Acceleration to PeV

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Cosmic-ray energy spectrum and composition up to the ankle – the case for a second Galactic component

S. Thoudam[1,2,⋆], J.P. Rachen[1], A. van Vliet[1], A. Achterberg[1], S. Buitink[3], H. Falcke[1,4,5], J.R. Hörandel[1,4]

arXiv:1605.03111

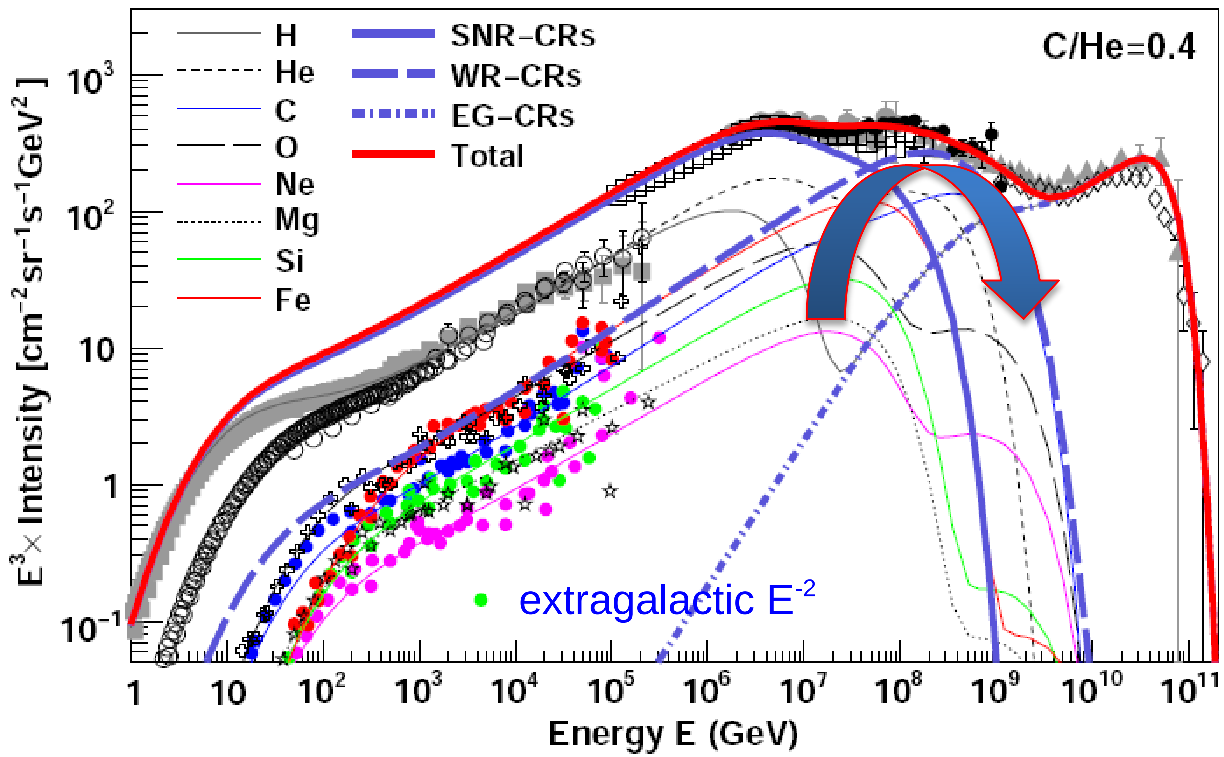


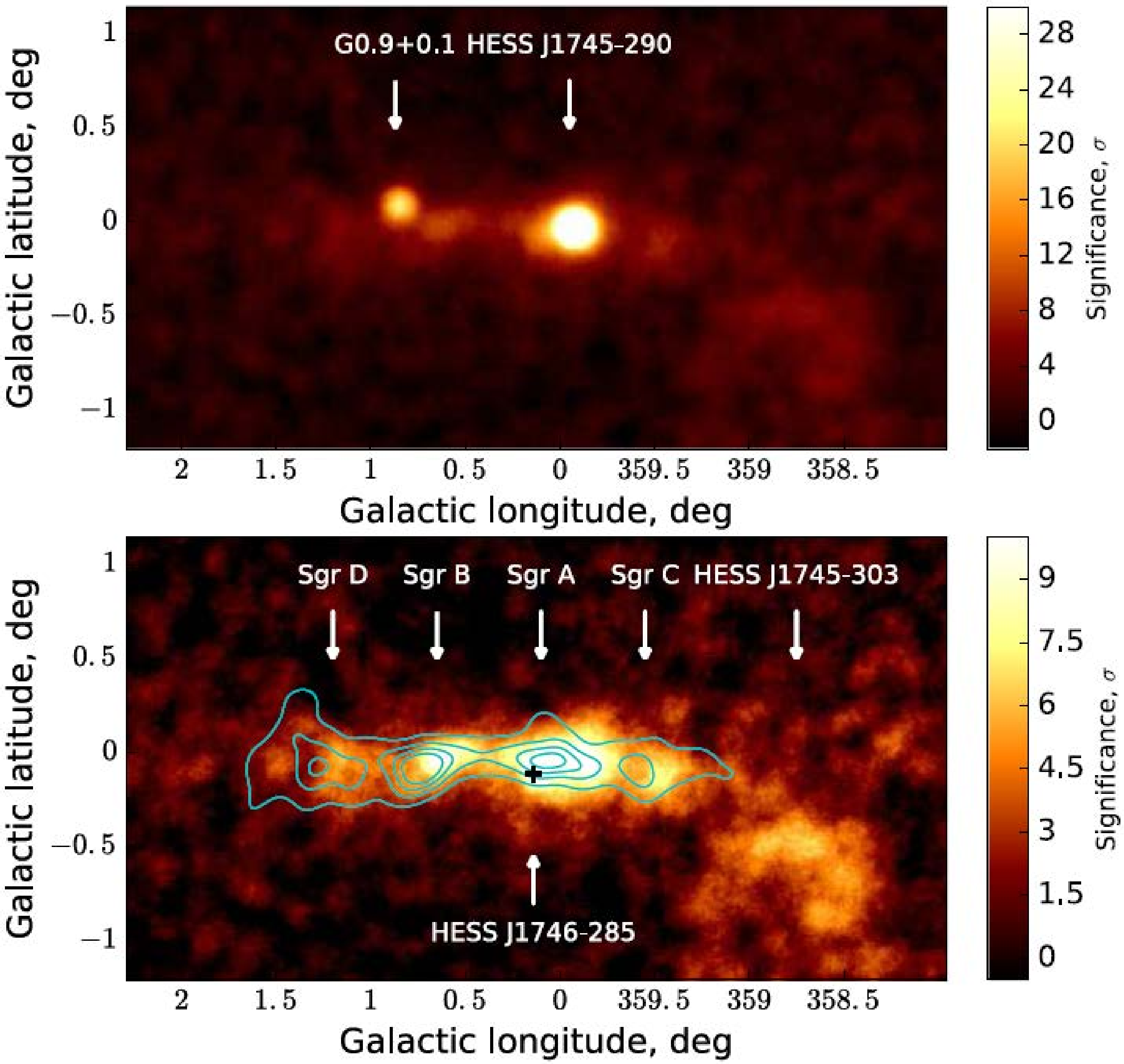
Fig. 6. Model prediction for the all-particle spectrum using the Wolf-Rayet stars model. *Top*: C/He = 0.1. *Bottom*: C/He = 0.4. The thick solid blue line represents the total SNR-CRs, the thick dashed line represents WR-CRs, the thick dotted-dashed line represents EG-CRs, and the thick solid red line represents the total all-particle spectrum. The thin lines represent total spectra for the individual elements. For the SNR-CRs, an exponential energy cut-off for protons at $E_c = 4.1 \times 10^6$ GeV is assumed. See

WHY extragalactic E^{-2} ?

How can we identify galactic sources producing the second component in the CR spectrum?

Multi-TeV Gamma-rays
TeV-PeV neutrinos
Synchrotron X-rays from TeV leptons …

H.E.S.S. multi-TeV sources in the GC region



H.E.S.S. collaboration A&A 512, A9, (2018).

H.E.S.S. multi TeV sources in the GC region

A&A 612, A9 (2018)

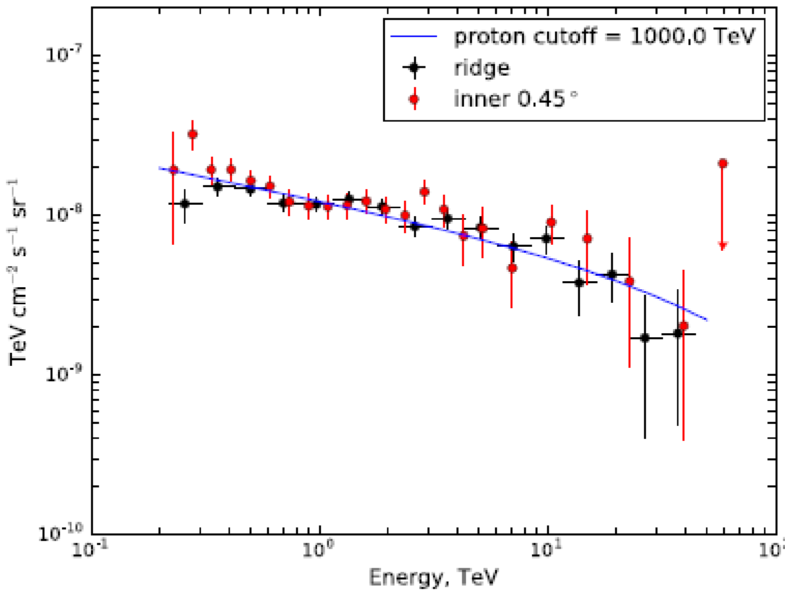


Fig. 5. Very high-energy γ-ray flux per unit solid angle in the Galactic centre region (black data points). The spectrum of the GC ridge region, $|\ell| < 1°$, $|b| < 0.3°$, is shown. All error bars show the 1σ standard deviation and are corrected to account for some background double counting due to the stacking procedure. The spectrum is fitted over an energy range up to 45 TeV. It can be described by a power law with a photon index of $2.28 \pm 0.03_{stat} \pm 0.2_{syst}$ and a differential flux at 1 TeV of $1.2 \pm 0.04_{stat} \pm 0.2_{syst} \times 10^{-8}$ TeV^{-1} cm^{-2} s^{-1} sr^{-1}. For comparison, the blue line is the γ-ray spectrum resulting from a power-law proton spectrum with a cut-off at 1 PeV.

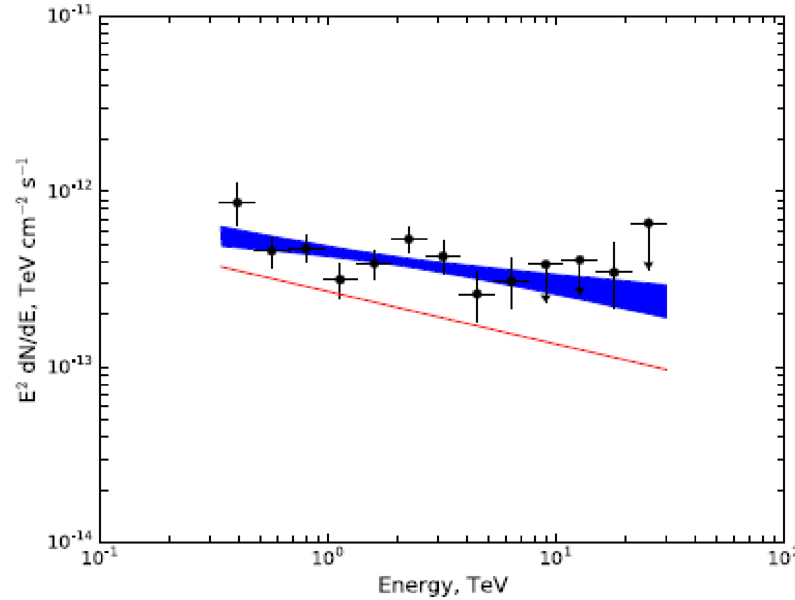
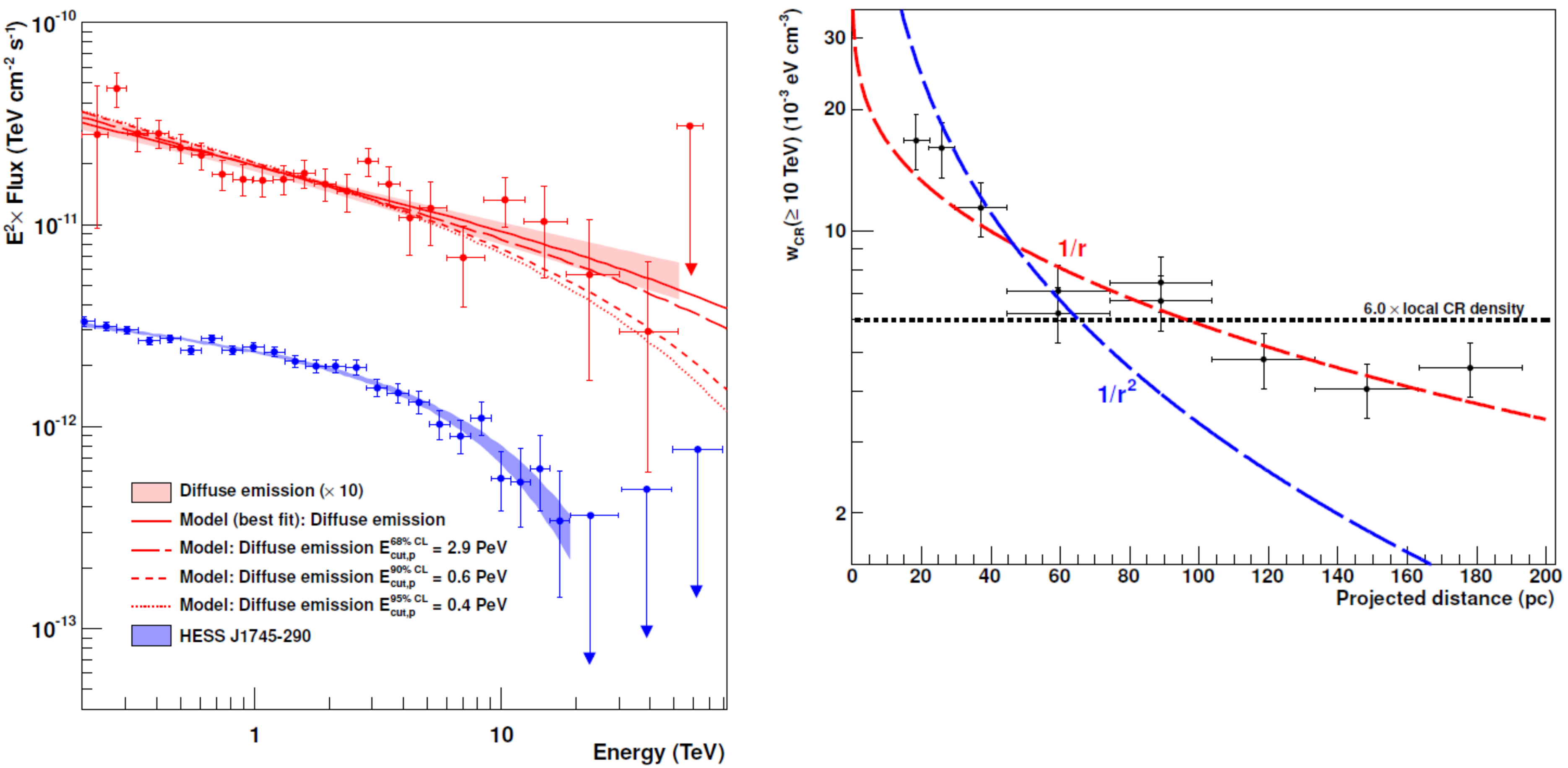


Fig. 6. Very high-energy γ-ray spectrum of the region centred on the position of HESS J1746−285, fitted with the sum of two power laws. The GC ridge contribution is fixed and the intrinsic source spectrum of HESS J1746−285 is fitted to the data. In red, we show the fixed ridge power-law contribution to the total spectrum. The intrinsic spectrum of HESS J1746−285 was estimated to have a flux normalisation of $F(1\,\mathrm{TeV}) = (1.8 \pm 0.5) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} and an index of 2.2 ± 0.2 for the energy range above 0.350 TeV. The errors include the uncertainty of the GC ridge emission, which are obtained by varying the ridge component parameters by their statistical errors.

