Massive star clusters as Sources of Galactic Cosmic Rays

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Galactic Cosmic Rays (GCR)

Current Consensus

- Single power law spectrum from 10 GeV up to 1 PeV

- Injection rate of ~ 10^{40} erg/s in the Galaxy

- Supernova remnants (SNR) as sources?

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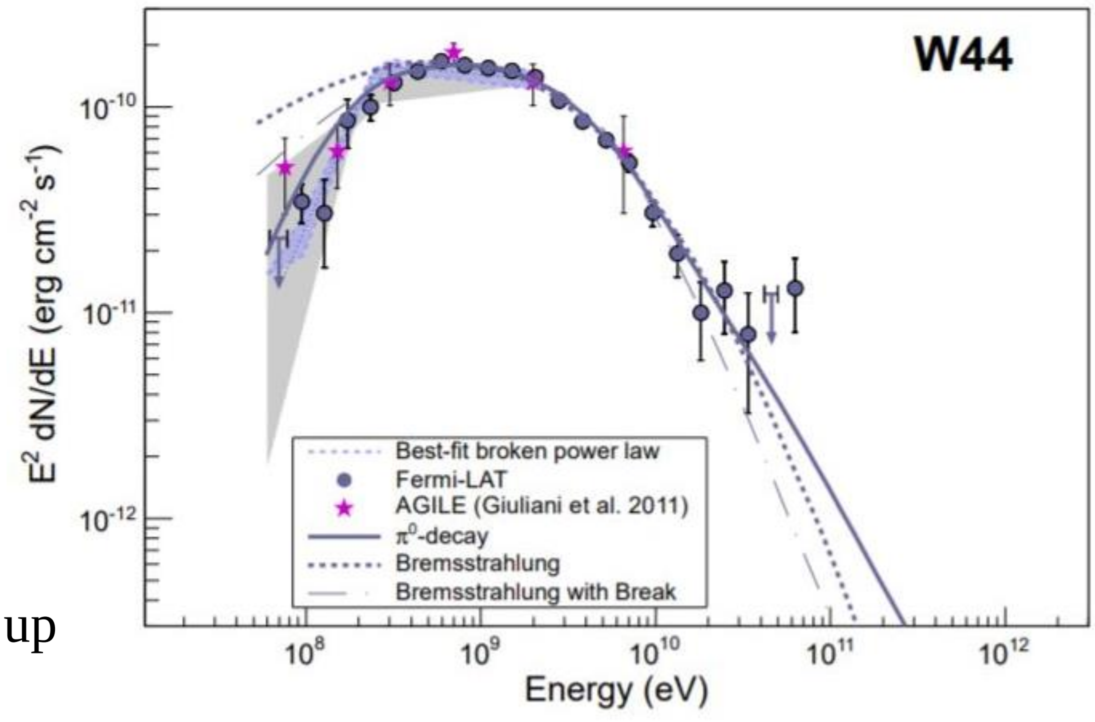
SNRs as CR source

Mid-age SNRs

- Clear Pion-decay feature.
- Hadronic origin
- Break at ~ 10 GeV
- Cannot account for all CRs up to PeV

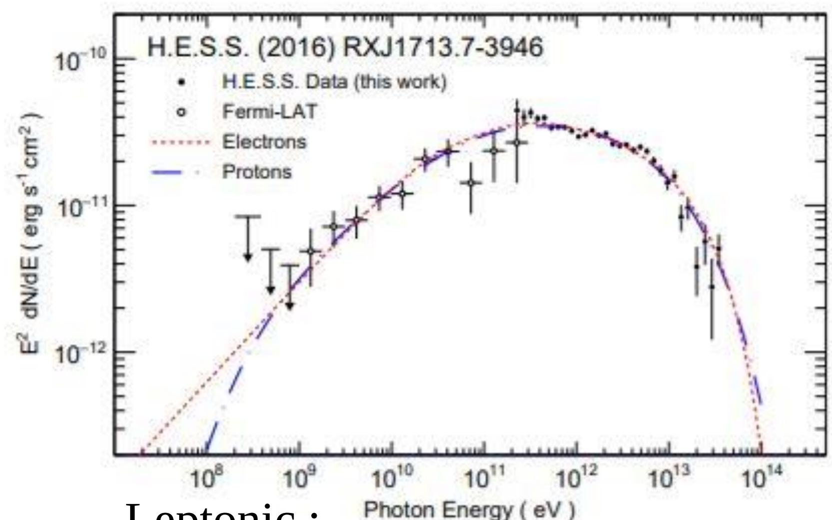


Fermi Collaboration 2013

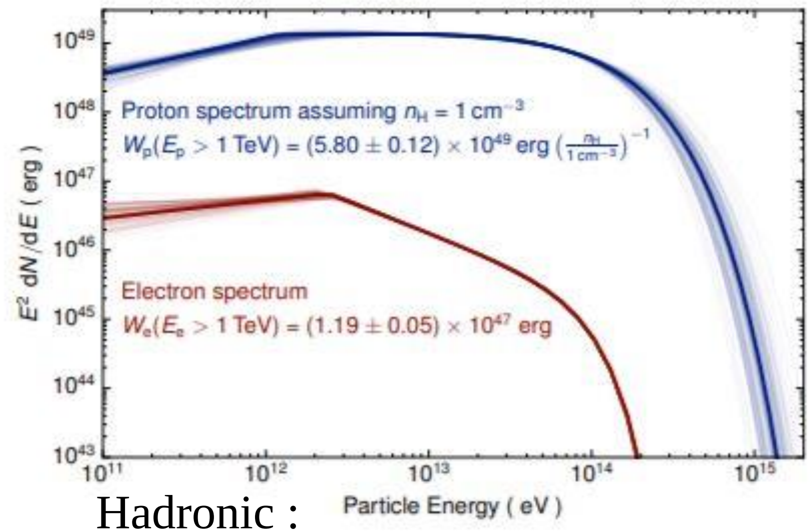
Young SNRs

- *Hadronic or Leptonic?*

The case for RX J1713 (HESS 2017)



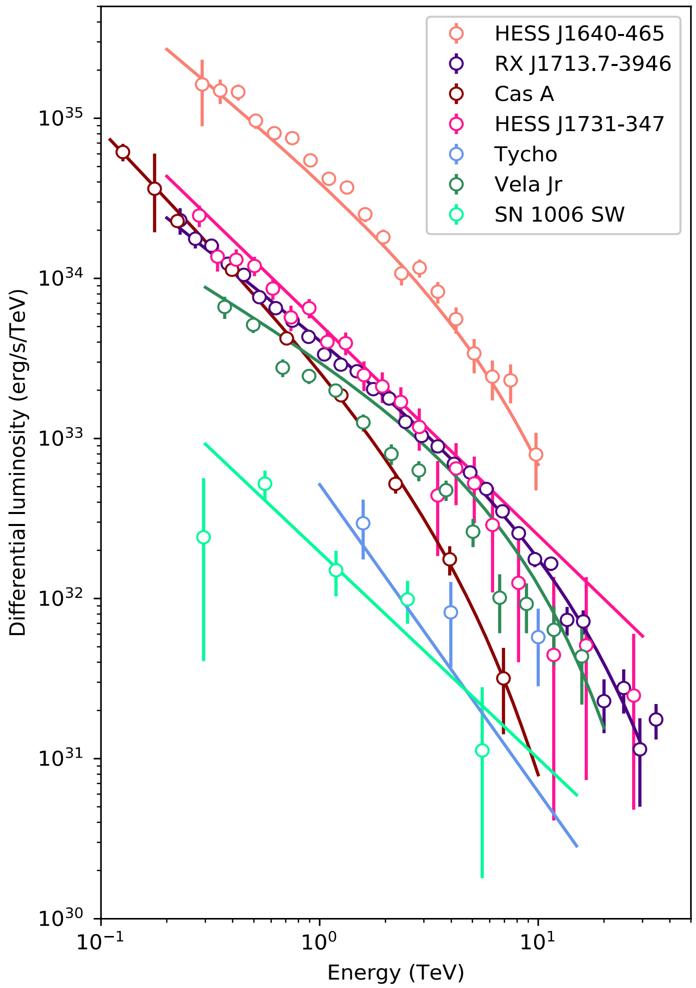
Leptonic :
B=15 μG
We ≈3.4 e47 erg



Hadronic :
B=200 μG
Wp ≈2 e50 erg

Cannot give preference, both have attractive features but also serious problems

Gamma-ray observation of Young SNRs



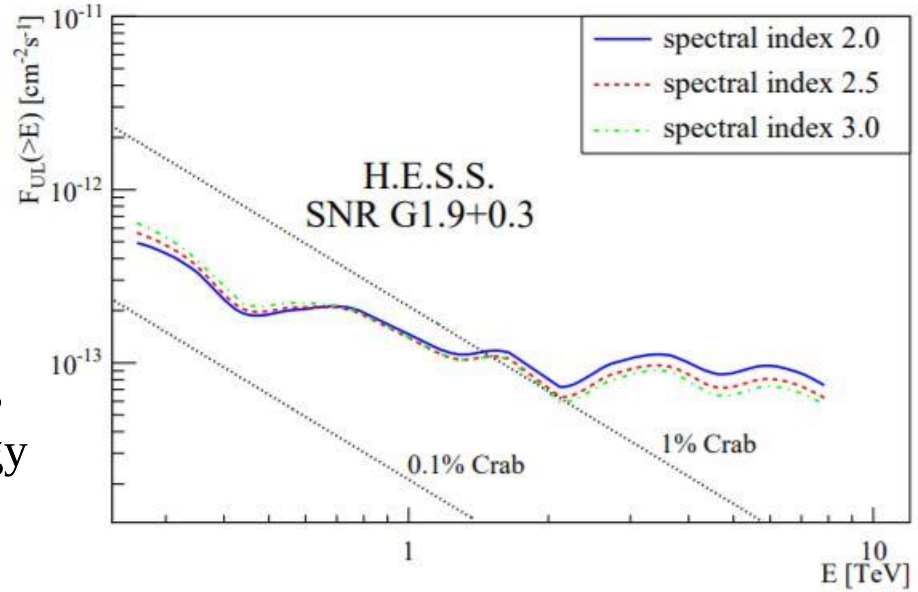
- All gamma-ray spectrum young SNRs shows soft spectrum or early cutoff at ~ 10 TeV
- corresponding to CR energy of 100 TeV
- Hard to address a single power law spectrum of CRs up to PeV

