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Galactic Cosmic Rays: From MeV to PeV

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Outline

1. Galactic Cosmic rays: spectra and distributions
2. Low energy CRs (LECRs)
3. PeV CR sources (PeVatrons)
4. Prospect

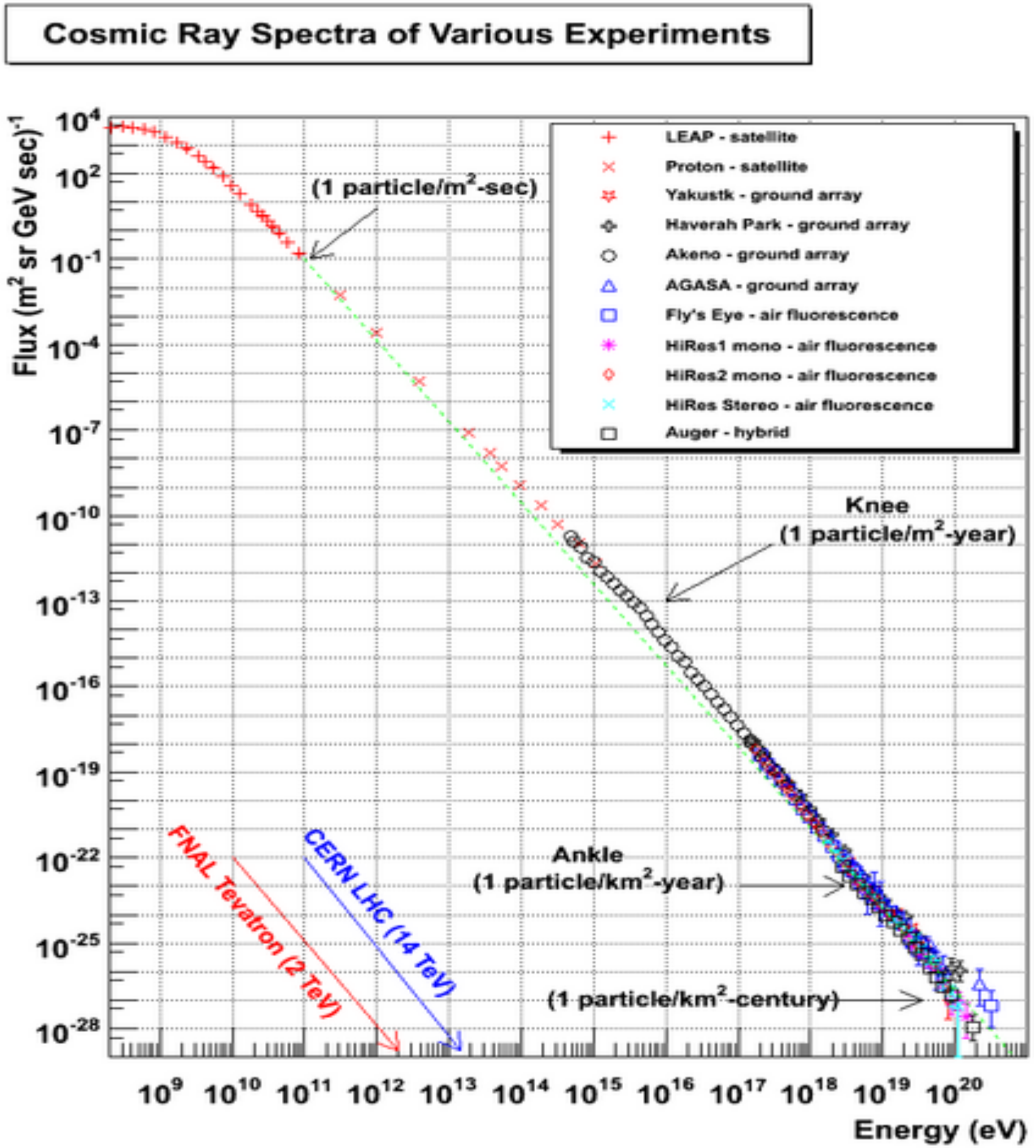
Galactic Cosmic Rays (GCR)

Cosmic Rays: Relativistic particles (mainly protons) in interstellar medium (ISM)

Consensus

- Single power law spectrum from 10 GeV (10^{10} eV) up to 1 PeV (10^{15} eV)
- Energy-dependent confinement in the Galactic halo
- Supernova remnants (SNR) as sources

Spectrum



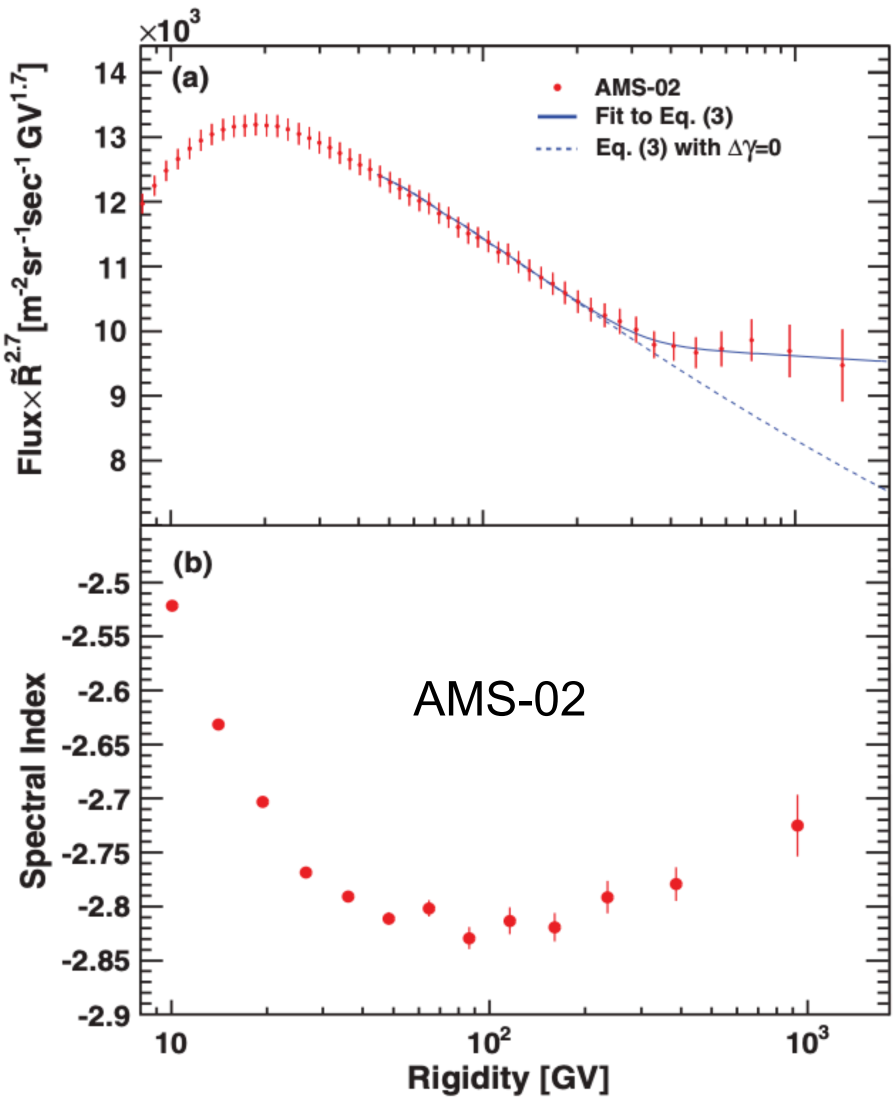
https://www.physics.utah.edu/~whanlon/spectrum.html

Detection method

- Direct measurement (ballon, satellite or extensive air shower array), measure the local spectrum and anisotropy

- Indirect measurement (via Gamma-rays). spectrum and distribution in the Galaxy

Direct measurement



Phys. Rev. Lett. 114, 171103 (2015)

Direct measurement

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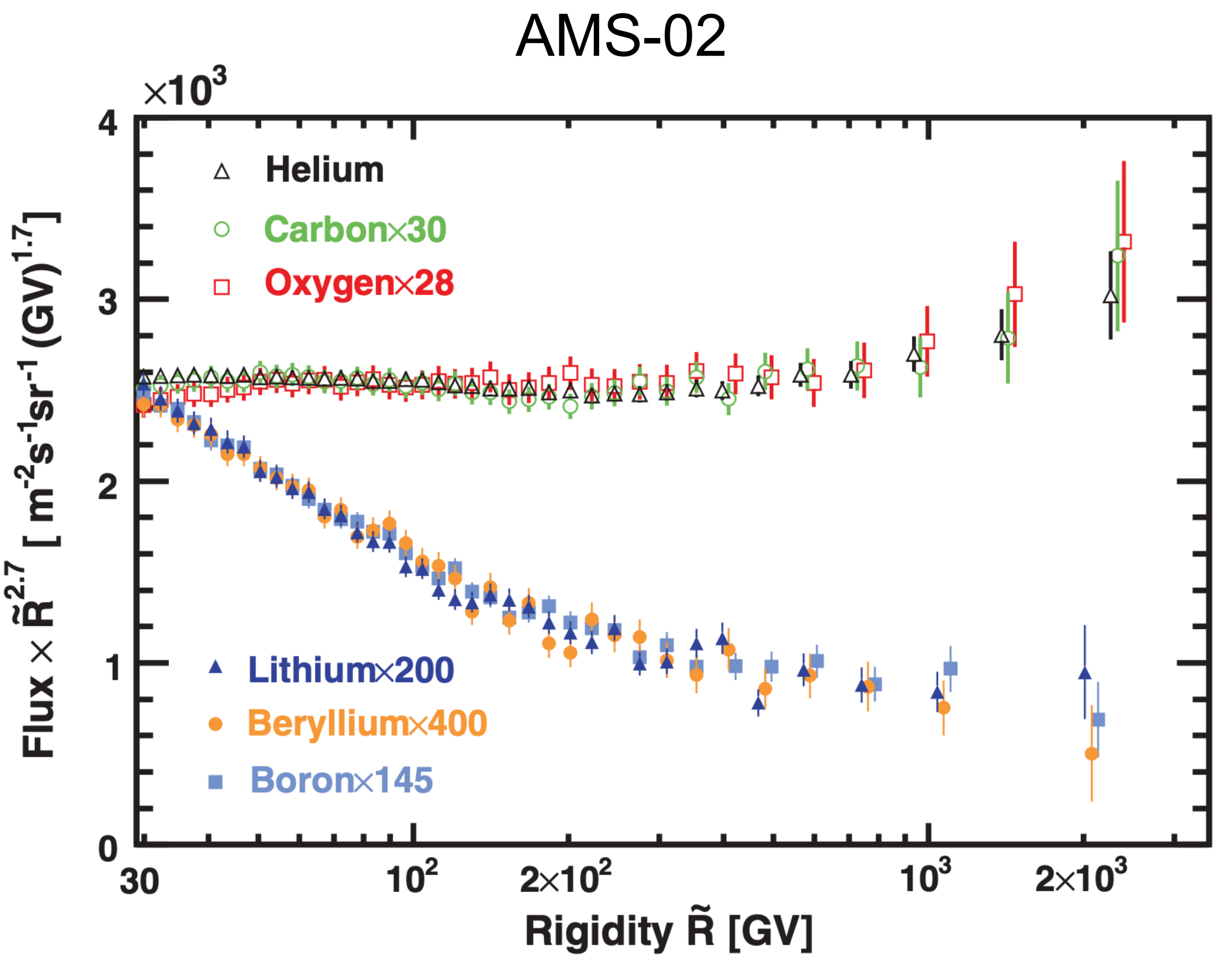
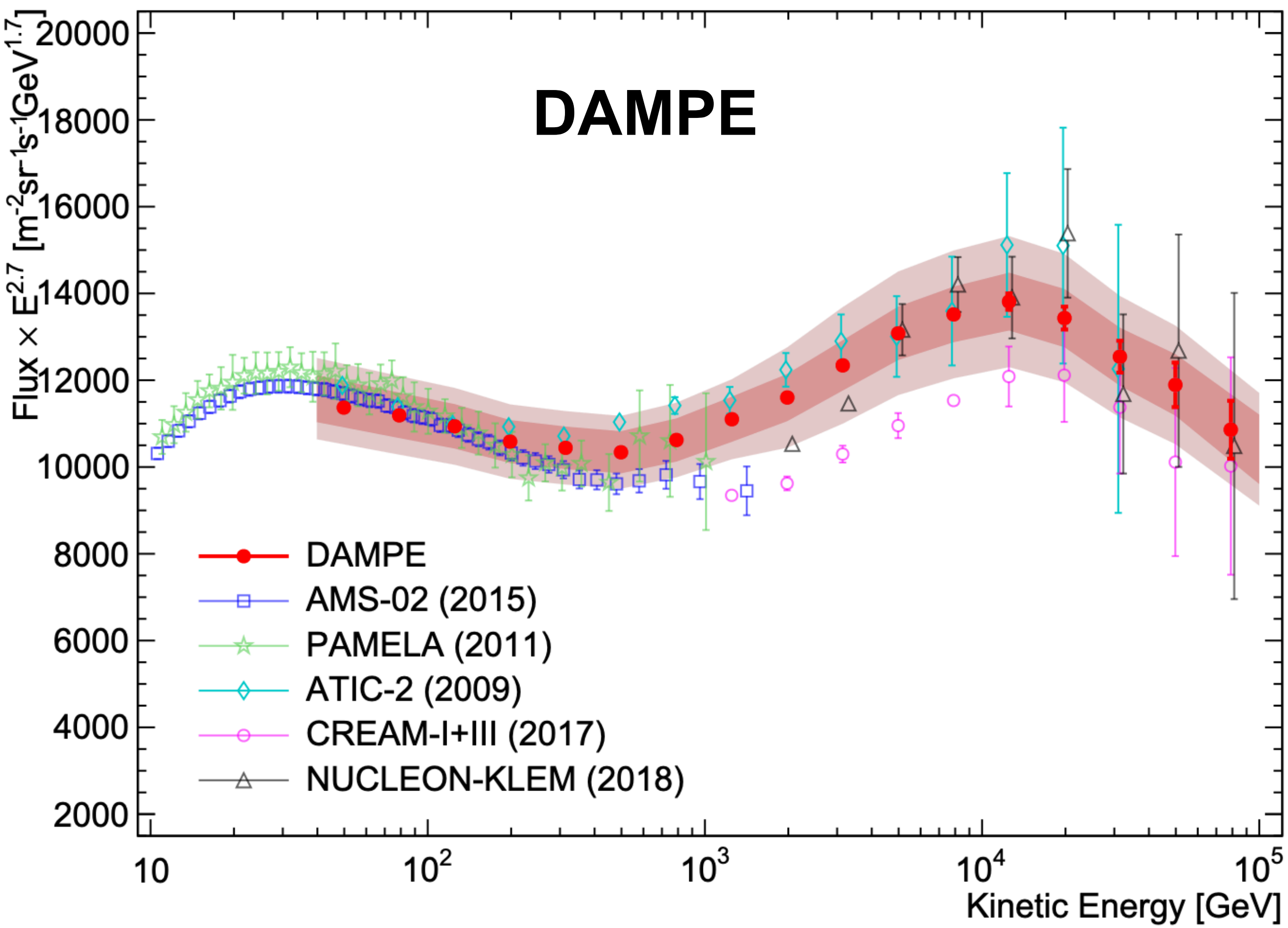


Phys. Rev. Lett. 120, 021101 (2018)

Direct measurement



Science Advances, Vol. 5, no. 9 (2019)

From gamma-rays

- Gamma-ray emission (in molecular clouds or diffuse):

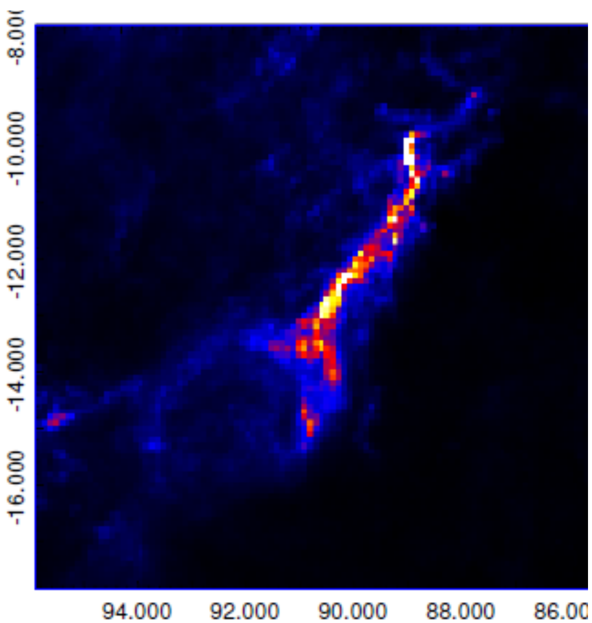
Point sources+ CR interaction with ambient gas + ICs +isotropic

- CR interaction with gas dominates in dense environment.