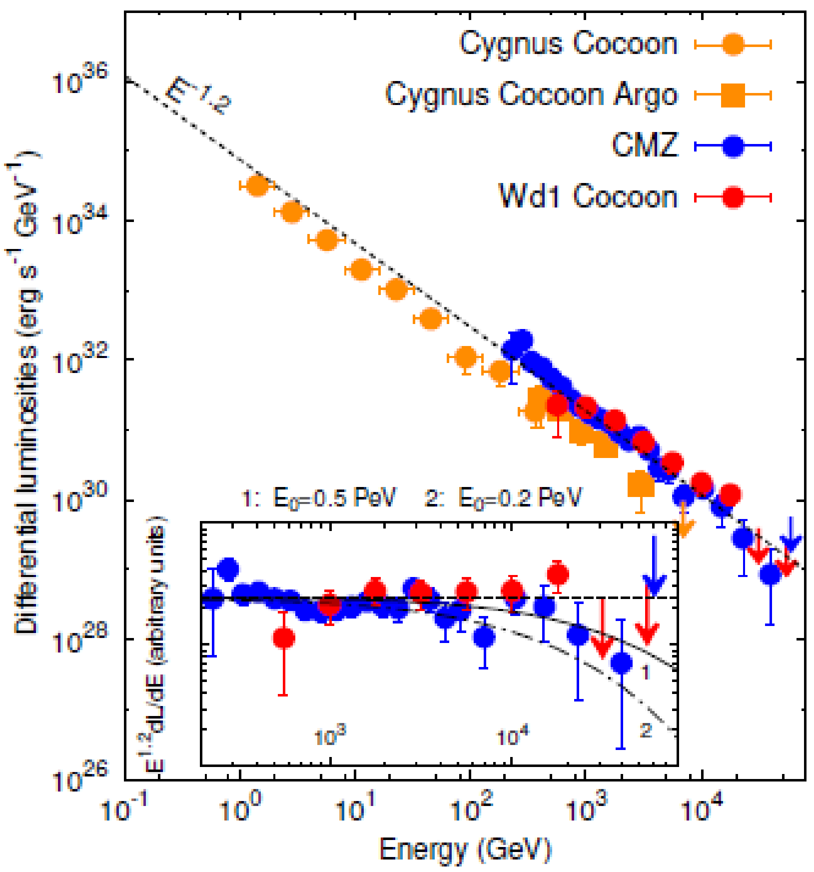
H.E.S.S. multi TeV sources in the GC region

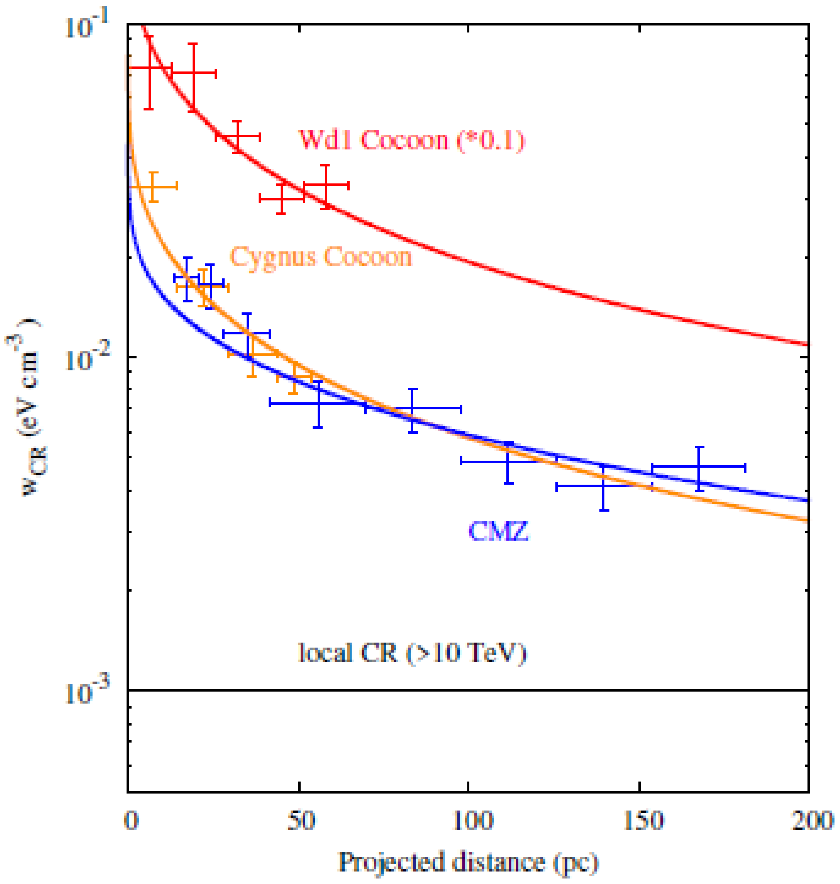
Acceleration of Petaelectronvolt protons in the Galactic Centre



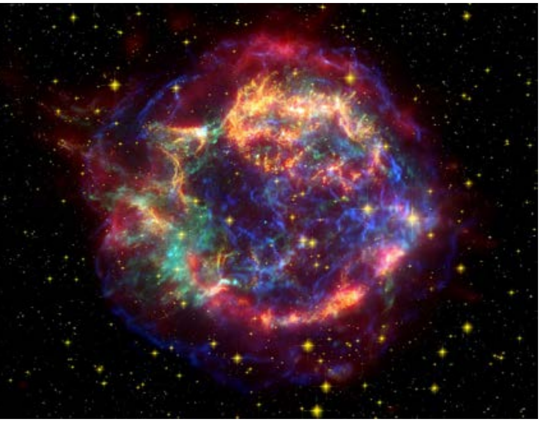
H.E.S.S. collaboration Nature v.531, pp. 476-479 (2016).

TeV observations of HECR sources

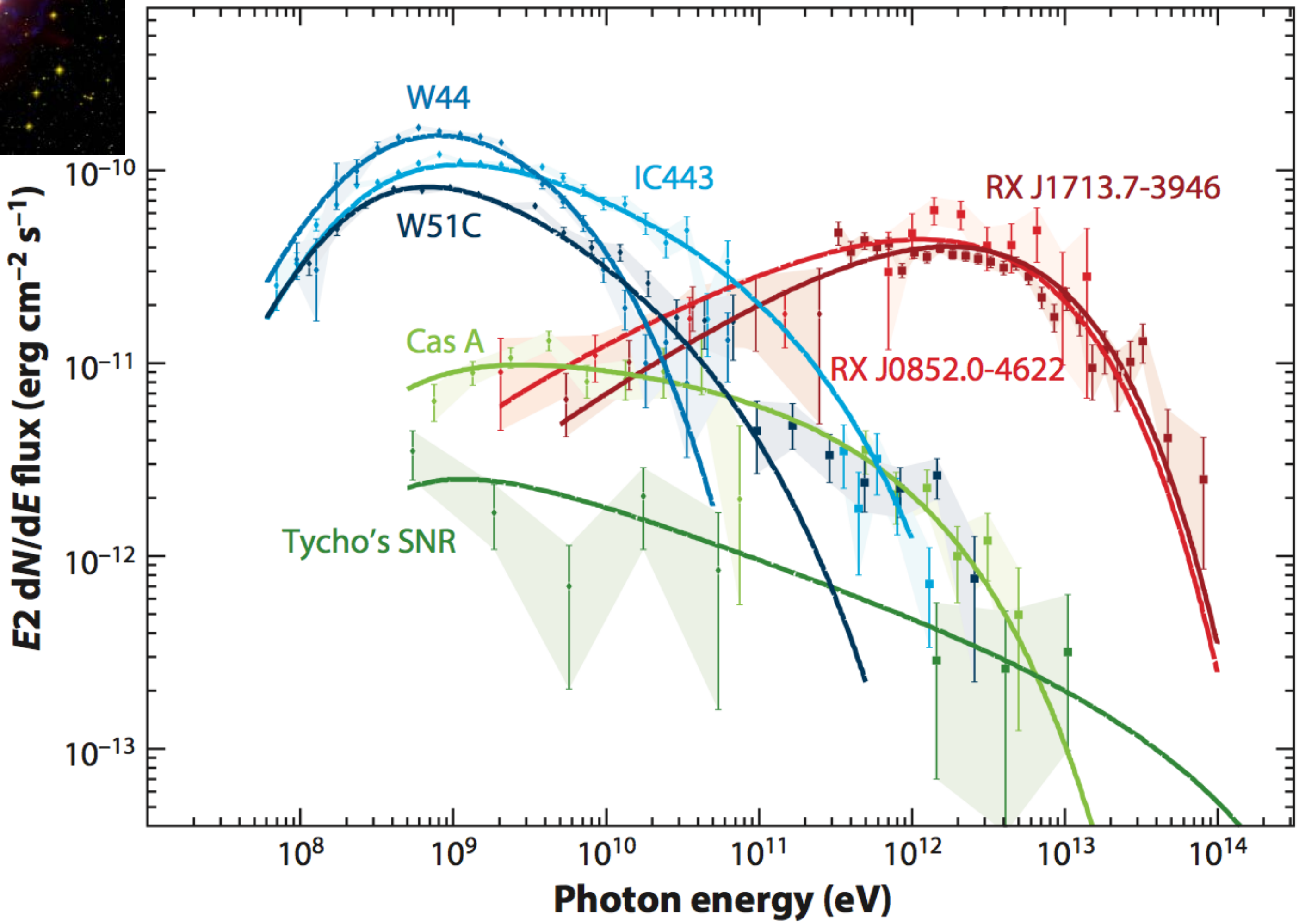




Aharonian, Ona Wilhelmi. Yang Nat. Astron. 2019



Observed gamma-ray spectra of young SNRs



•*What are the sources of PeV regime CRs?*

S. Funk 2015

How to get PeV energy CRs?

Rare SNe with a special CSM type IIn?

Rare magnetar-driven SNe?

Clustered YMS-SNRs (superbubbles)?

SNR- Stellar/Custer Wind collision?

Models of PeV proton acceleration in rare type SNe

A general constrain on the max energies of CR accelerated by MHD flow of a given power:

$$E_{\rm max} \approx Z \times 10^{14} \cdot \frac{\beta_{\rm flow}^{1/2}}{\Gamma_{\rm flow}} \left(\frac{\dot{E}}{3 \times 10^{33}\ {\rm erg\ s^{-1}}} \right)^{1/2} {\rm eV},$$

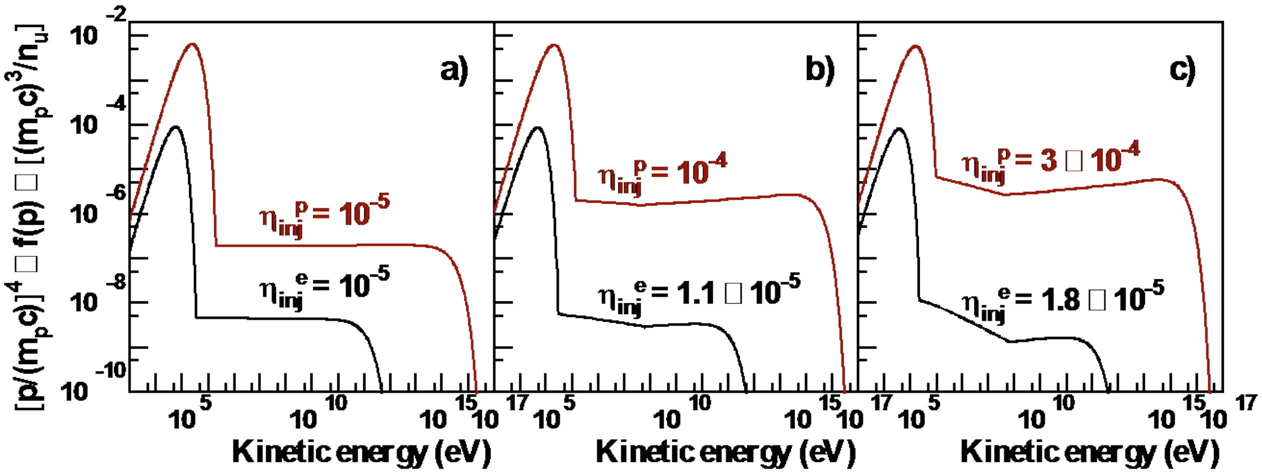
for a SN in SSC (age 400 yrs)

$$L_{\rm kin} \leq 10^{40}\, {\rm erg\, s^{-1}}$$

cf Lemoine & Waxman 2009 …

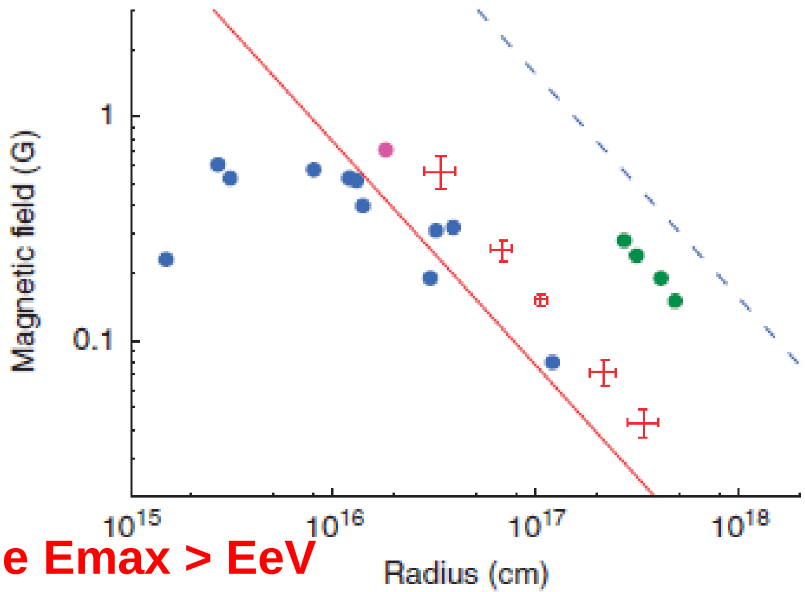
CR proton acceleration by radio SNe and trans-relativistic SNRs

V. Tatischeff: Radio emission and nonlinear diffusive shock acceleration in SN 1993J



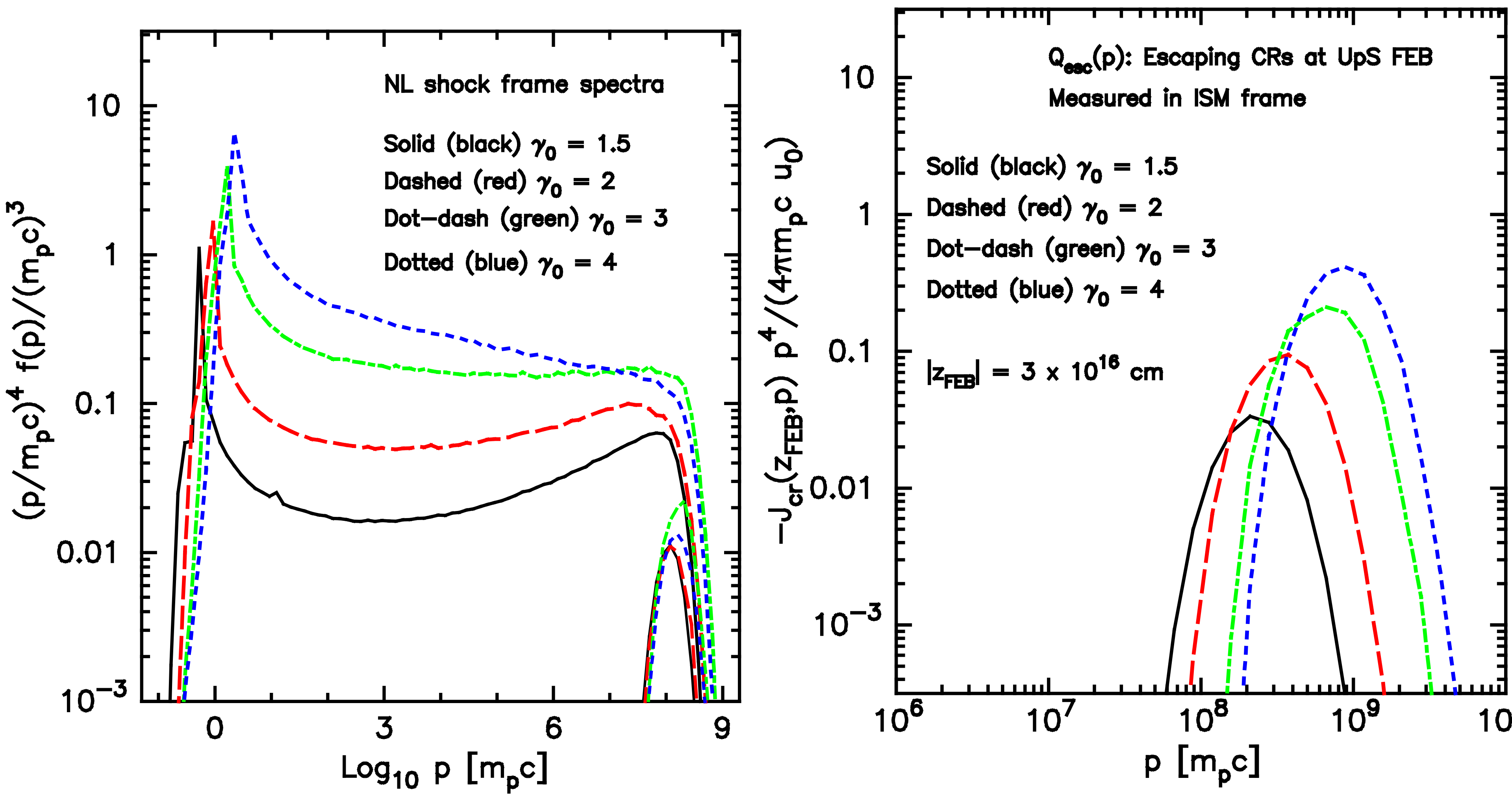
S.Chakraborti, A.Ray, A.Soderberg+ 2011

V.Tatischeff 2009



SN 2009bbb Hillas value Emax > EeV

Non-linear Monte Carlo modeling of CR acceleration in relativistic SNe
(with magnetic field amplification)