On the hadronic scenario

- lack of thermal emission in RXJ 1713.7-3946
- almost the entire available energy goes to acceleration?
- very low gas density but γ rays are produced in "clumps“ (e.g., inoue 2012)
- relatively steep spectra of VHE gamma-rays ($\Gamma \sim 2.3 - 2.5$) in all young SNRs
- “early cutoffs” - in all SNRs < 100 TeV
- Maybe we can relax and accept that SNRs are the main contributors to GCRs but until 10-100 TeV, and other sources (PeVatrons) responsible for the knee around 1 PeV ?

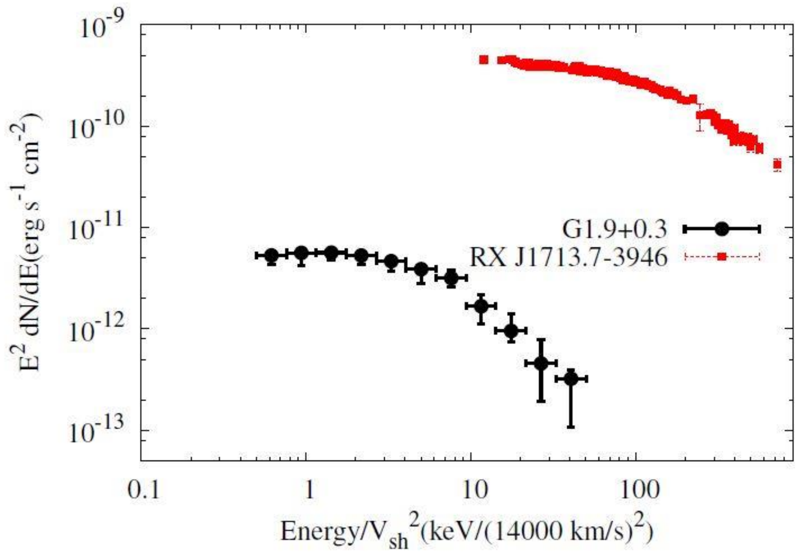
Very young SNRs?

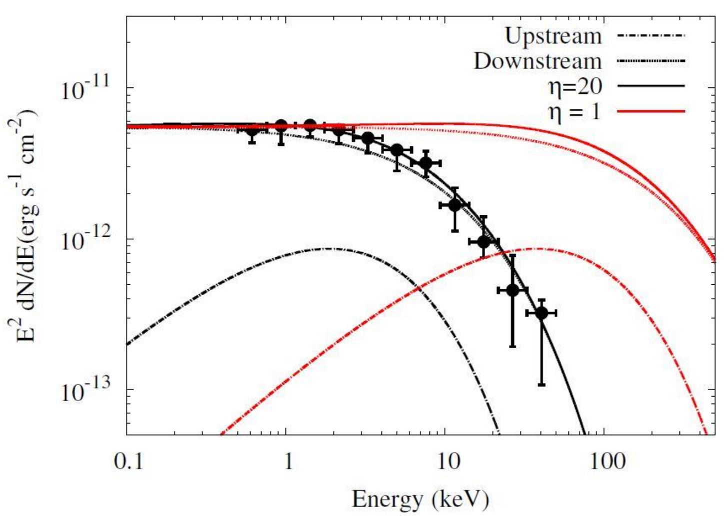
- PeVatron phase could be accomplished only during the first years of the explosion (e.g., Bell et.al 2013)
- The youngest SNR in the Galaxy:
  G1.9+0.3, t~ 100 yr
- VHE protons cannot propagate more than 30 pc.
- HESS reveals L(>1 TeV) < 1e32 erg/s can be used to set limit on proton energy budget.
- Considering a high density in the vinicity (near GC), the total energy on VHE protons are below 1e45 erg. Not enough to account for the CR flux up to the knee.



Very young SNRs?

- X-ray observations on G1.9+0.3 (Aharonian et.al 2016)
  - Shock speed ~ 14,000 km/s
  - in the Bohm diffusion limit the synchrotron peak should be at around 20 keV but is detected at 1 keV
  - Not efficient accelerator





Massive star clusters: Alternative CR sources?

- GCR distribution reveals a similar peak as that for OB stars.
- Isotope measurement favor a superbubble origin. (W.R Binns 2016)
- Most of OB stars exist in associations or clusters, stellar wind can accelerate CRs (Cesarsky & Montmerle 83).
- Efficiency may even better than SNR (high speed wind lasts much longer than SNR shock)
- Sufficient wind power (10^{38} - 10^{39} erg/s for each cluster, more than -10^{41} erg/s in the Galaxy) to account for CRs
- Could be visible in gamma-ray due to CR-gas interaction.

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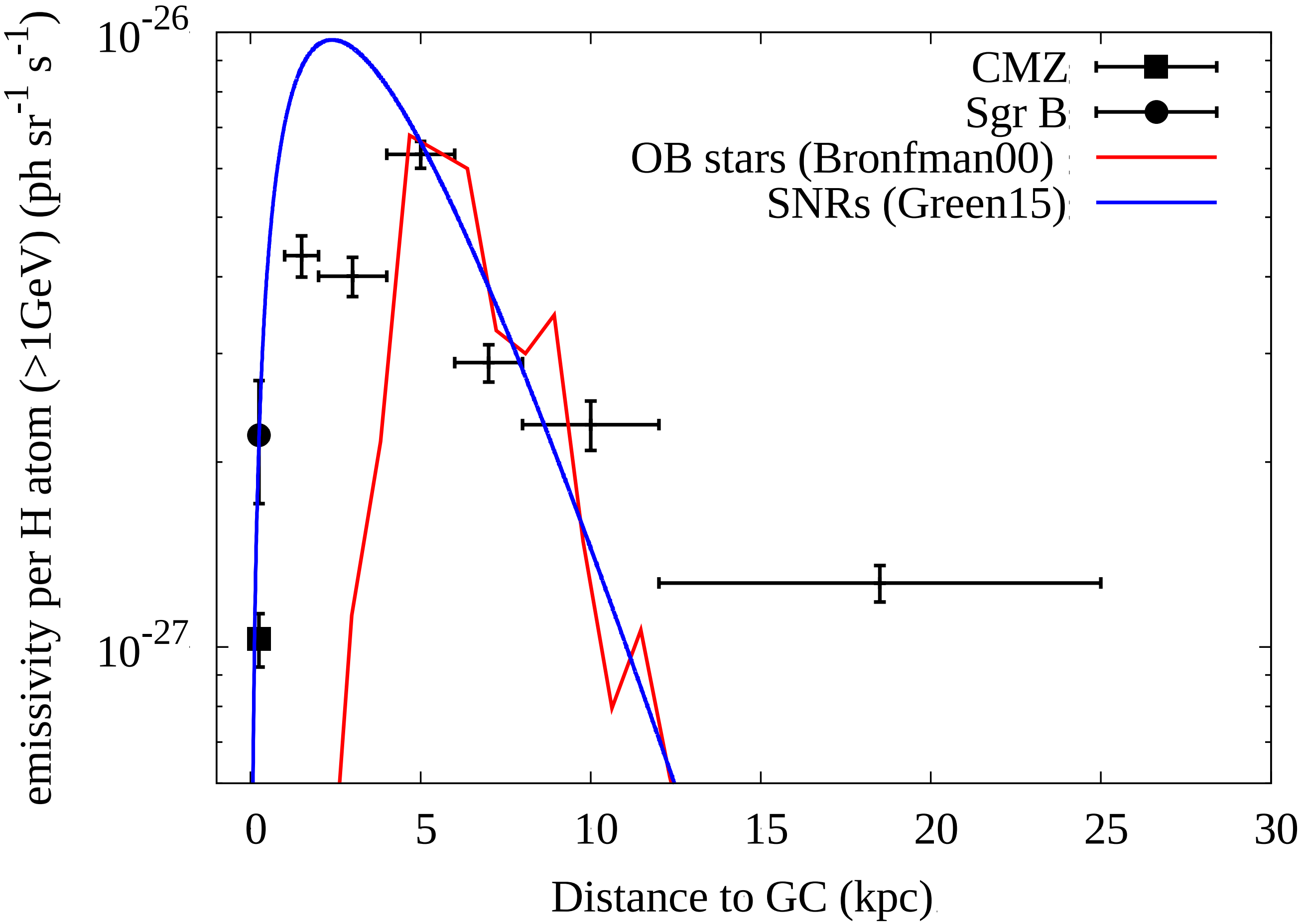
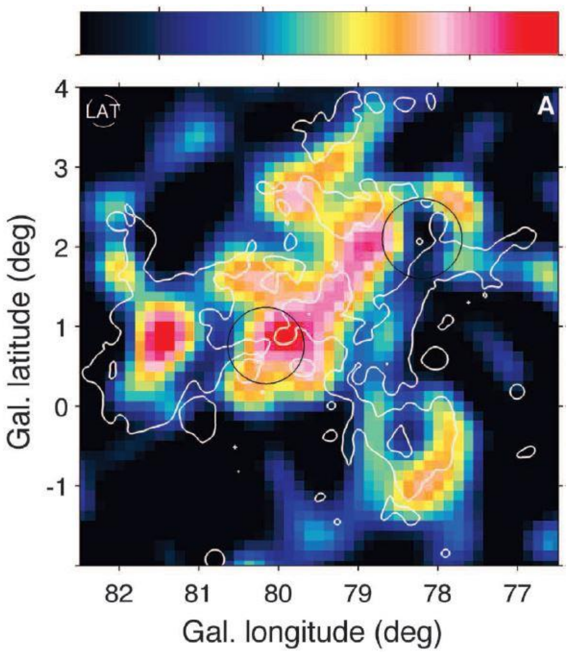
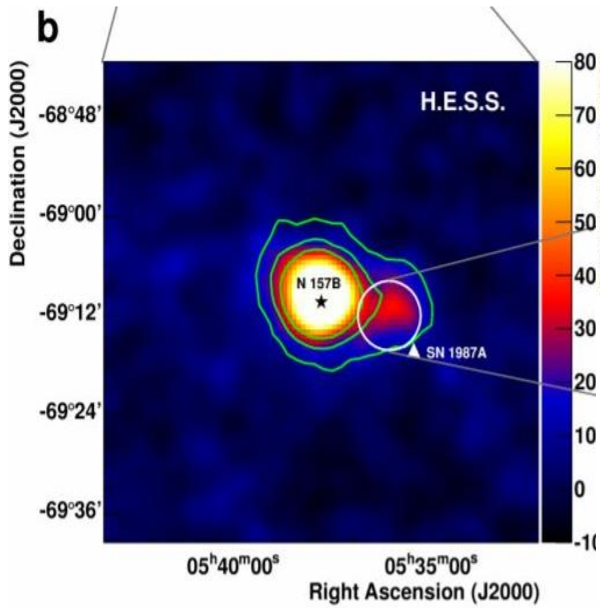
CR distribution VS Source distributions in the Galaxy