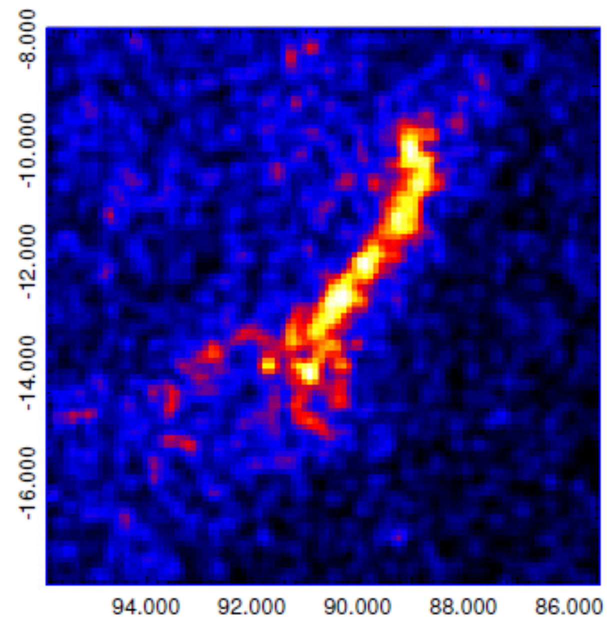
- Gamma-ray map + gas distribution -> CR distribution

gamma-rays from giant molecular clouds (GMCs)

- Gamma-rays show good correlation with gas (CR uniformly distributed inside GMCs)
- Can be used to study the CR spectra



Gas (CO) distribution



gamma-ray observations (GeV)

Derived CR spectrum

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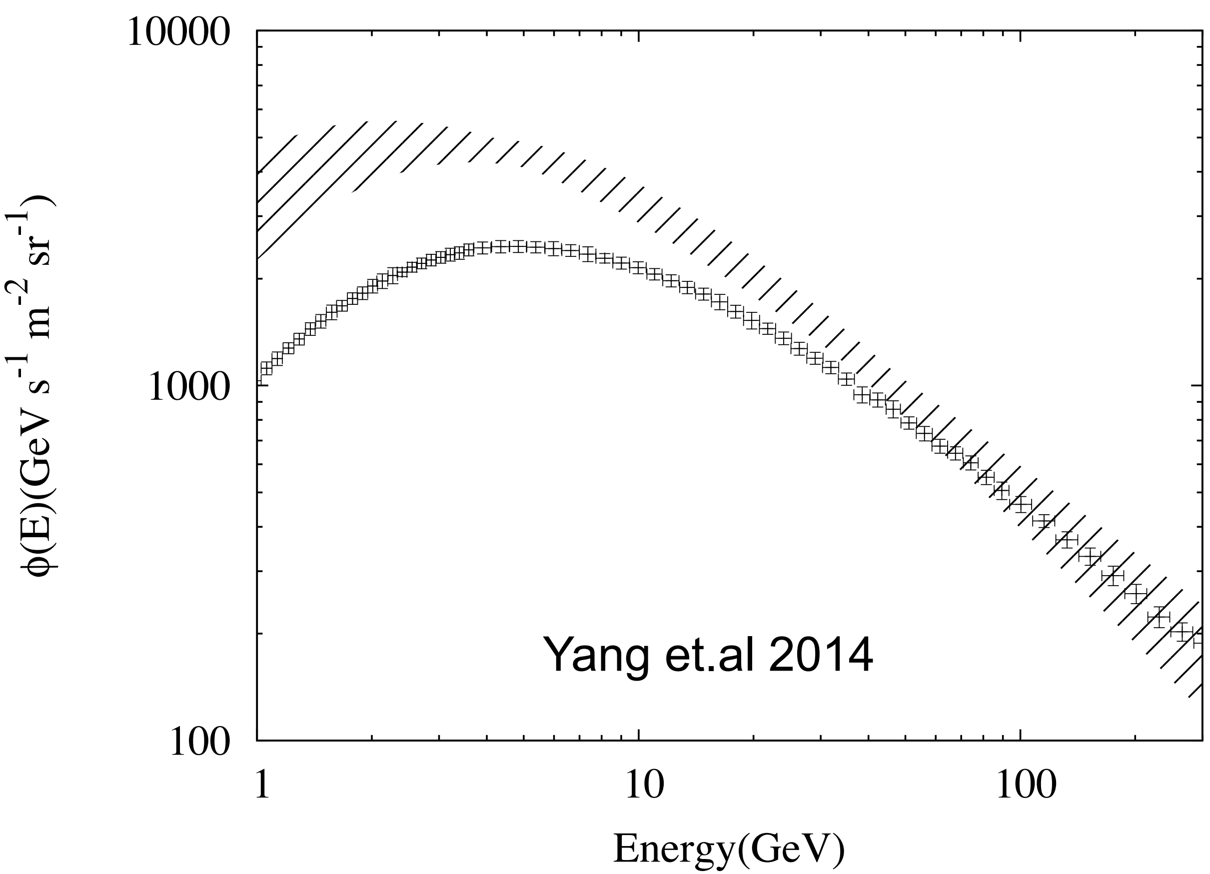

In comparison with the Local Measured CR:
consistent above 10 GeV (solar modulation)

uniform or not?

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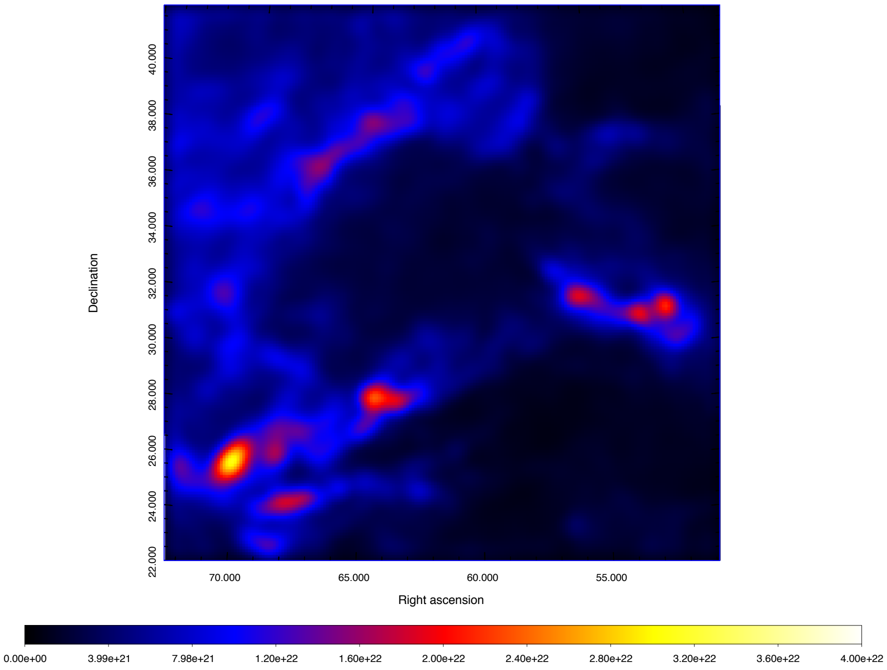
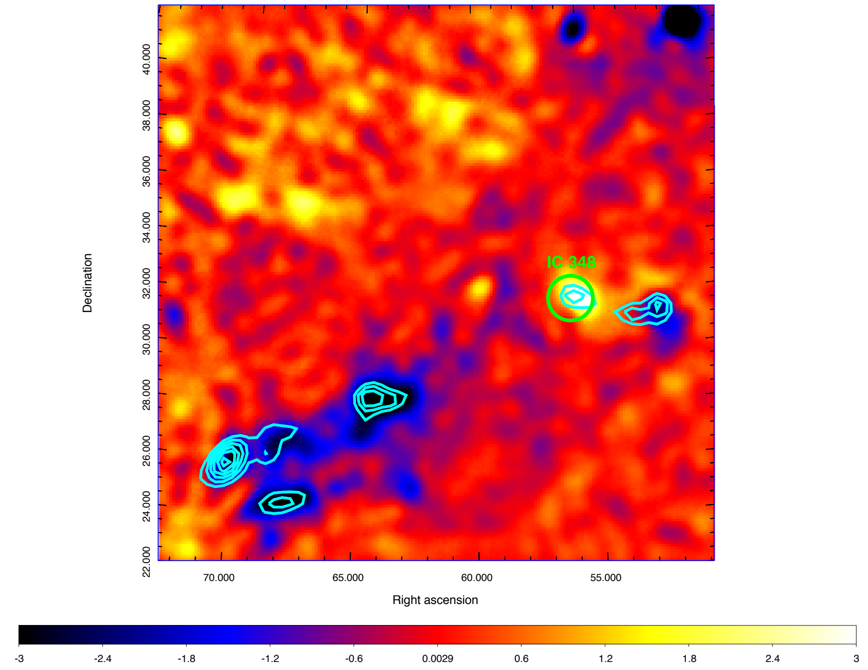
Test the uniformity of CRs

- Some hint of inhomogeneous distribution in Taurus-Perseus region



Dust opacity (gas distribution)

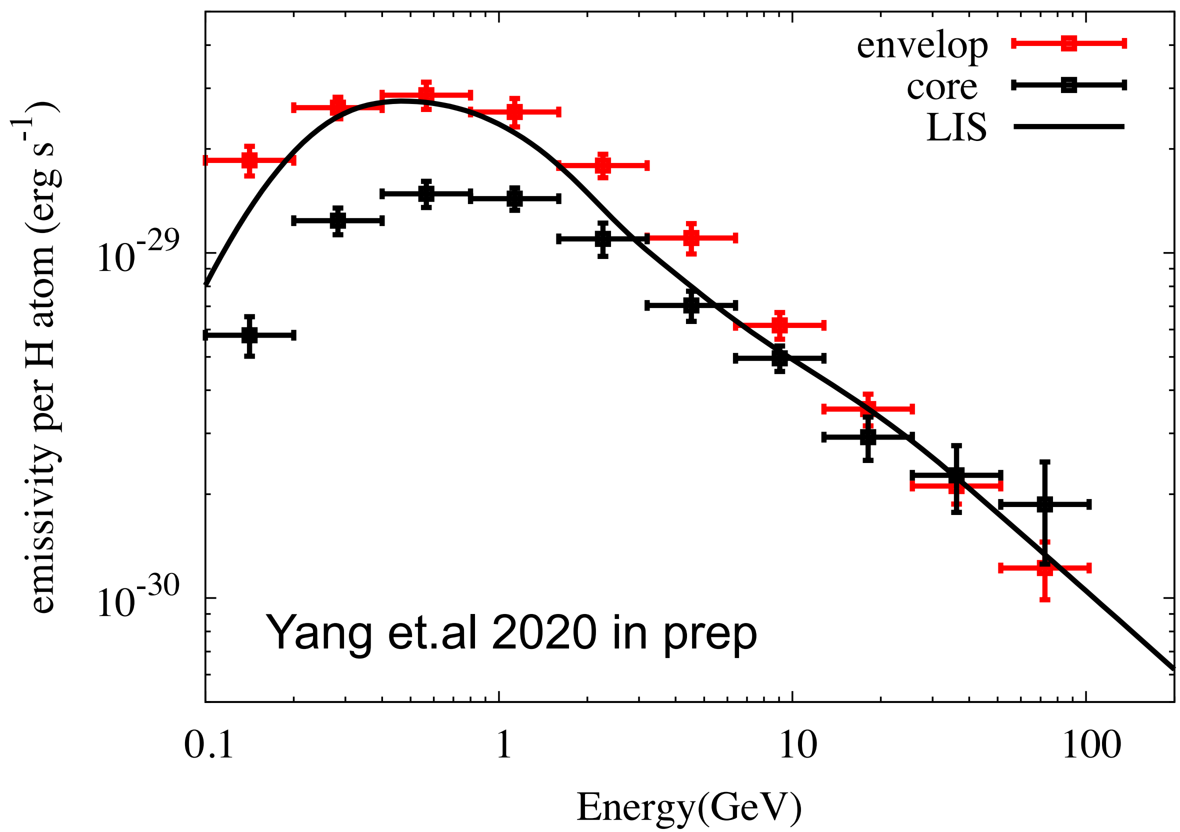


gamma residual (CR density)

Uniform or not?

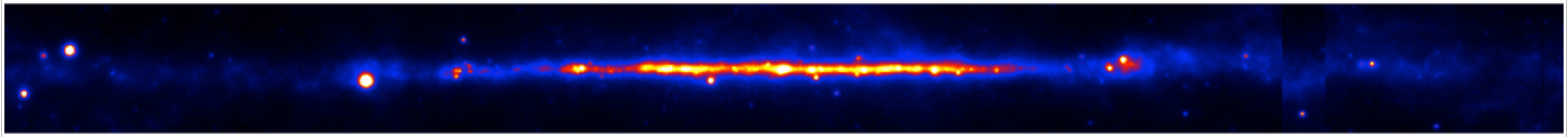
Test the uniformity of CRs

- Low energy CRs cannot penetrate into the core: slower diffusion due to higher turbulence inside GMCs?

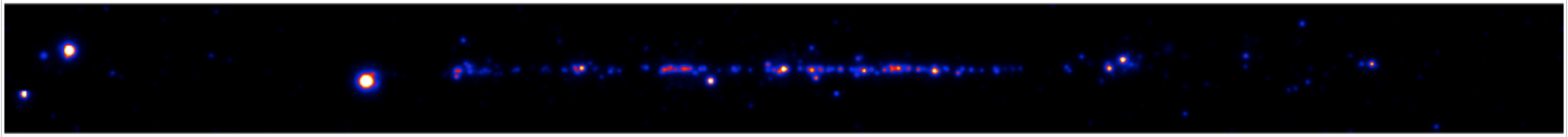


Diffuse gamma-ray emission

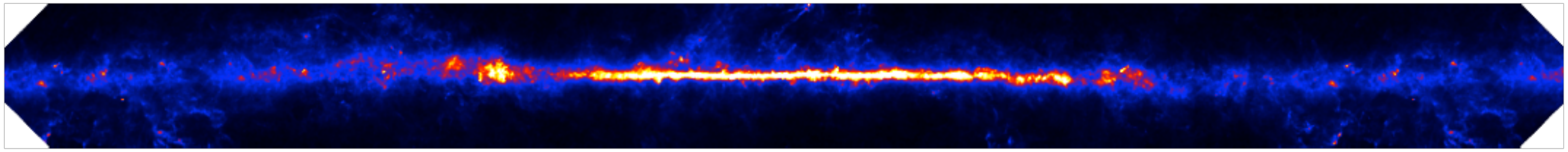
Gamma-ray counts map



Point source contribution



Dust opacity map (gas column)



