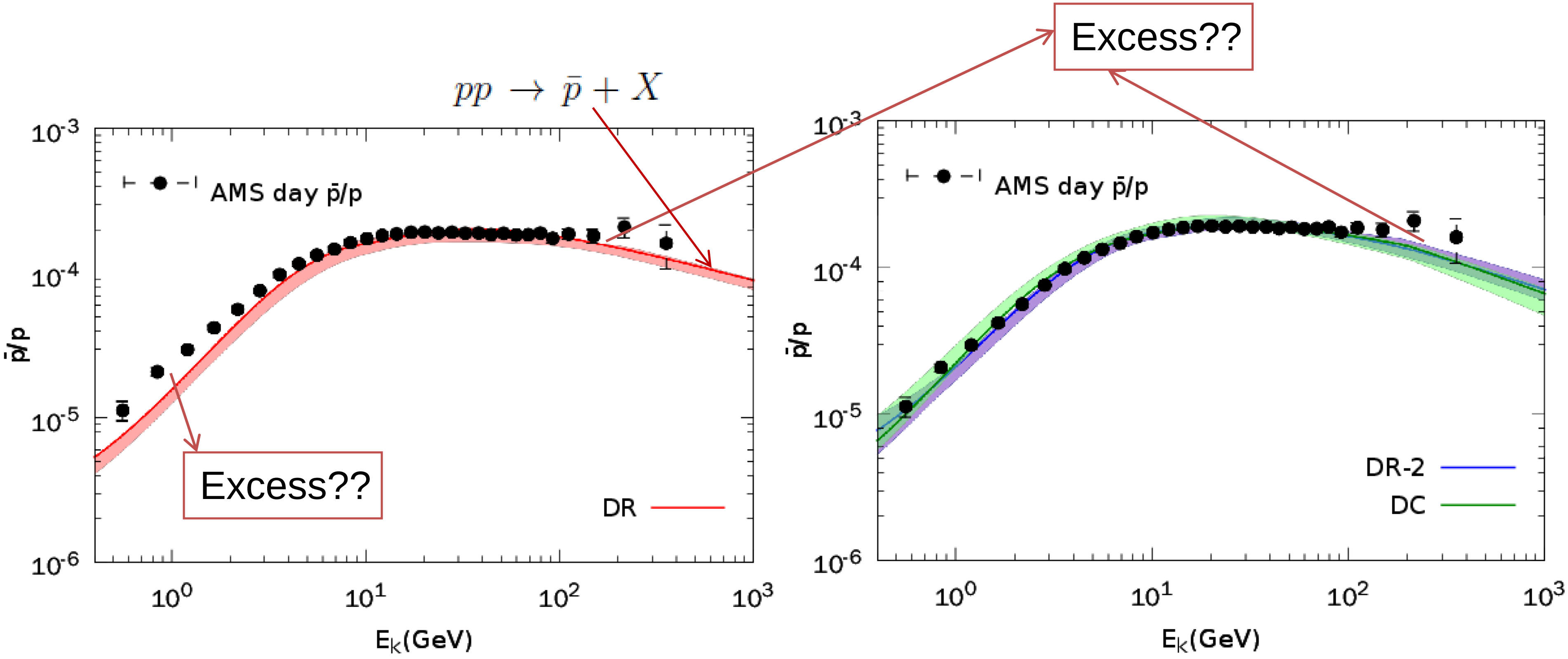


A non-Poissonian template fitting (NPTF) method [Lee et al. Phys. Rev. Lett. 116(5), 051103 (2016)] was developed and found pulsar templet is favored over the DM contribution. Search directly for faint hotspots using wavelet methods [Bartels et al. Phys. Rev. Lett. 116(5), 051102 (2016)] gave the same conclusion.

More understanding for the diffuse bkg gamma emission is essential for resolution of the GCE anomaly.

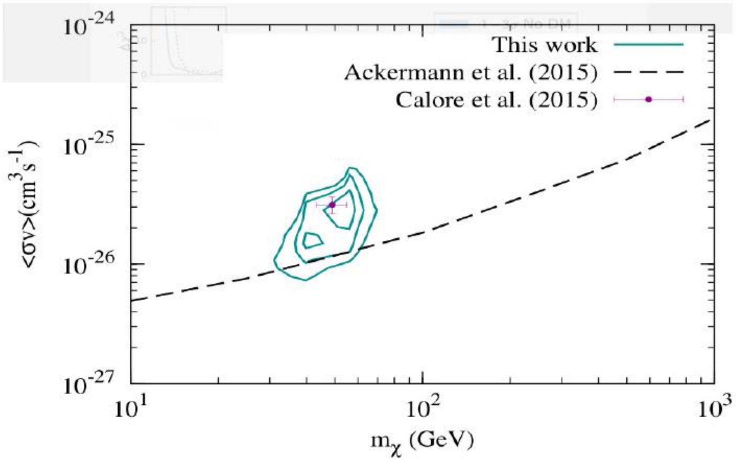


Excess in the AMS-02 pbar/p data

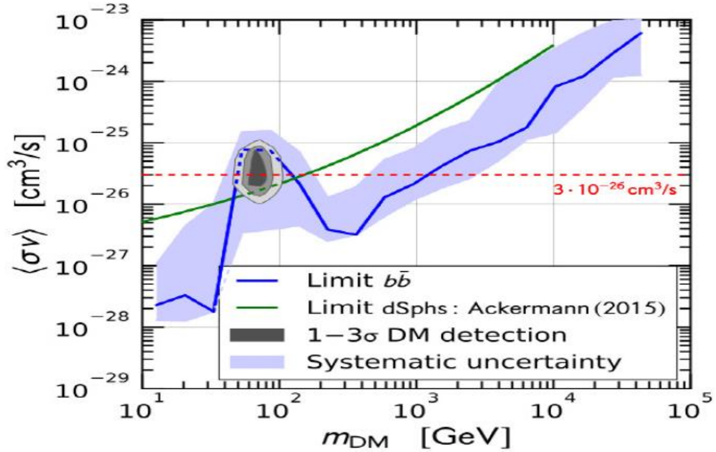


Data show excesses at high and low energies.

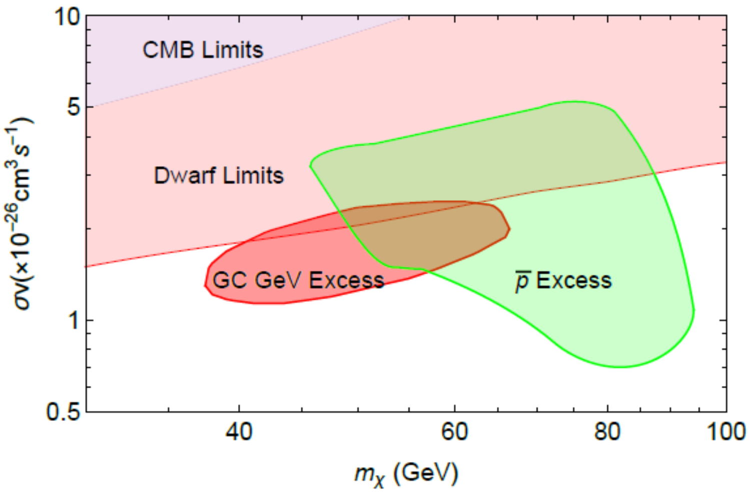
Antiproton signals at low energy?



[Cui et al., 1610.03840]



[Cuoco et al., 1610.03071] 1903.01472



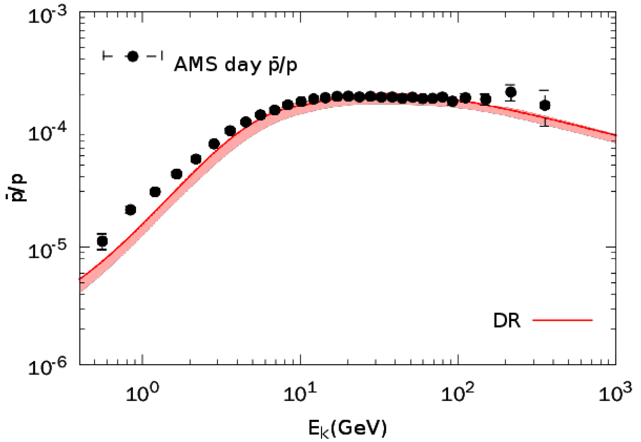
Cholis et al. 1903.02549

All these works found an excess in the AMS-02 antiproton data with significance ≥ 3σ;

The results do not account for the full **correlation matrix of the dataset**. Attempts to estimate the covariance suggest the significance of the excess can be removed. It is critical for the AMS-02 collaboration to release their correlation matrix to establish the antiproton excess. Boudaud et al. Phys. Rev. Res. 2(2), 023022 (2020)

Uncertainties in prediction

- Besides the error in data, more importantly there are larger uncertainties in theoretical calculation including:



  - Propagation models and parameters
  - Hadronic interaction models
  - Solar modulation

Lin, Bi, Yin
arXiv:1903.09545

We gave a systematically study on the CR background taking all the uncertainties into account.

CRs propagation

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r},p) + \nabla \cdot (D_{xx}\nabla\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

- CRs propagation is a very complicated process with the key parameter $D=\beta^{\eta} D_0(\rho/\rho_0)^{\delta}$. The diffusion reacceleration (DR) model is $\eta=1$ and the DR2 model η free, which affects propagation at low energy (excess).

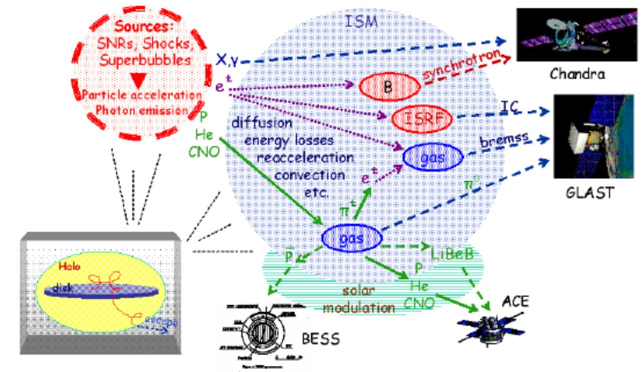
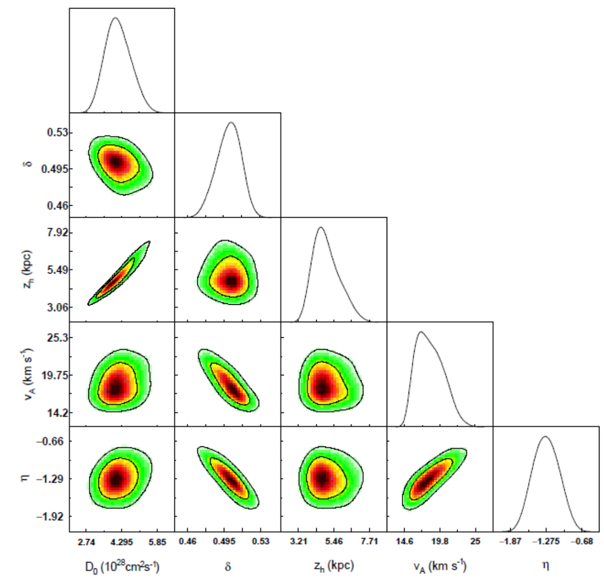


Figure 3. A schematic view of cosmic ray propagation in the interstellar medium (ISM), production of secondary nuclei, particles and γ-rays.