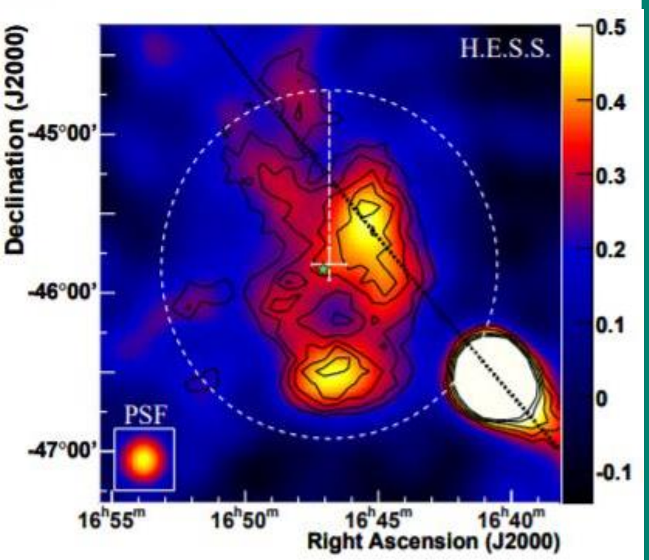


Yang et.al 2016

Known candidates







Cygnus Cocoon
(Fermi Collaboration 2012)

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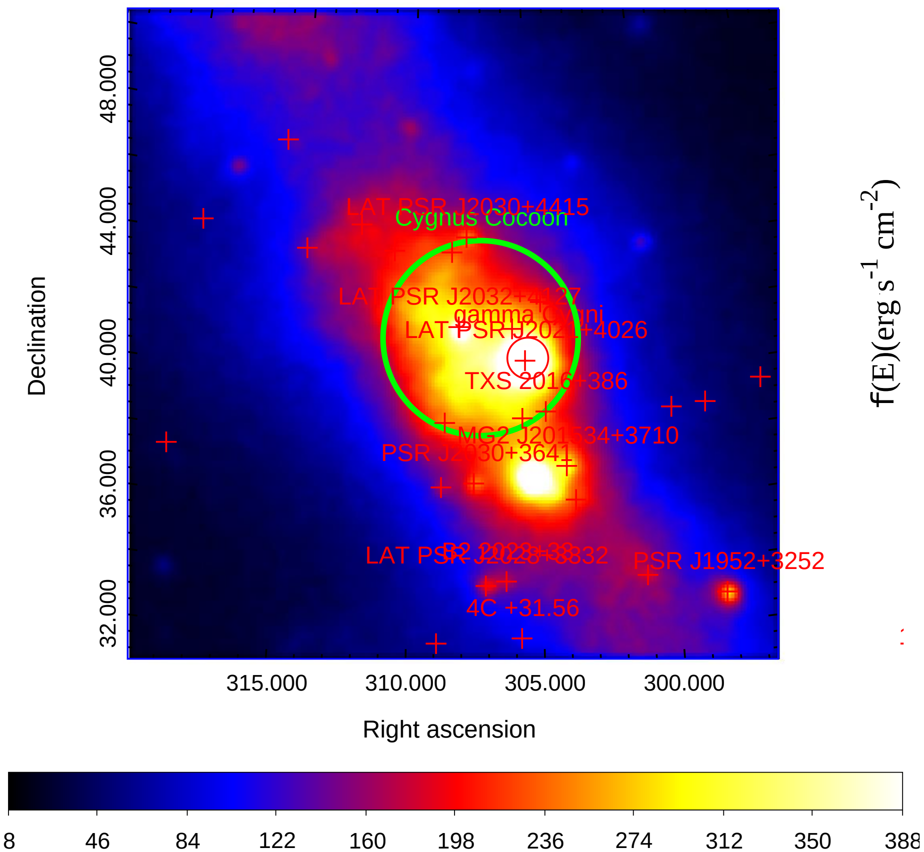
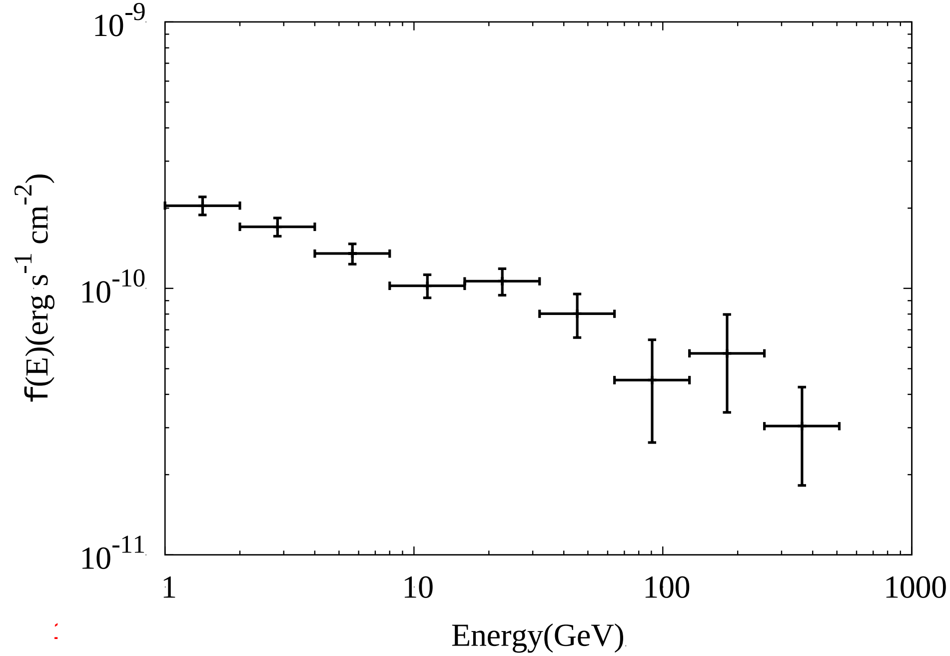
(H.E.S.S Collaboration 2015)

Westerlund 1
(H.E.S.S Collaboration 2011)

Cygnus cocoon

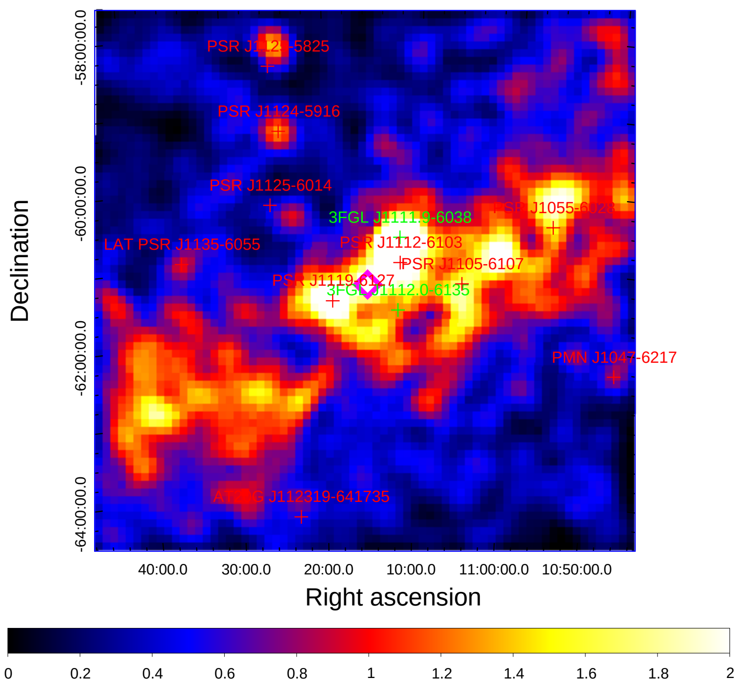


Fermi LAT counts map (>1 GeV)