CR Radial distributions

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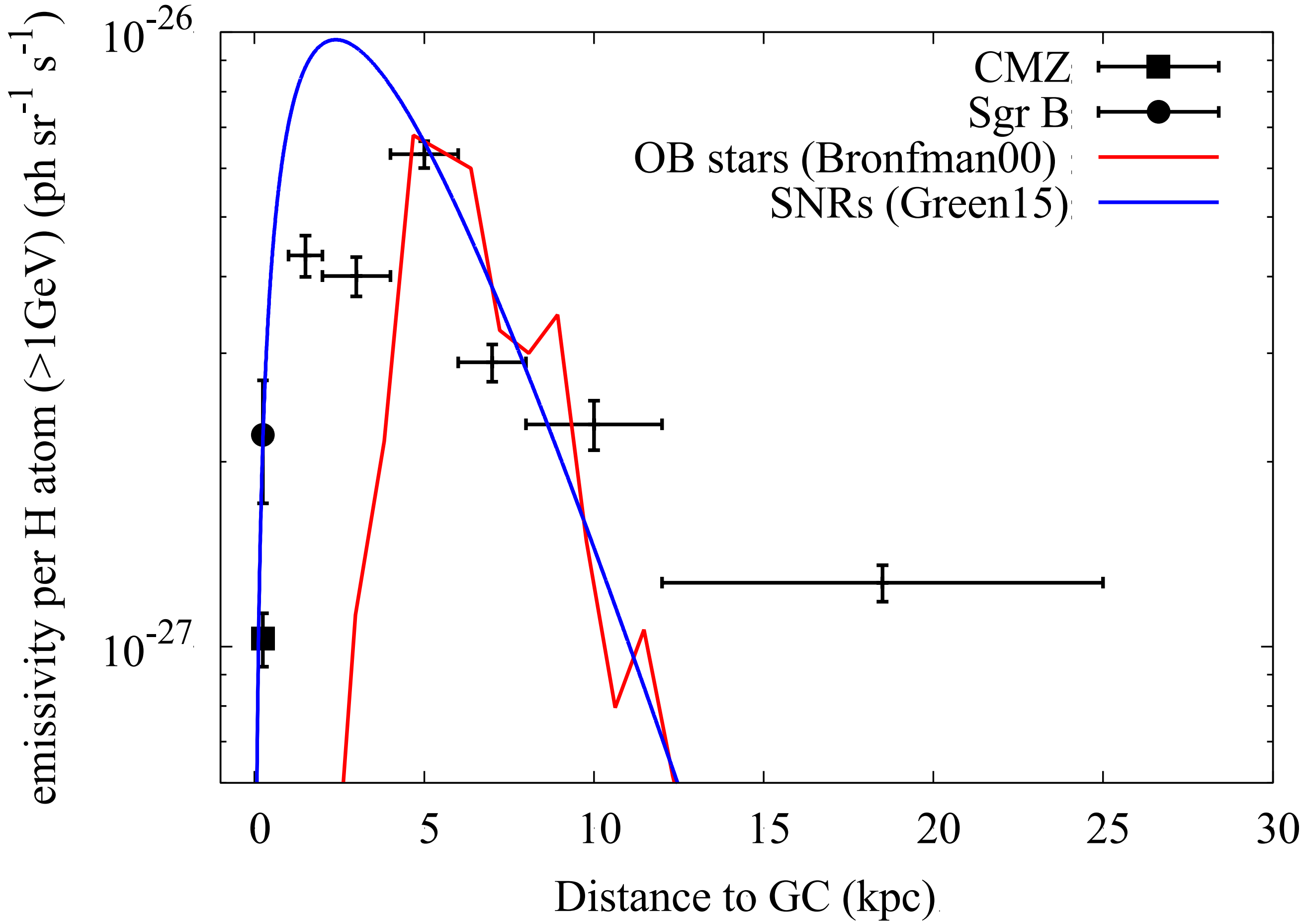
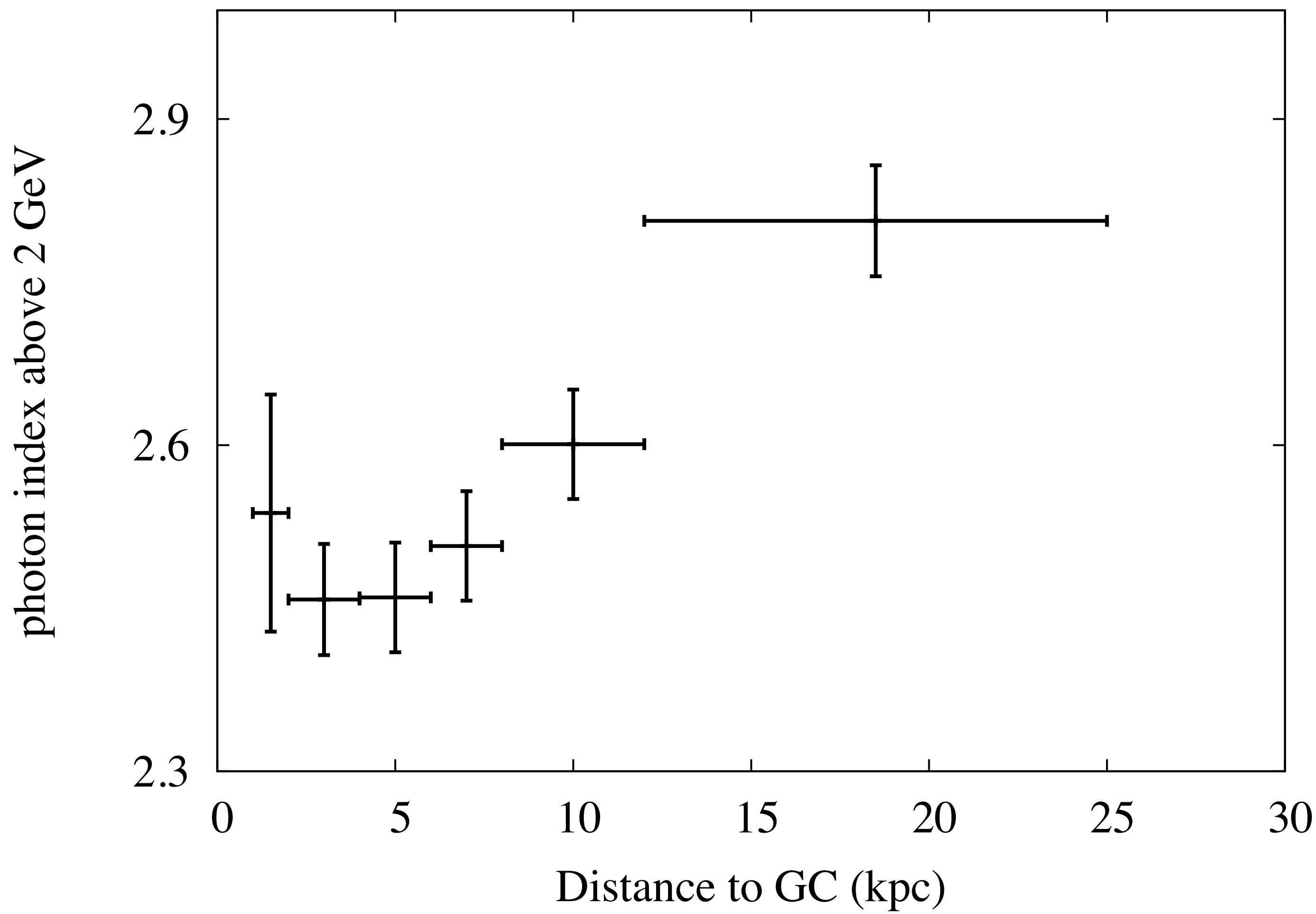


Yang et.al 2016

Cylindrical Symmetry assumed!

Hardening towards GC



Yang et.al 2016

More GMCs!

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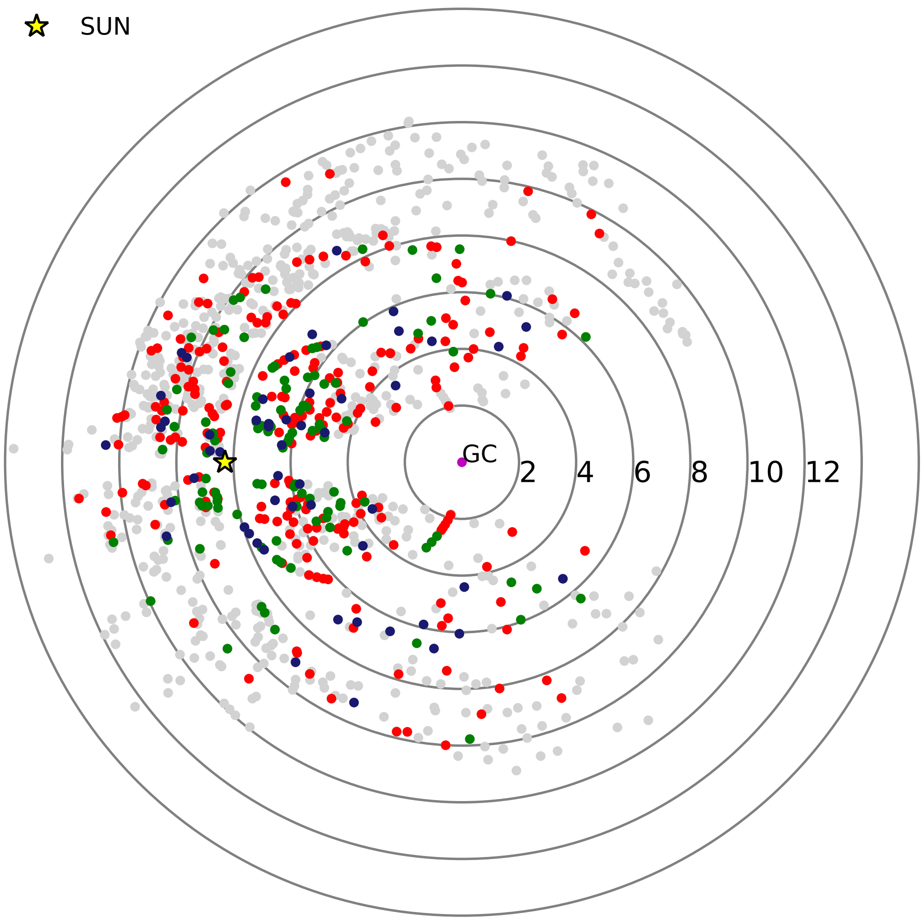

Aharonian et.al 2019

- Rice et.al (2016) have identified thousands of Molecular Clouds in the Galaxy
- Possible to measure CR density in each position of the Galaxy.

More GMCs

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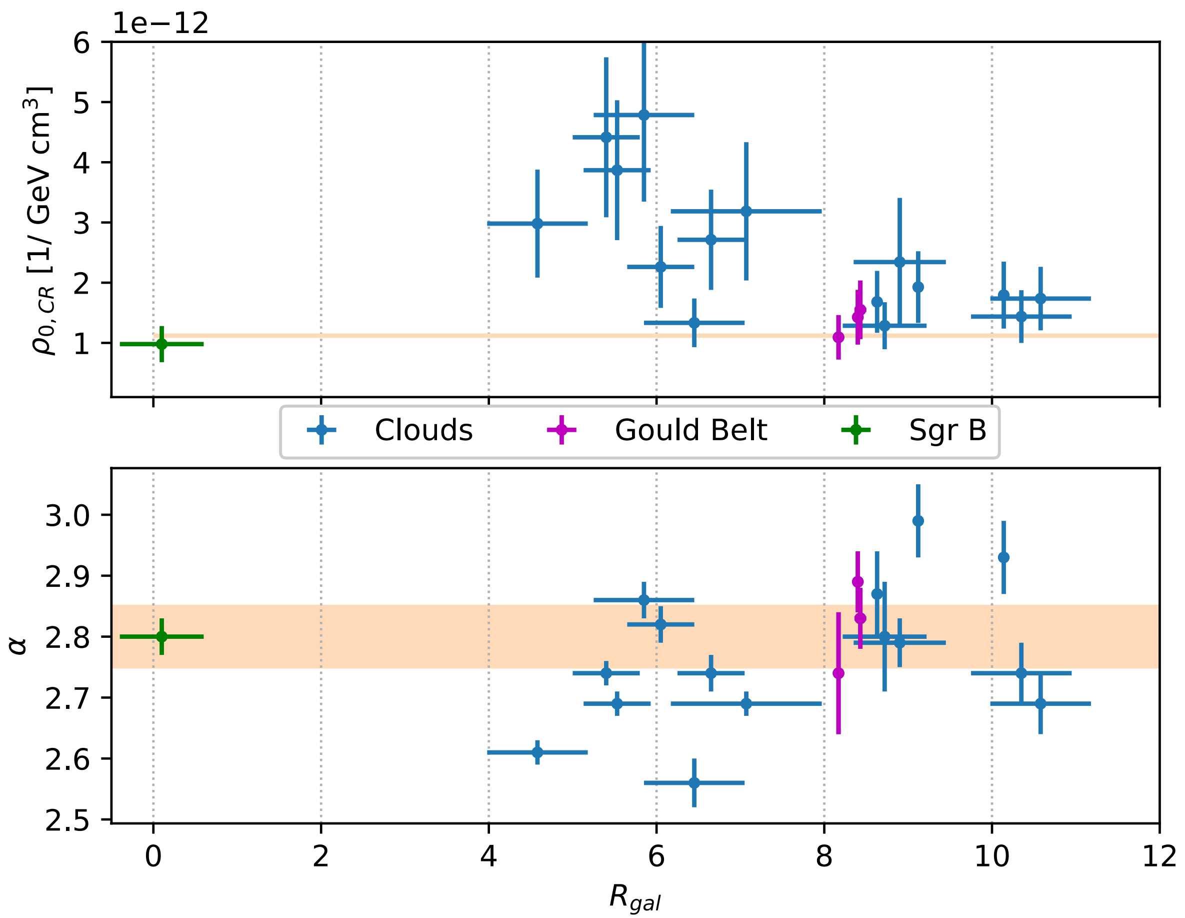
- radial distribution of CR density and indices



Aharonian et.al 2019

More GMCs

- The enhancement and hardening is caused due to the CR sources?
- A uniform CR “sea” plus some “islands” with higher density and harder spectra?

Further test

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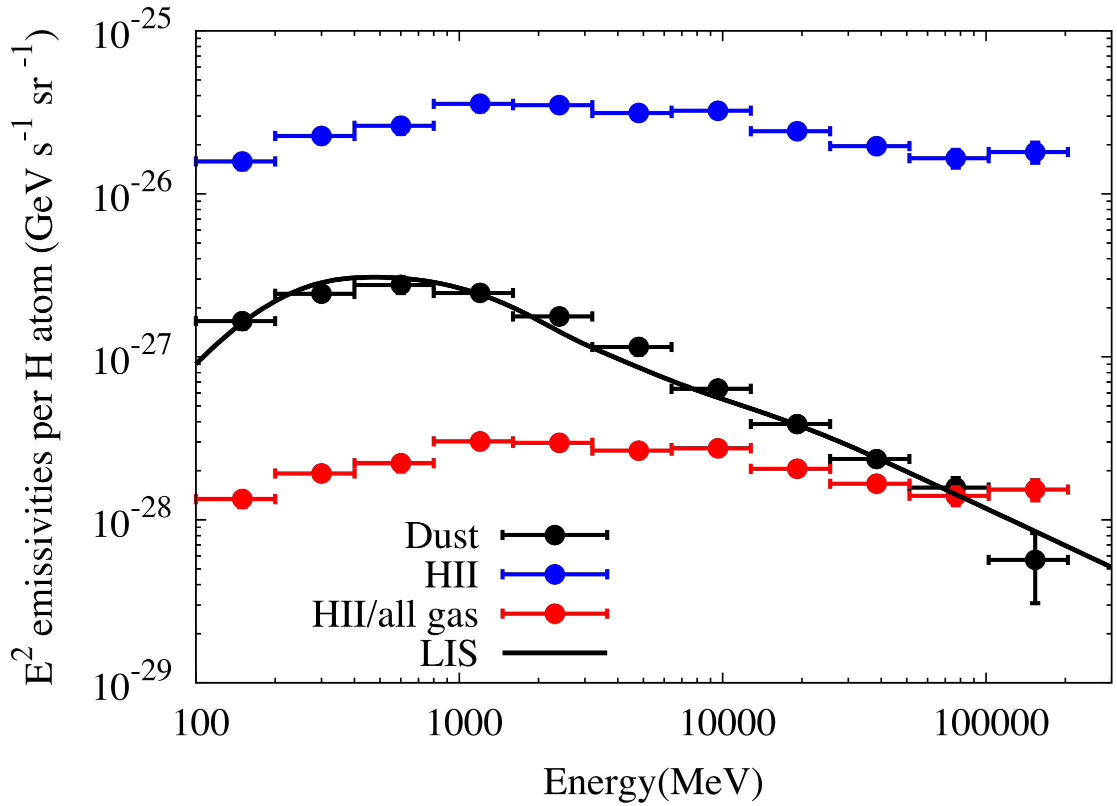
- use HII gas to trace massive star forming regions (potential CR sources)
- Diffuse gamma can be separated into two components
- One associated with total gas column (dust opacity), with soft spectra. CR "sea"?
- Another with HII gas, with harder spectrum, CR "islands" near sources?