- The propagation and original CR spectra have totally 12 parameters {D0,δ,Va,η,Zh|B/C; proton δ1,2,3, E1,E2; Φ0,1}
- The parameters are determined by fitting the B/C data; therefore we have a huge parameter space



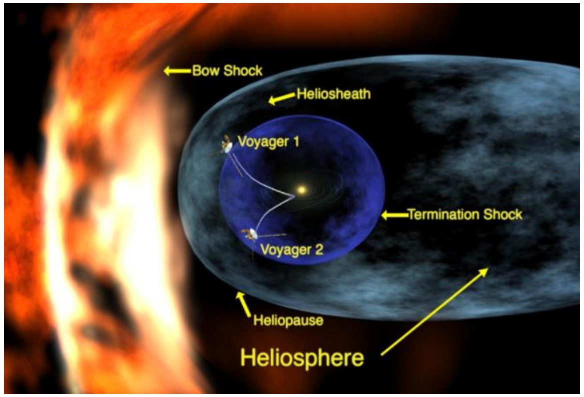
Hadronic interaction

- Antiprotons are produced by cosmic proton collision of $pp \to \bar{p} + X$ the interstellar gas which can not be calculated for the multi-particle production with low transverse momentum by QCD.
- Phenomenological models are developed and model parameters are determined to fit the fixed target data.
- Some empirical models may give semi-analytical formula by fitting to data directly.
- The following models are available:

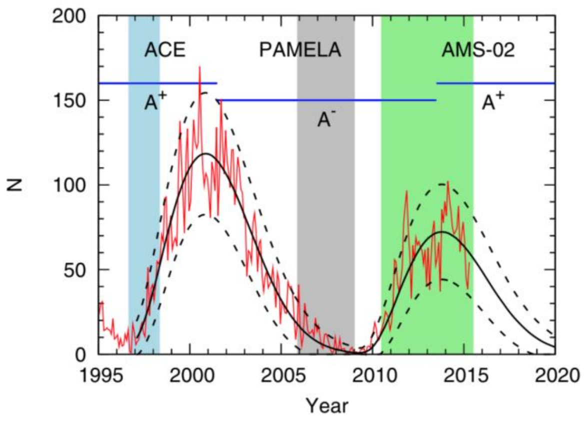
phenomenological	empirical
EPOS LHC	Tan et al.
EPOS 1.99	di Mauro
QGSJET II-04m	Winkler, J

Solar modulation

- When CR enters the solar system it is affected by solar wind for low energy CR. The strength is time-dependent.



- The effect is described by a parameter $$\Phi = \Phi_0 + \Phi_1 \times \frac{N(t)}{N_{\max}}$$

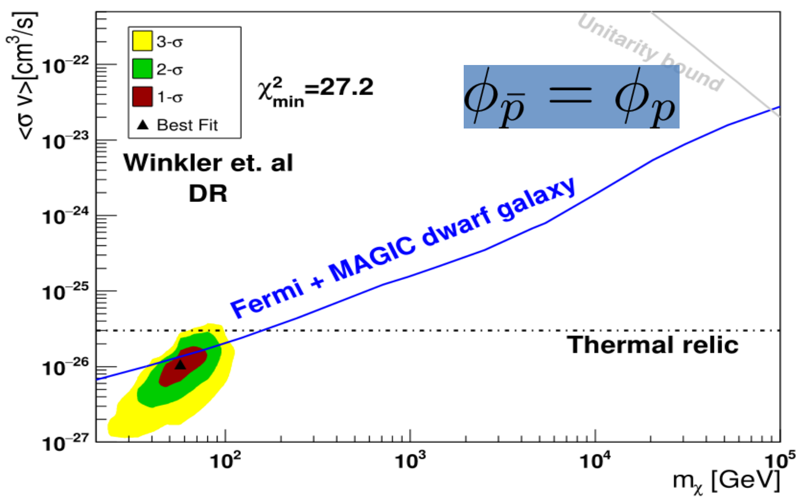


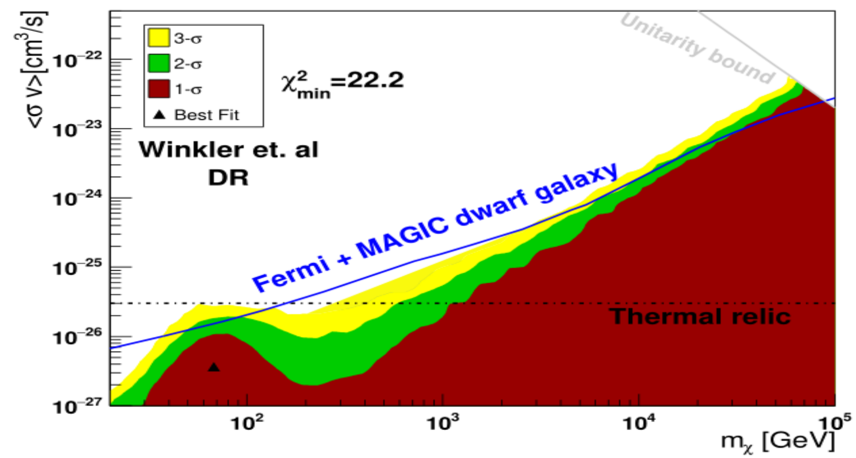
- The effect may be charge-dependent with ϕ+ ≠ ϕ-

Results - Excess at the low energy – 1, solar modulation

- The signal depends on the solar modulation sensitively.