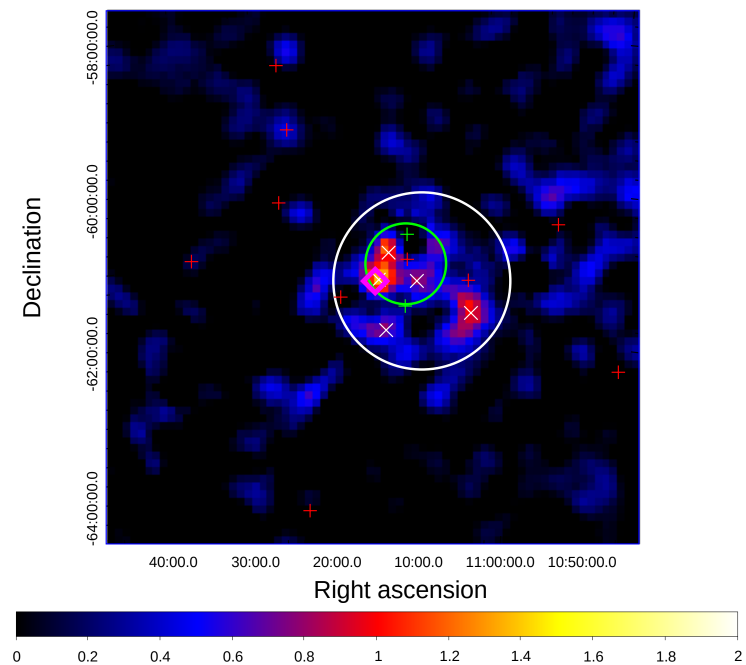


Spectral Index of -2.2, up to 500 GeV with PASS 8 data.

NGC 3603 (sky maps)

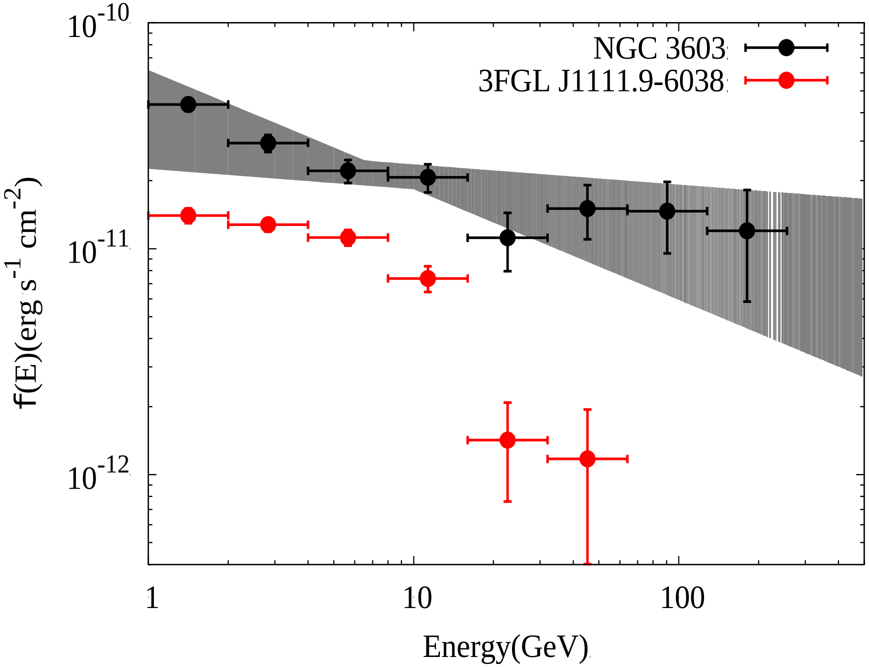


Counts map (>10 GeV)

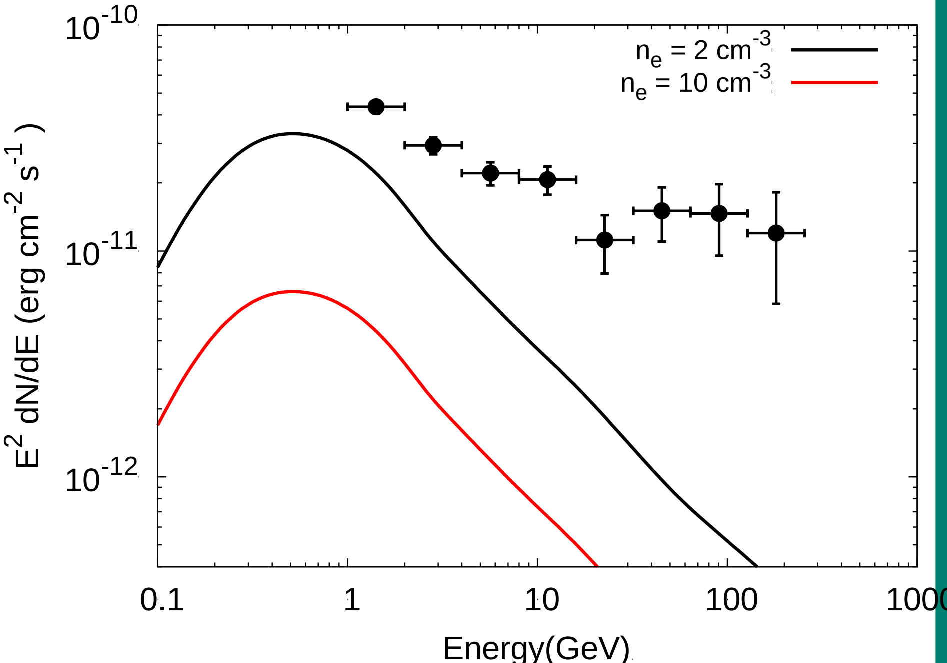


Residual map (>10 GeV), known source removed

NGC 3603 (SEDs and CR content)

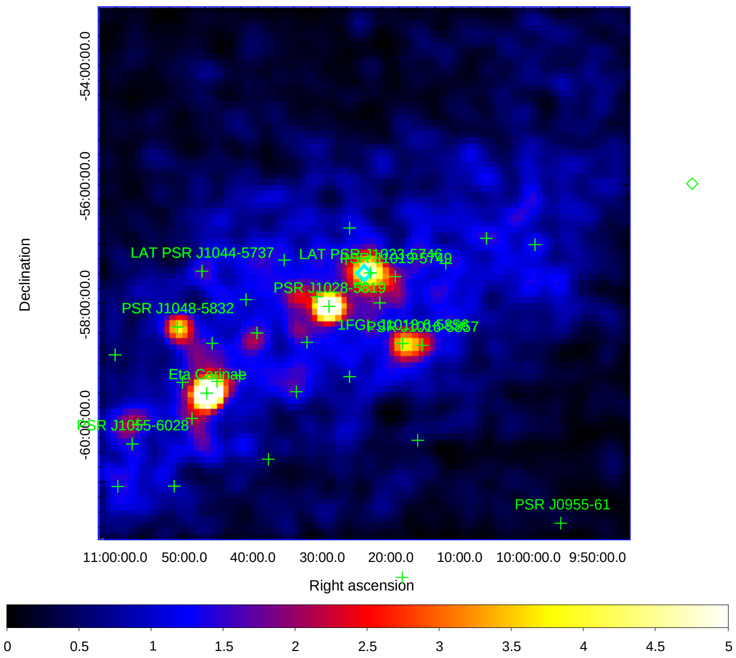


Gamma-ray SEDs
Index ~ -2.3, up tp 300 GeV

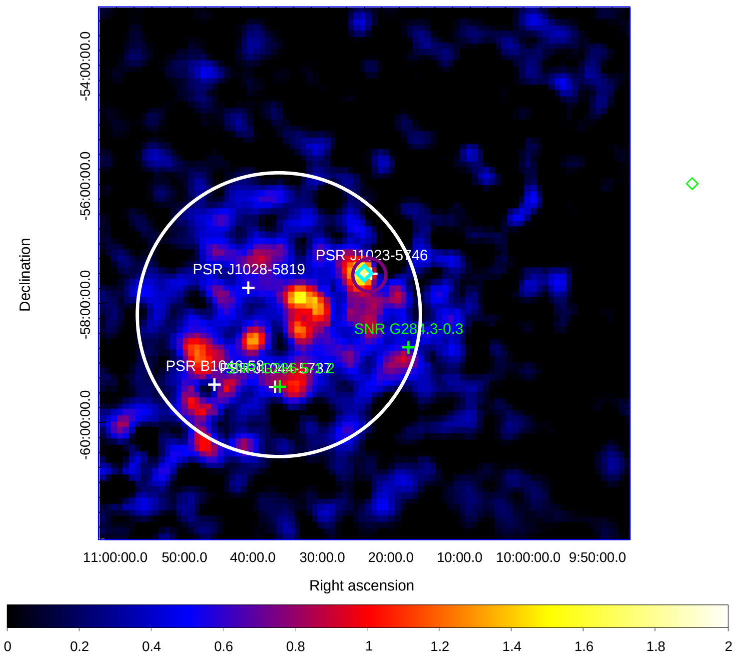


Compared with LIS emissivities

Westerlund 2 (sky maps)