Yang and Liu 2020, in prep

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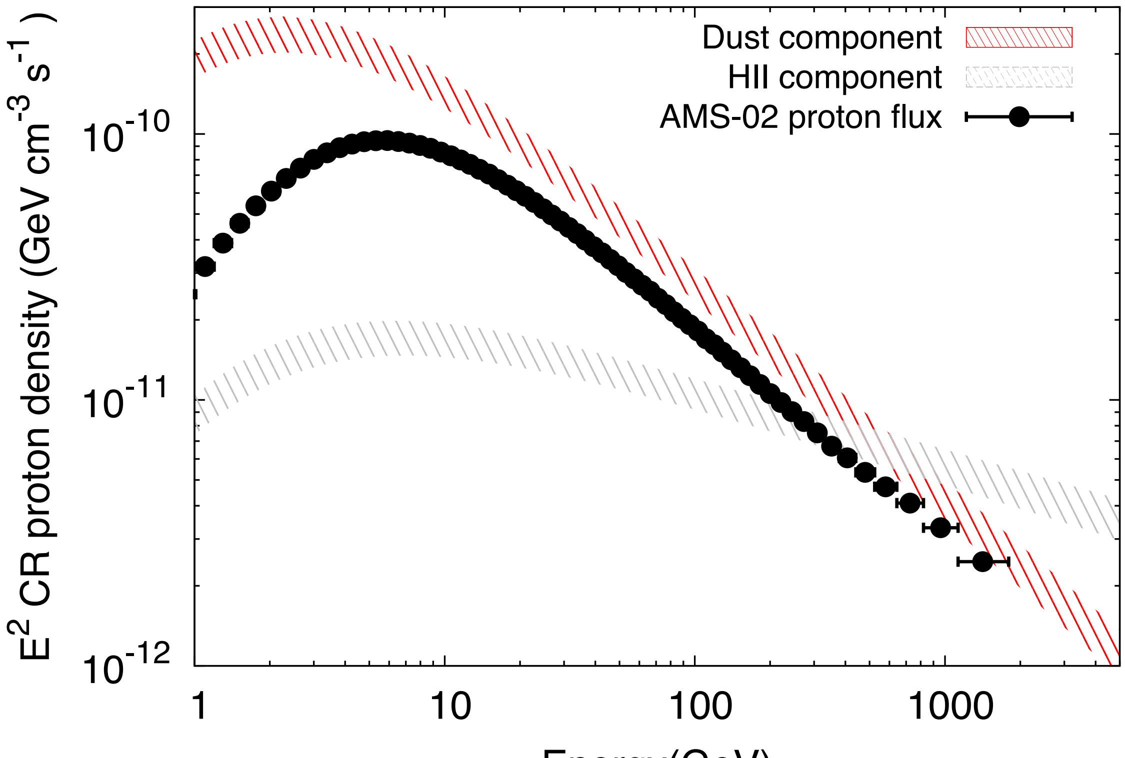

Yang and Liu 2020, in prep

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LECRs

(Yang, Liu and Aharonian 2020 in prep)

Low energy (LE) CRs

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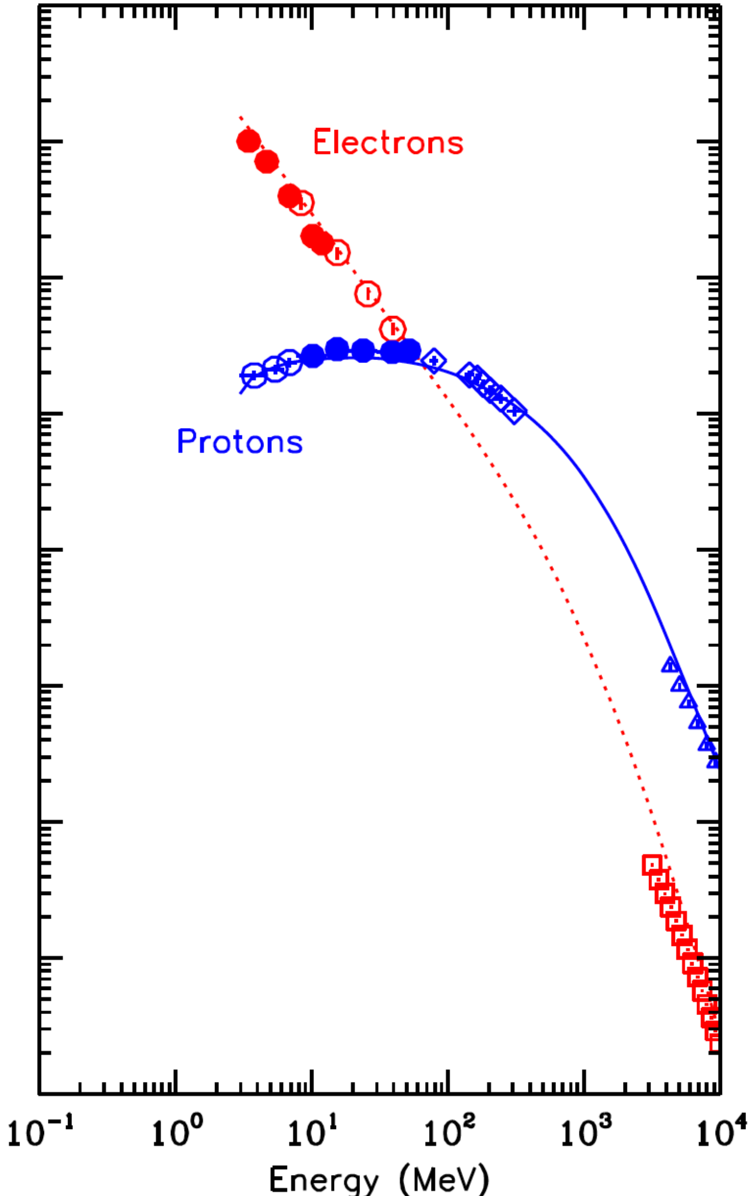
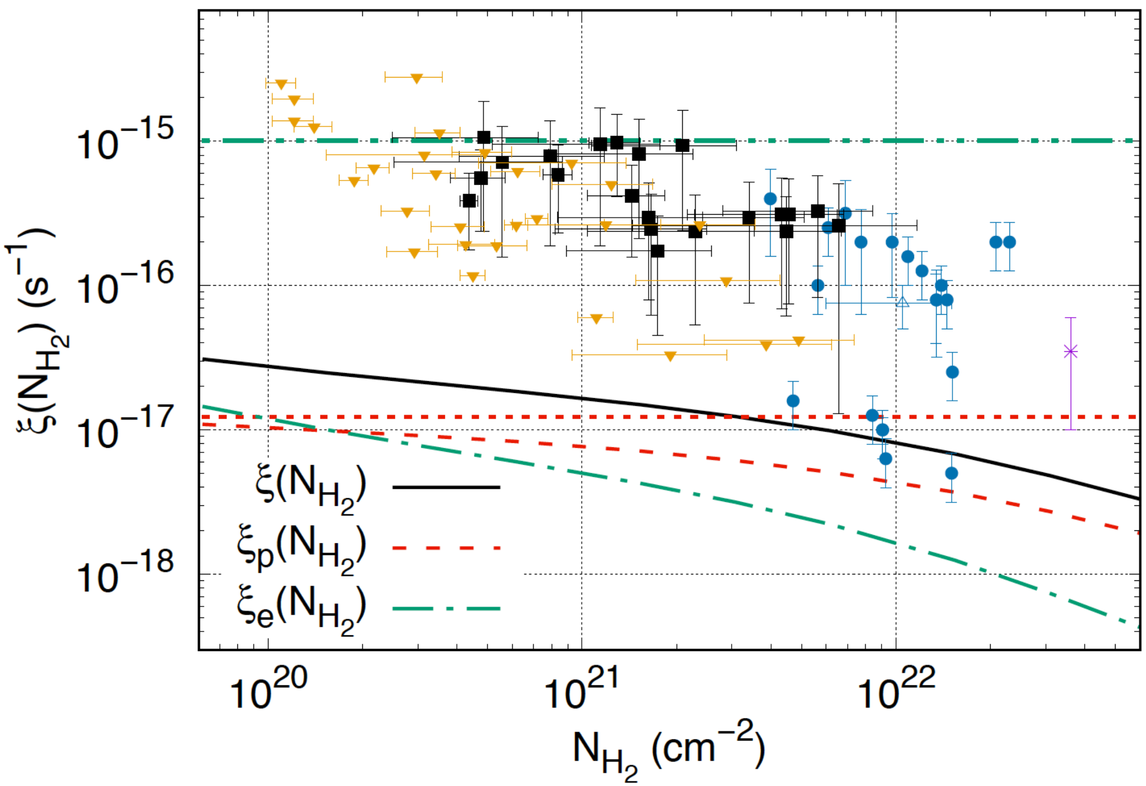
- E < 100 MeV, No pion-decay gamma-rays
- significant contribution to the energy density of ISM (~ eV/cm^3)
- Heating the gas
- Govern the astro-chemistry
- dominate ionization in MCs
- At MeV energy ionization dominate cooling
- Voyager measurement in ISM (Cummings et.al 2016)



LECRs: Ionization

- CR dominates ionization inside MC cores (UV shielded)
- The measured Ionization rates from astro-chemistry are larger than expected



Calculation from Phan et.al 2018, Black curve is the ionization rate assuming voyager measurement is the universal LECR spectrum

LE CR propagation

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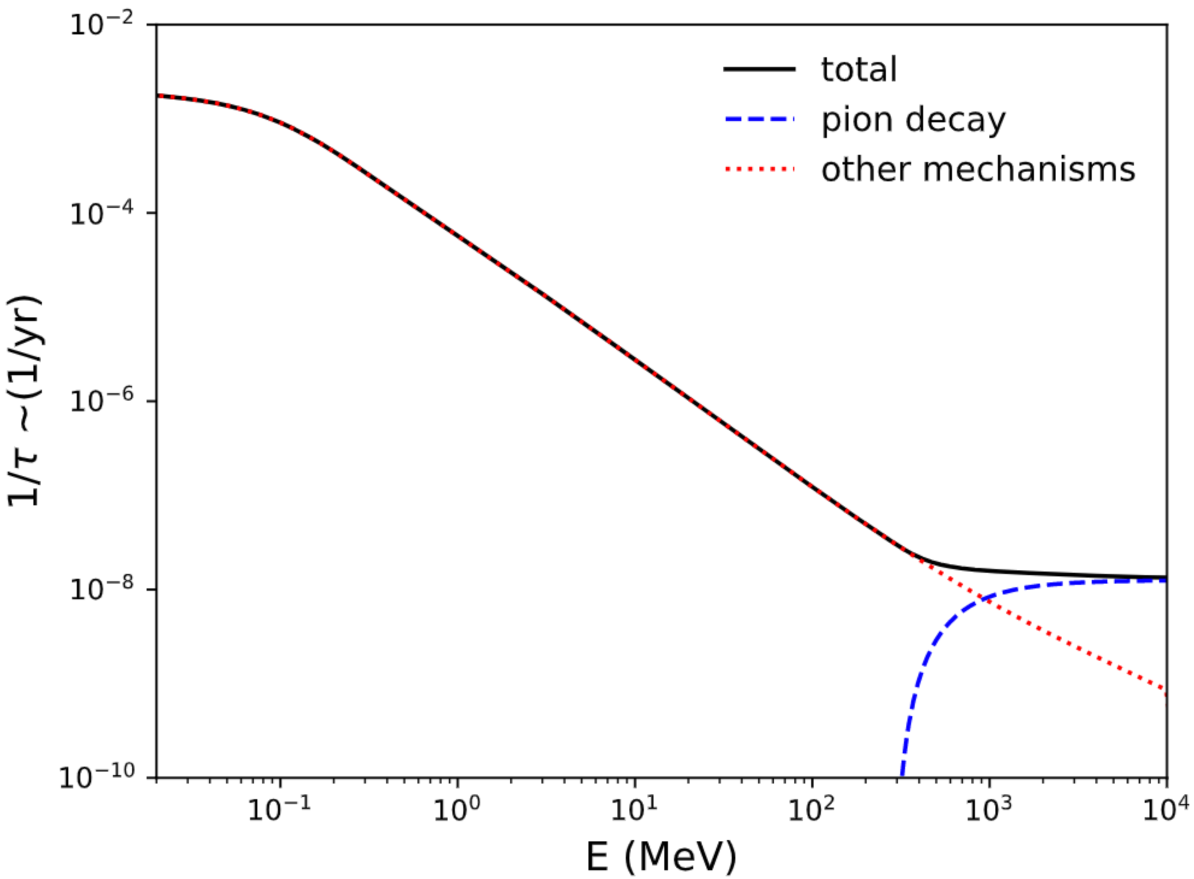
- But is the LECR spectrum universal?
- For LECR ionization cooling (see below) is significant in MeV range and the propagation is slow



LECR propagation

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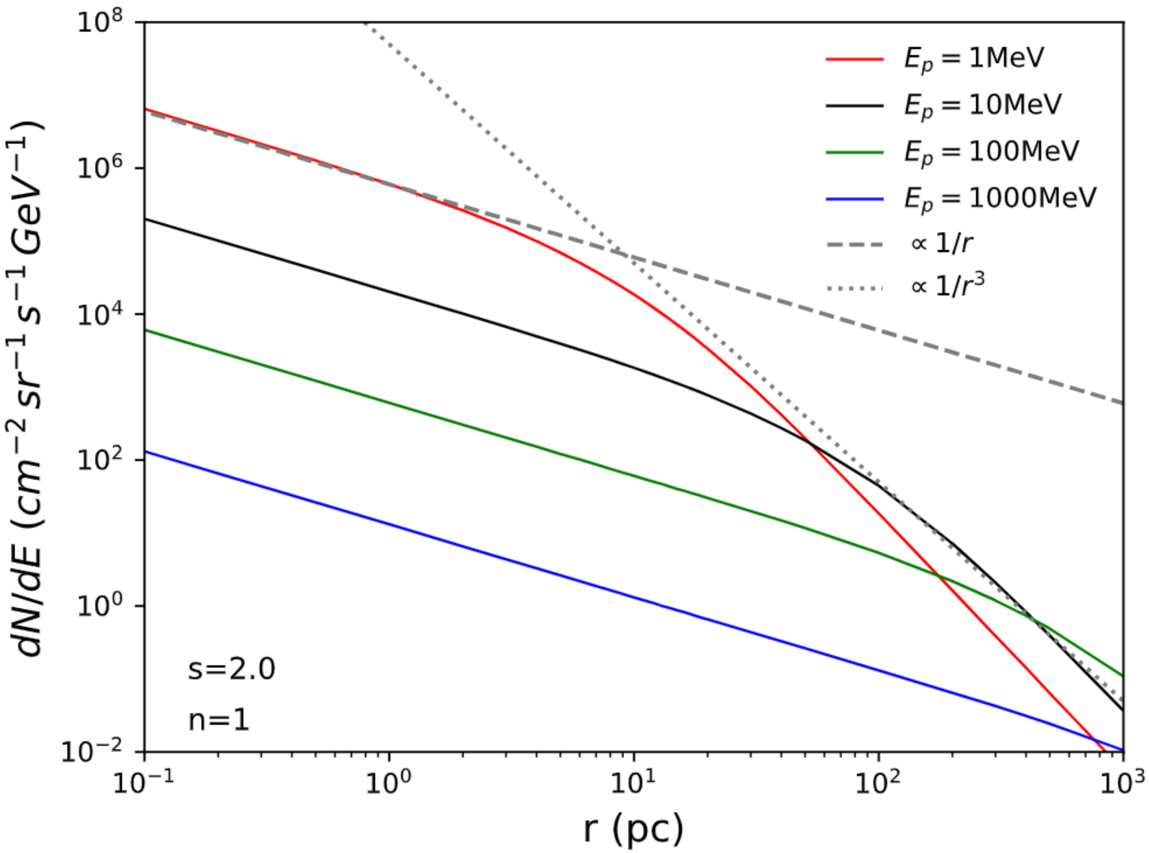
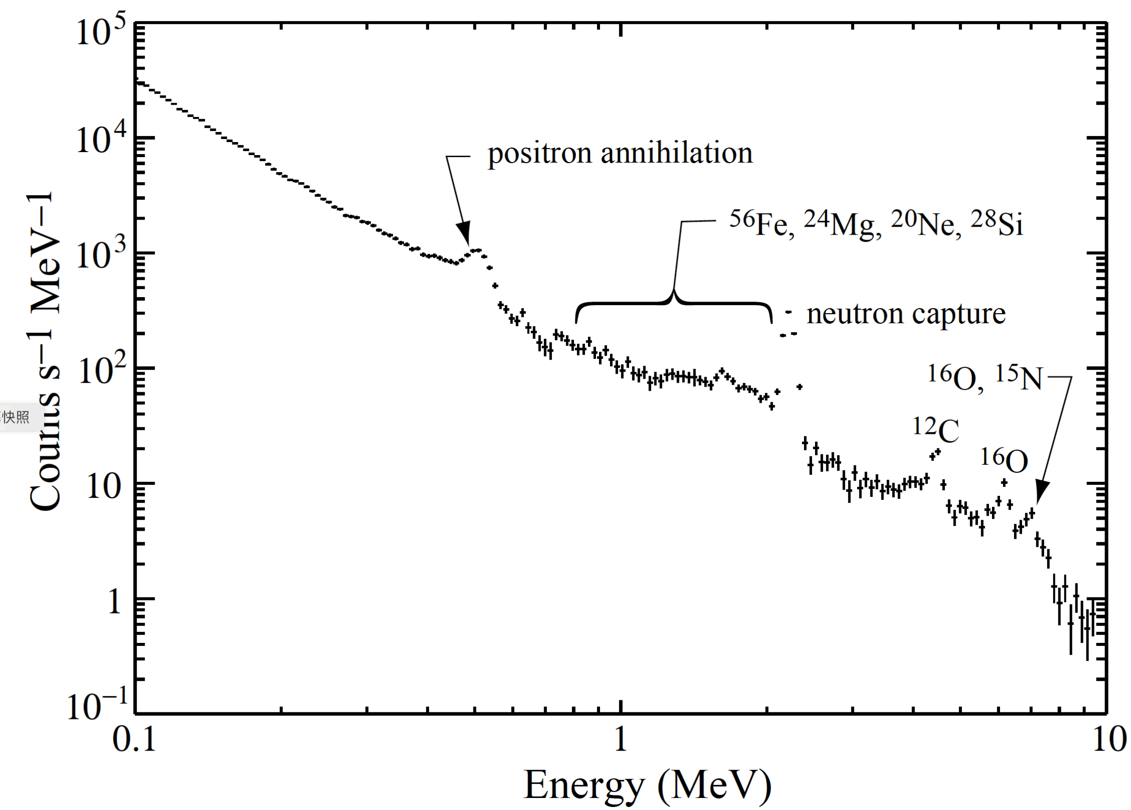
- LECR should be similar to VHE electrons, cannot propagate far
  Flux can be very different at different distances to the source