$$\phi_{\bar{p}} \sim \left[\frac{1}{1.5}, 1.5\right] \phi_p$$

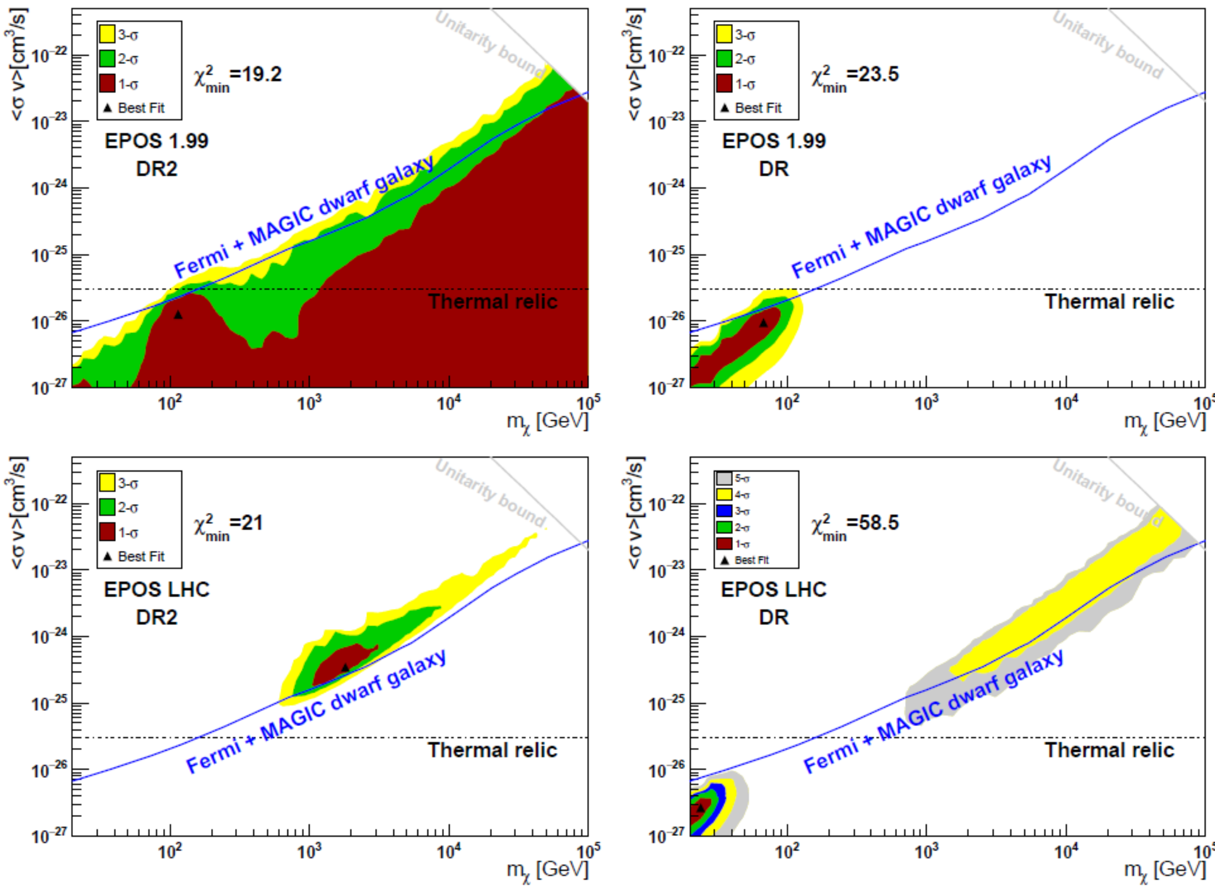




Lin, Bi, Yin, PRD
Phys.Rev.D 100 (2019) 10, 103014

Excess at the low energy – 2, propagation

- Excess only in DR model not in DR2 model



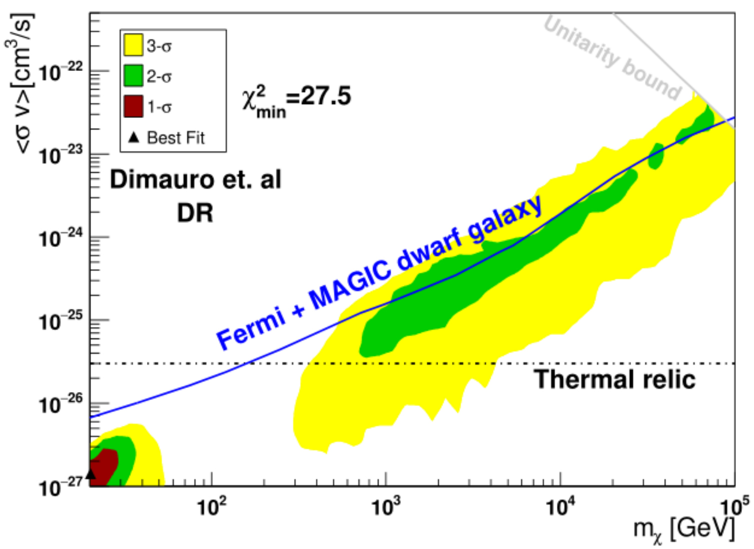
$$\phi_{\bar{p}} = \phi_p$$

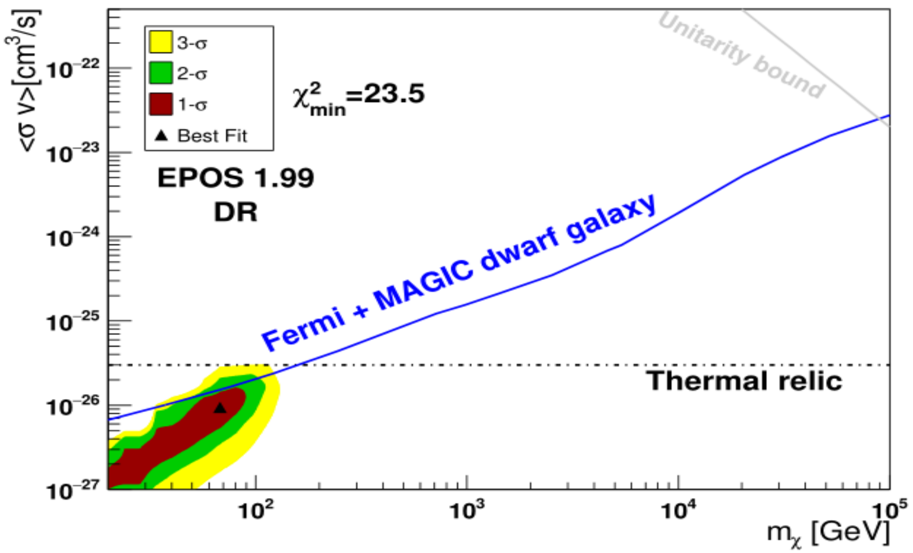
$D=\beta^{\eta}D_0(\rho/\rho_0)^{\delta}$

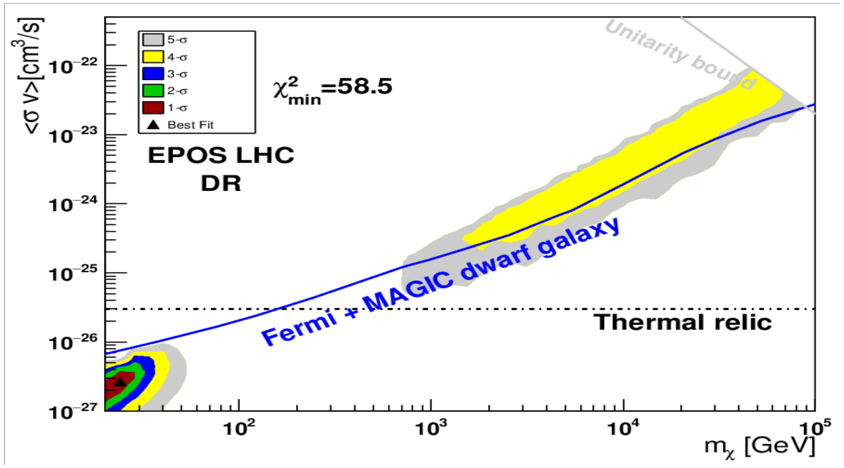
DR for η =1

DR2 for η free

Excess at the low energy –
3, hadronic interactions lead to different signals



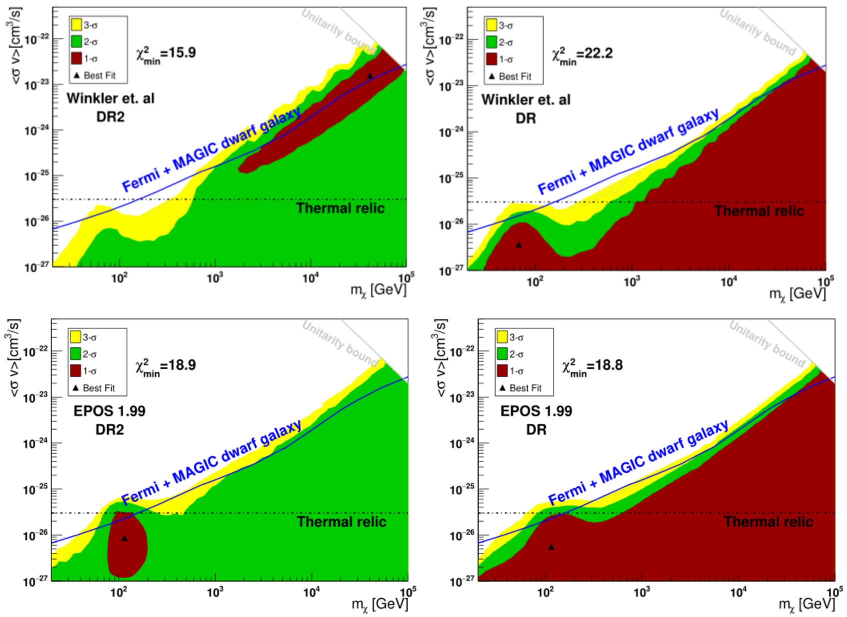




$$\phi_{\bar{p}} = \phi_p$$

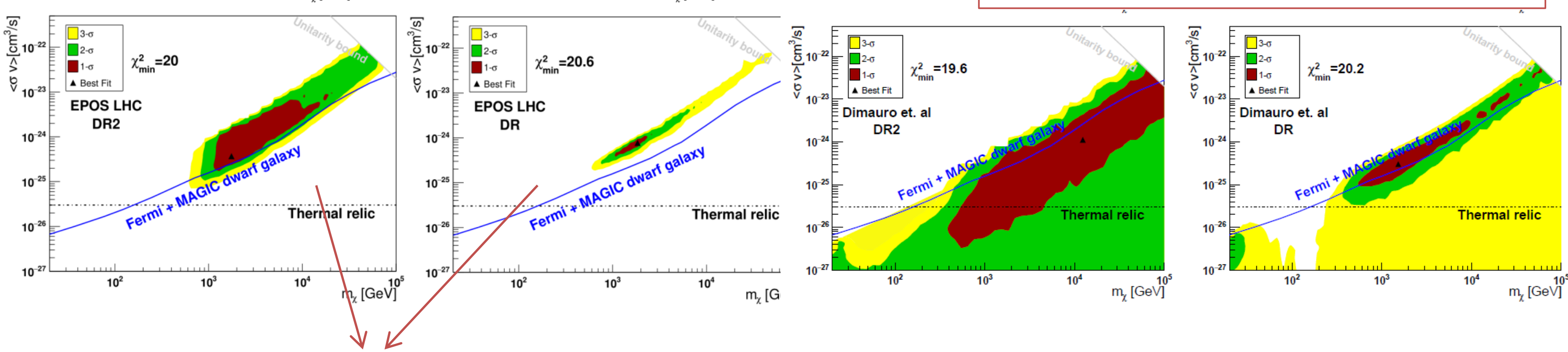
Results - Excess at the high energy end

- Different propagation/hadronic interaction



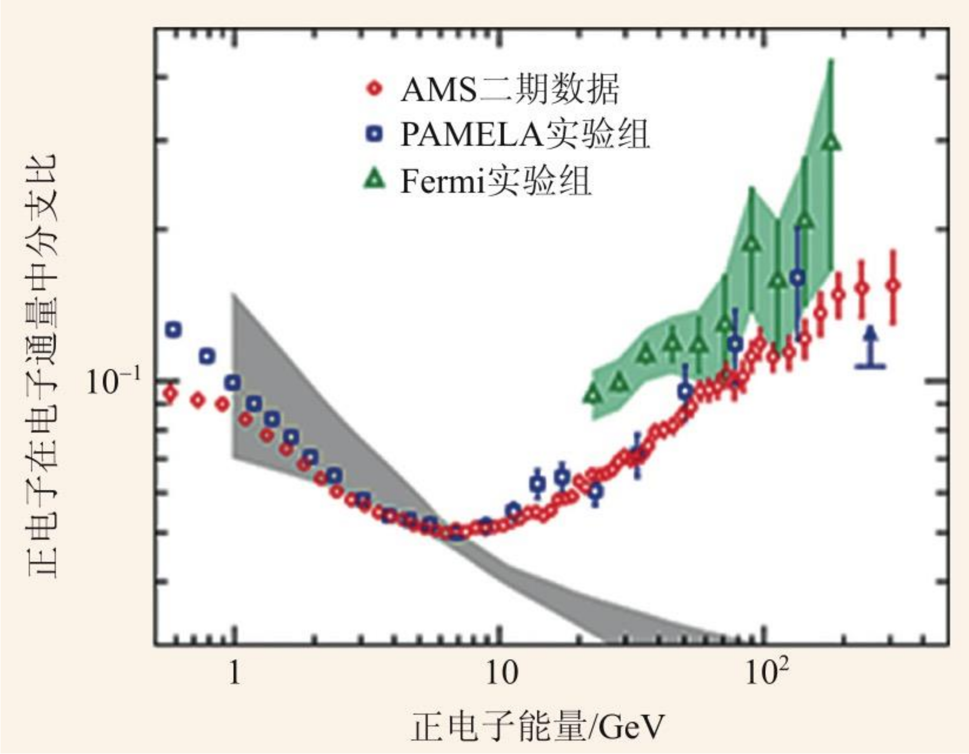
If there is an excess or not depends on the hadronic models. For most hadronic models we only get an upper limit on the annihilation cross section; for EPOS-LHC there is a ~3σ excess.