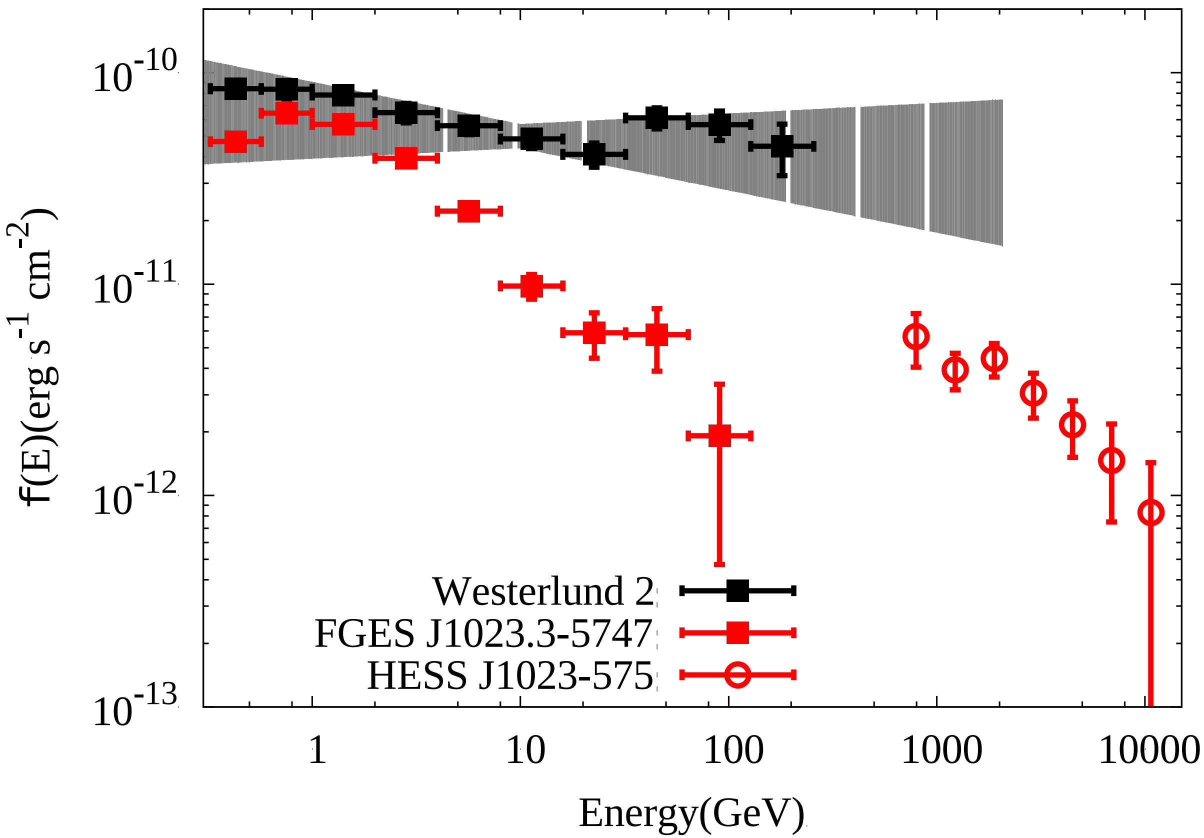


Counts map (>10 GeV)



Residual map (>10 GeV), known source removed

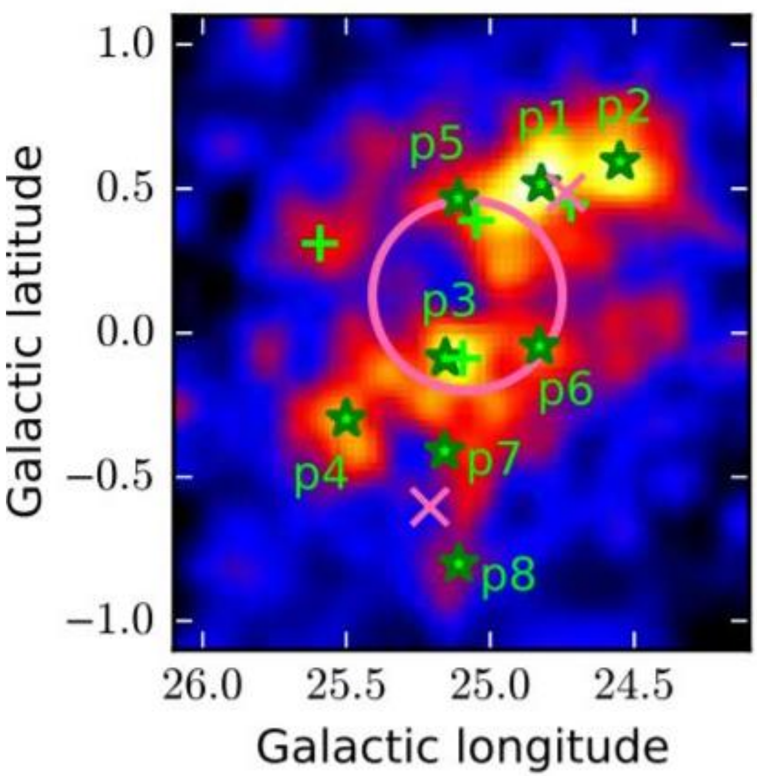
Westerlund 2 (SEDs)

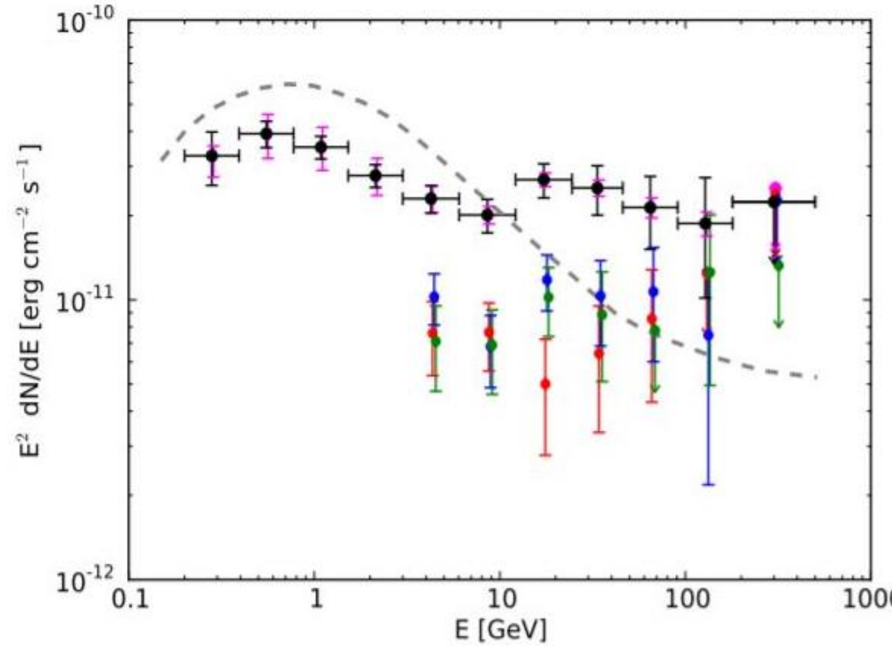


- Index ~ -2.1, up tp 300 GeV.
- FGES J1023 is the GeV counterpart of HESS J1023, which has a much smaller spatial extension, is believed to be a PWN.

G25.0+0.0

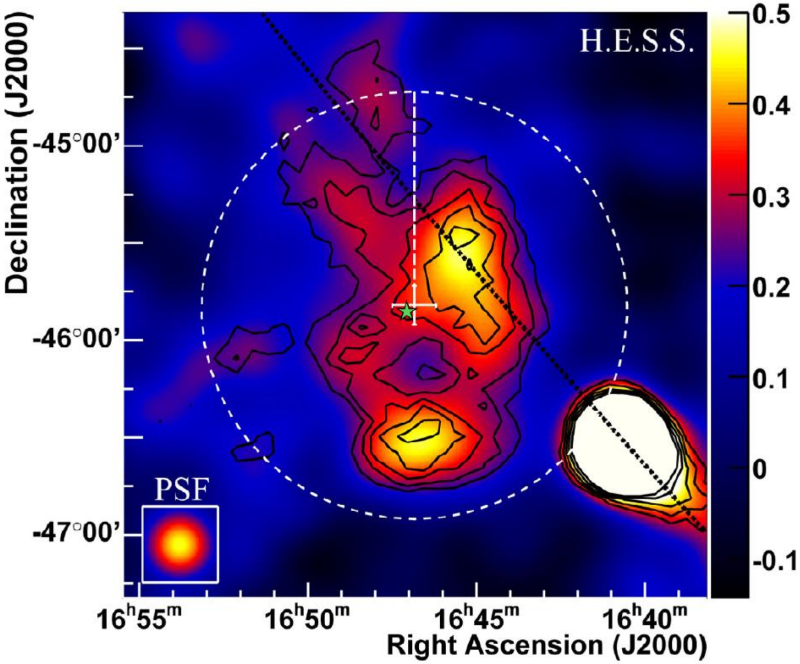
(Katsuta et.al 2017)