Gamma-ray line

- The same CRs can be studied also in gamma-rays through de-excitation line of nuclei
- Well studied in solar flare (Kozlovsky et.al 2002)



Gamma-ray line

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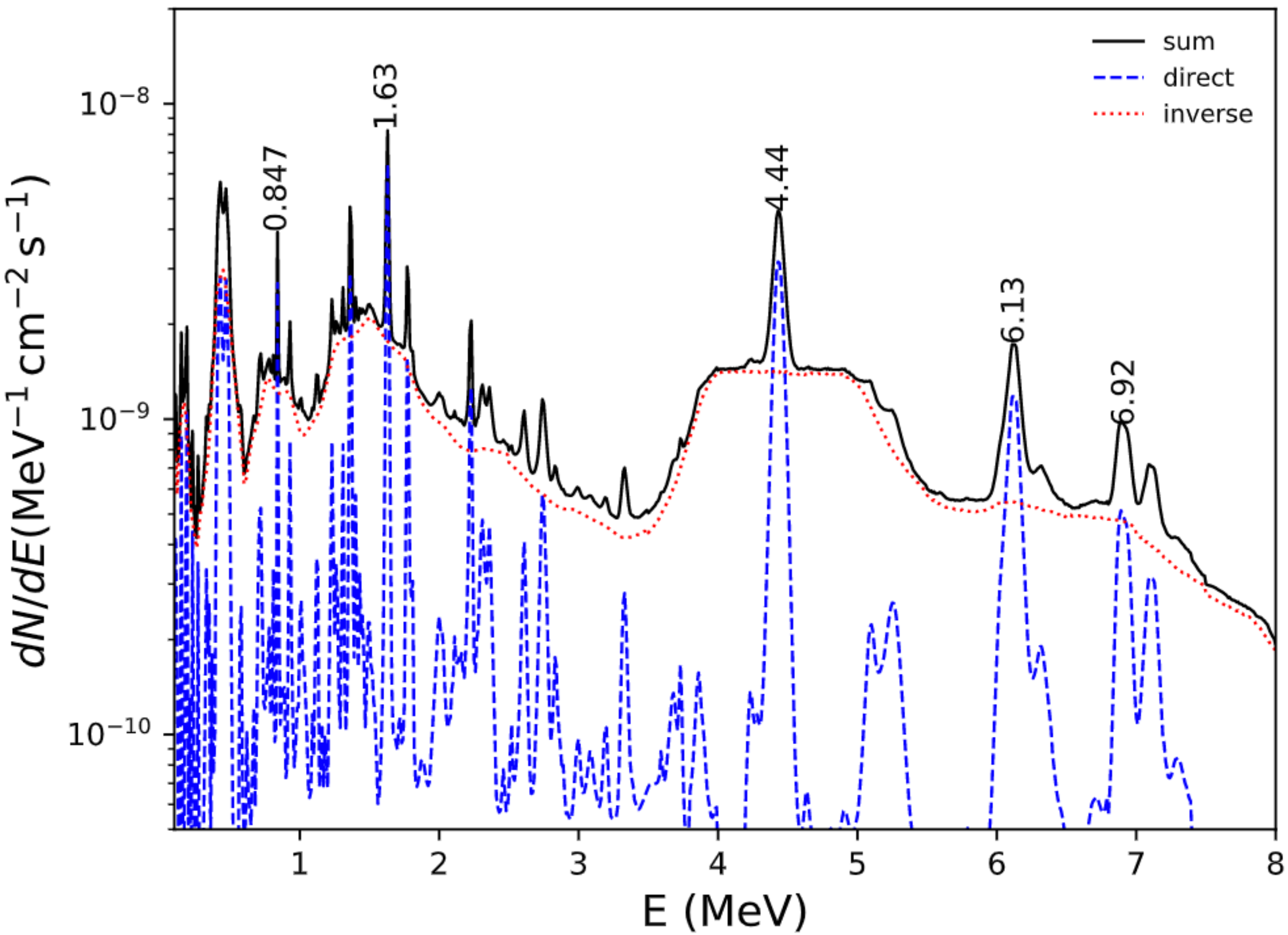
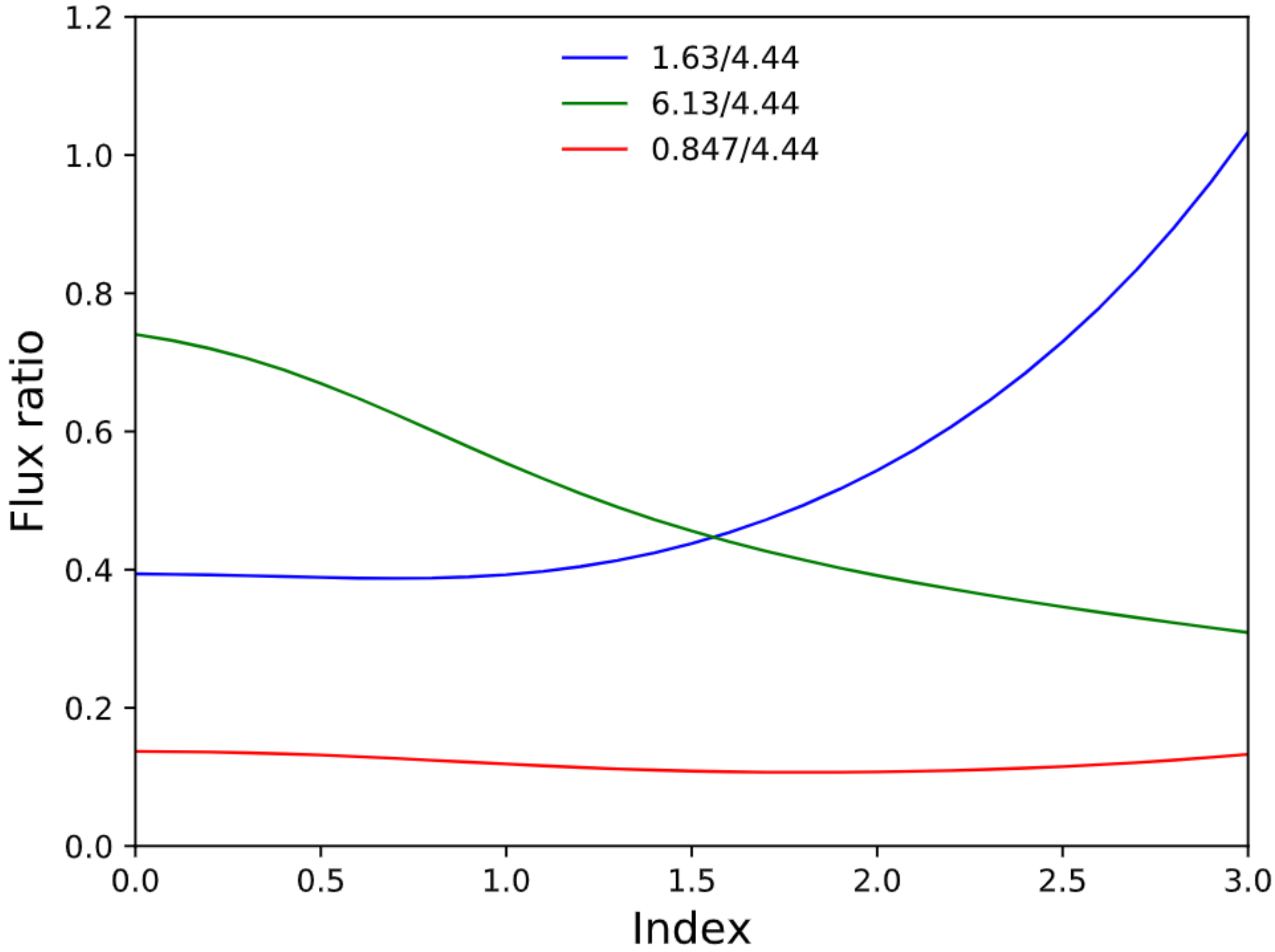


Inverse and direct process

line ratios

Use line ratio to diagnose CR spectrum



line ratios

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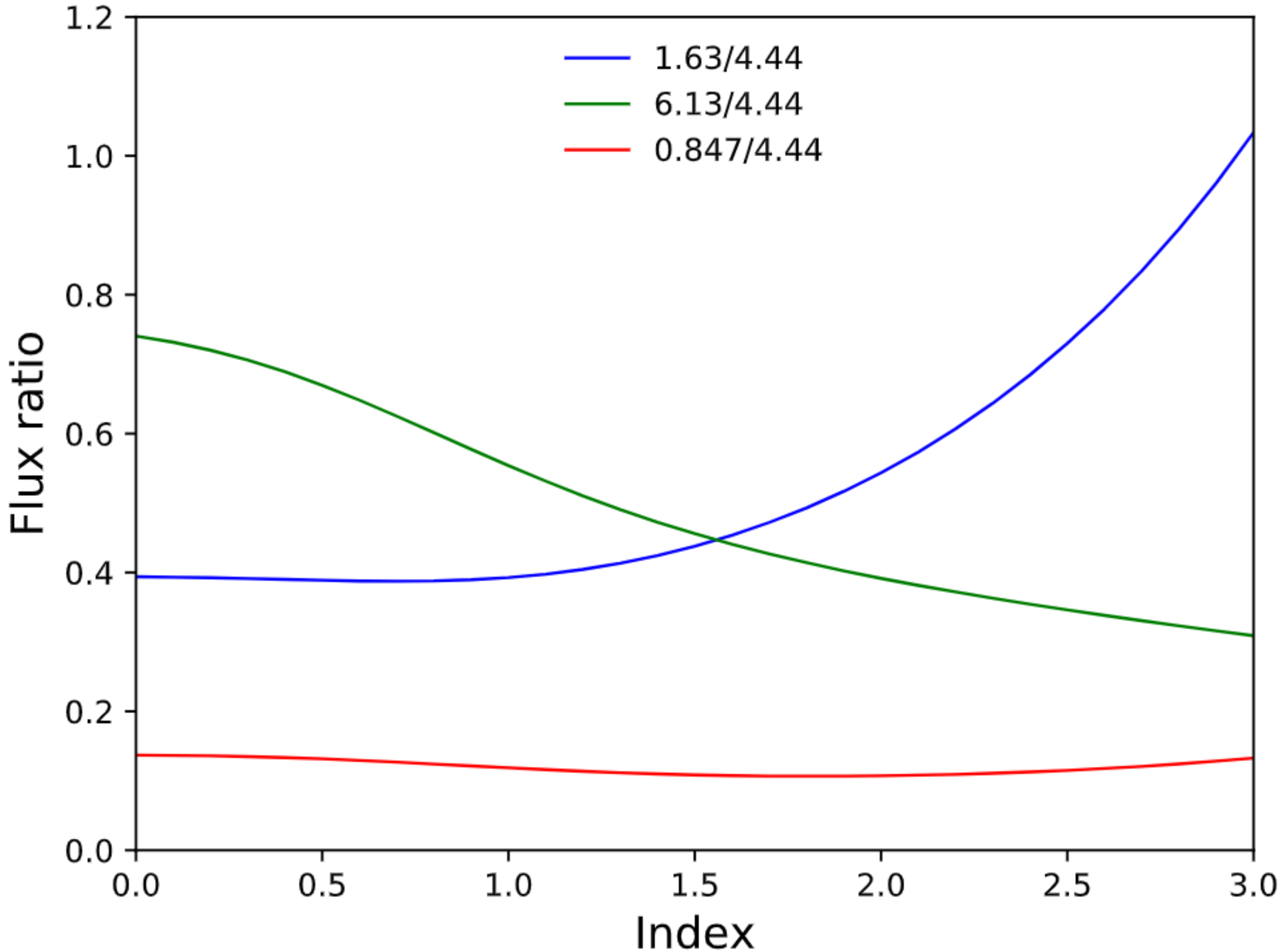
Use line ratio to diagnose CR spectrum



MeV gamma-ray, "LAST" electromagnetic window and interesting physics

Why SNRs?

- Energy budget reasonable: 1e40 erg/s considering 10% efficiency
- Acceleration: 1st order Fermi acceleration in the shock front
- Observation proofs

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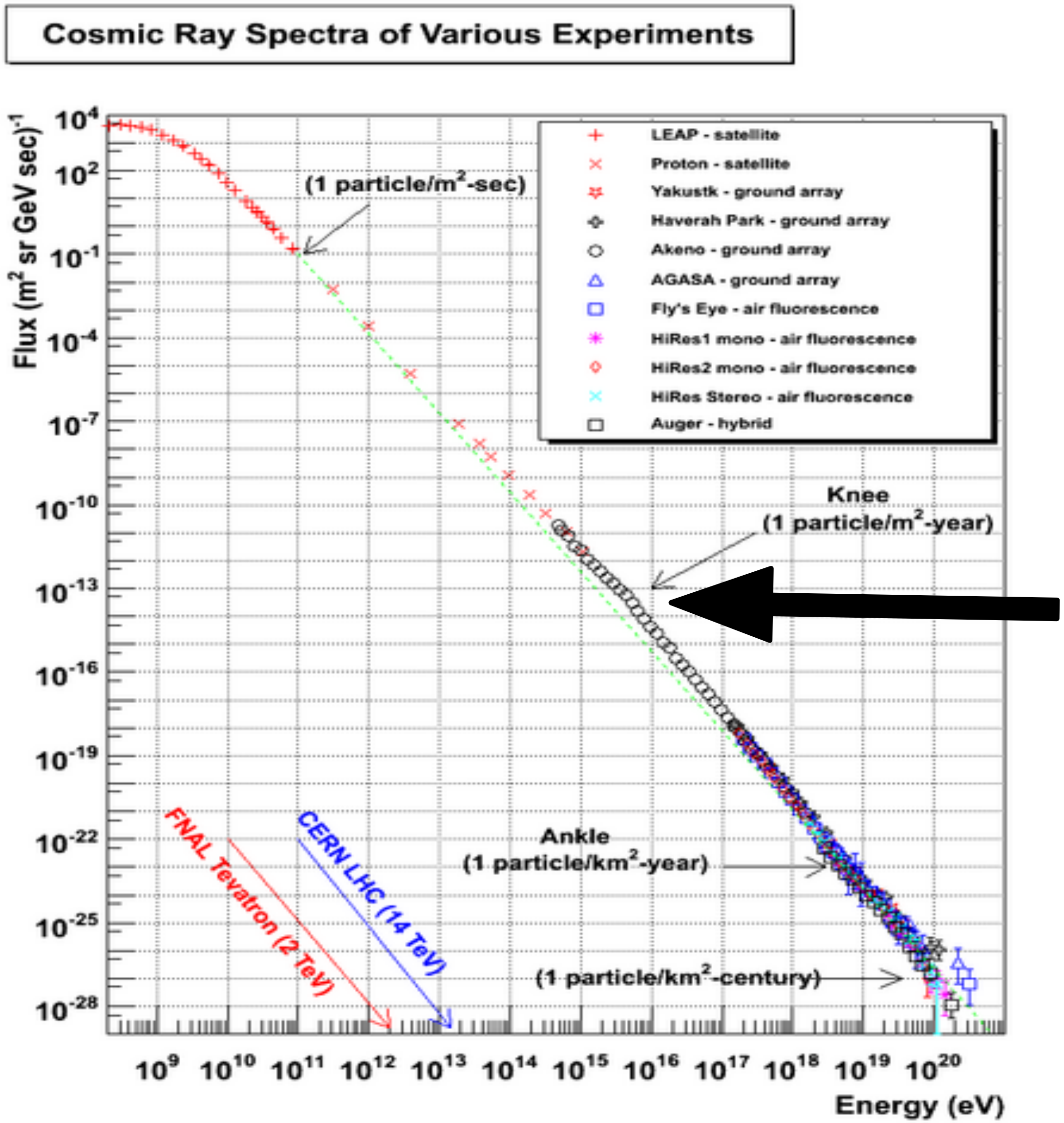
PeVatrons

(Yang, Liu and Aharonian 2020 in prep)

Spectrum



Knee: GCR at least to PeV

https://www.physics.utah.edu/~whanlon/spectrum.html

SNRs as CR source?