Lin, Bi, Yin arXiv:1903.09545



EPOS LHC is the latest model adjusted to fit LHC data

Positron excess and extra e+ sources

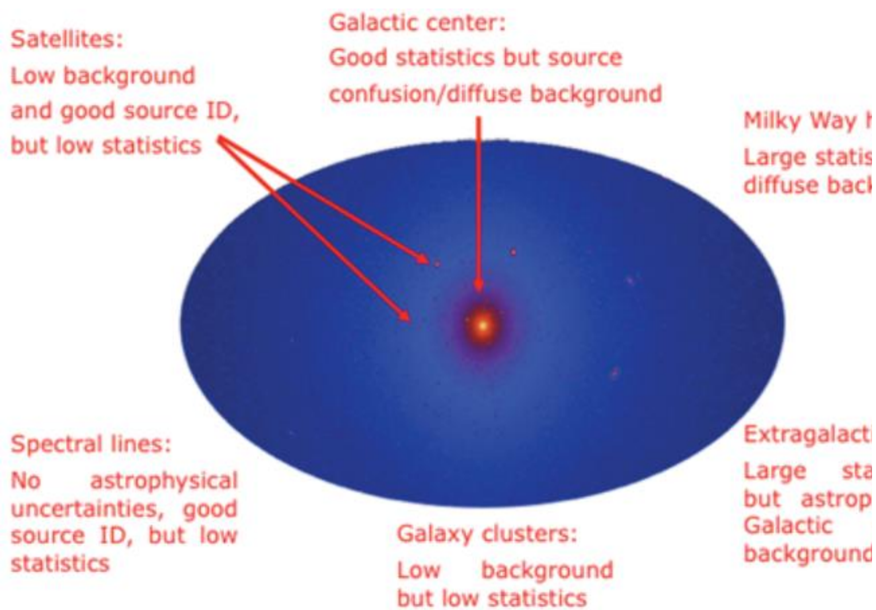


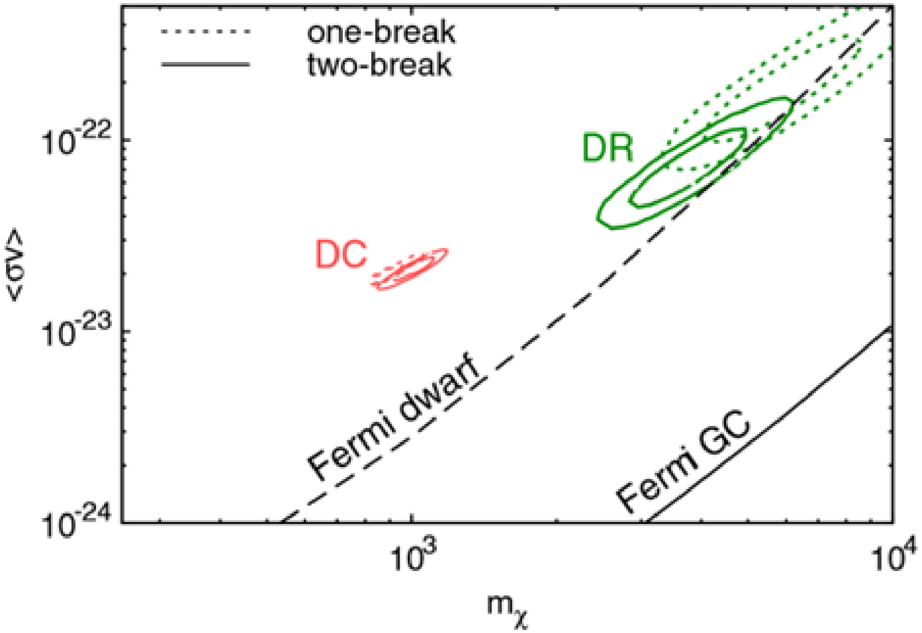
Positron excess detected by PAMLEA is confirmed by AMS-02 with higher precision.

Extra positron sources:

- Dark matter X X ⟶ 。 。 。 ⟶ e^-e^+
- Astrophysical sources – pulsars ⟶ e^-e^+

Constraints on the DM models





Channels	m_χ(TeV)	AMS-02 (2σ)	Fermi limits	Planck limits
$\mu^+\mu^-$	0.89	$3.79 \times 10^{-24} < \langle\sigma_{\rm ann}v\rangle <$ 6.4[illegible] $\times 10^{-24}$	2.95×10^{-24}	2.58×10^{-24}
$\tau^+\tau-$	3.89	$5.29 \times 10^{-23} < \langle\sigma_{\rm ann}v\rangle < 1.06 \times 10^{-22}$	1.25×10^{-23}	1.06×10^{-23}

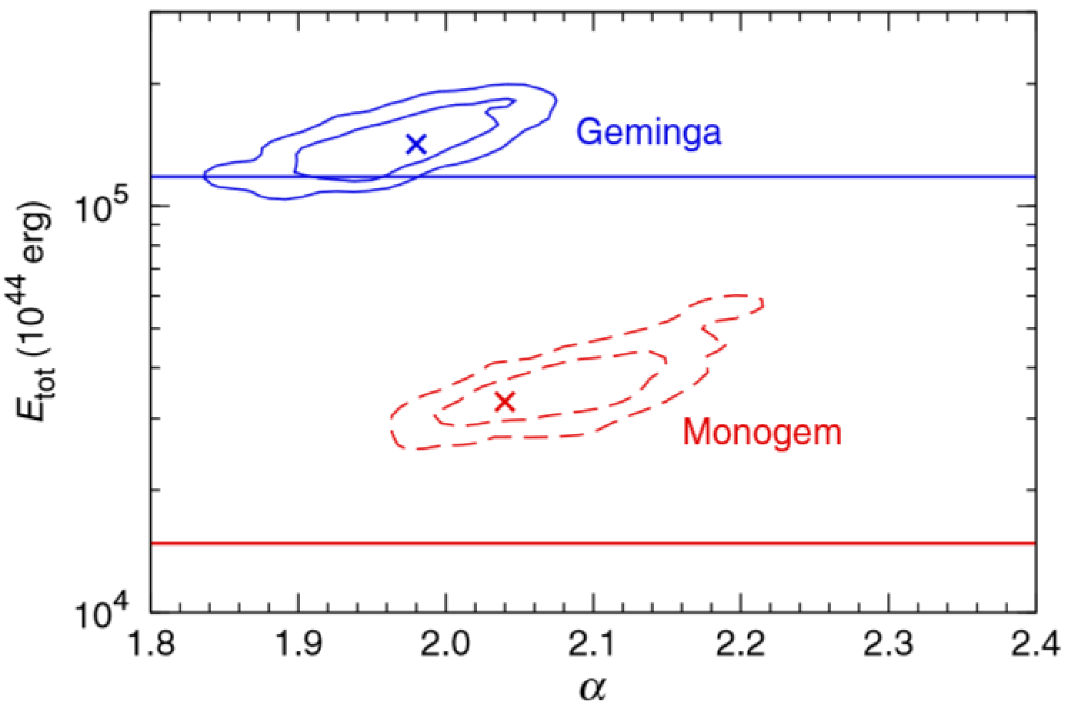
Excluded!?

Q. Xiang, X. Bi, S. Lin, P. Yin 2017

Fermi PRD2014

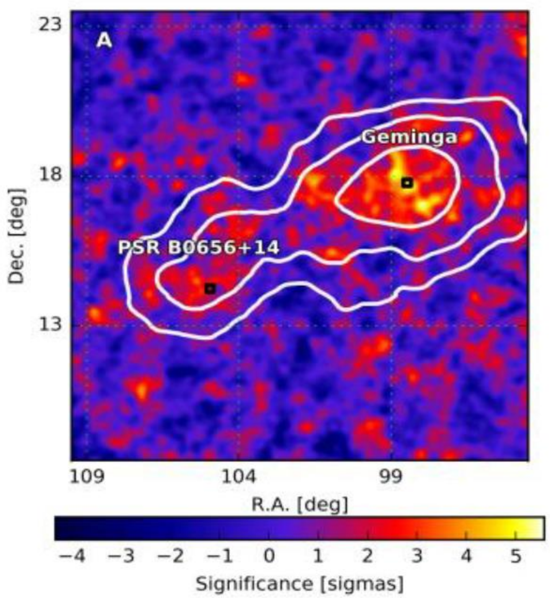
DM needs very large annihilation cross, but severely constrained by Fermi and Planck observations.

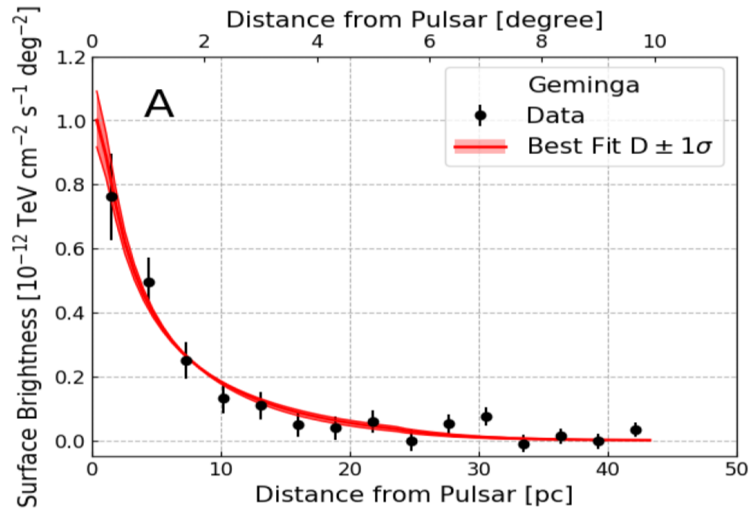
Geminga and Monogem are most possible candidates



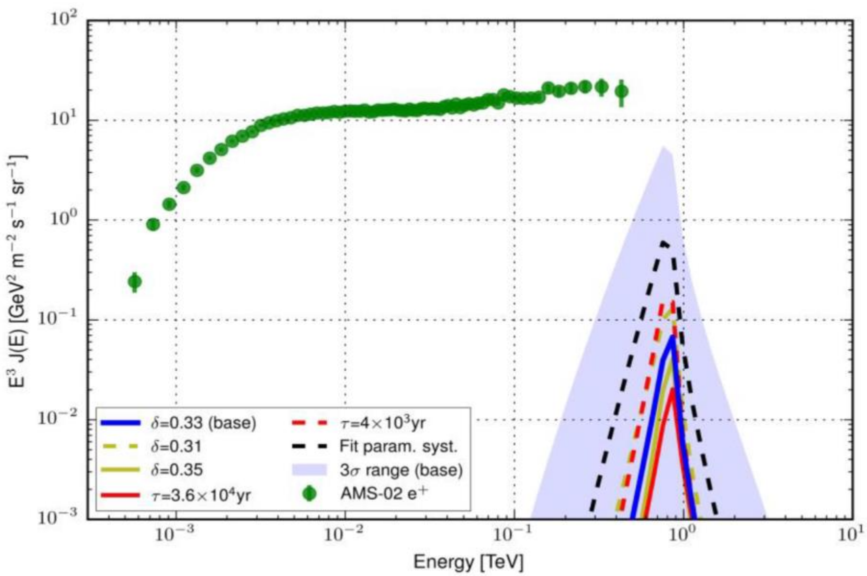
Considering all possible uncertainties, pulsars can explain the positron excess marginally assuming 100% spin-down energy transferred to e+-.