Bykov Ellison Marcowith Osipov

Space Sci. Rev. 2018 v,214, 41

CR proton acceleration by SNe type IIn with **dense pre-SN wind**

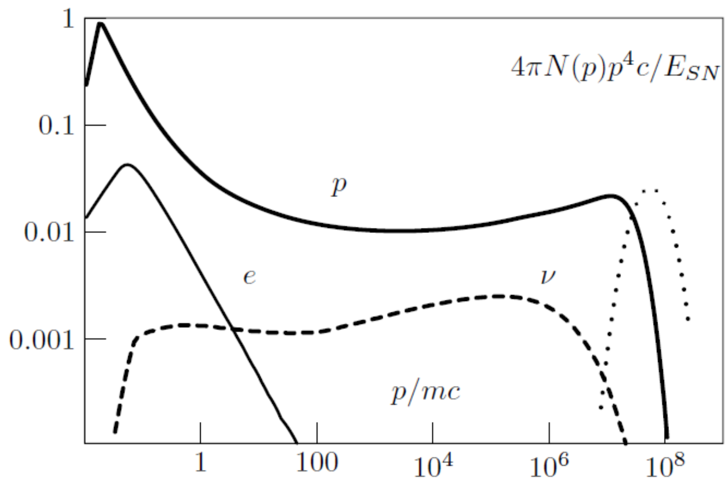
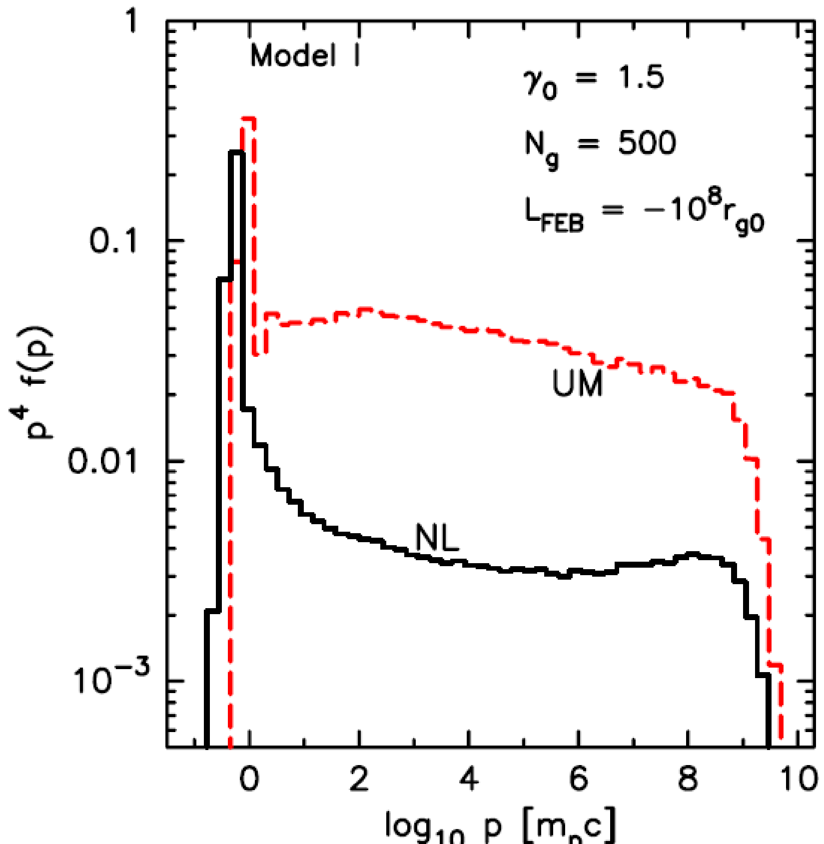


Figure 4: Spectra of particles produced in the supernova remnant during 30 yr after explosion. The spectrum of protons (thick solid line), the spectrum of secondary electrons (multiplied on 10^3, thin solid line), the spectrum of neutrinos (thick dashed line) are shown.

CR proton acceleration by Type IIn SNe
V. Zirakashvili & V. Ptuskin 2015

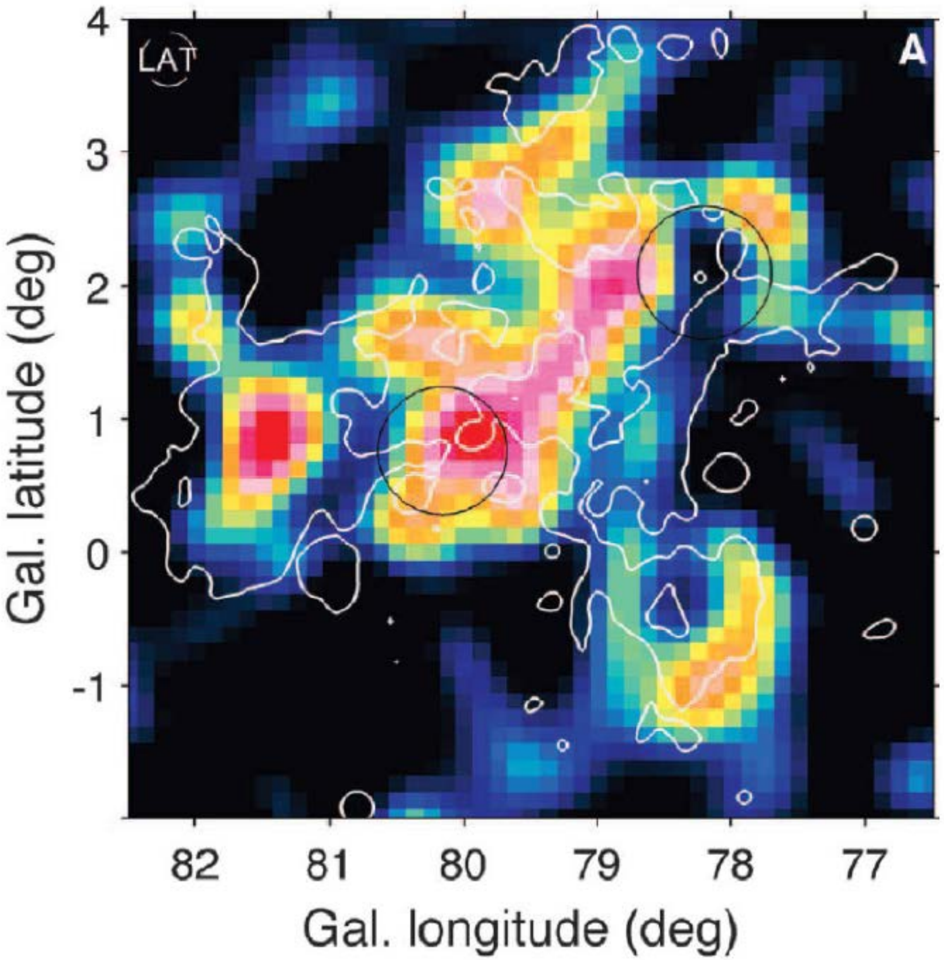
CR proton acceleration in **trans-relativistic** SNe Ibc
SNe Ibc occur mostly in gas-rich star-forming spirals



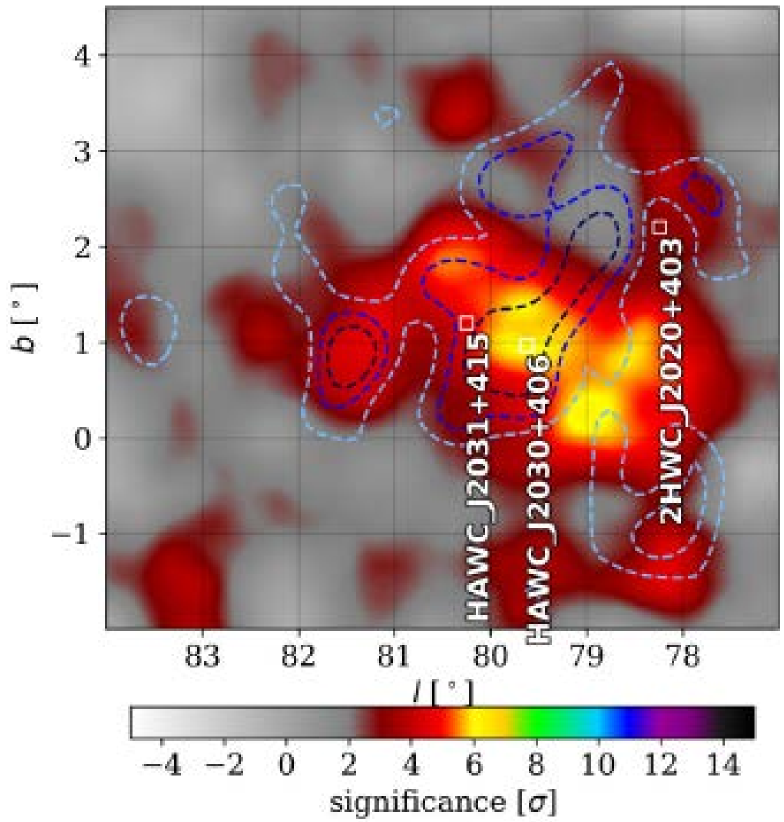
CR proton acceleration by
trans-relativistic SNe $\beta/\Gamma \sim 1$
Ellison, AB
ApJ v.776, 46, 2013