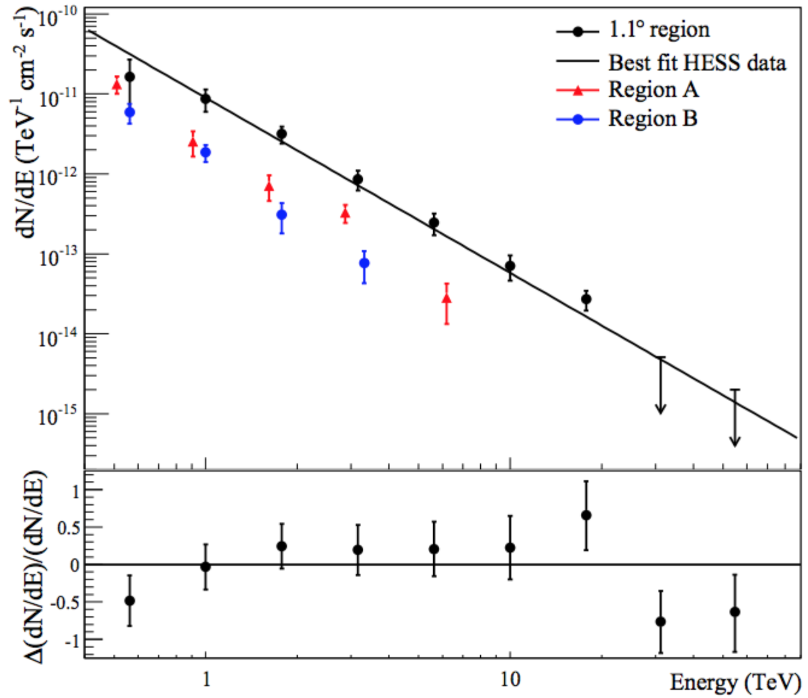




Index ~ 2.1, up to more than 500 GeV

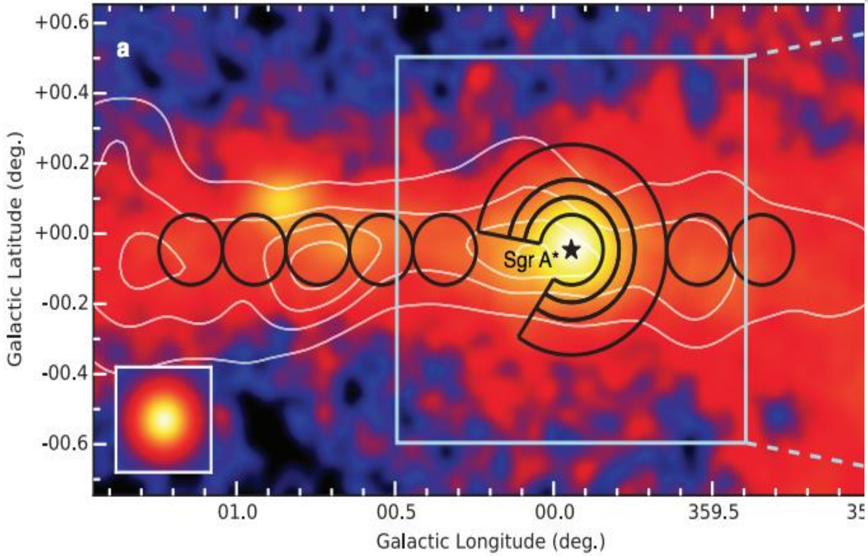
Westerlund 1

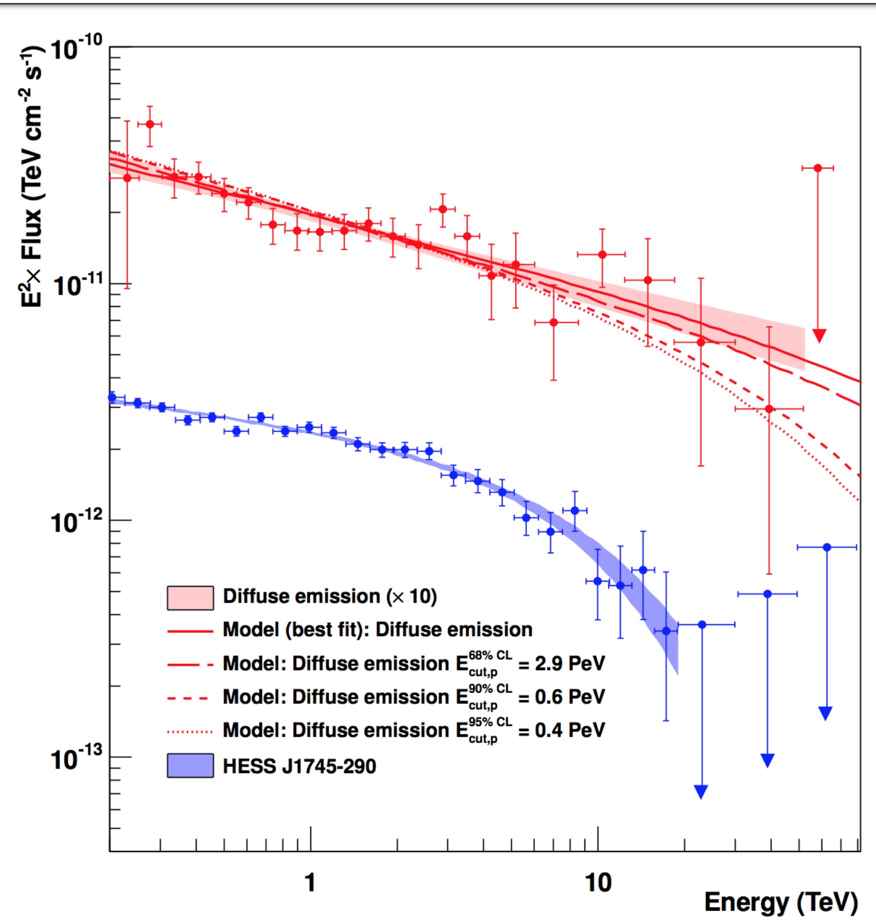




- Extended emission (>1.5 degree)
- hard spectrum (index ~ 2.2 above 1 TeV)

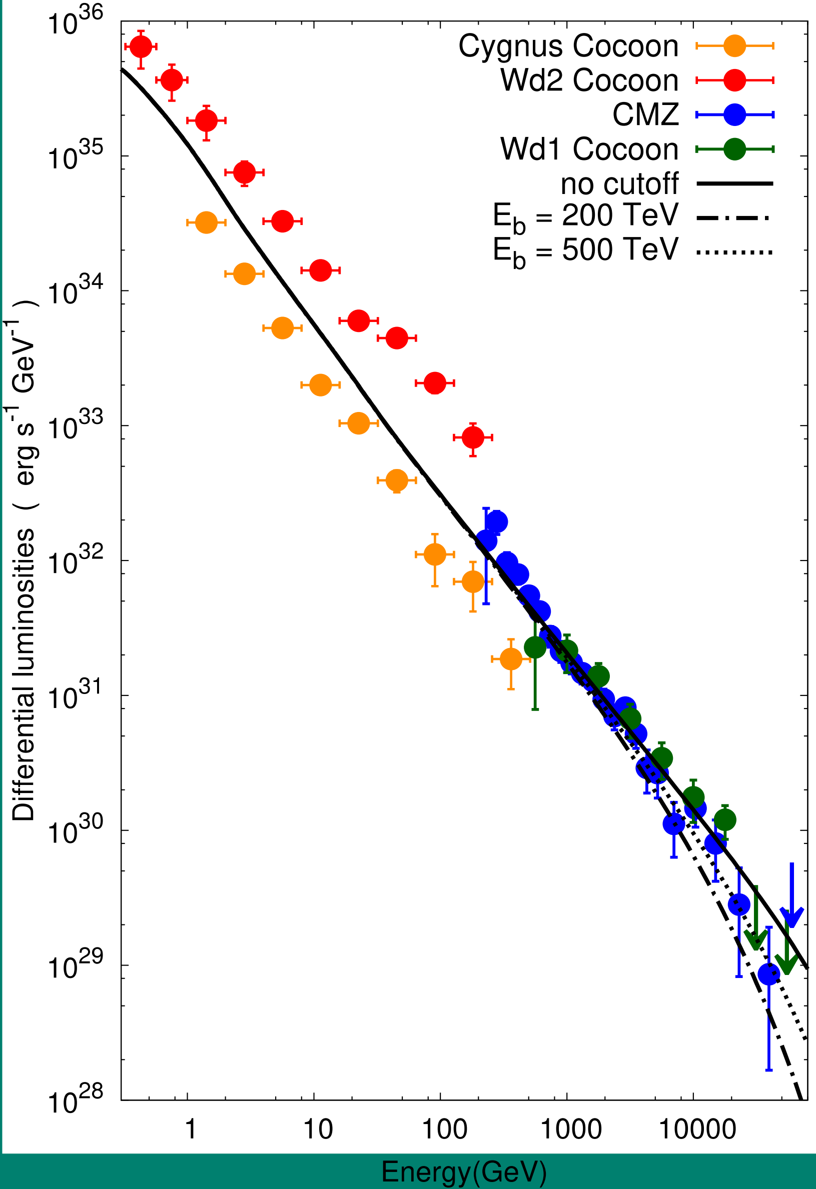
Galactic Center (HESS 2016)