New development --TeV gamma-ray halo of Geminga/Monogem



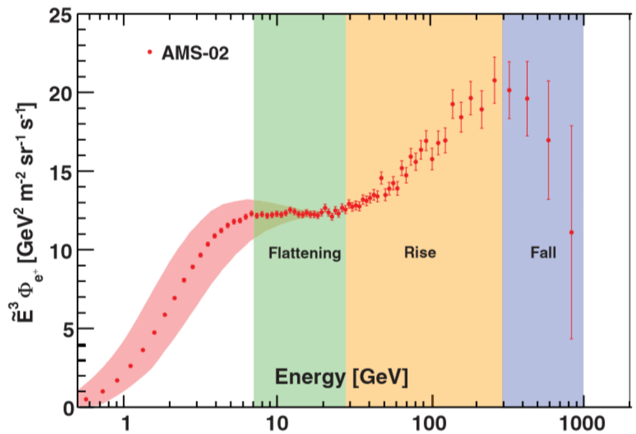


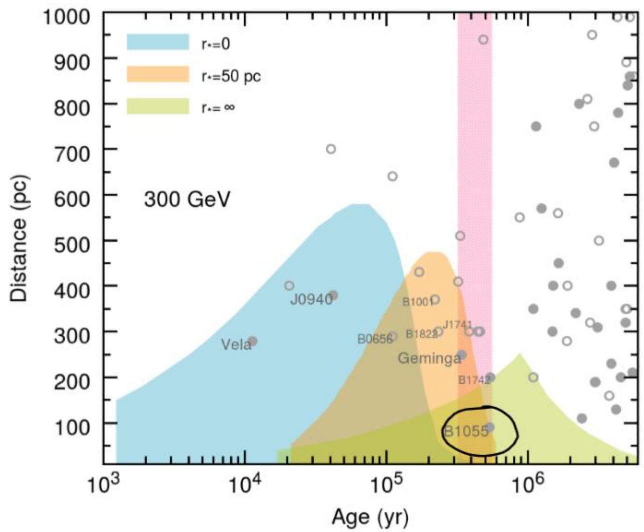
A.U. Abeysekara et al. HAWC collaboration, Science 2017

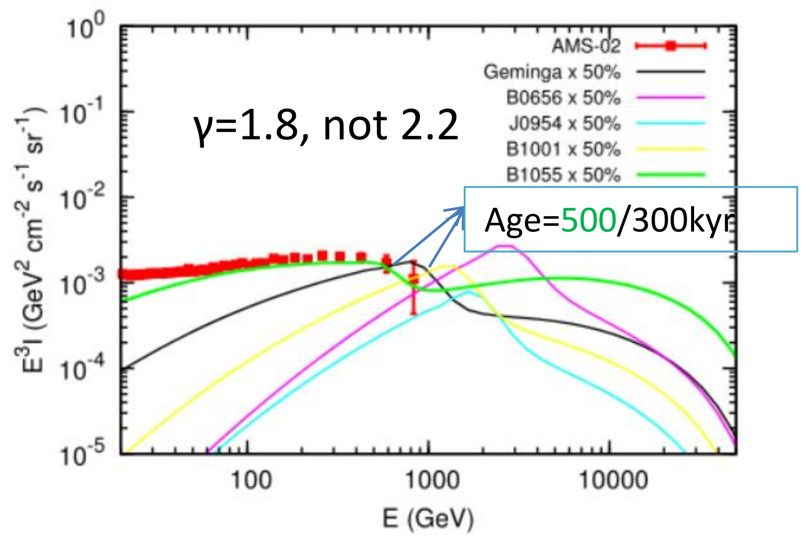


- ➢ PWN accelerate high energy e+- !
- ➢ The diffusion coefficient is hundreds times **smaller** than the conventional value at the ISM derived by B/C !
- ➢ In slow diffusion, the positron flux from the pulsar is negligible to AMS-02 data! Need exotic sources!

Our new analysis





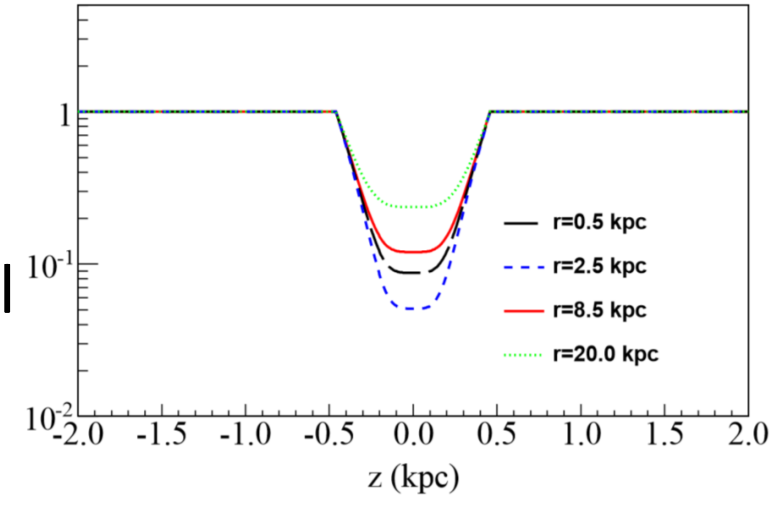


- Reanalyzed the pulsars contribution in a two-zone diffusion model.
- A older and closer pulsar is an ideal source to account for AMS-02. B1055 is the best one.

Non-uniform propagation

- Considering that 1-3 SNs are generated each 100 years with a lifetime ~10^6 years, there are about ~10^4 such slow diffusion regions (r*~50pc), which take significant fraction at the Galactic disk. Therefore we expect the disk diffusion on average is slower than that outside of the disk. We call it a non-uniform CR propagation in the Galaxy.

- Such a picture is different from the conventional one may lead to different bkg and dark matter signal



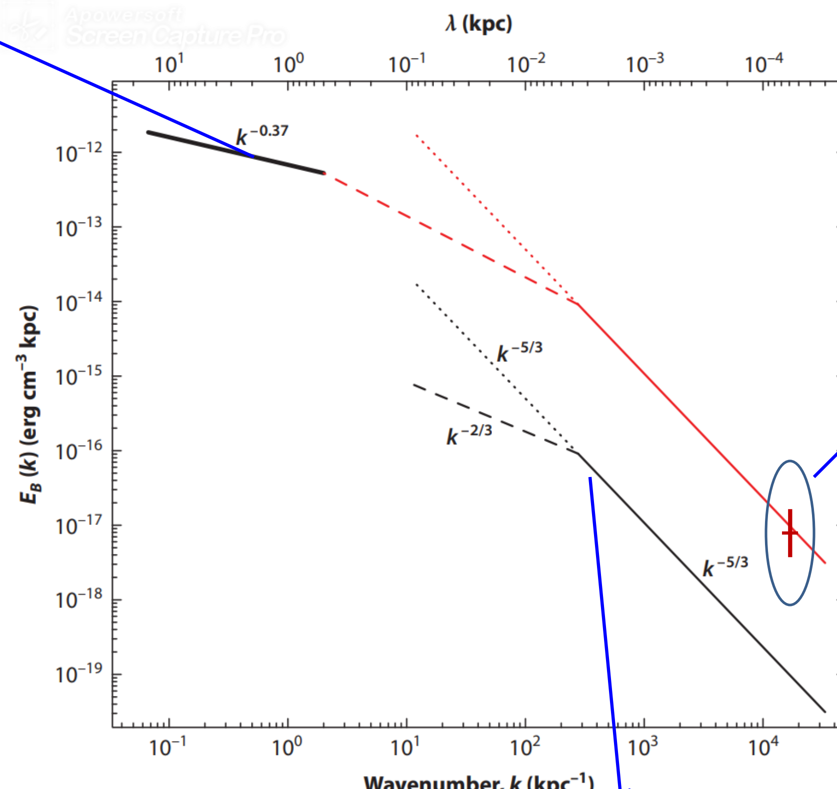
Different magnetic field power in the disk and halo

- Magnetic field is measured at disk and halo

Han, J., ARA&A55:111,2017

银盘上磁场
功率谱

- It is astonished that **the power spectrum at large scale in disk is consistent with that at the very small scale!!**



HAWC结果

高纬度盘外磁场

CR propagation with a slow disk

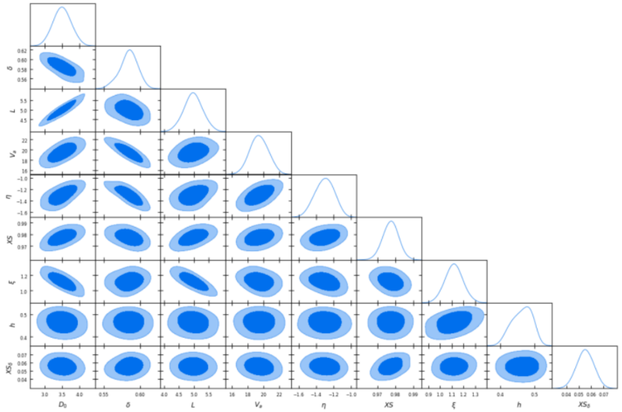
Zhao, Fang, BI PRD 104 (2021) 12, 123001