PeV proton acceleration in superbubbles

Gamma-ray images of Cygnus Cocoon

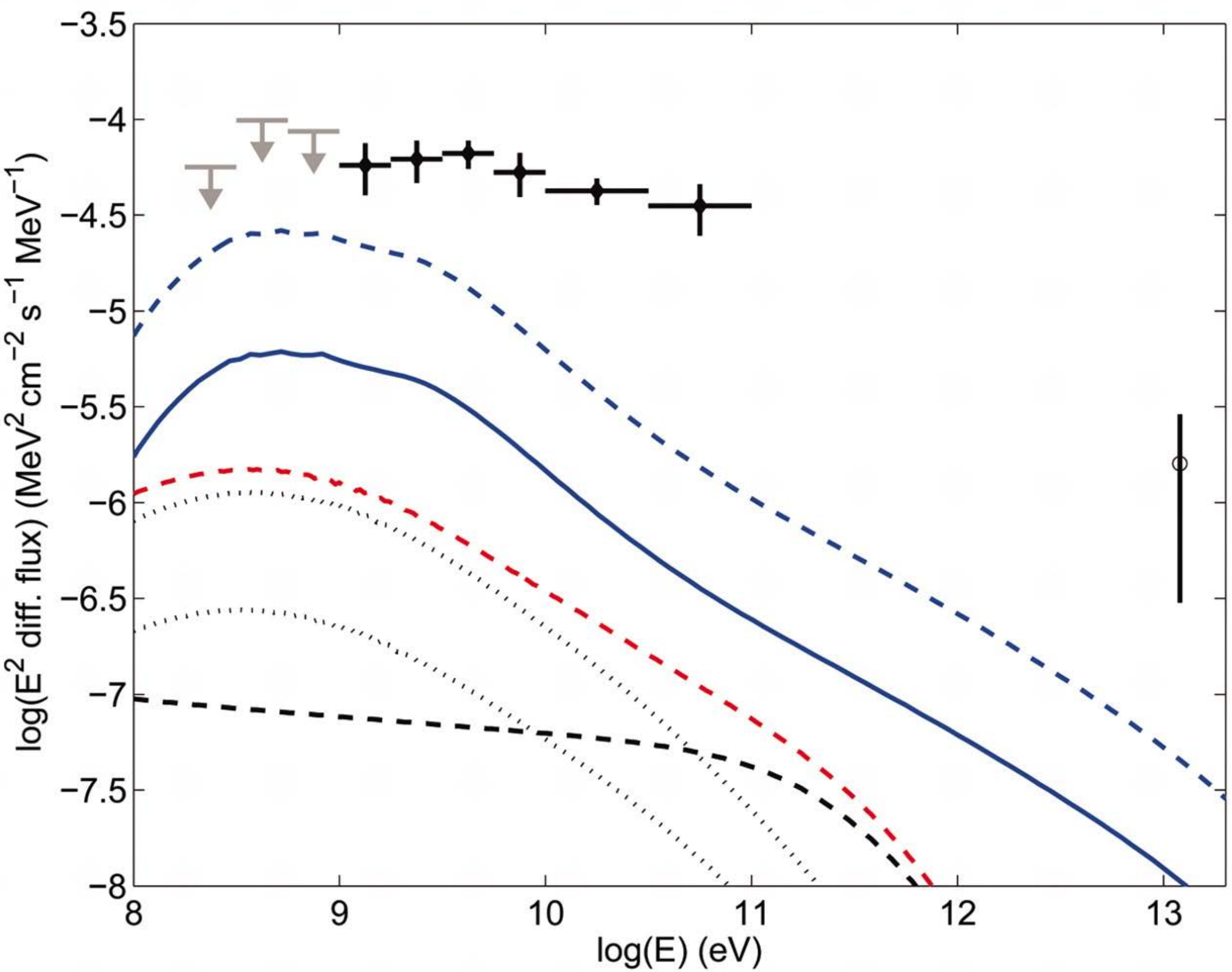


Ackermann + Fermi team 2011



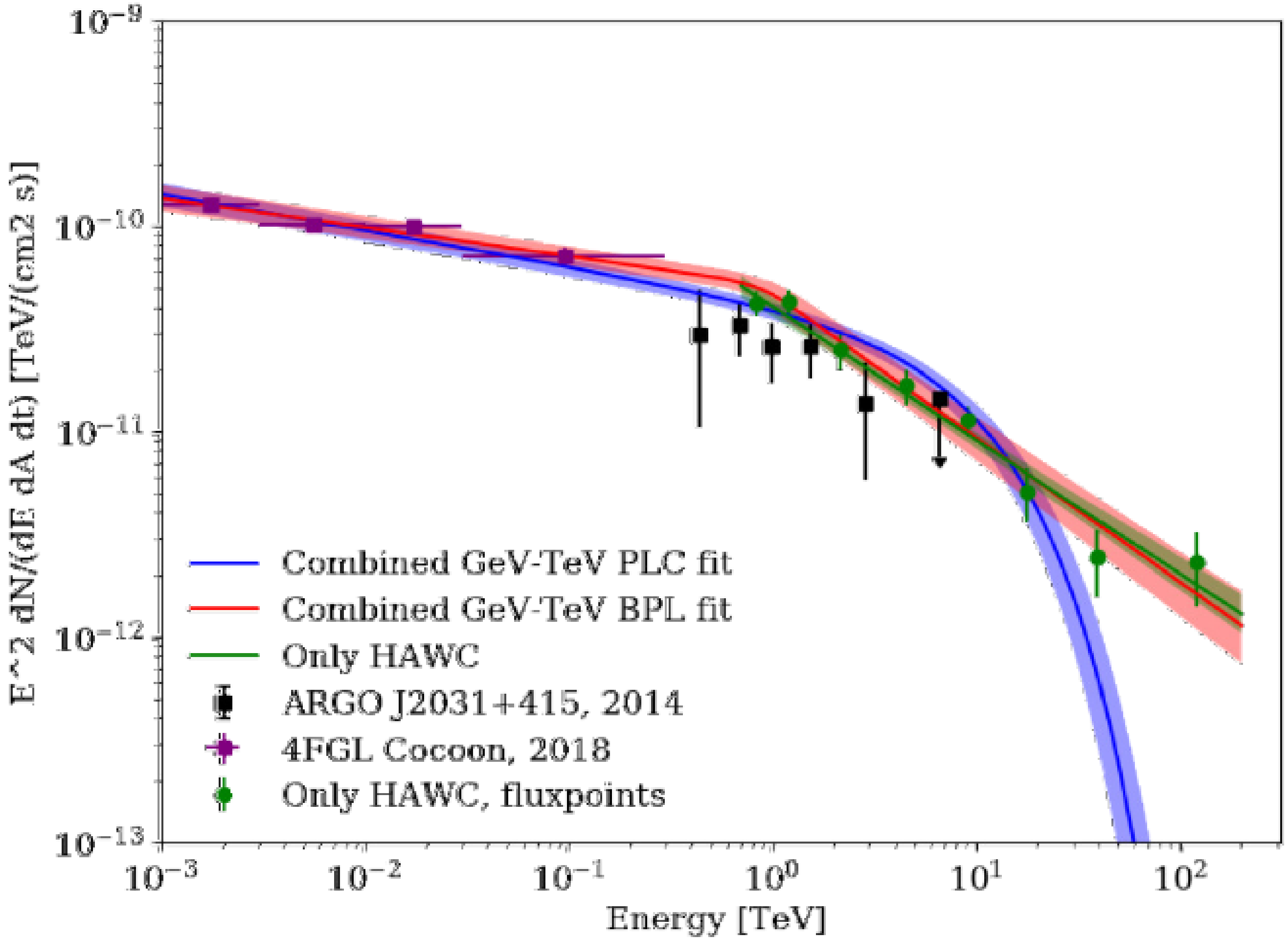
B.Hona HAWC 2020

Fermi spectrum of Cygnus superbubble



Ackermann + 2011

Observed gamma-ray spectra of Cygnus Cocoon



B. Hona 2020

Fermi, ARGO, HAWC data

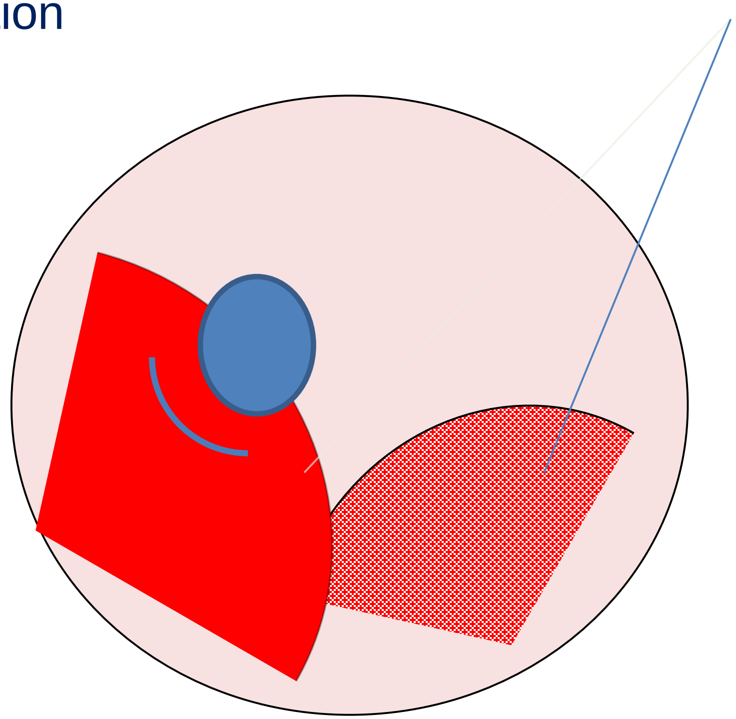
The Fermi source is extended of about 50 pc scale size and anti-correlate with MSX

Cygnus X is about 1.5 kpc away. Contain a number of young star clusters and several OB associations. Cygnus OB2 association contains 65 O stars and more than 500 B stars. There is a young supernova remnant Gamma-Cygni and a few gamma-pulsars.

Particle acceleration at different stages of superbubble evolution

Primary SN shocks and rarefactions

Multiscale, highly intermittent problem



Microscopic scale of collisionless shock structure is AU while the macroscopic scale size of the merger shocks is ~ Mpc…

Particle acceleration by shock ensemble

(renormalized kinetic equations)

Kinetic equation for the **mean** distribution function F(**r**,**p**,t) (phase space) in a highly **intermittent** system

$$\frac{\partial F}{\partial t} - \frac{\partial}{\partial r_\alpha} \chi_{\alpha\beta} \frac{\partial F}{\partial r_\beta} - \frac{1}{p^2}\frac{\partial}{\partial p} D(p) \frac{\partial F}{\partial p} =$$

Fermi II due to large-scale turbulence

$$G\widehat{L}F + A\widehat{L}^2 F + 2B\widehat{L}\widehat{P}F$$

Shocks

Shock-rarefactions

$$\widehat{L} = \frac{1}{3p^2}\frac{\partial}{\partial p} p^{3-\gamma} \int_0^p dp' p'^{\gamma} \frac{\partial}{\partial p'}$$

$$\widehat{P} = \frac{p}{3}\frac{\partial}{\partial p}$$

Astron. Astrophys. Rev (2014) 22:77
Space Sci. Review (2020) v. 216, 42

Turbulence model

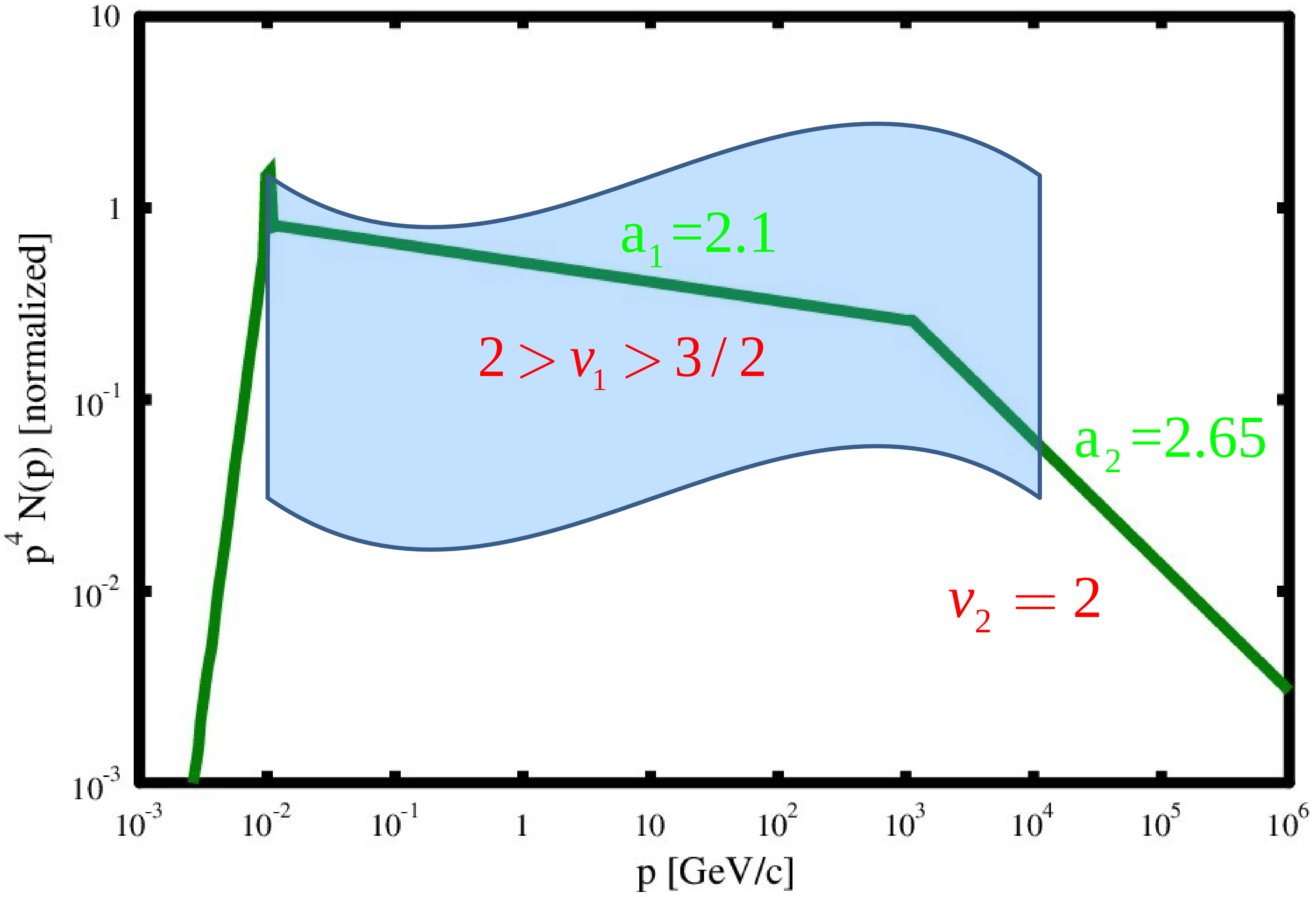
$$\frac{\partial S}{\partial t}+\frac{\partial \Pi^{s}}{\partial k}=\gamma_{vs}T-\gamma_{cr}S-\gamma_{ds}S$$

$$\frac{\partial T}{\partial t}+\frac{\partial \Pi^{v}}{\partial k}=\gamma_{vv}T-\gamma_{vs}T-\gamma_{dv}T$$

The CR acceleration model is nonlinear since we require the total energy [CRs + turbulence] conservation
The model is time dependent, but statistically homogeneous

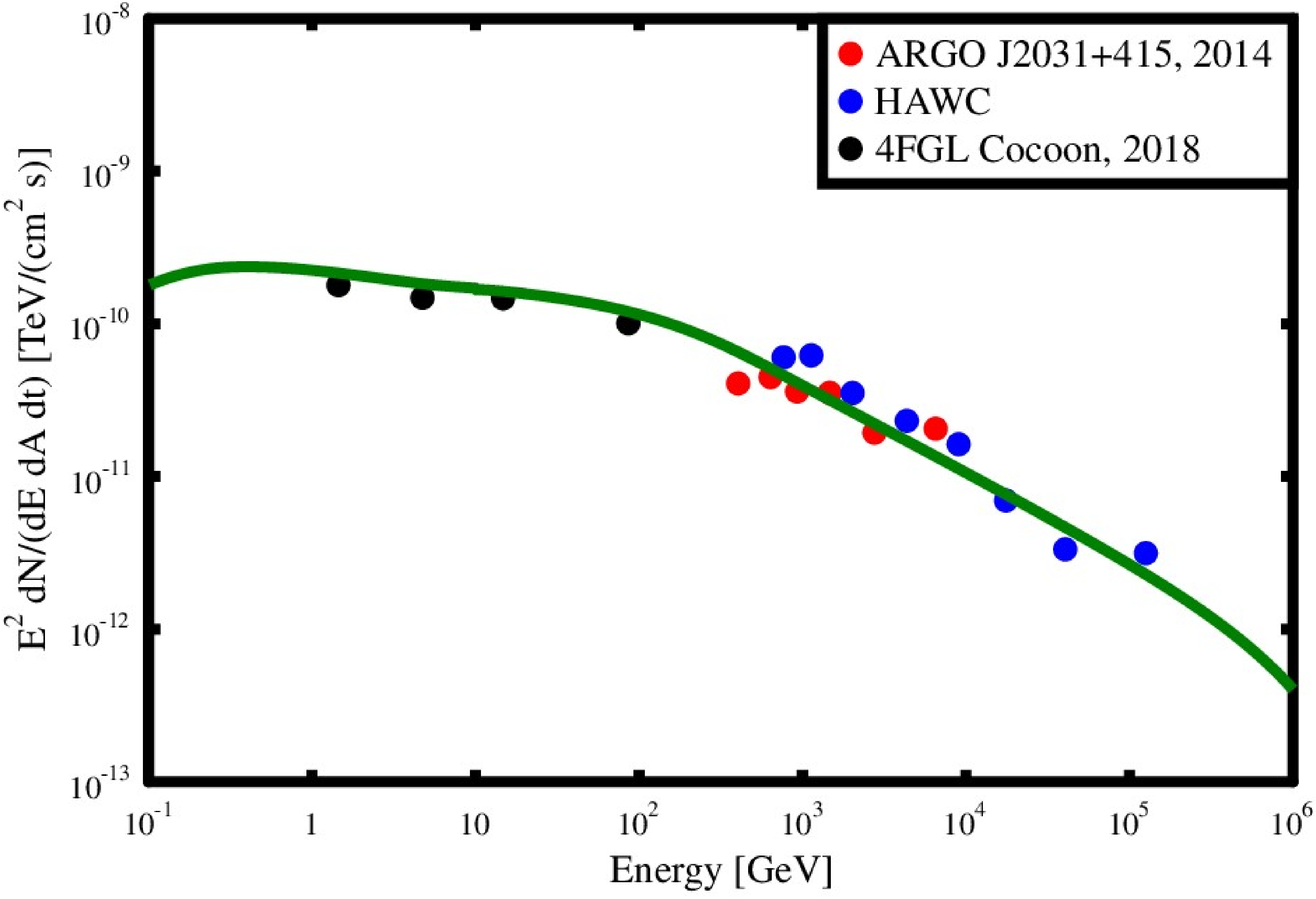
CR proton spectra of a superbubble for different turbulent models

L=85 pc, l_corr=1.5 pc, u=3*10^3 km/s, B=3*10^-5 G



A model gamma-ray spectrum of the Cygnus Cocoon

L=85 pc, l_corr=1.5 pc, u=3*10^3 km/s, B=3*10^-5 G

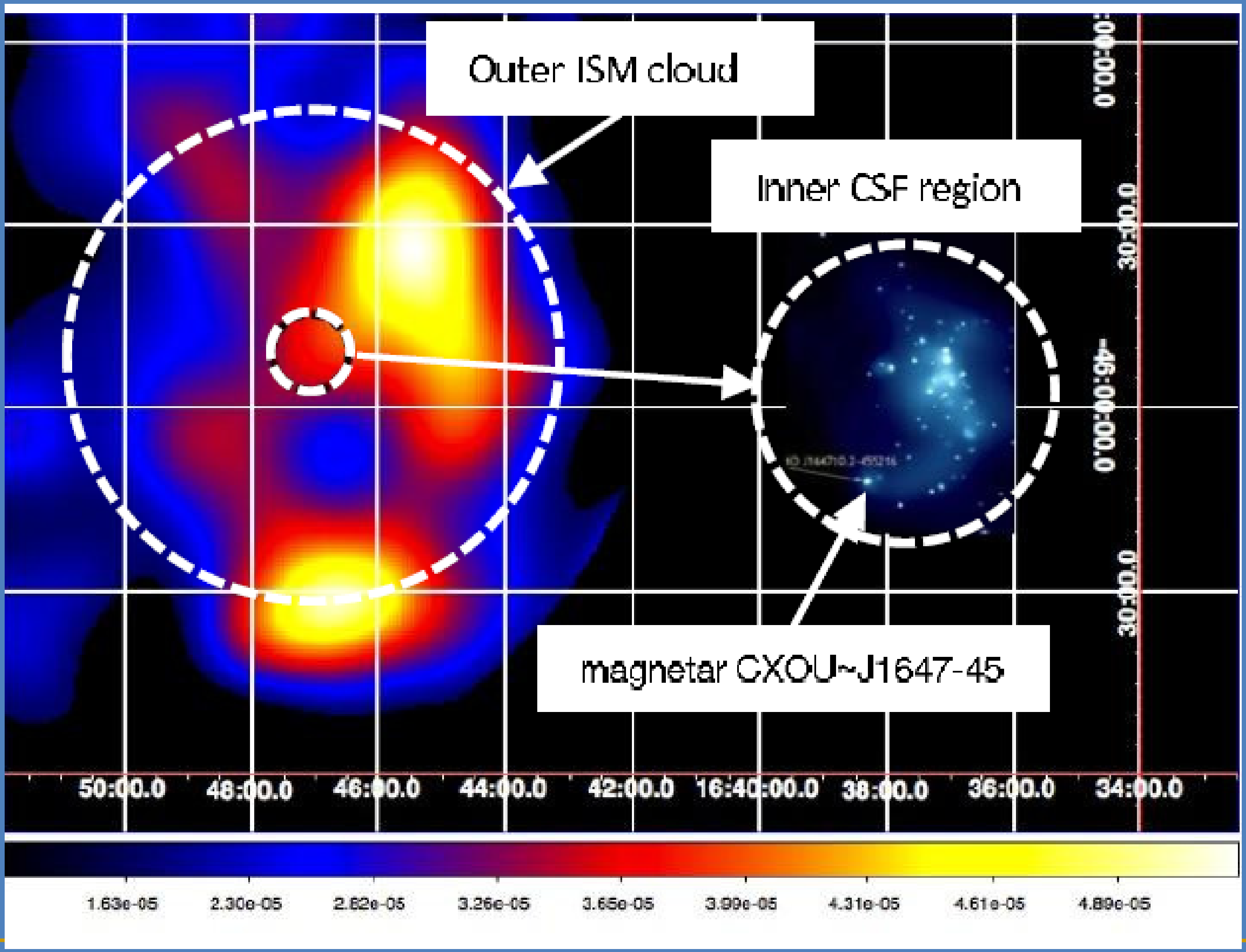


PeV proton acceleration by SNe in young compact stellar clusters & starbursts

A Galactic Super Star Cluster

- Distance: 5kpc
- Mass: 10^5 M_{sun}
- Core radius: 0.6 pc
- Extent: ~6 pc across
- Core density:~10^6 pc^{-3}
- Age: 4 +/- 1 Myr
- Supernova rate: 1 every 10,000 years