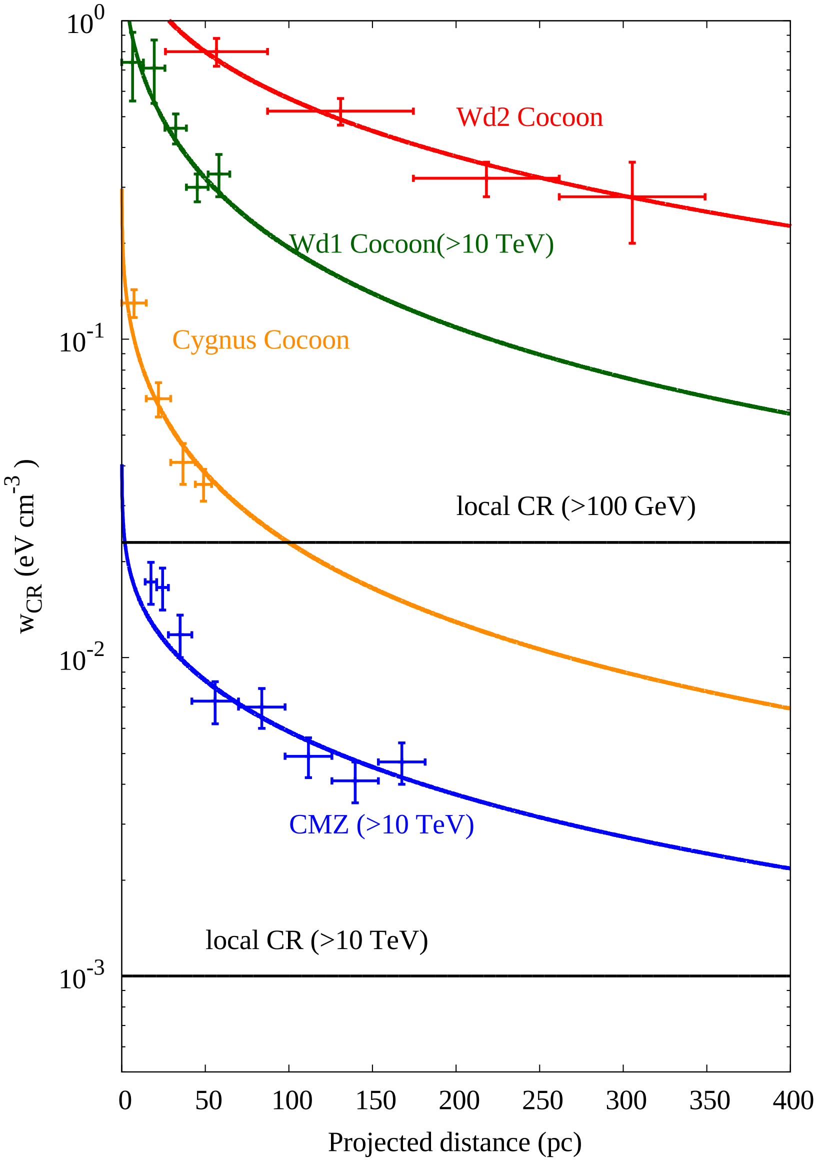
- Also reveal extended emission and hard spectrum (index ~ 2.2)
- GC region harbors Arches, Quintuplet and Nuclear cluster

Summary on Gamma-ray observations



- Extended gamma-ray emissions around young star clusters (50 ~ 200 pc), hard to be addressed as SNR/PWNs. Gamma-ray luminosity ~ 1e36 erg/s.
- Hard spectrum (index ~ 2.2, without cutoff)
- TeV observations of GC and Westerlund 1 reveal that they are PeVatrons
- Crowded region, need to check possible contribution from unknown SNR/PWNs.

Radial distribution of Cosmic Rays



- CR distribution derived by gamma-ray profile and gas distributions
- All four sources (Wd1, Wd2, Cygnus cocoon, GC) show 1/r distribution of CRs
- In diffusion, 1/r profile implies a continuous injection (in the lifetime of clusters)

PeVatrons?

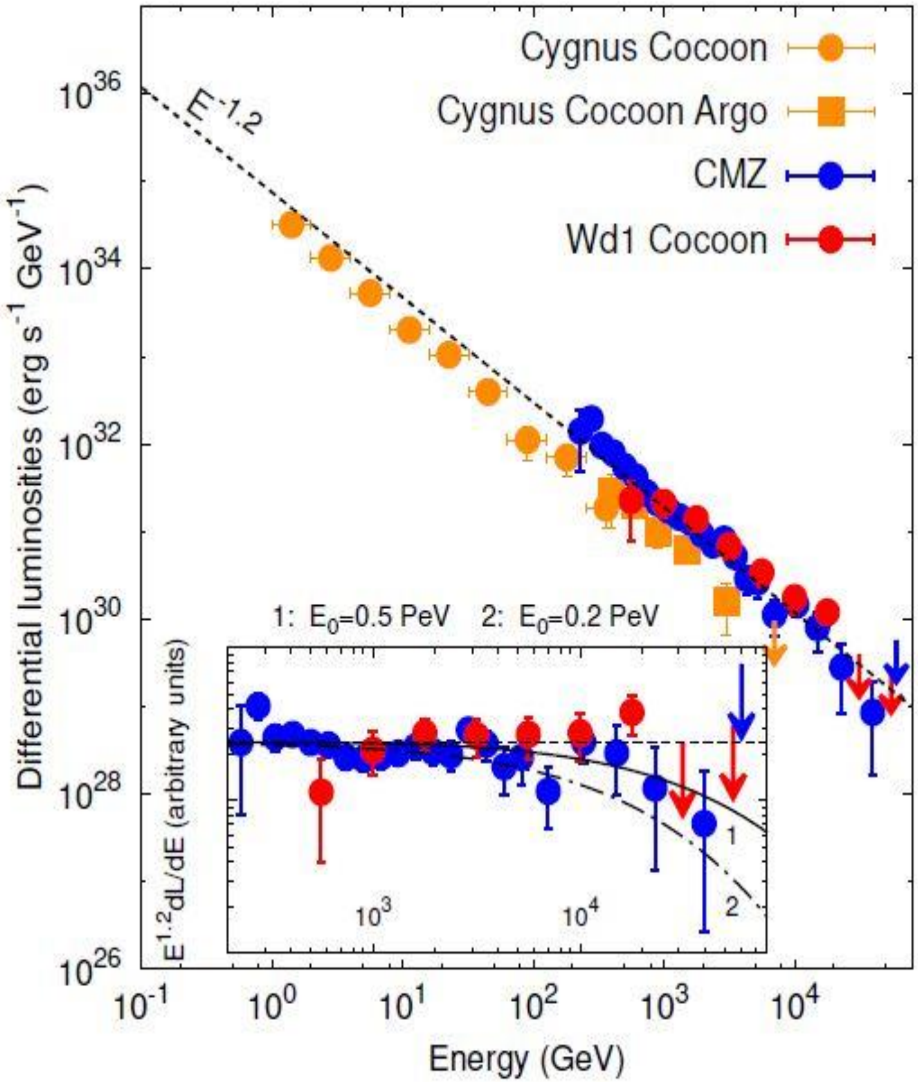
- Hard gamma-ray spectrum without cutoff can hardly be addressed in leptonic model (cooling and KN effects).

- no-cutoff in the gamma-ray spectrum up to 25 TeV

  => no-cutoff in the parent proton spectrum up to ~ 1 PeV.

- GC harbors PeVatron(s).

PeVatrons?



- Cygnus cocoon, Wd 1 and CMZ all emit multi-TeV gamma-ray.
- The spectrum of CMZ and Wd1 put lower limit of cutoff of parent proton spectrum to be several hundred TeV
- Promising Pevatron candidate

two-population CR sources?

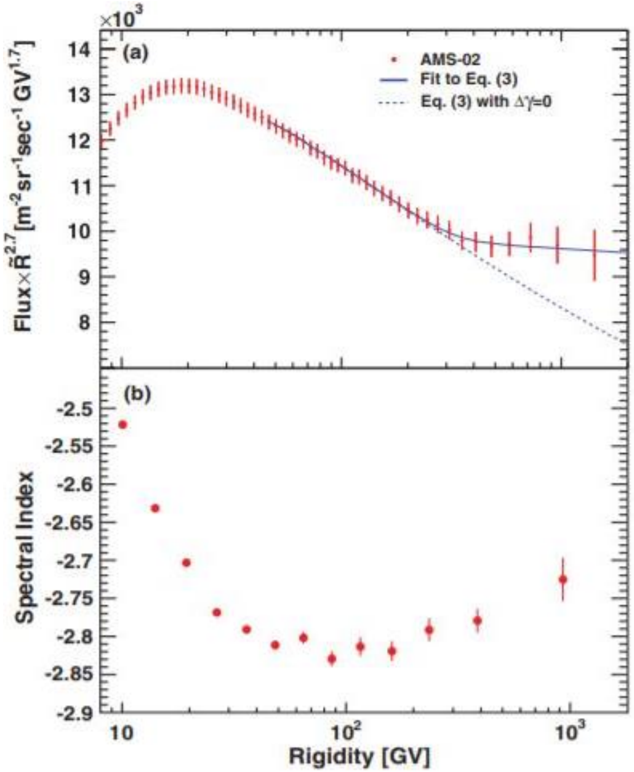
- To fit the locally observed B/C ratio and CR proton spectrum, the acceleration spectra index of the main sources should ~ 2.4.