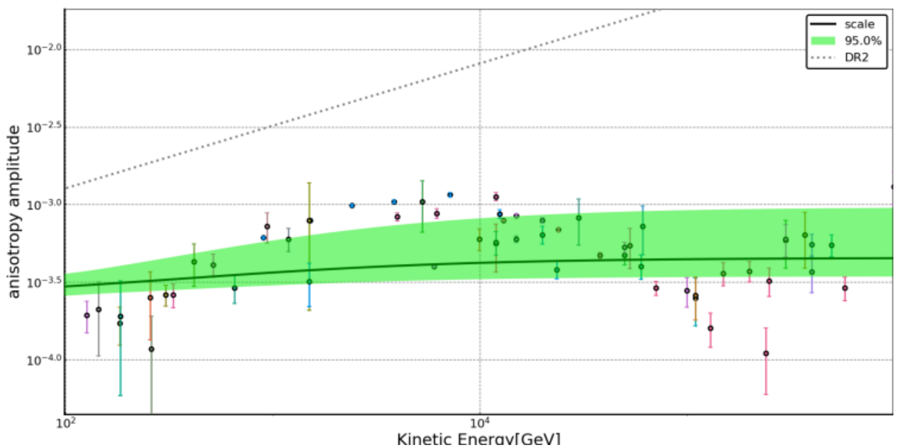
- Fit the AMS-02 C, B/C, Be/B data by MCMC
- We get the slow disk assuming different Ds in disk and halo
- The derived anisotropy of CRs is consistent with the observation

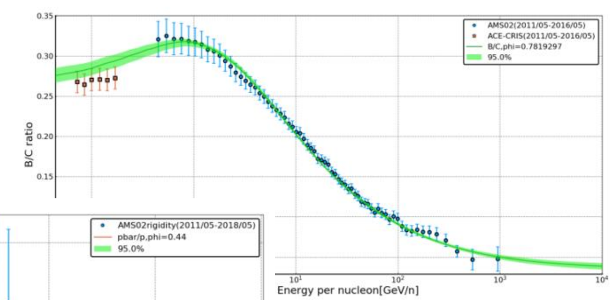
TABLE I. Data Used in This Analysis

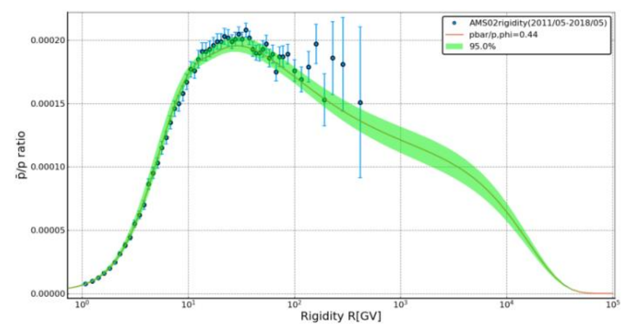
Experiment	Energy Range	data points
	B/C	
AMS-02(2011/05-2016/05)	2-2100 GV	67
ACE-CRIS(2011/05-2016/05)	0.07-0.17 GeV/n	6
	Be/B	
AMS-02(2011/05-2016/05)	2-2100 GV	67
	^{10}Be/^{9}Be	
ISOMAX(1998/08/04-08/05)	0.5-1.6 GeV/n	2
ACE-CRIS(1997/08/27-1999/04/09)	0.08-0.14 GeV/n	3
	C	
NUCLEON(2015/07-2017/06)	250-17000 GeV/n	10
CREAM-II(2005/12-2006/01)	85-7500 GeV/n	9
CALET(2015/10-2019/10)*1.27[a]	10-1700 GeV/n	22
AMS-02(2011/05-2016/05)	0.4-1200 GeV/n	68
ACE-CRIS(2011/05-2016/05)	0.06-0.2 GeV/n	7
Voyager1-HET(2012-2015)	0.02-0.13 GeV/n	8
	B	
Voyager1-HET(2012-2015)	0.02-0.11 GeV/n	8
	Be	
Voyager1-HET(2012-2015)	0.06-0.1 GeV/n	2

[a] a multiplication of 1.27 is described in [19] to get aligned with AMS-02









Antiproton spectrum

Summary

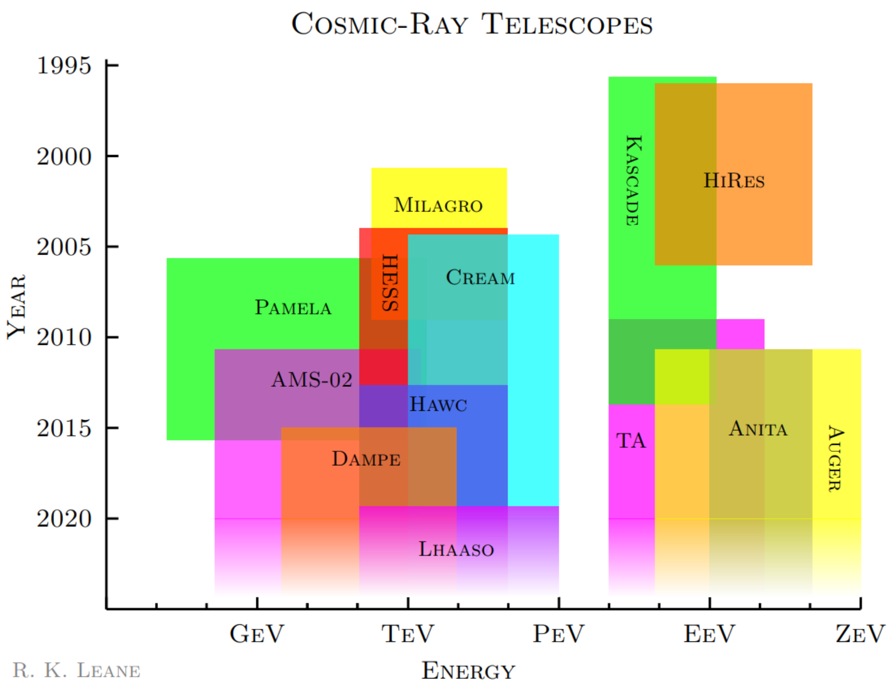
- Small scale structure observations give model independent constraints on the DM particles. There are indications of deviation from the CDM scenario.
- It is promising that powerful instruments will be able to disentangle the baryonic effect and DM effect in the near future.

- GCE origin is controversial – depending on our understand of the bkg diffusion emission.

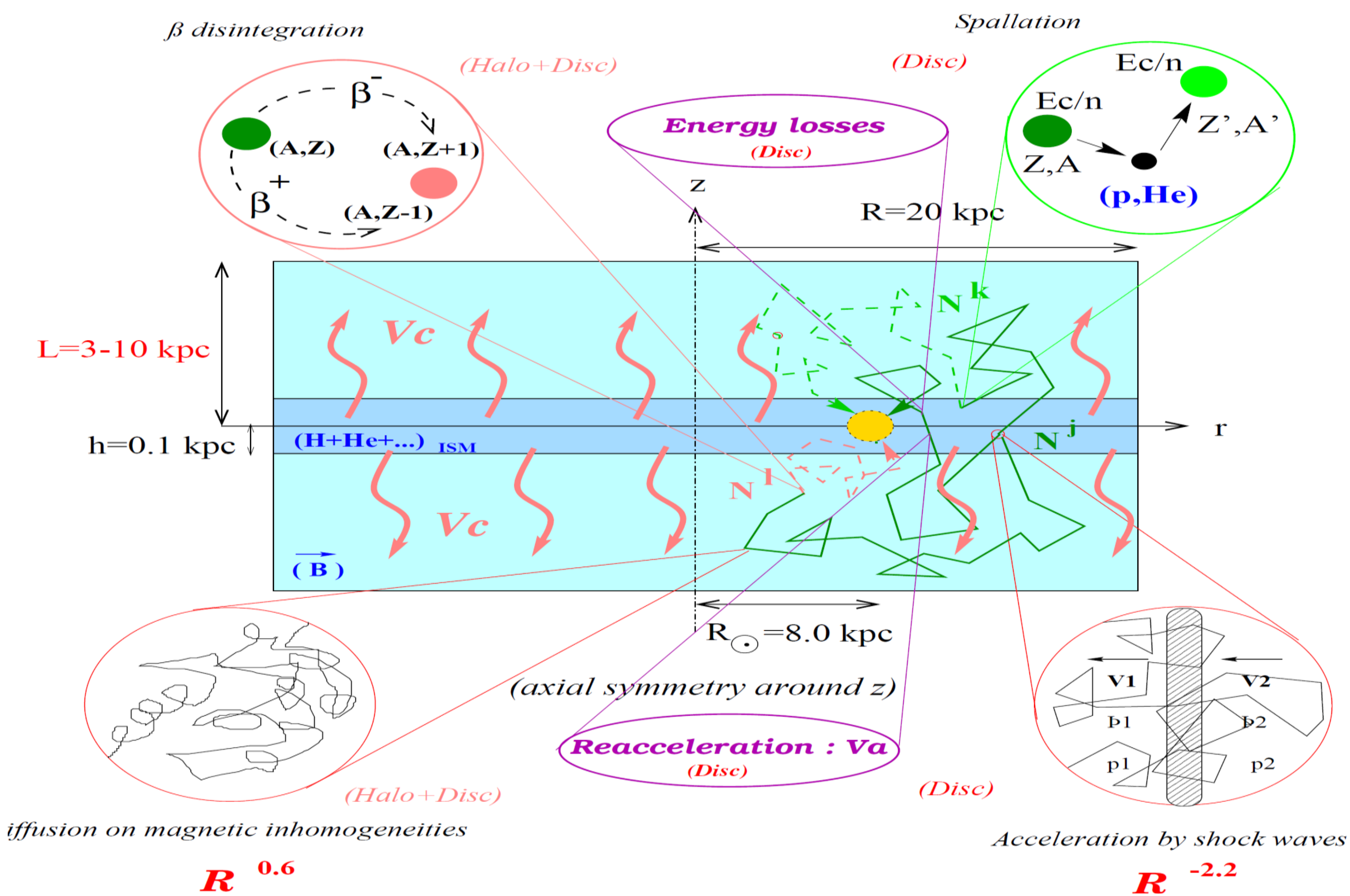
- Antiprons excess has both data error and larger theoretical errors. If there is such an excess is not conclusive at all.

- Positron excess seems originate from pulars.

- Slow diffusion model is established. The bak and signal need be considered again in the new model.