H.E.S.S. image of Westerlund I



MNRAS v. 453, p. 113, 2015

H.E.S.S. J1808-204

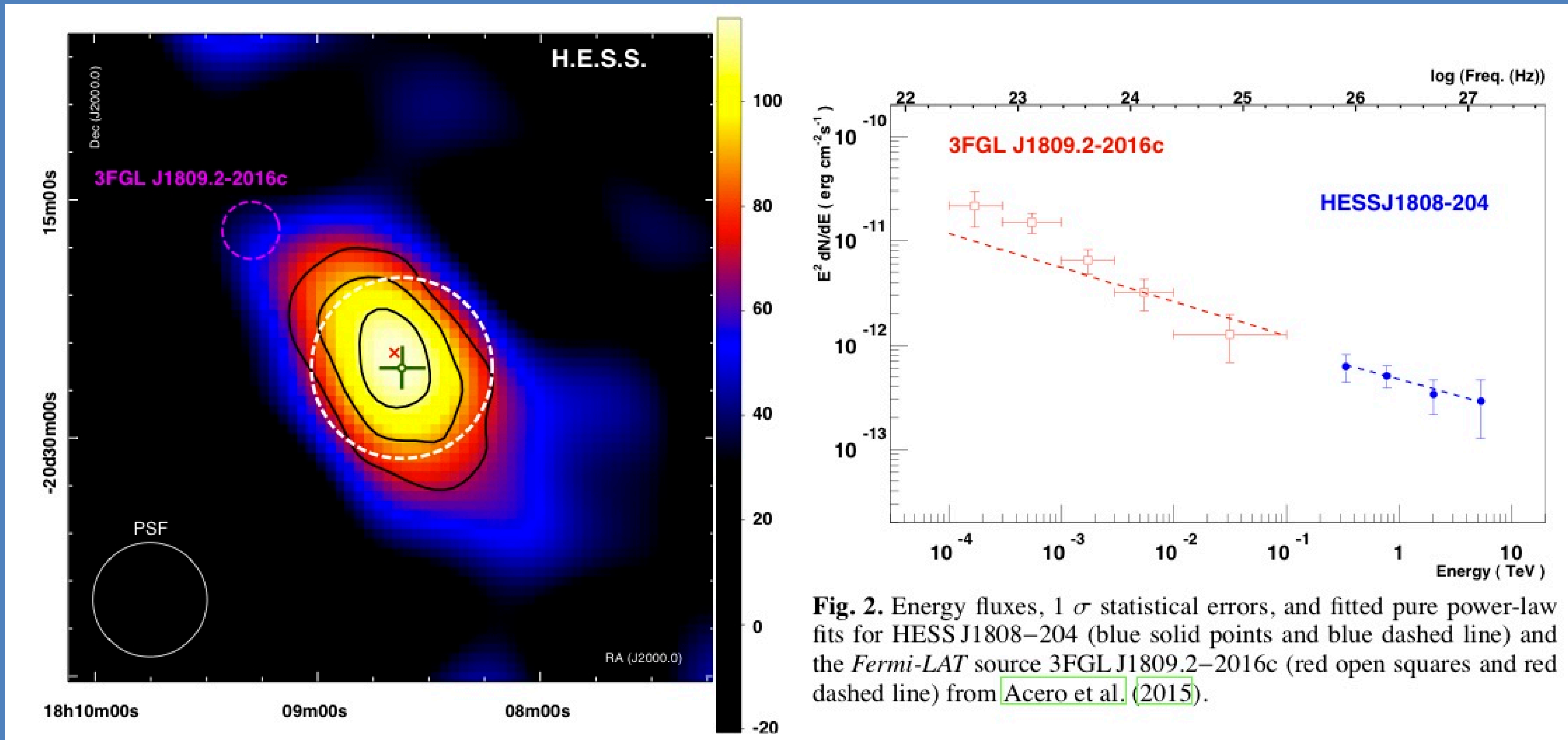


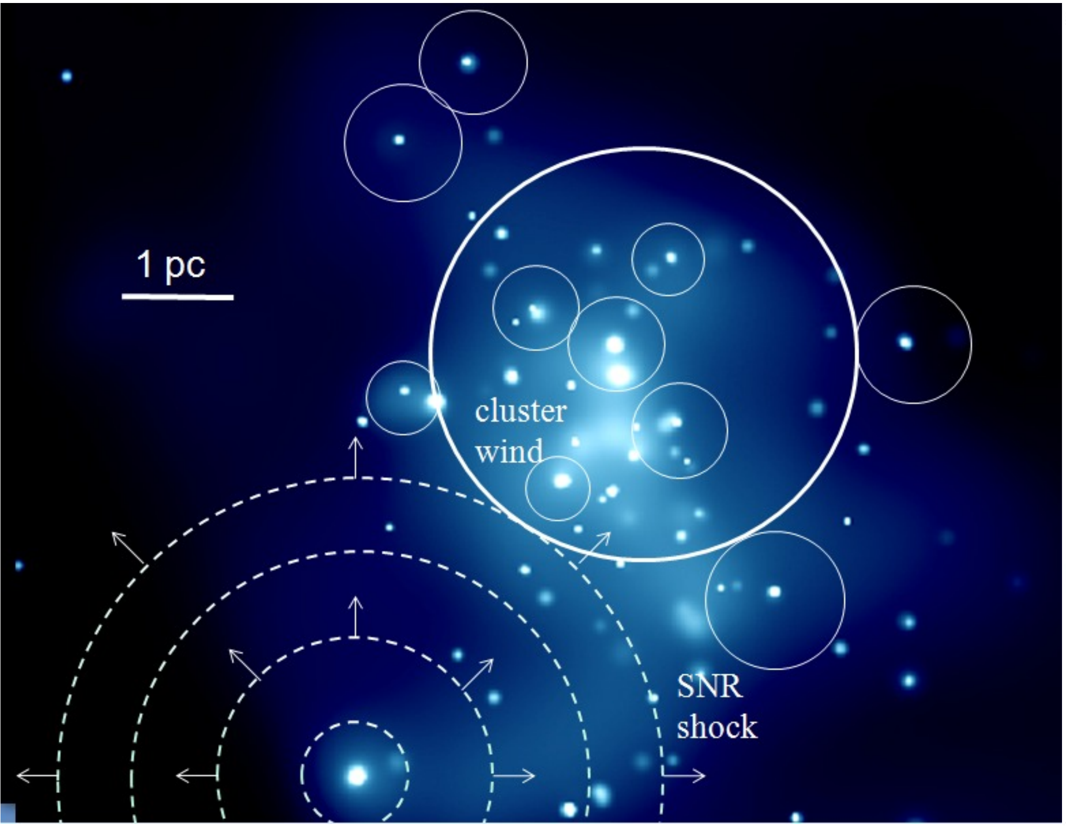
Fig. 2. Energy fluxes, 1 σ statistical errors, and fitted pure power-law fits for HESS J1808–204 (blue solid points and blue dashed line) and the *Fermi-LAT* source 3FGL J1809.2–2016c (red open squares and red dashed line) from Acero et al. (2015).

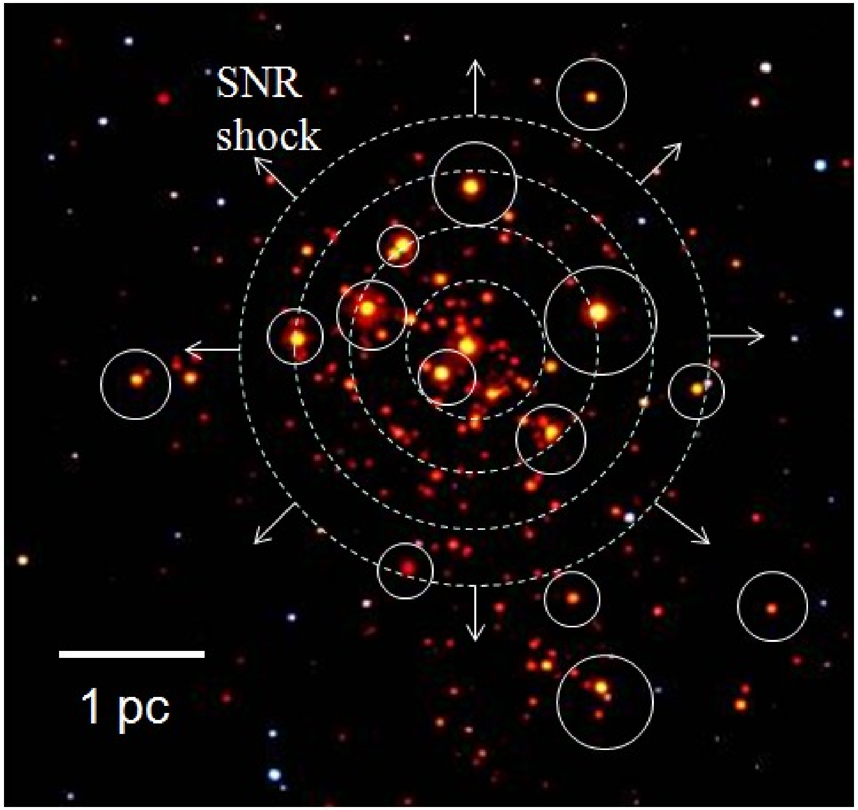
power-law photon index of 2.3 ± 0.2stat ± 0.3sys
Lvhe ~ 1.6 × 10^(34)[D/8.7 kpc]^2 erg/s

Extended very high-energy gamma-ray source towards the luminous blue variable candidate LBV 1806−20, massive stellar cluster Cl* 1806−20, and magnetar SGR 1806−20 of estimated age about 650 years.