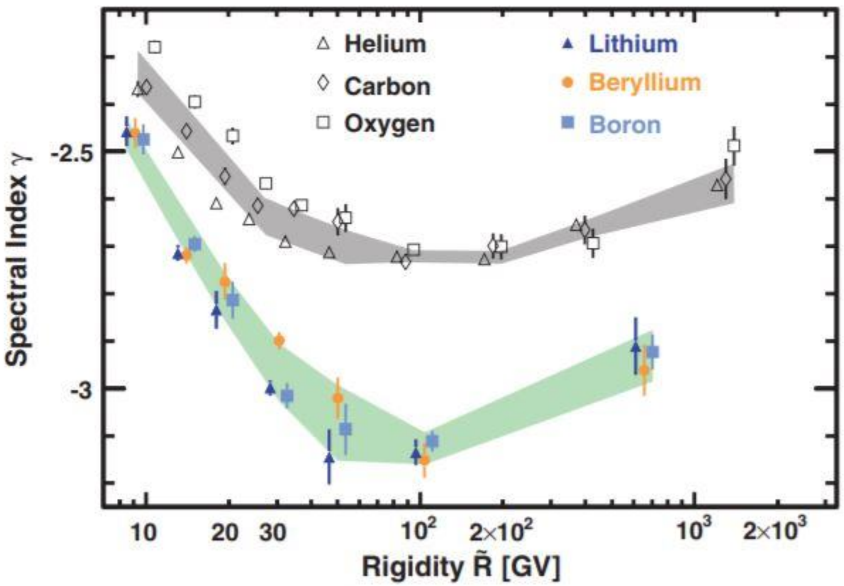
- Assuming a Kolmogolov type turbulence spectrum and continuous CR injection near massive star clusters, the gamma-ray spectrum 2.2 translate into a proton acceleration spectra index of ~2.0.

- SNR dominates lower energy (with acceleration index 2.4) and star clusters (with a acceleration index of 2.0) dominate higher energy ?

two-population CR sources?

- Hint of the second component? A hardening at about 200 GeV for all CR species.

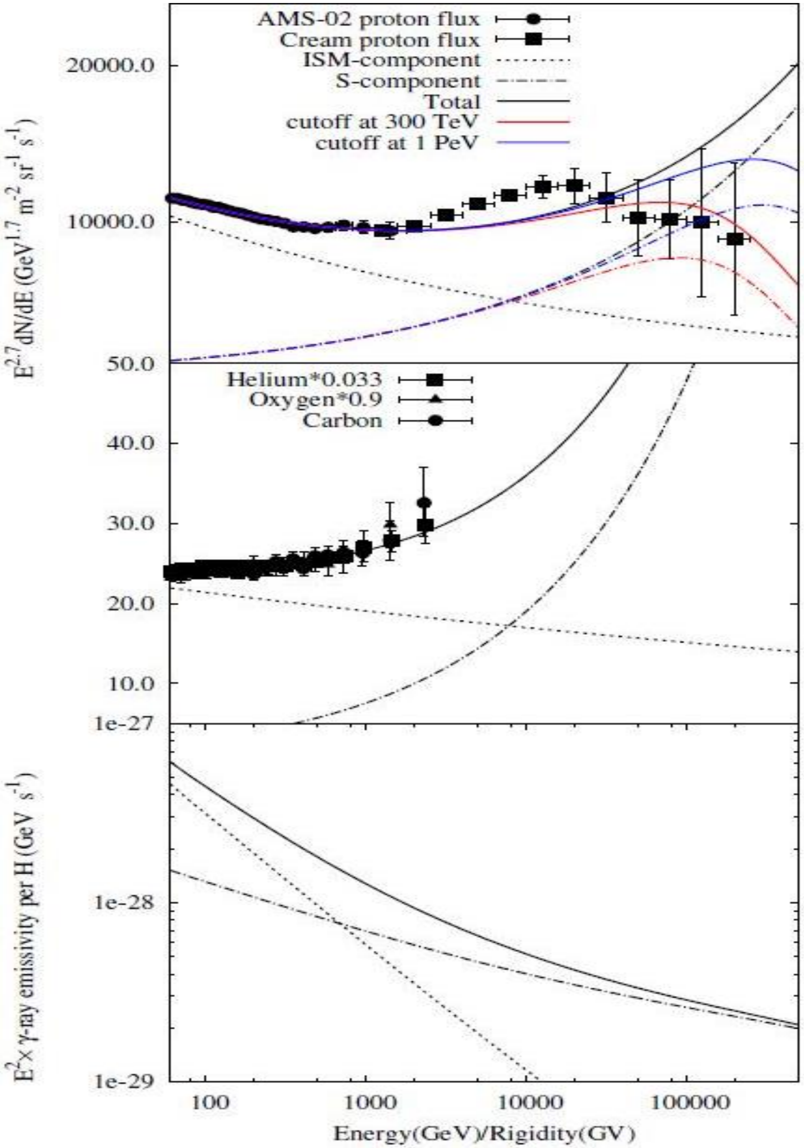




(AMS-02 Collaboration 2015, 2018)

two-population CR sources?

- A harder source population (star clusters?) can account for such hardening



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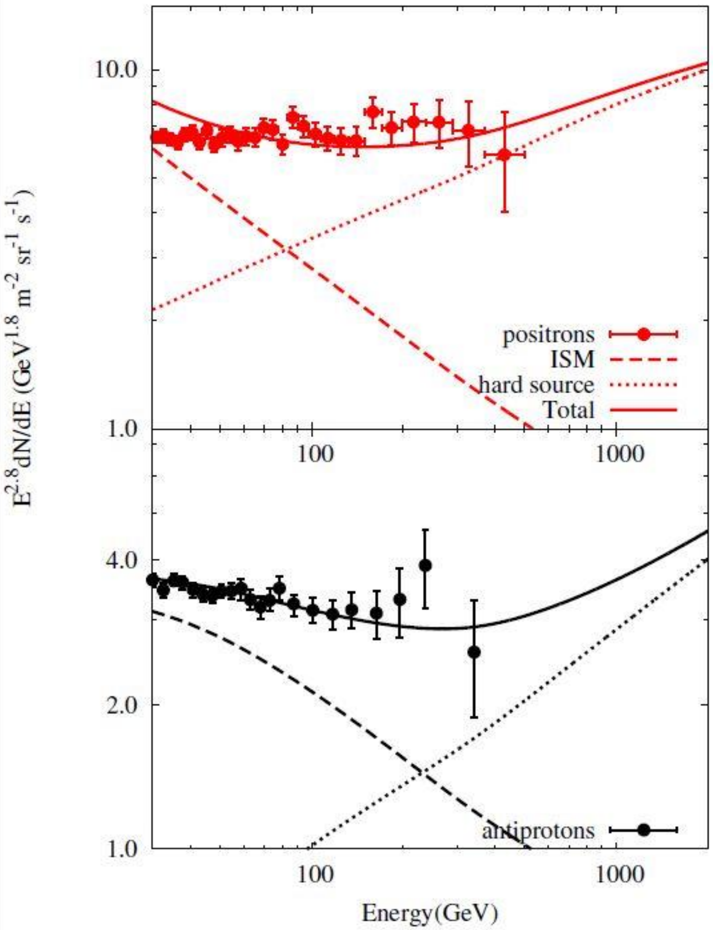
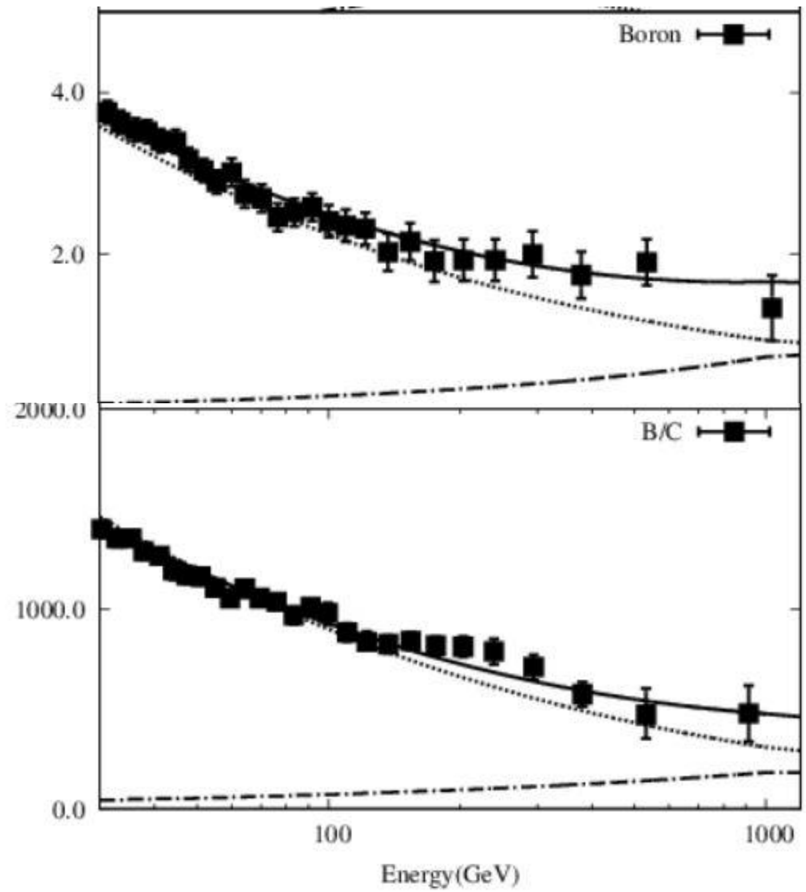
two-population CR sources?

Further assumption of a grammage of ~1g/cm^2 inside these “hard” source population also provide explanation for the secondary anomaly (for more detail, see arXiv: 1812.04364)





Conclusion

- Extended gamma-ray emission near young star clusters detected.
- Best explained as CRs interaction with ambient gas, reveal universal 1/r CR distributions and hard spectra (index ~ -2.2)
- Potential CR accelerators (even main accelerators in high energy)
- Two-component CR model.

Thanks!