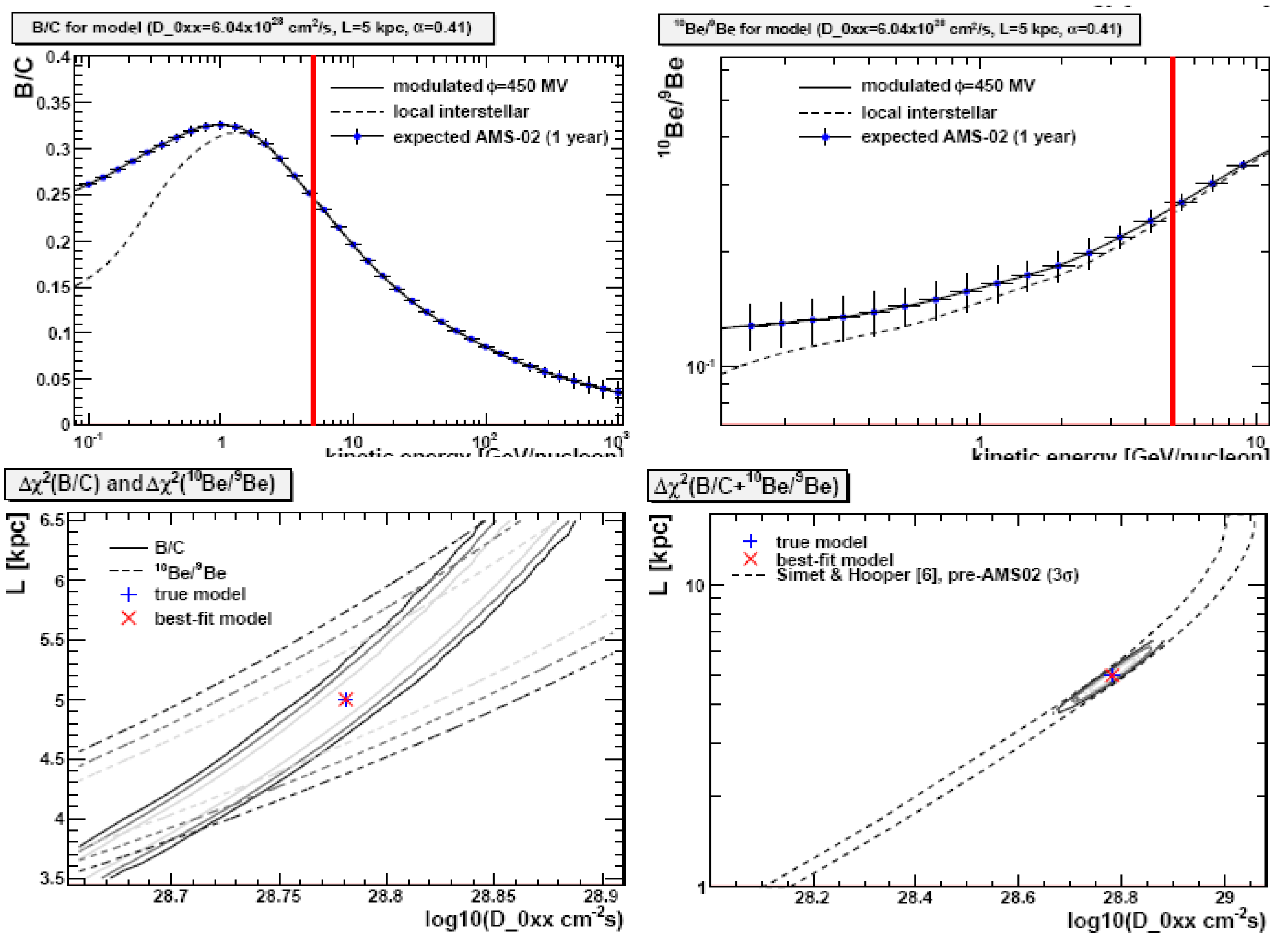

Cosmic-Ray Telescopes
Year
1995
2000
2005
2010
2015
2020
Milagro
HESS
Cream
Pamela
AMS-02
Hawc
Dampe
Lhaaso
Kascade
HiRes
TA
Anita
Auger
GeV
TeV
PeV
EeV
ZeV
Energy
R. K. Leane

银河系宇宙线的传播


β disintegration
(Halo+Disc)
β⁻
(A,Z)
(A,Z+1)
β⁺
(A,Z-1)
Spallation
(Disc)
Ec/n
Ec/n
Z',A'
Z,A
(p,He)
Energy losses
(Disc)
z
R=20 kpc
L=3-10 kpc
h=0.1 kpc
Vc
Vc
N k
N j
N l
(H+He+...) ISM
r
(B)
R⊙ =8.0 kpc
(axial symmetry around z)
Reacceleration : Va
(Disc)
(Halo+Disc)
(Disc)
V1
V2
p1
p2
p1
p2
iffusion on magnetic inhomogeneities
R 0.6
Acceleration by shock waves
R -2.2