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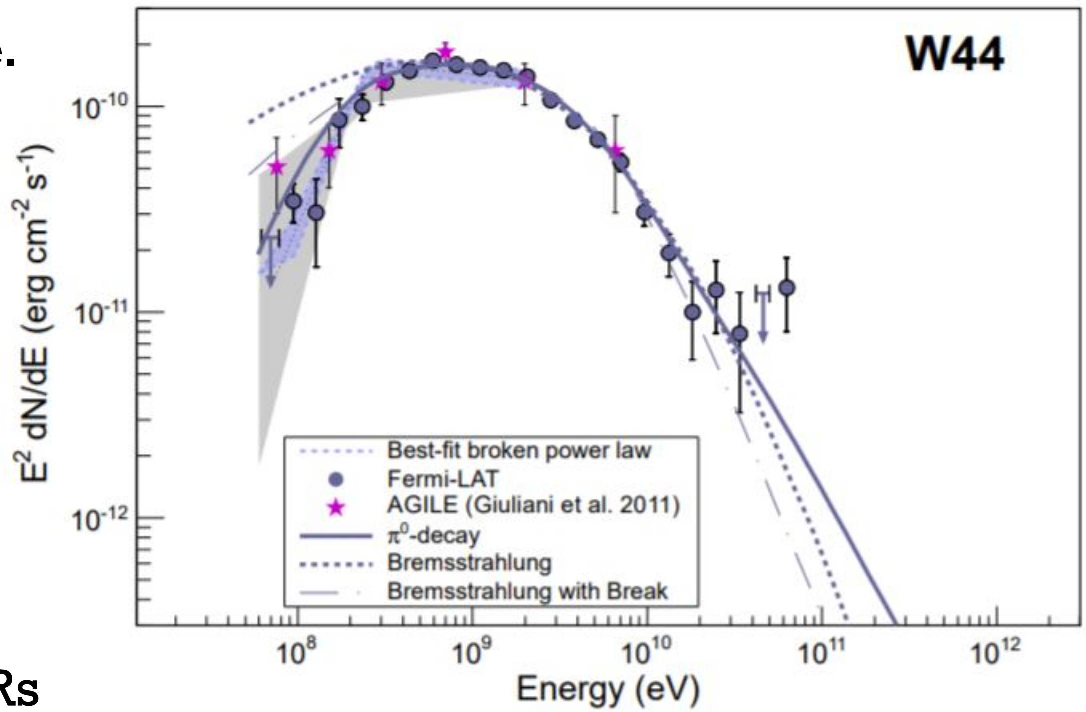
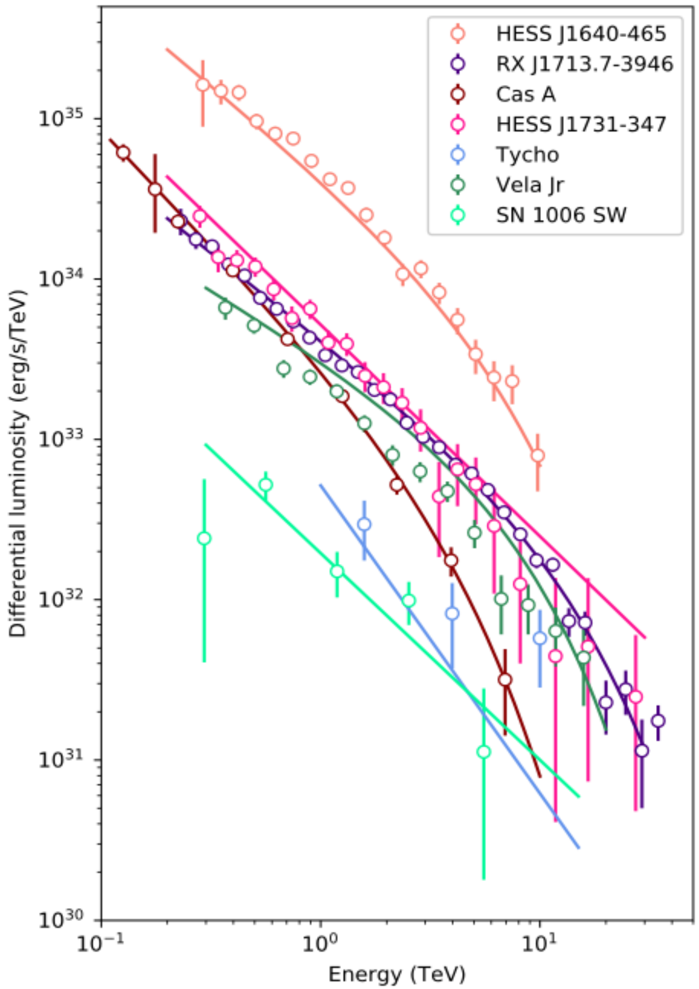
Mid-age SNRs

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



Fermi Collaboration 2013

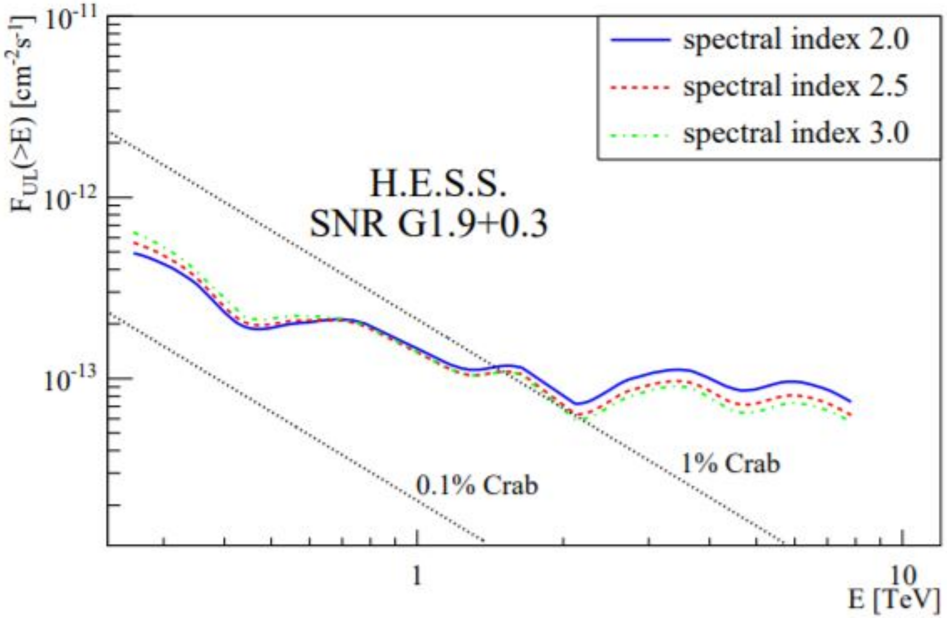
Gamma-ray observation of Young SNRs



- All gamma-ray spectrum of 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

Very young SNRs?

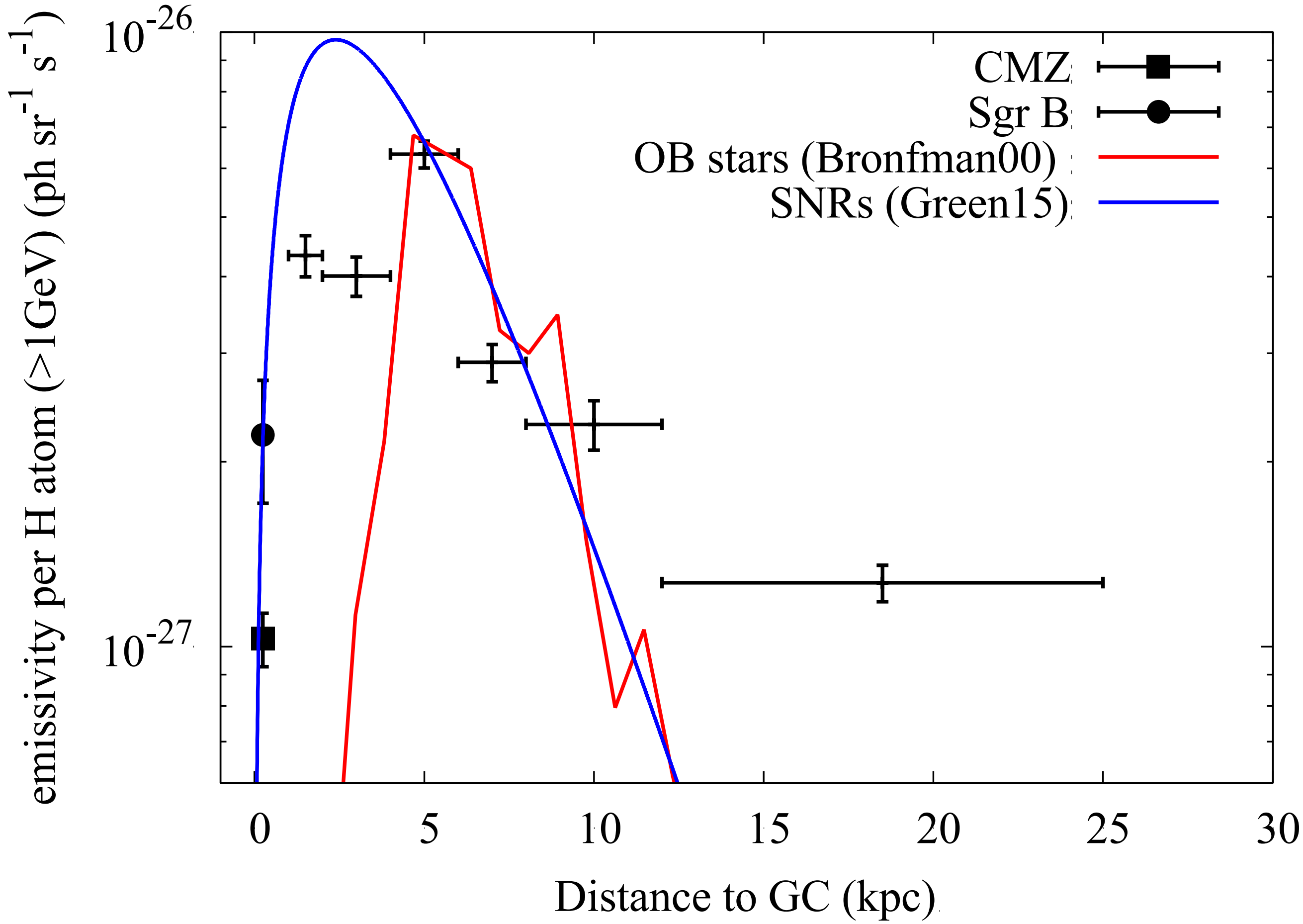
- PeVatron phase could be accomplished only during the first years of the explosion (e.g., Bell et.al 2013)
- The youngest SNR in the Galaxy:
  G1.9+0.3, t ~ 100 yr
- VHE protons cannot propagate more than 30 pc.
- HESS reveals L(>1 TeV) < 1e32 erg/s can be used to set limit on proton energy budget.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



Alternative sources： Young massive clusters

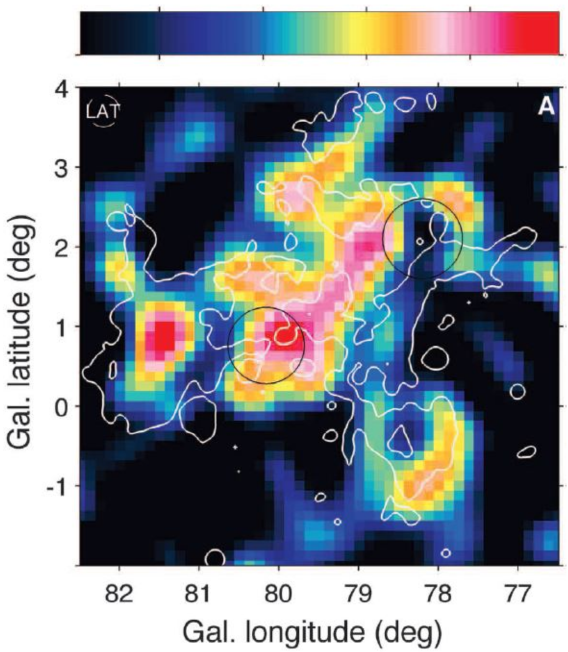
- Isotope measurement favor a superbubble origin. (W.R Binns 2016)
- Most of OB stars exist in associations or clusters, stellar wind can accelerate CRs (Cesarsky & Montmerle 83).
- Efficiency may even better than SNR (high speed wind lasts much longer than SNR shock)
- Sufficient wind power (10^{38}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

CR Radial distributions

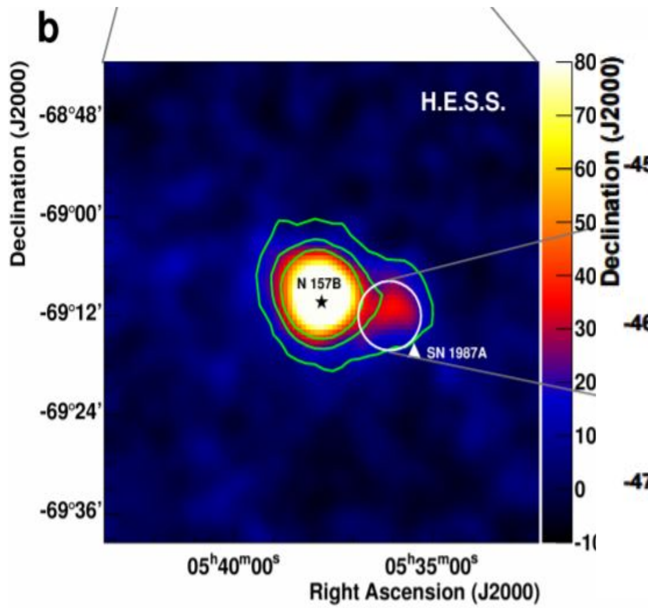


Yang et.al 2016

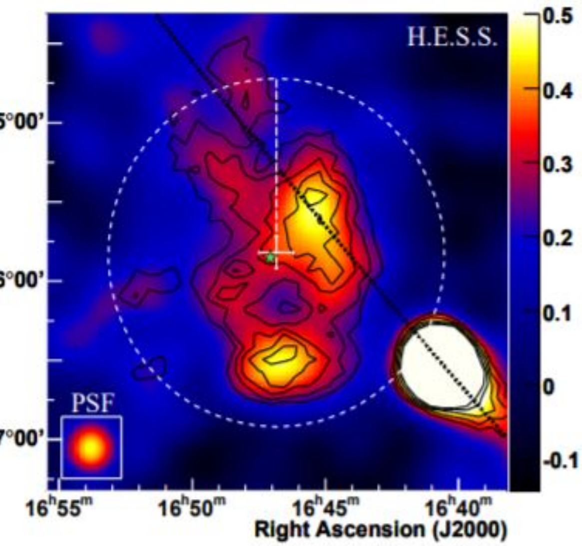
Alternative sources：Young massive clusters