H.E.S.S. collaboration arxiv 1606.05404 2016

Westerlund 1

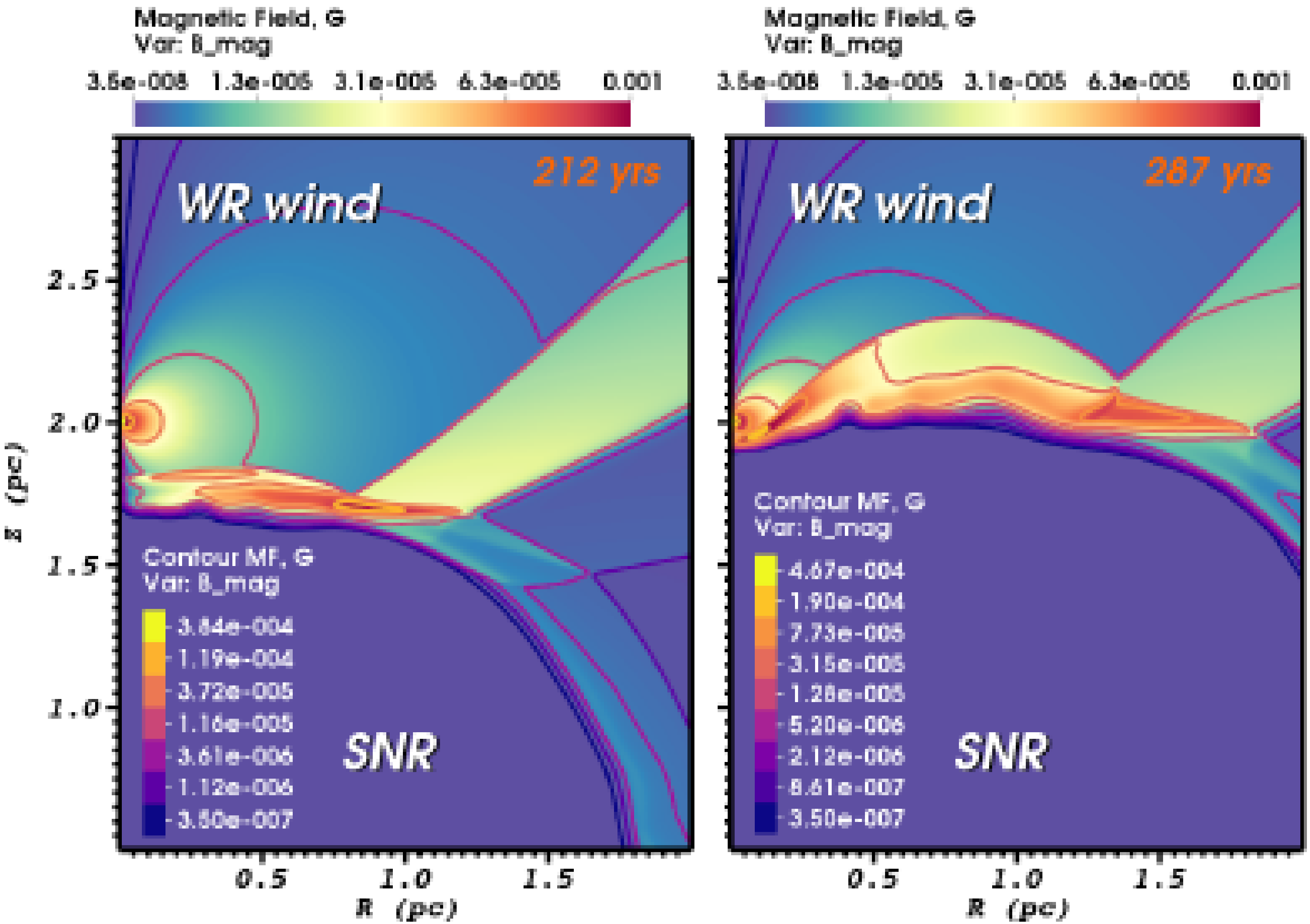




Muno+ 05

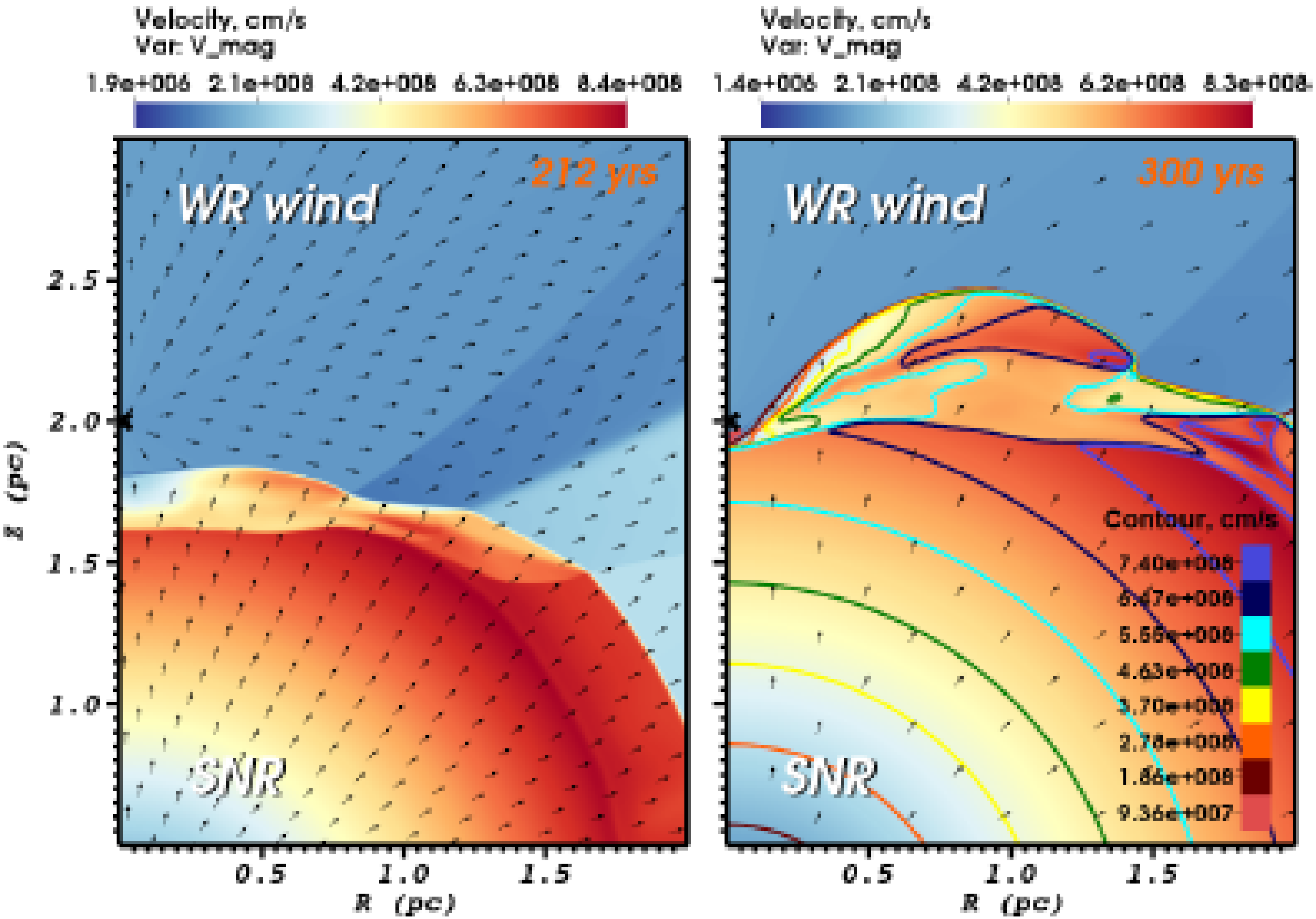
Clark+ 05

Supernova – Stellar Wind Interaction nodel



Badmaev Bykov 2019

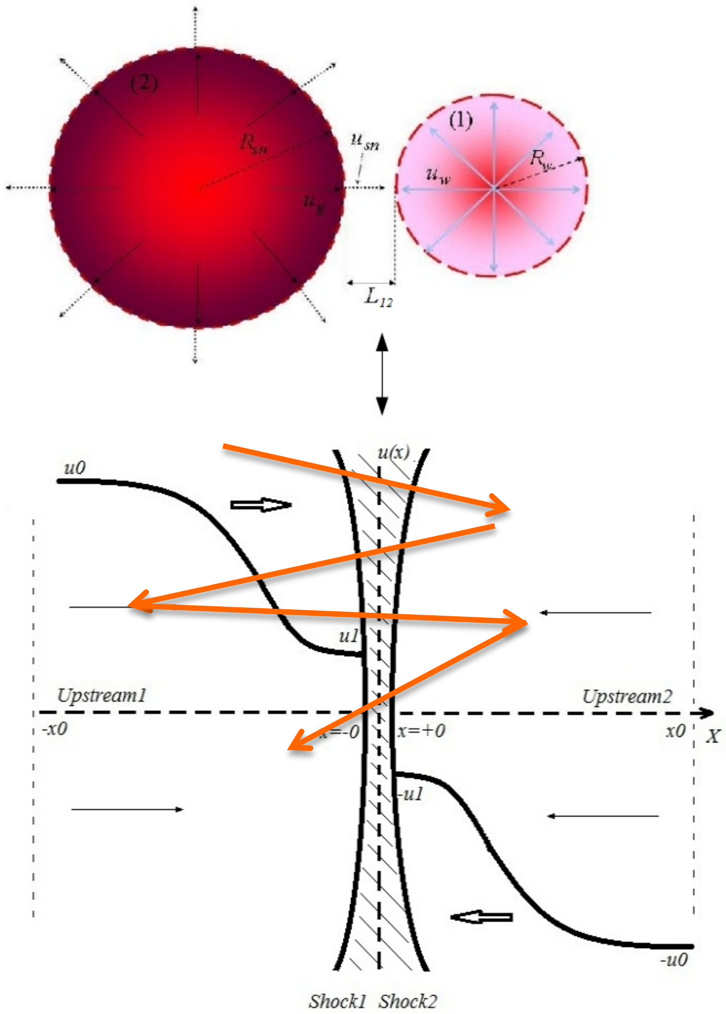
Supernova – Stellar Wind Interaction



Badmaev Bykov 2019

Particle acceleration between approaching shocks is the most efficient version of Fermi I acceleration

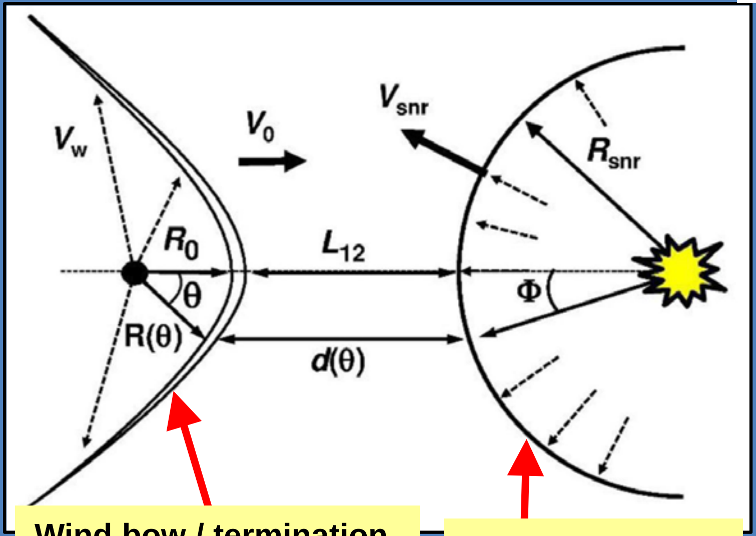
Fermi I: SNR - cluster wind accelerator



MNRAS V. 429, 2755, 2013

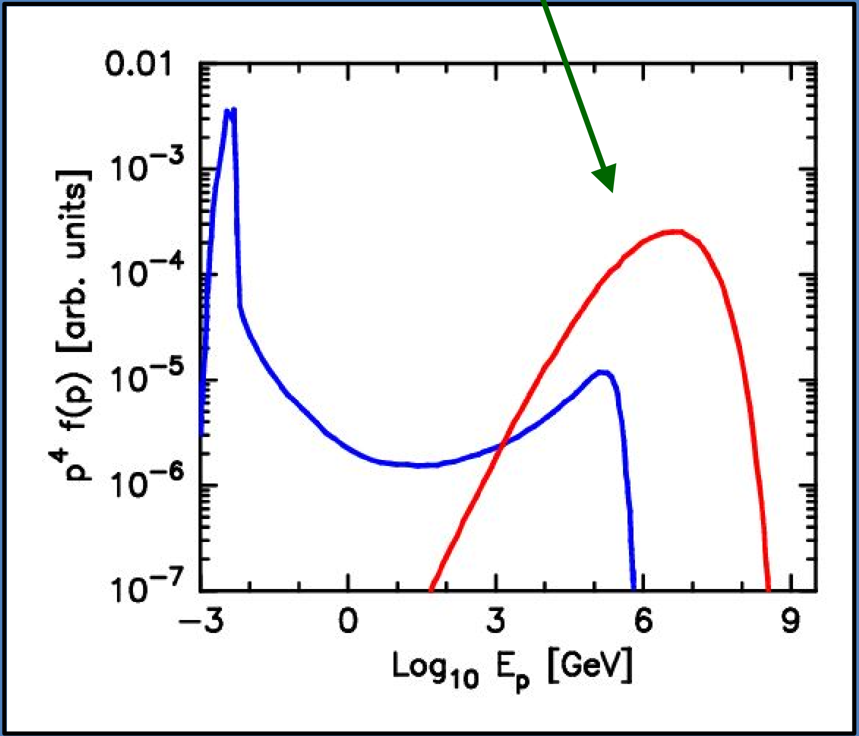
Enhanced acceleration as CRs bounce between shock and wind

Strongly peaked because only high energy CRs can efficiently “bounce” between SNR shock and wind for further acceleration



Wind bow / termination shock from young star

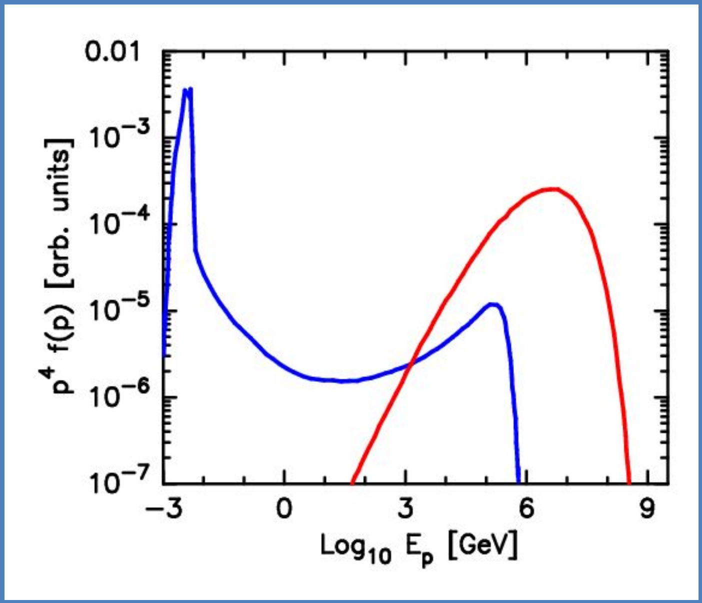
SNR blast wave



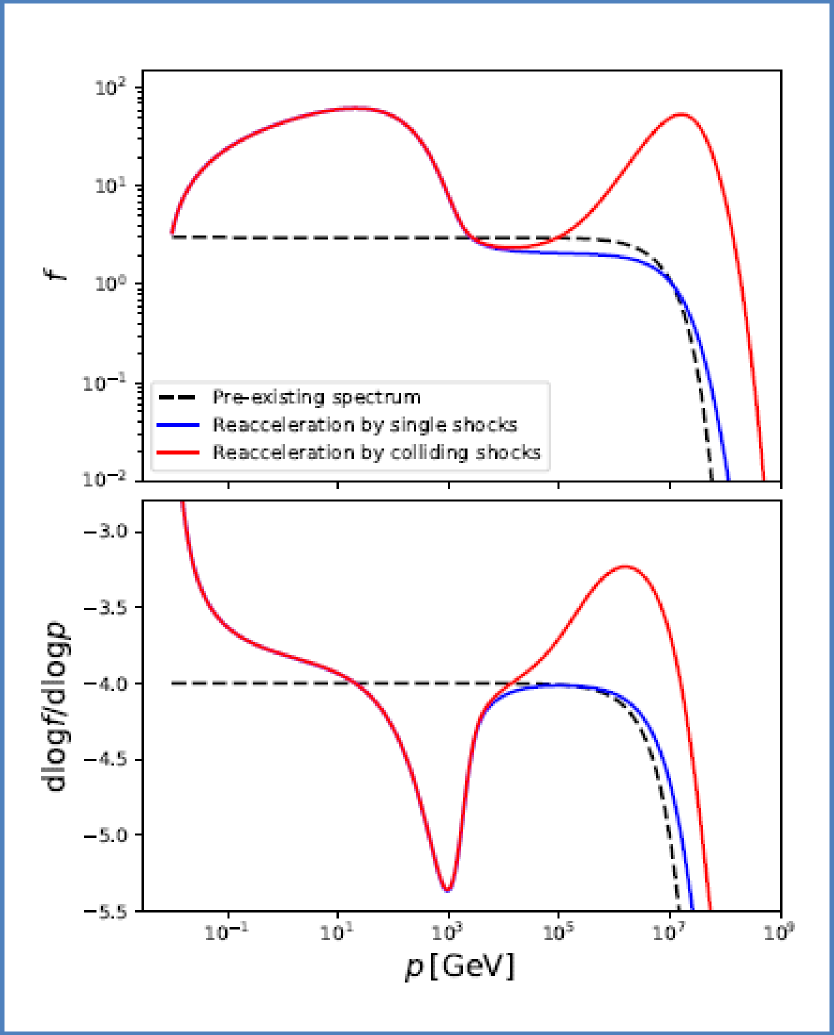
Bykov et al, MNRAS 2015

CRs re-accelerated by colliding shocks

CR accelerated by colliding shocks at SNR – WR-wind



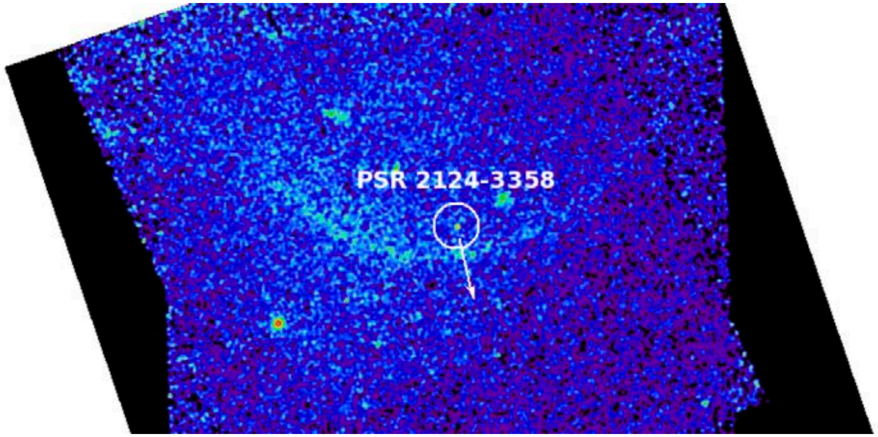
Bykov et al, MNRAS 2015

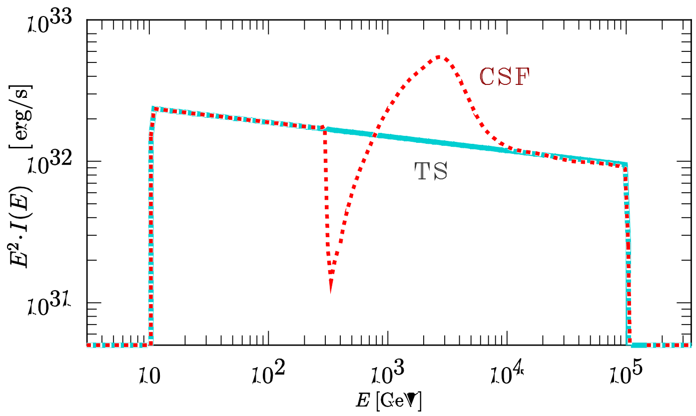


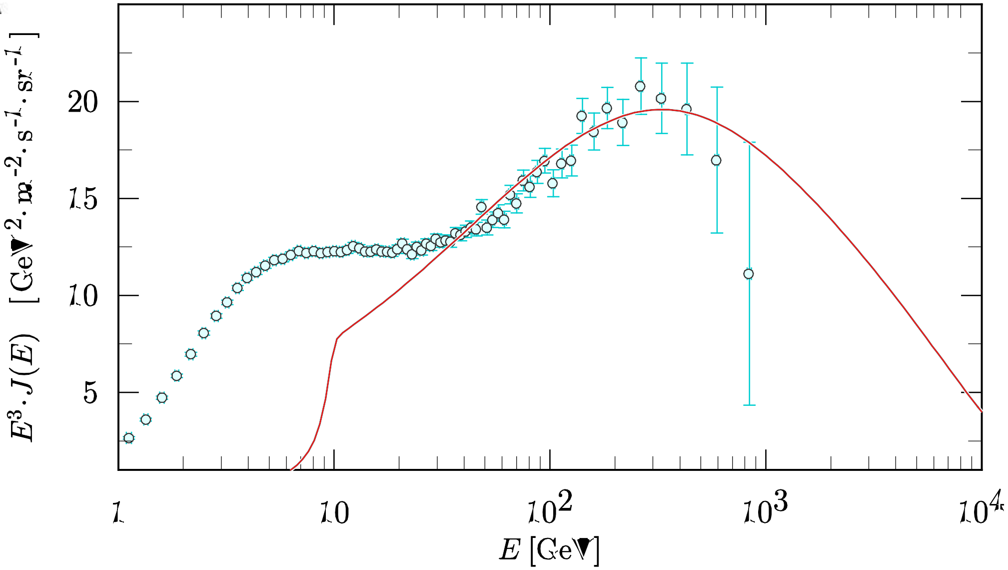
Vieu Gabici Tatischeff, MNRAS 2020

The case of positron acceleration at a colliding shock flow

GeV-TeV Cosmic Ray positrons in the Solar System from the Bow Shock Wind Nebula of the Nearest Millisecond Pulsar J0437-4715