1. B/C, (Sc+Ti+V)/Fe, ^{10}Be/^{9}Be, ^{26}Al/^{27}Al

- 通过次级元素和原初元素的比例研究宇宙线传播

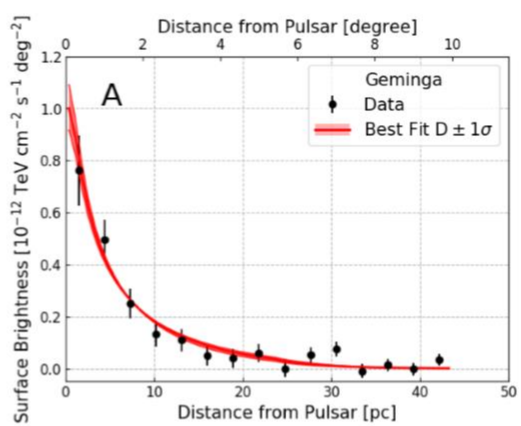


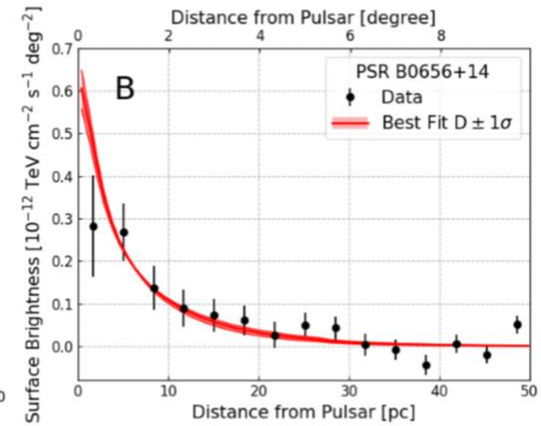
Pato et al. 2010, JCAP

HAWC的结果

Abeysekaraa et al. Science 2017

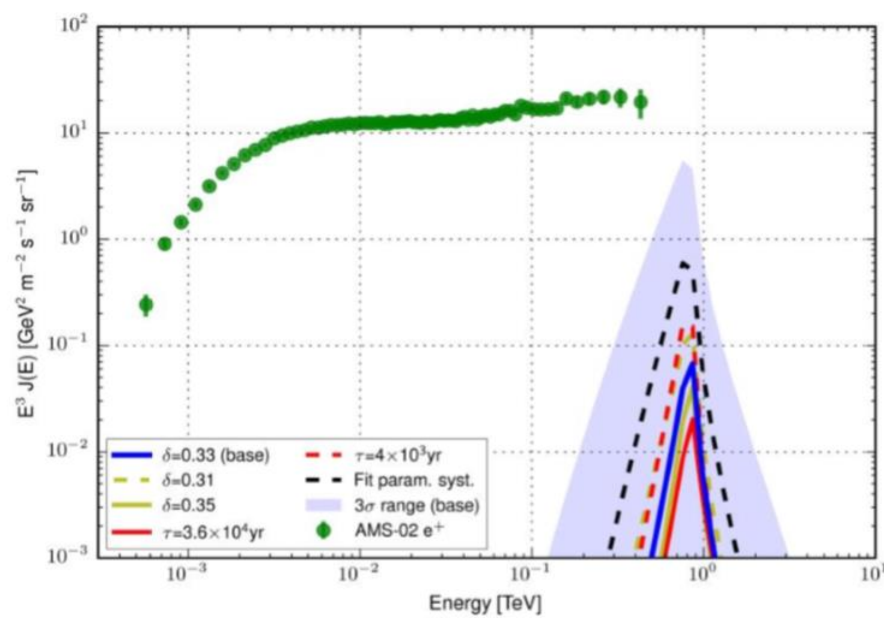
- 扩散系数非常小（远远小于B/C定出的扩散系数）



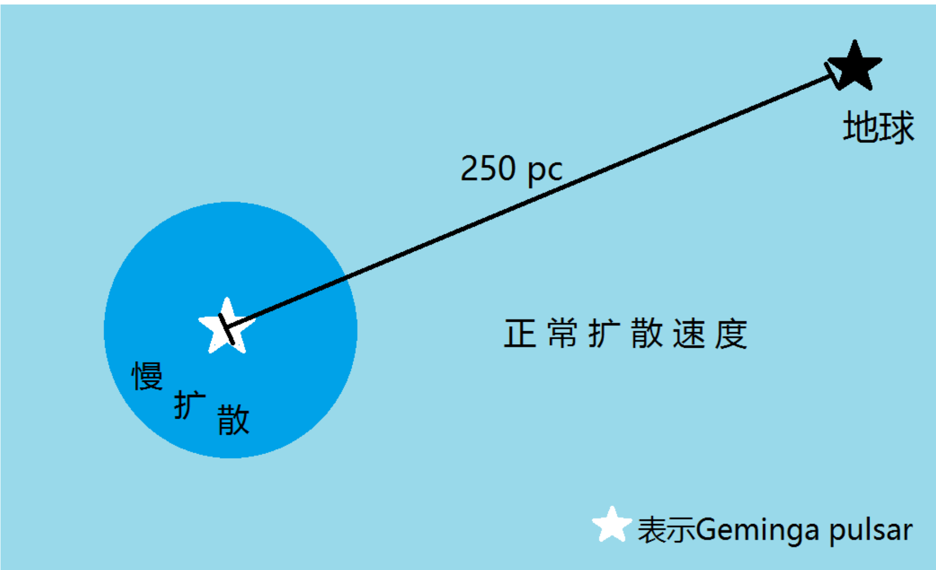


- 电子流强非常小

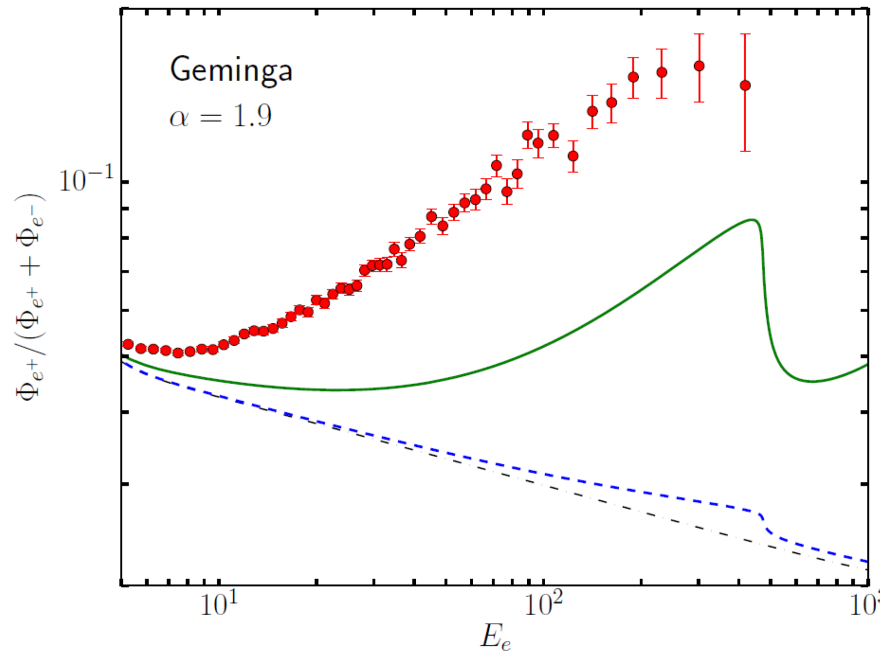
- 高能电子传播->是否来自于邻近天体？



双区扩散模型与Geminga



双区扩散



D. Hooper et al. 2017
绿色实线表示强对流
蓝色虚线表示弱对流

- 需要慢扩散区域有对流？HAWC的观测不支持对流
- Geminga的距离为250 pc，而按正常扩散速度，1 TeV的电子在Geminga的寿命内扩散距离为1.7 kpc，是前者的7倍

双区扩散模型与Geminga

传播方程： $$\frac{\partial N}{\partial t} - \nabla(D\nabla N) - \frac{\partial}{\partial E}(bN) = Q\,,$$

扩散系数： $$D(E,r) = \begin{cases} D_1(E), & r < r_\star \\ D_2(E), & r \geq r_\star \end{cases}\,,$$

其中D1是HAWC给出的扩散系数，D2是通常的扩散系数

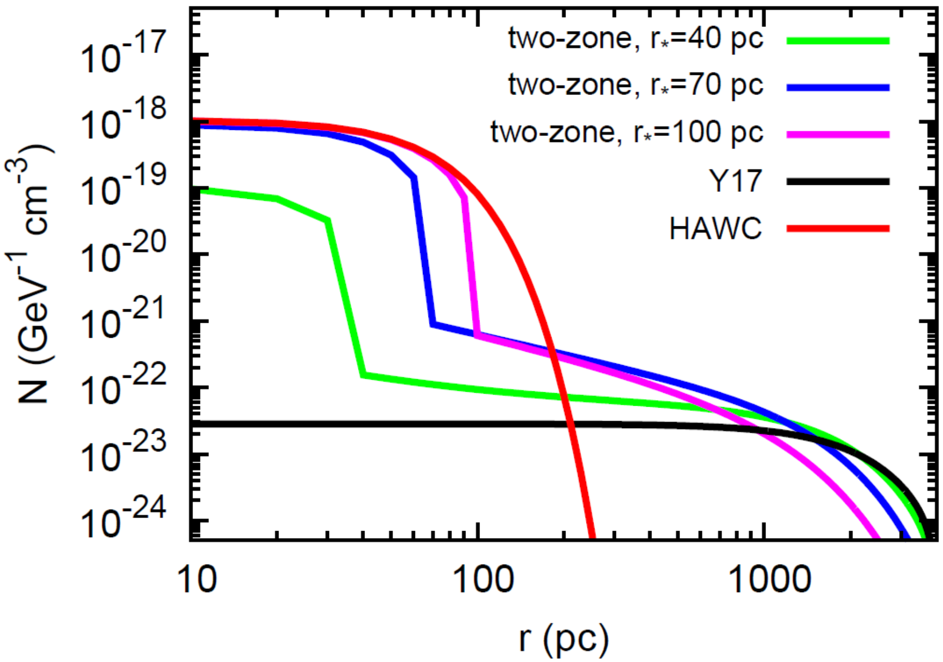
传播方程需要以数值方法求解

算子分裂法：
$$\mathcal{L}_r = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(r)\frac{\partial}{\partial r}\right]\,,$$
$$\mathcal{L}_E = b\frac{\partial}{\partial E} + \frac{\partial b}{\partial E}\,.$$

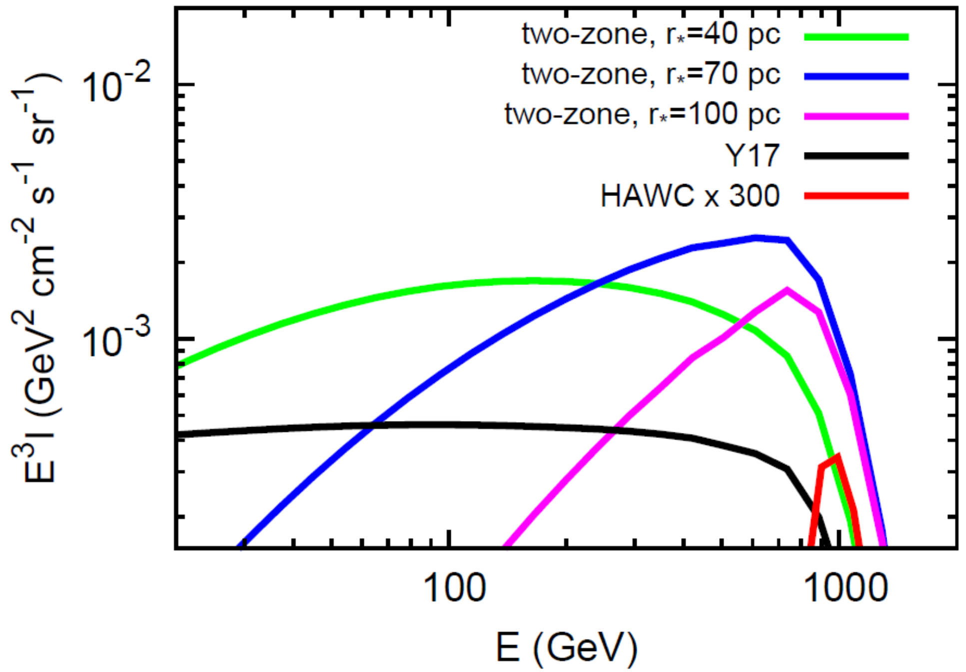
- 有限体积法处理扩散算子（保证粒子流量的守恒）
- Galprop和Dragon仅适用于扩散系数变化连续且缓慢的情况

双区扩散模型与Geminga

1 TeV电子空间分布



电子能谱

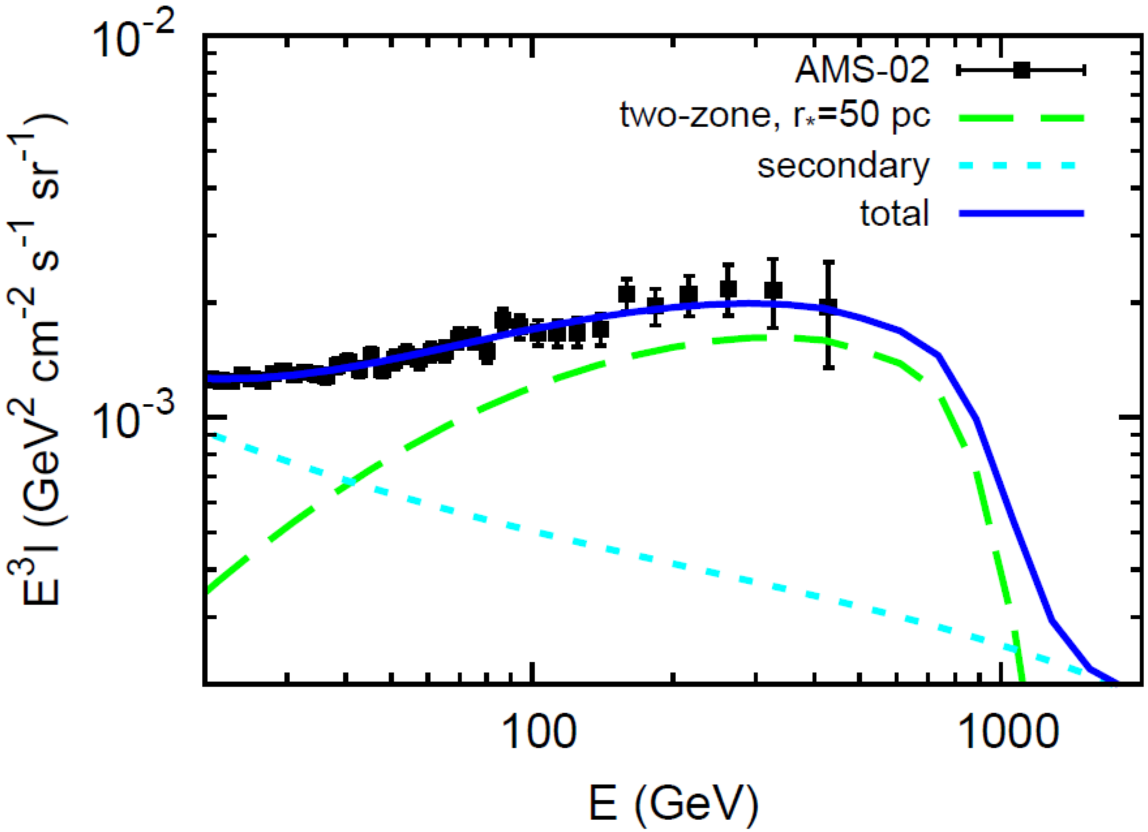


K. Fang, X. Bi, P. Yin, Q. Yuan 2018

- 黑色代表正常快扩散
- 红色代表HAWC给出的慢扩散
- 其它颜色分别对应不同的r_star：40 pc，70 pc，100 pc

双区扩散模型与Geminga

与AMS-02正电子能谱的对比



- 取r_star是50 pc
- 所需要的转动减慢能量到正负电子能量的转化率为75%

双区扩散模型下Geminga仍可以对正电子超出有显著的贡献！

K. Fang, X. Bi, P. Yin, Q. Yuan 2018