Cygnus Cocoon
(Fermi Collaboration 2012)



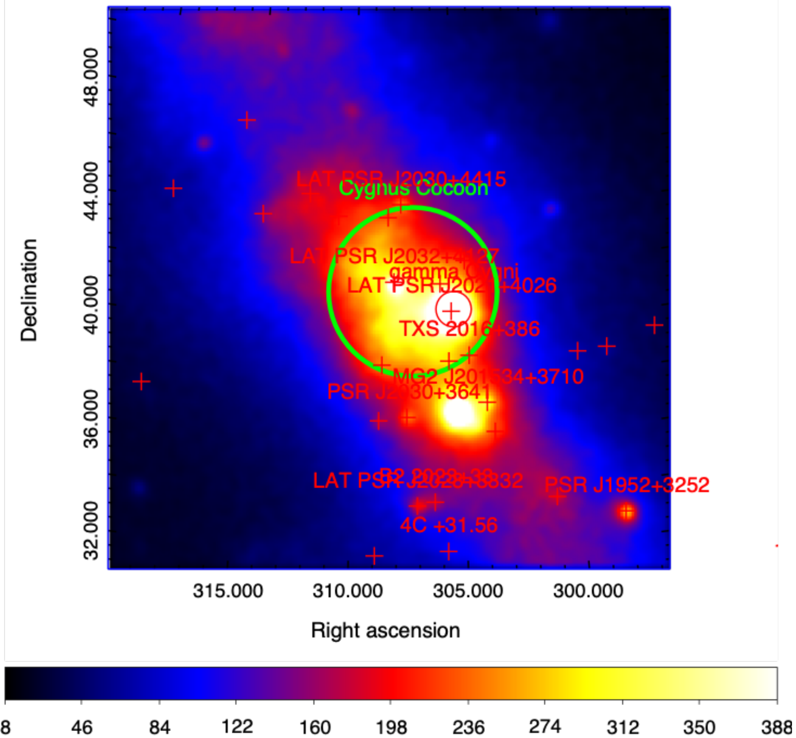
30 Doradus C
(H.E.S.S Collaboration 2015)



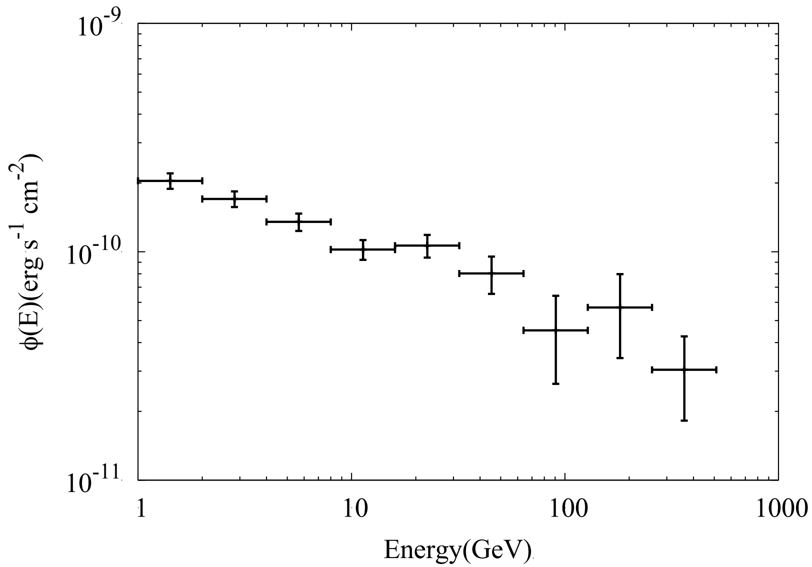
Westerlund 1
(H.E.S.S Collaboration 2011)

Source population

- Cygnus Cocoon



Fermi LAT counts map (>1 GeV)



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

- More: NGC3603 (Yang & Aharonian 2017), Westerlund 2 (Yang et.al 2018), W43 (Yang & Wang 2020), W40 (Sun et.al 2020) RSGC 1 (Sun et.al 2020)… and more to be discovered and investigated

- All reveal extended gamma-ray emission and hard (2.3 type) gamma-ray spectra

Radial distribution of Cosmic Rays

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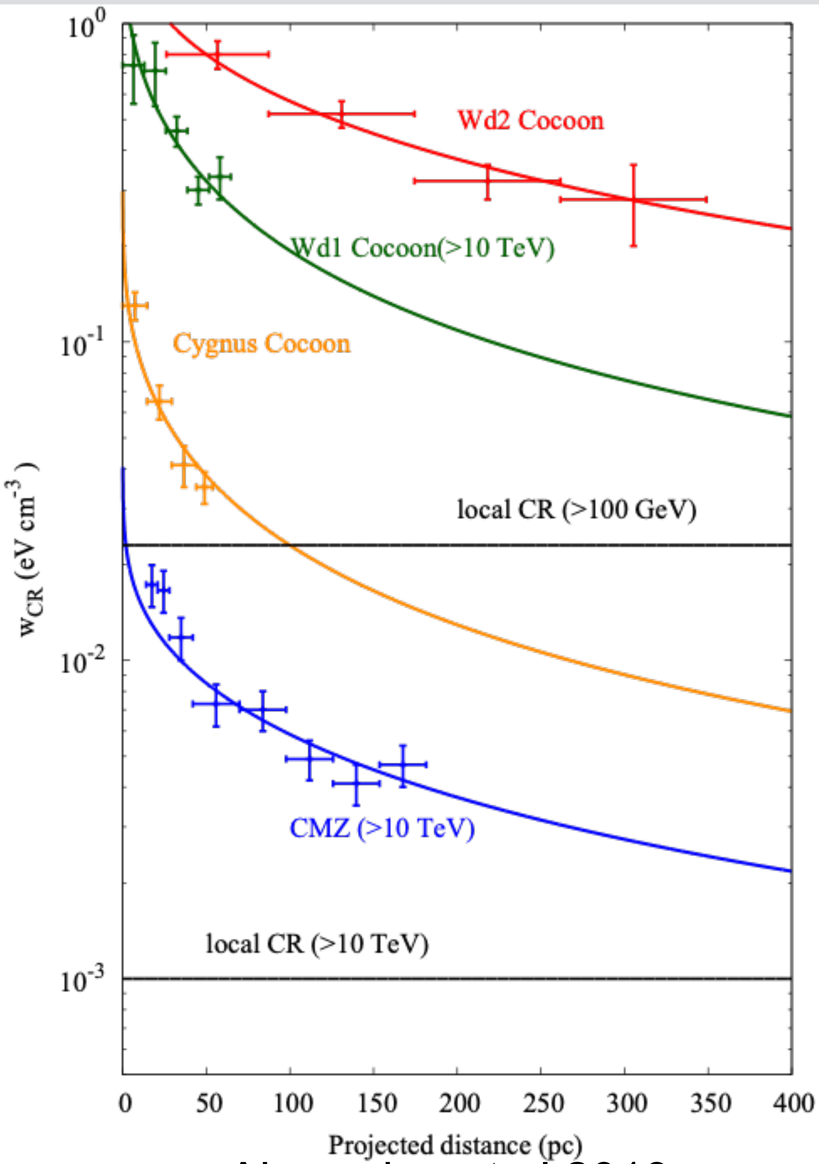

Aharonian et.al 2019

- 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)

Massive star clusters

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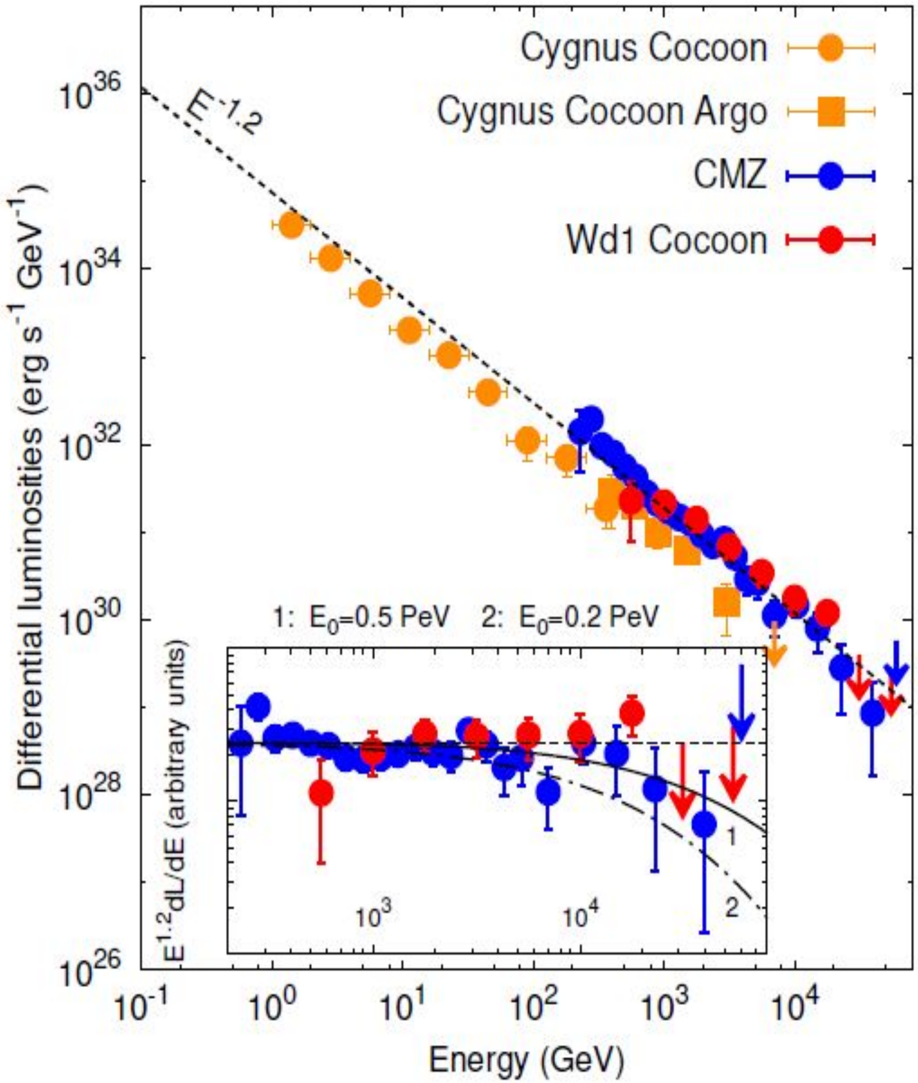

Aharonian et.al 2019

- 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
- PeVatrons?
- LHAASO is the ideal instrument!

Prospect

PeVatron searching

- 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.

- Size of these sources also against leptonic scenario

PeVatron searching

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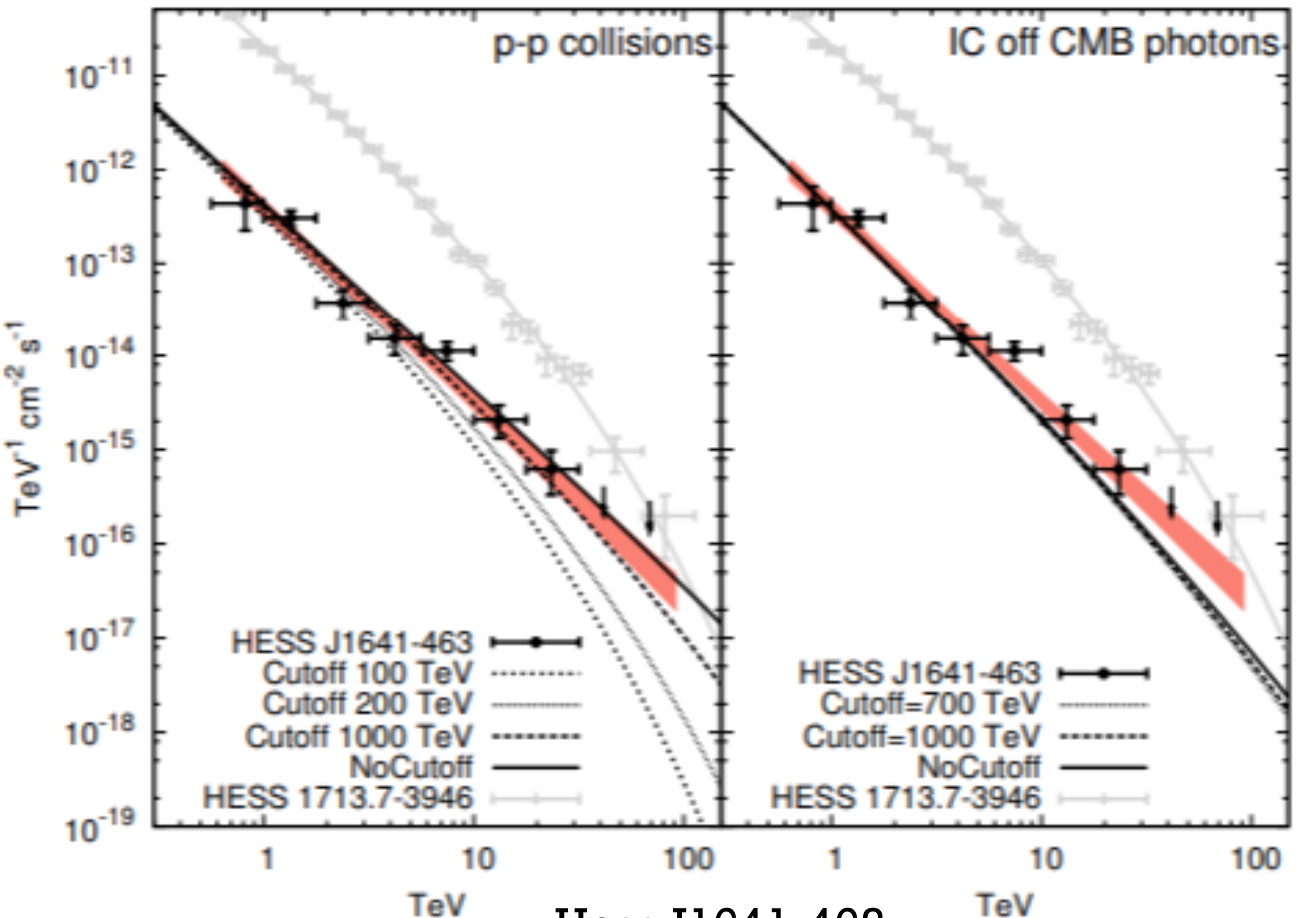
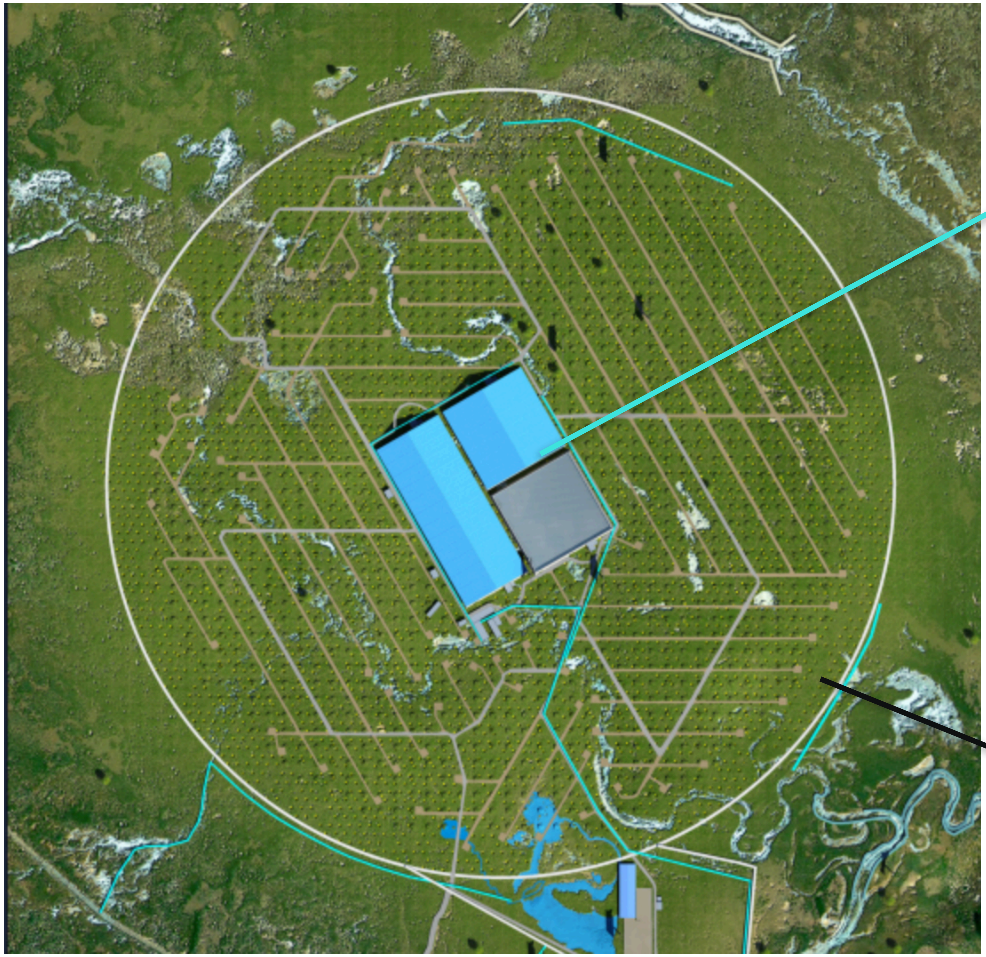