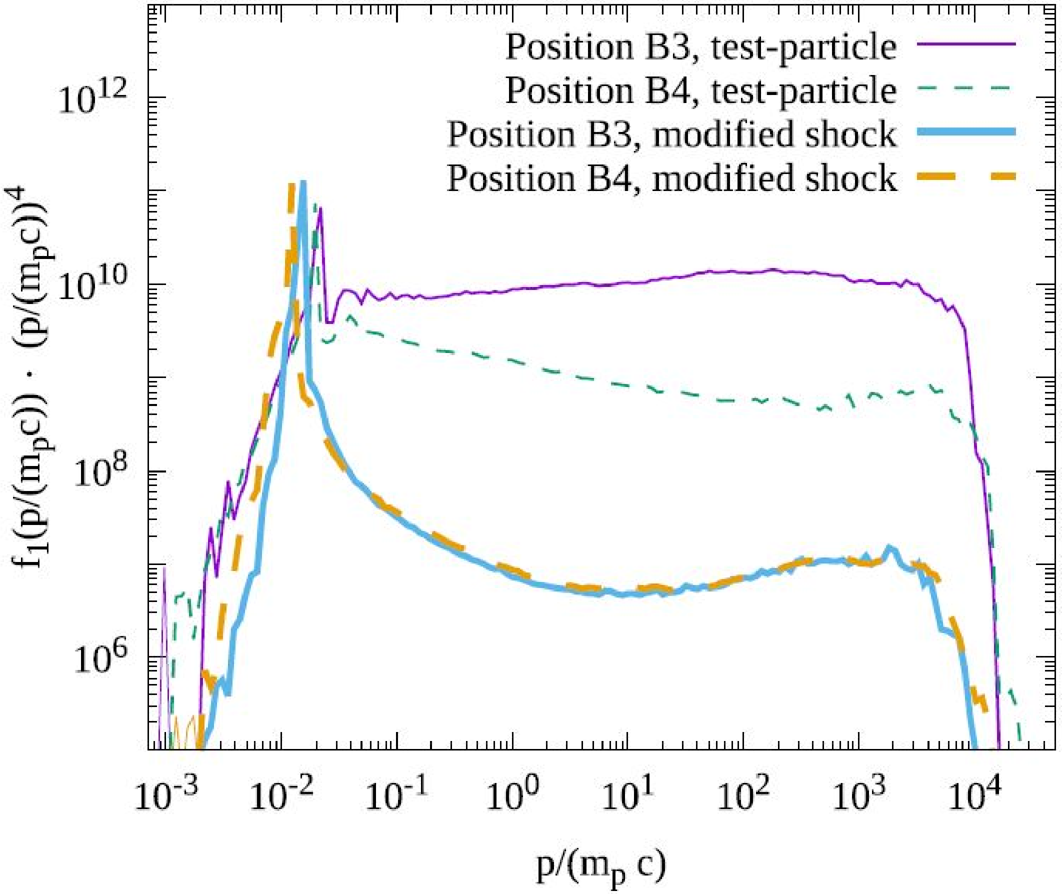




AB+ The Astrophysical Journal Letters v. 876, L8, 2019

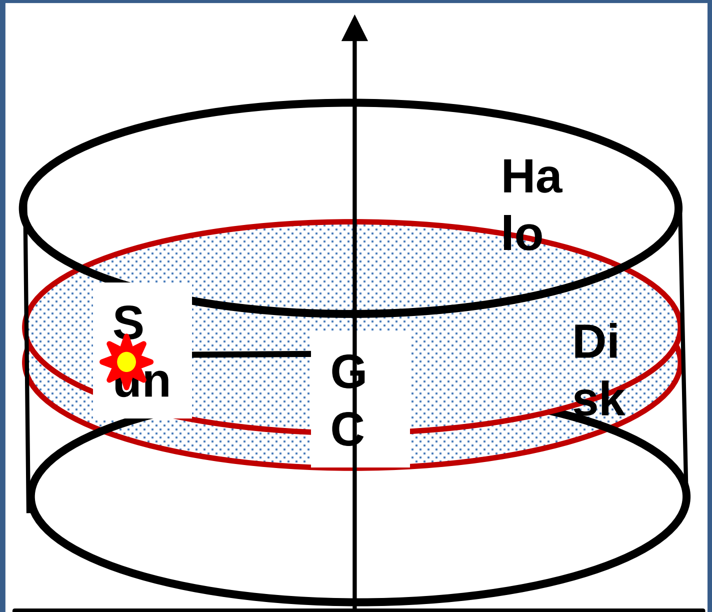
Nonlinear Fermi shock acceleration in stellar winds collision

Grimaldo et al. ApJ 2019



How can we constrain the model of PeV CR acceleration by SNe in compact clusters of massive stars?

CR propagation from the compact stellar clusters



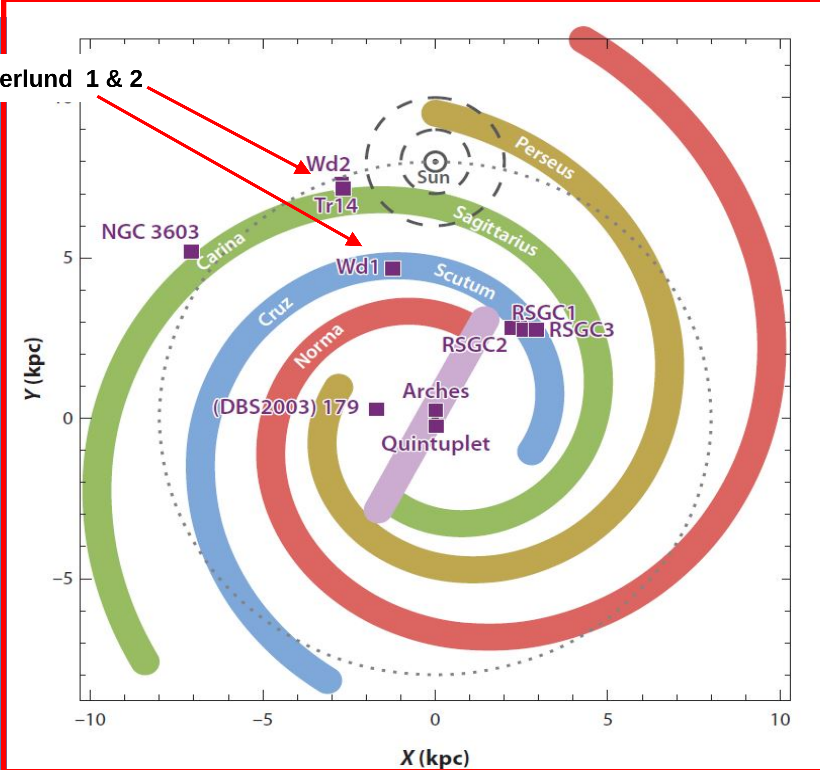
- Simple cylindrical model for Milky Way
- Compact clusters distributed in thin disk
- CRs diffuse in disk & halo

- Strong time variability at Sun for CSFs
- Flux and anisotropy depend on recent, nearby events

Here look at simple case: Sources concentrated at Galactic Center

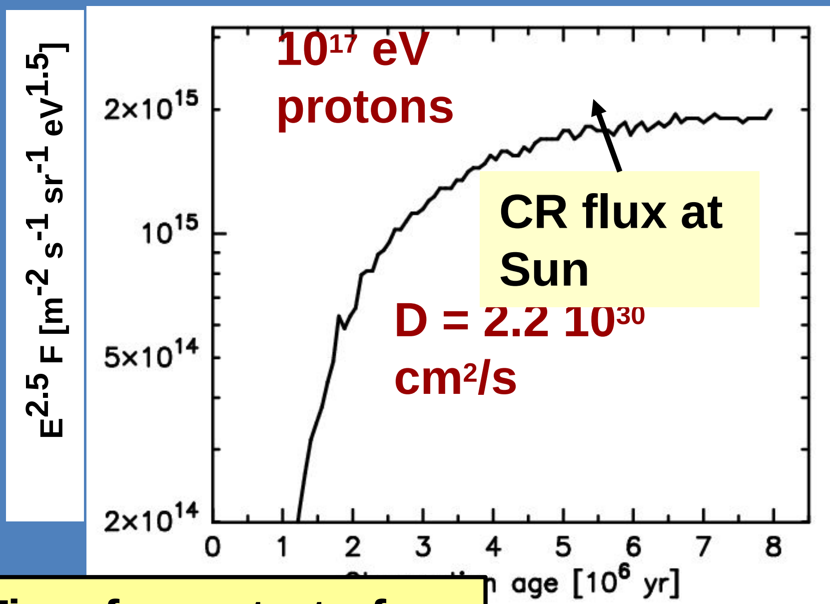
→ Good estimate of average flux and average anisotropy at Earth

Milky Way B-field structure from Farrar & Jansson, Han (2017)



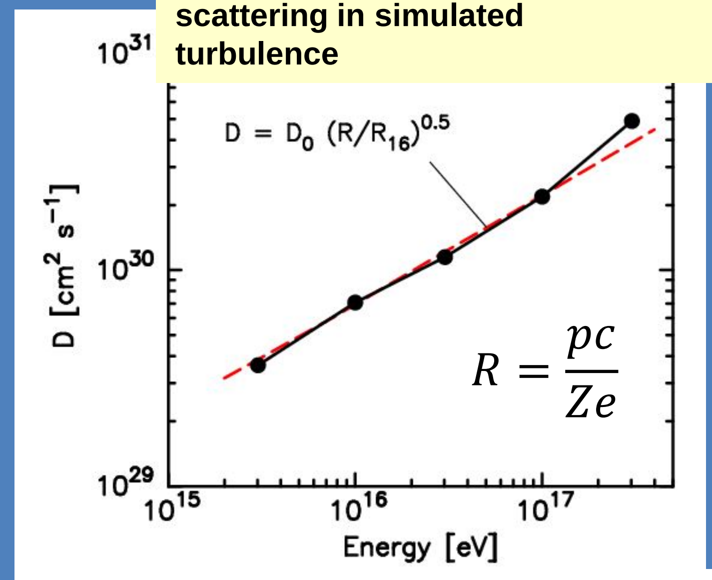
Portegies Zwart et al. 2010

What If the CSF sources were concentrated at Galactic Center?



Time from start of simulation

ISM diffusion coefficient from scattering in simulated turbulence



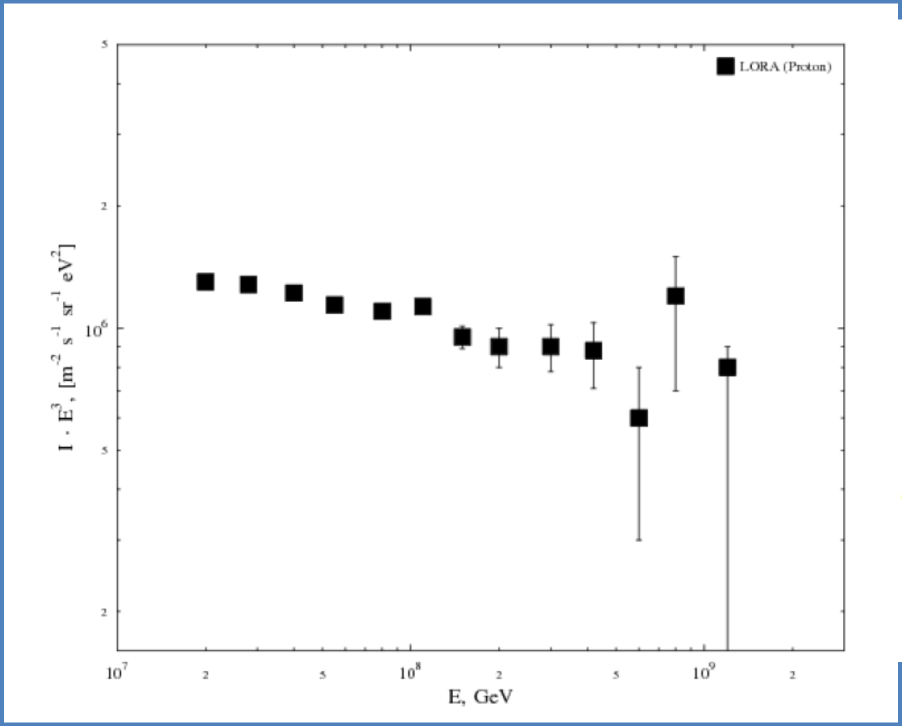
Bykov et al. 2019 using data from Farrar & Jansson and Han 2017

➔1 Colliding-shock-flow event / 4000 yr

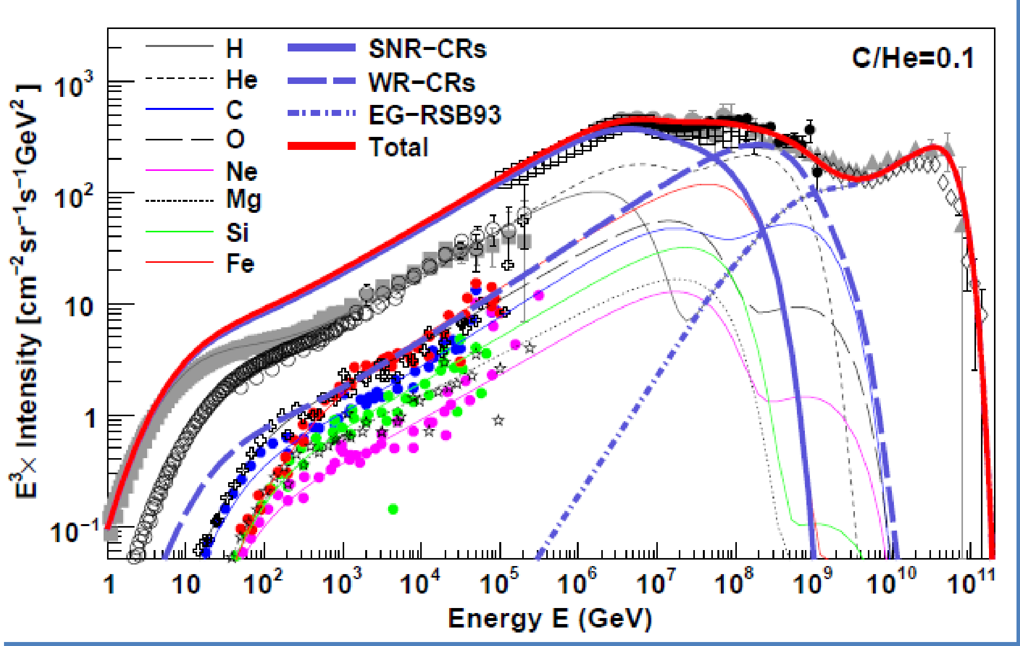
➔10^{51} erg released in each CSF event

➔Total shock acceleration efficiency = 10%

LOFAR: evidence for light CR component at 0.1 EeV?