Hess J1641-463
(H.E.S.S collaboration 2016)

LHAASO

- Large High Altitude Air ShowerObservatory



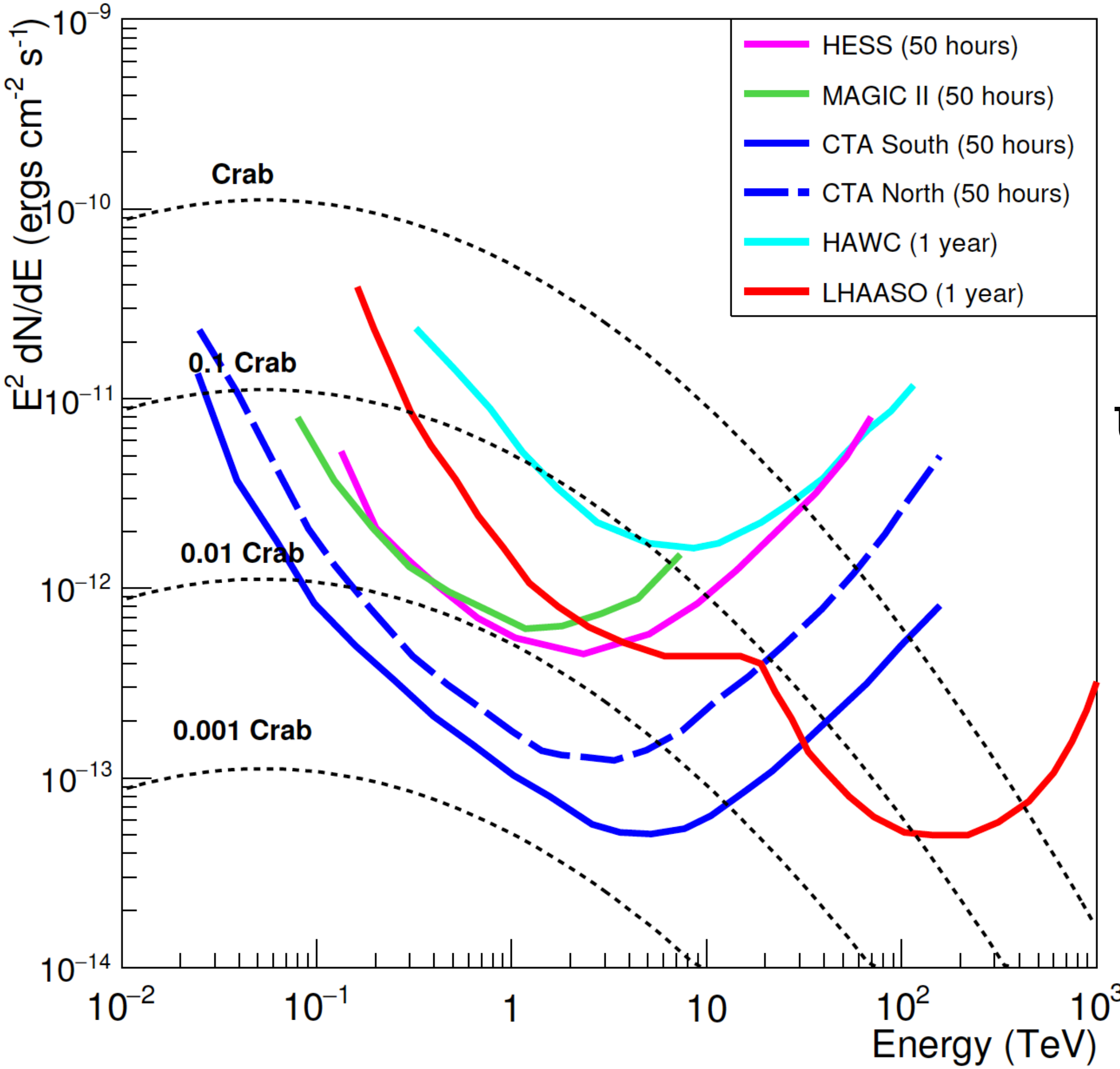
WCDA

KM2A

LHAASO

- KM2A: 1 km^2 scintillator (ED) and muon detector (MD) array, focus on the ultra high energy gamma-rays (>50 TeV)
- WCDA: Water Cherenkov detector arrays, mainly for TeV gamma-rays
- WFCTA: wide field of view Cherenkov telescope array, measure the shower shape, mainly for the direct measurement of Cosmic rays.

LHAASO sensitivities



Unprecedented above 50 TeV

ideal PeVatron hunter

LHAASO sensitivity for SNRs

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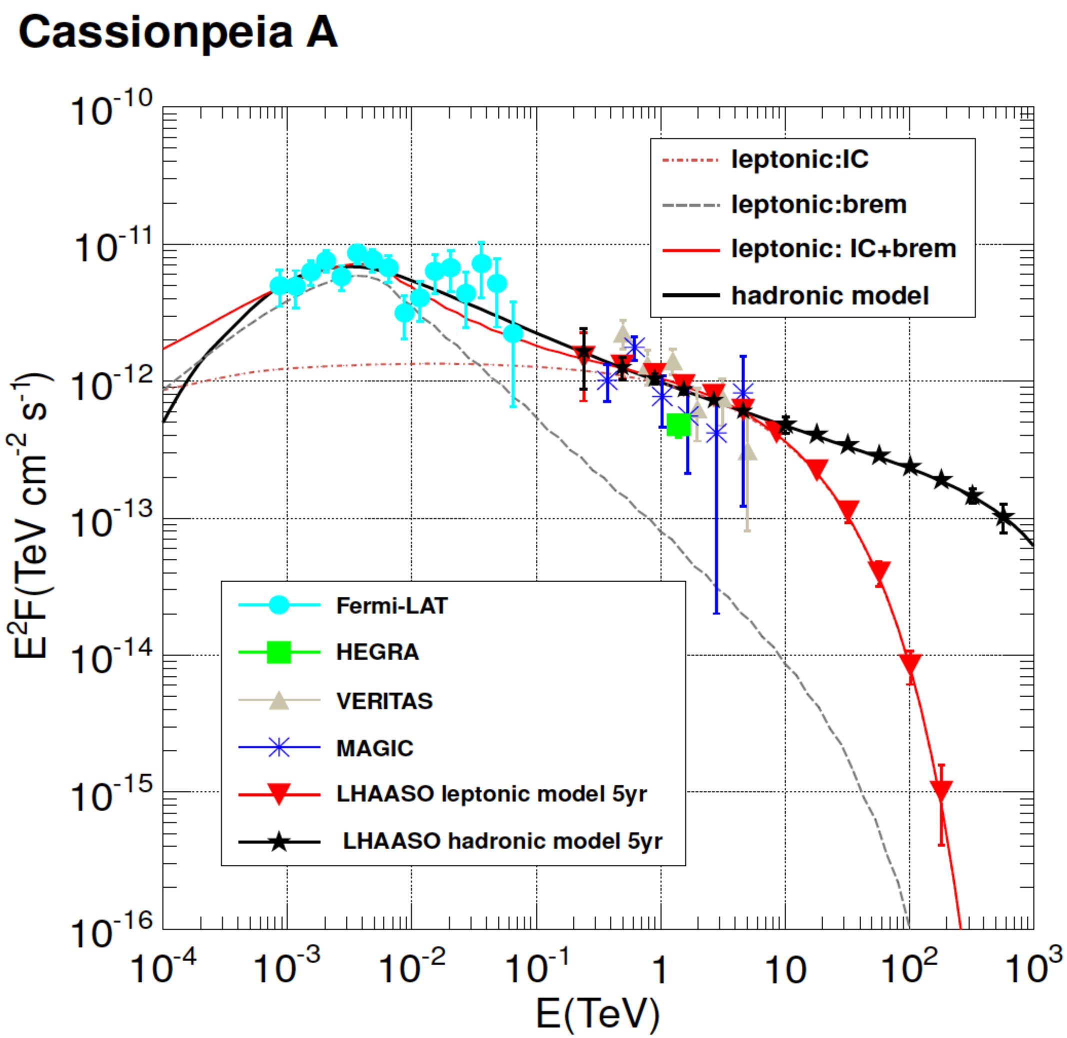
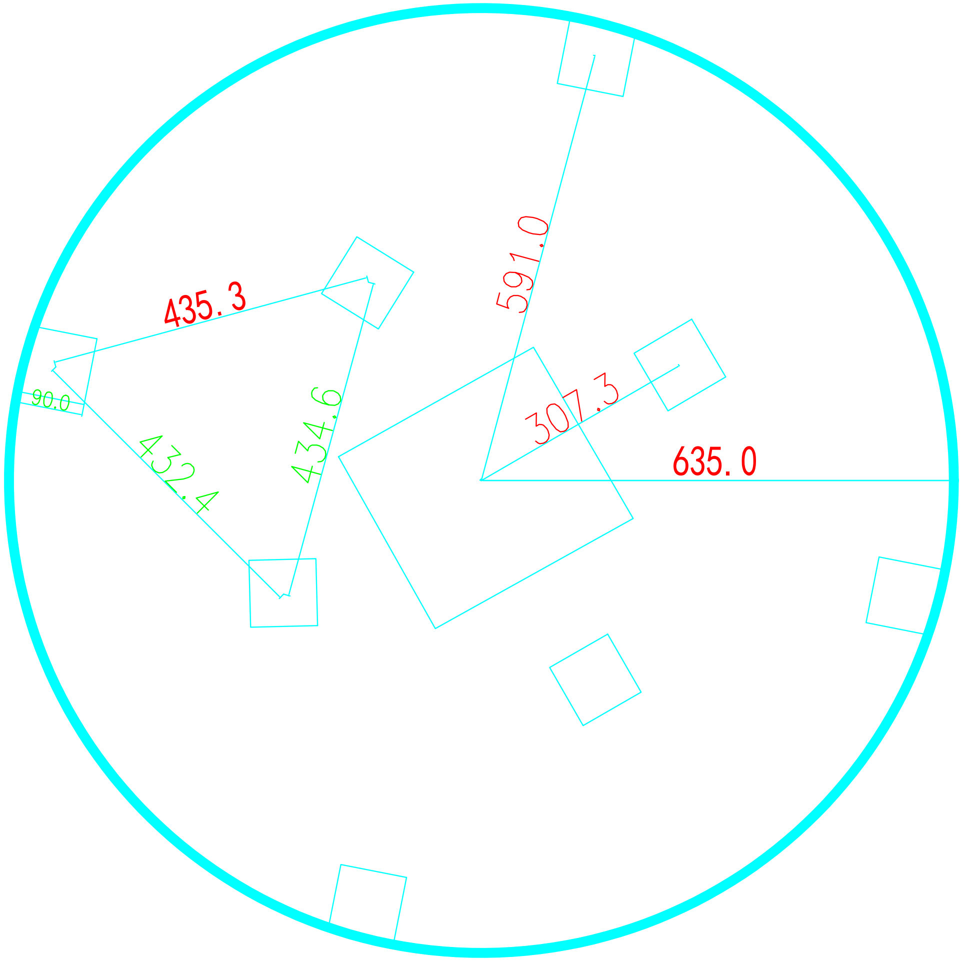


Liu et.al ApJ 826, 1

Chinese Cerenkov Telescope array (CCTA)



Preliminary plan:

32 Cerenkov telescopes

inside LHAASO site

CCTA Sensitivity

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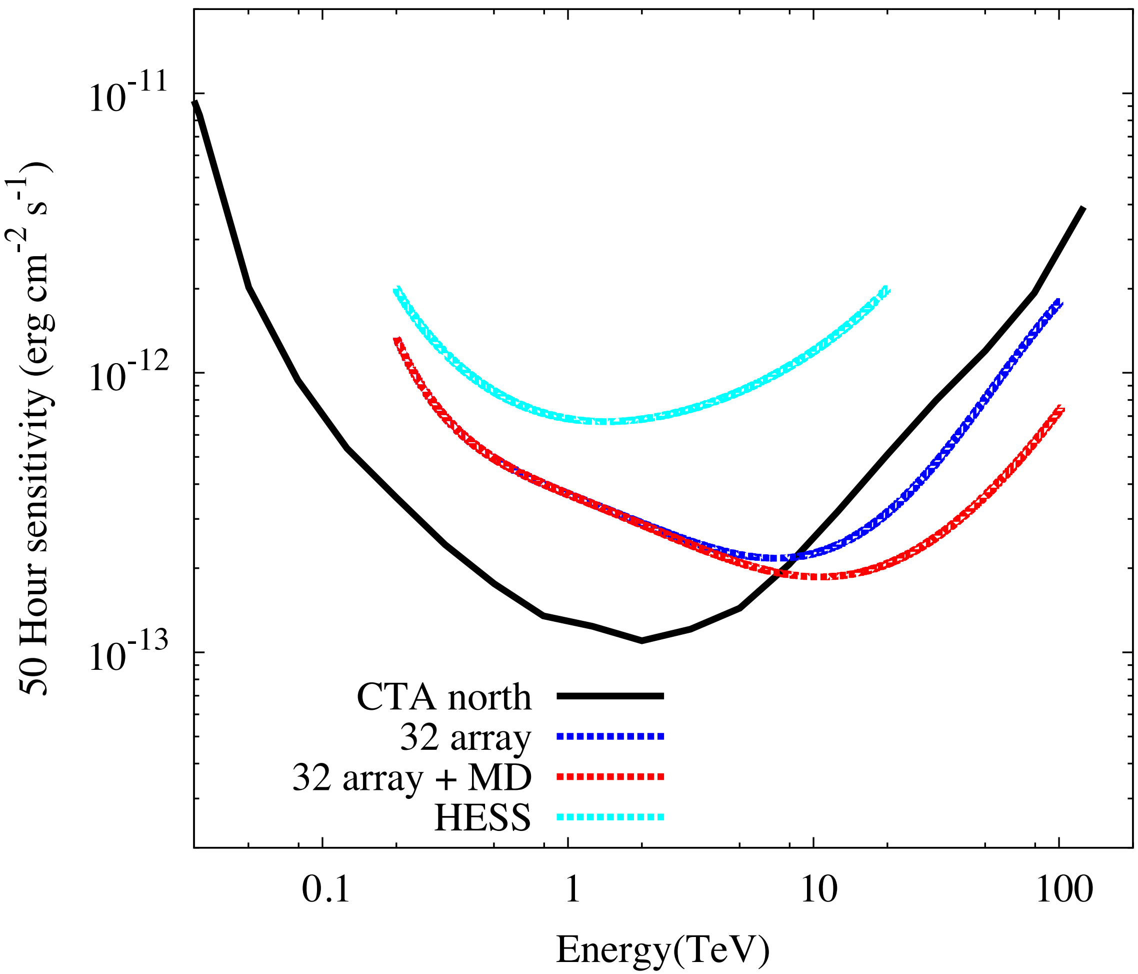

3-times more sensitive than CTA north (under construction) above 10 TeV
order of magnitude better than the running instruments (H.E.S.S, MAGIC, Veritas)

Concluding Remarks

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- CR distributions from the gamma-ray: origin and propagation
- Low energy end: interplay with the star forming/astro-chemistry, nuclear line may open a new window.
- High energy end : PeVatron searching, LHAASO will play a leading role.

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Thanks!