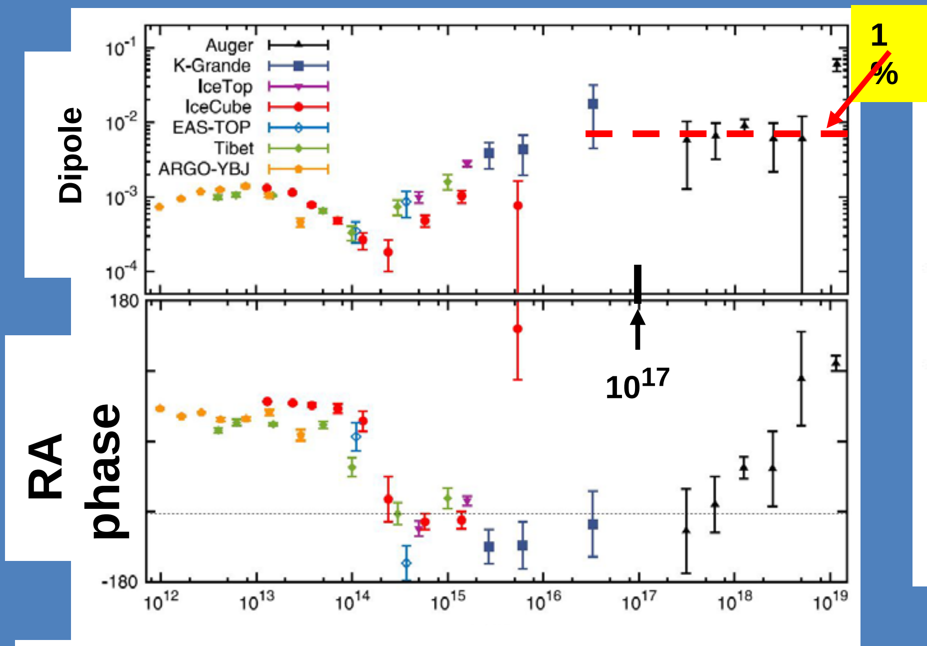


LOFAR Bujtink + 2016



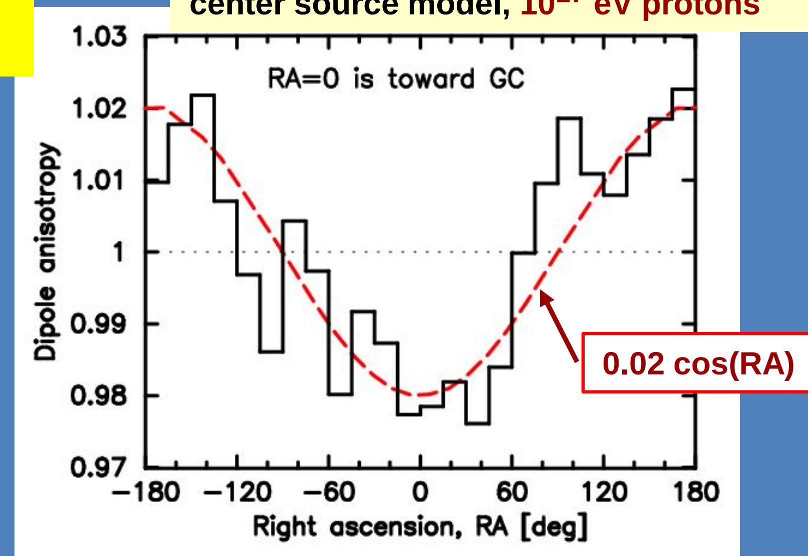
Thoudam + 2016

Important constraint for galactic sources is the low observed CR anisotropy



Mollerach & Roulet (2018)

Dipole anisotropy, A_{CSF}, for galactic center source model, 10^{17} eV protons



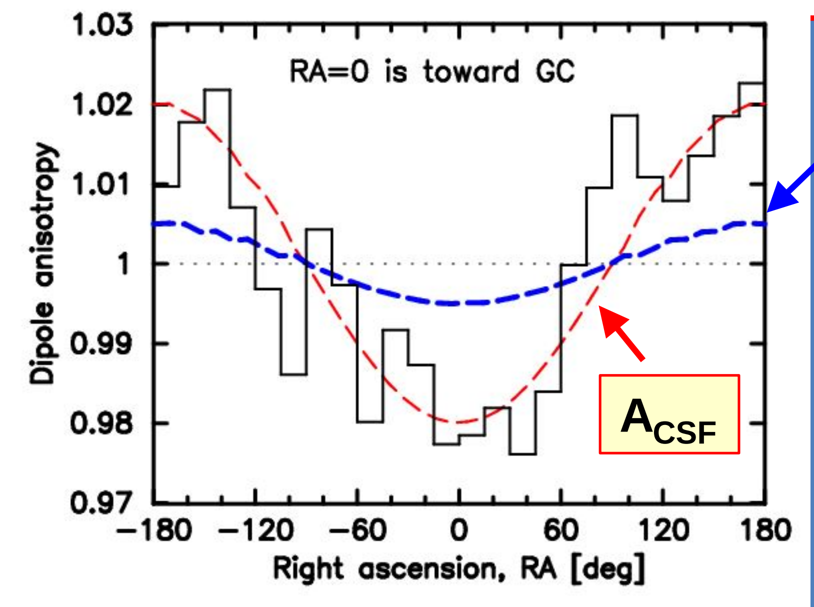
Dipole anisotropy for GC source at least a factor of 2 above observations for our parameters

om plane

Add isotropic extra-galactic source:

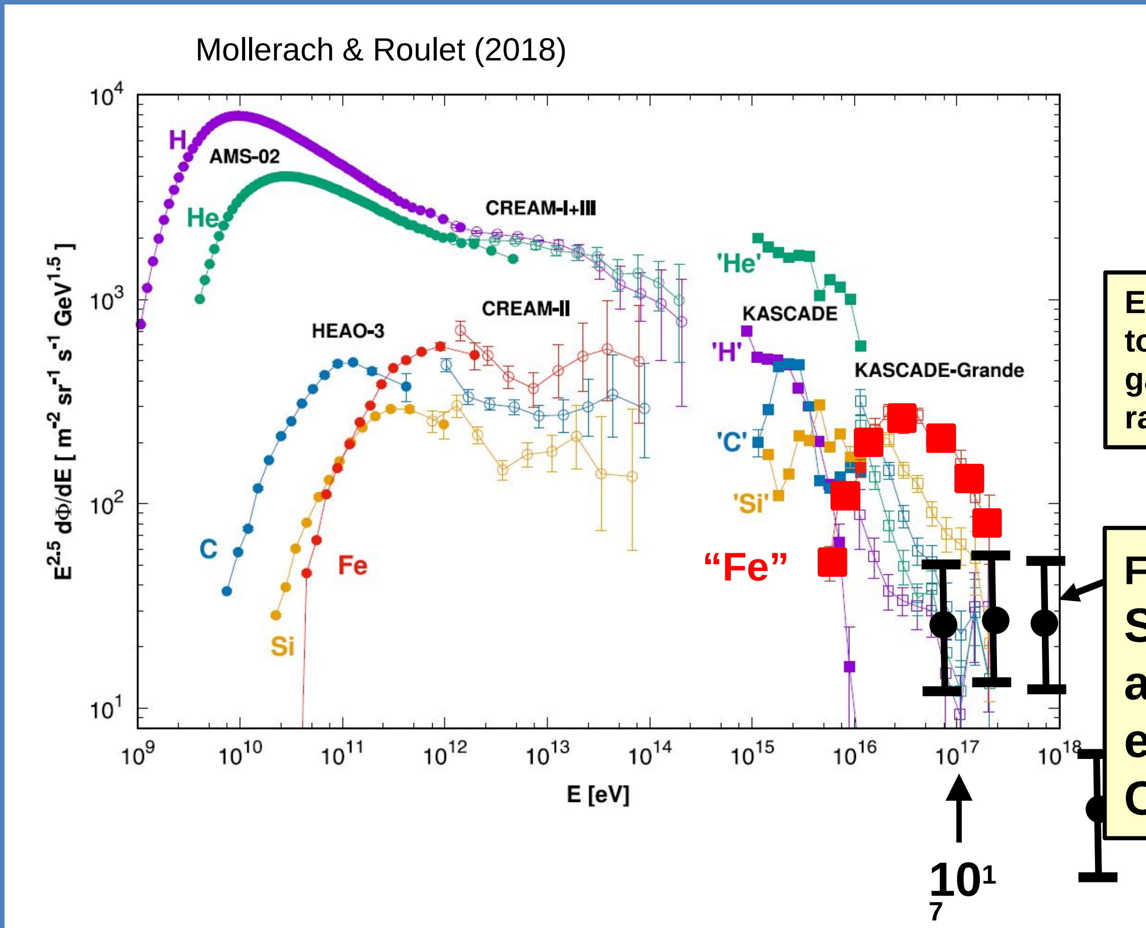
Assume isotropic extra-galactic flux is $F_{\text{ex}} = f_{\text{ex}} F_{\text{CSF}}$

Then total anisotropy is $A_{\text{tot}} = \frac{A_{\text{CSF}} + f_{\text{ex}}}{1 + f_{\text{ex}}}$



For $\frac{F_{\text{CSF}}}{F_{\text{ex}}} = 1/3$

Find ~30% of all 10^{17} eV CRs can be from a galactic source without violating isotropy constraints



Expect a significant contribution to all particle CR spectrum from galactic sources in 10^{17} – 10^{18} eV range

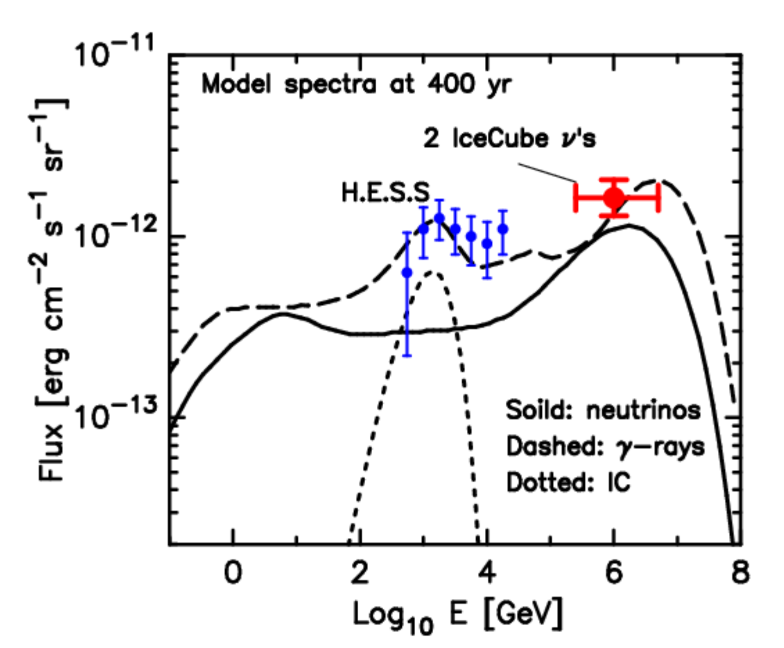
Fe from colliding-Shock-Flows assuming a few % of CSF event energy goes into all CRs

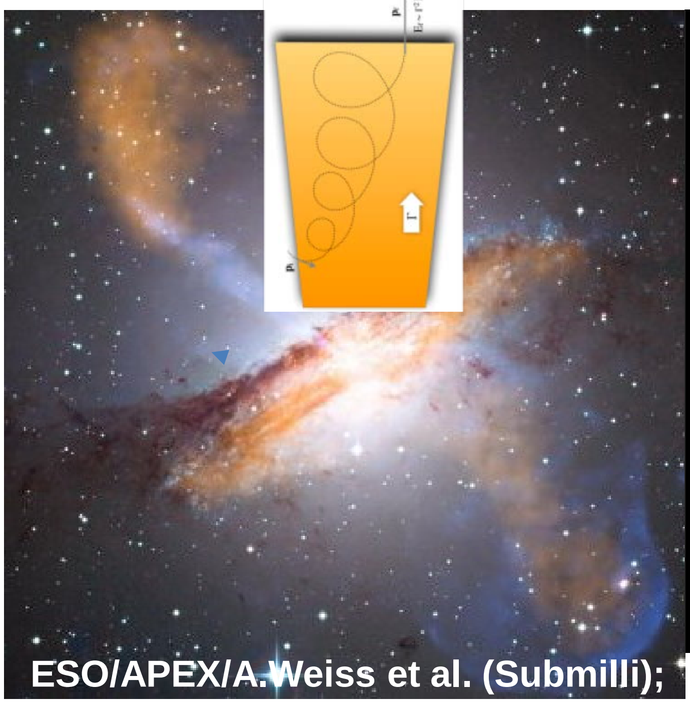
Conclusions

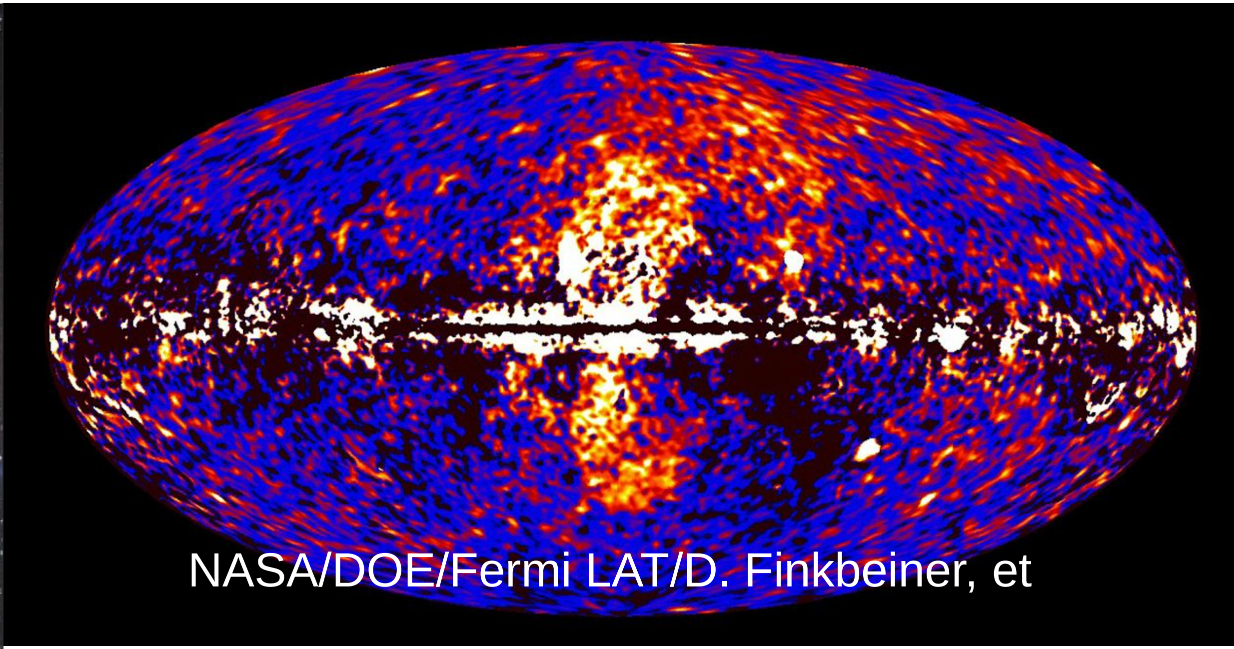
1) Massive, young, compact star clusters provide environment for accelerating strongly peaked CRs in PeV-EeV range ➔ may provide substantial fraction of CRs in galactic—extra-galactic transition region.

2) Peaked spectrum produced by CSFs may be important factor for neutrino production. Some IceCube neutrinos may come from CSFs

AB+ , MNRAS v. 453, p. 113, 2015







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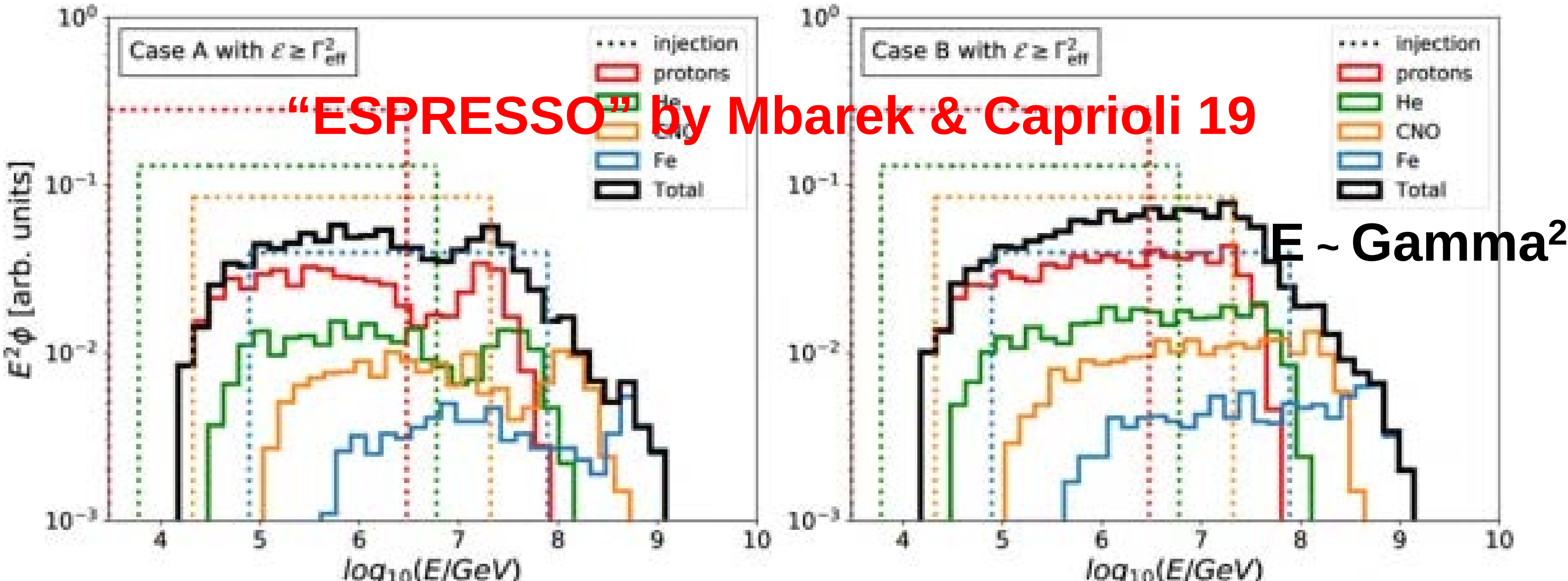

Thanks for your attention!

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