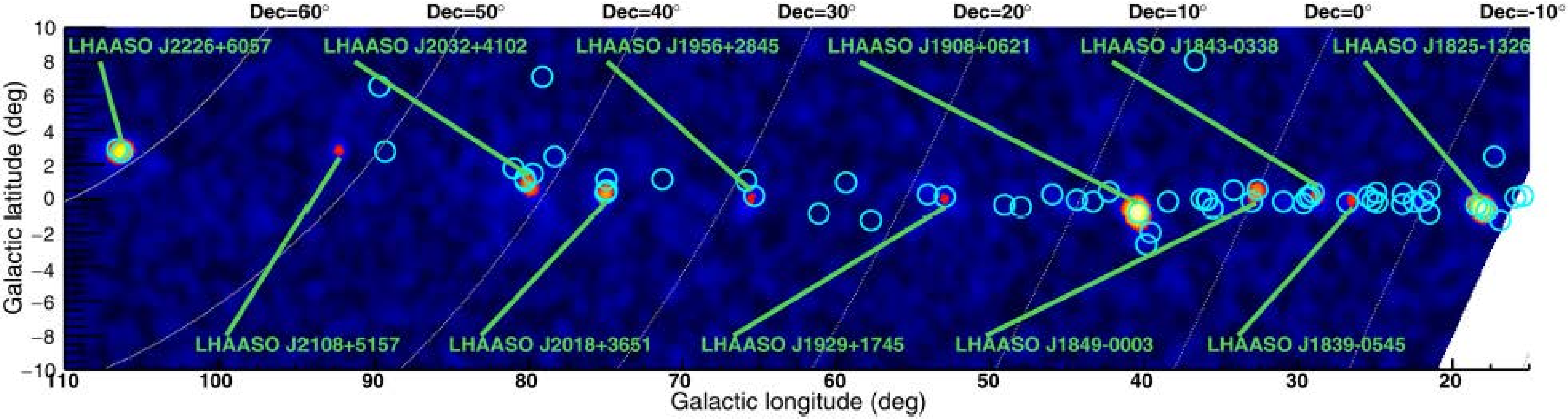
Modeling of Galactic Pevatrons

A.M.Bykov
Ioffe Institute, St Petersburg

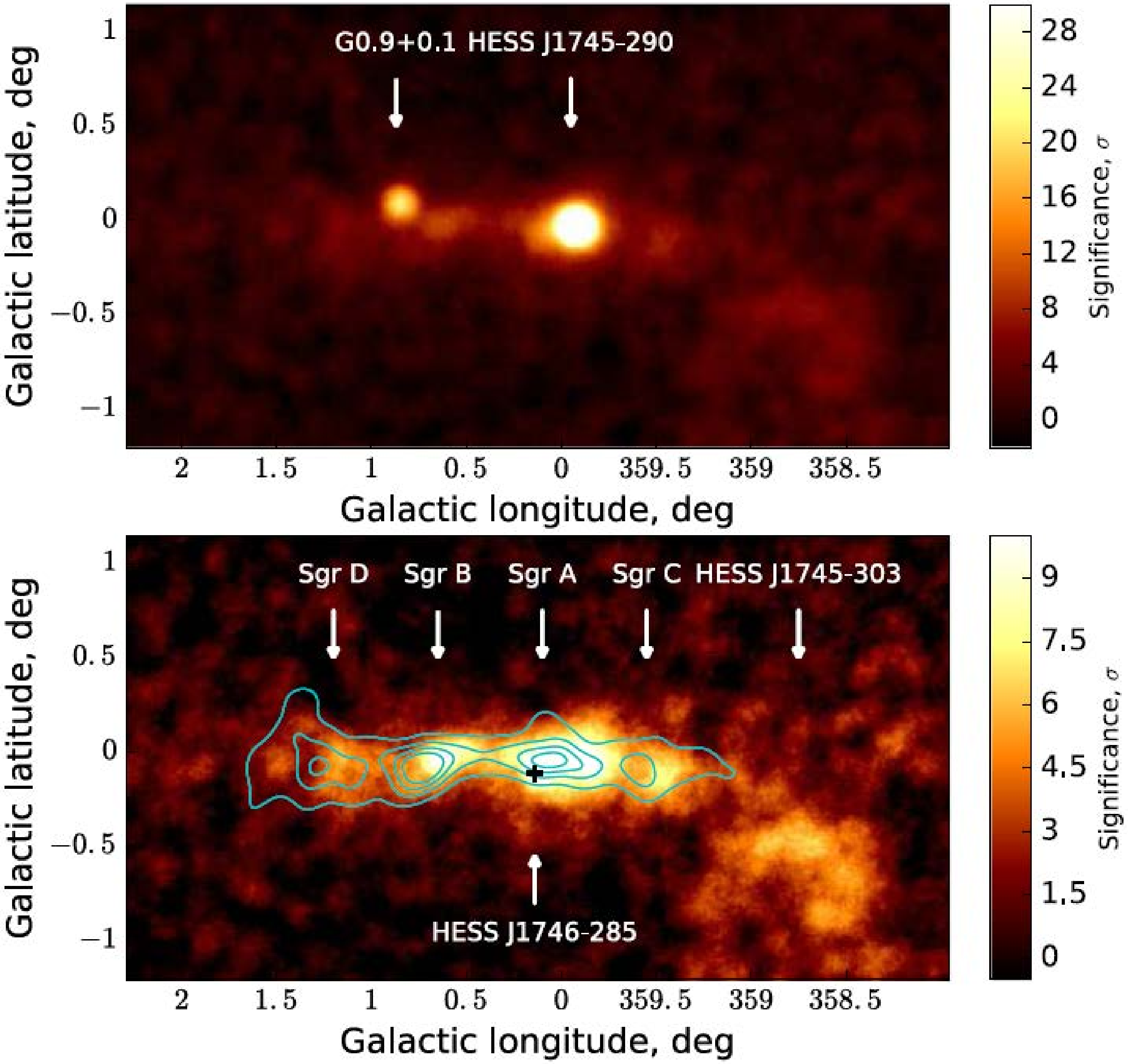
Co-authors: D.C.Ellison, M.Kalyashova, S.Osipov, A.Petrov

LHAASO sky map at energies above 100 TeV



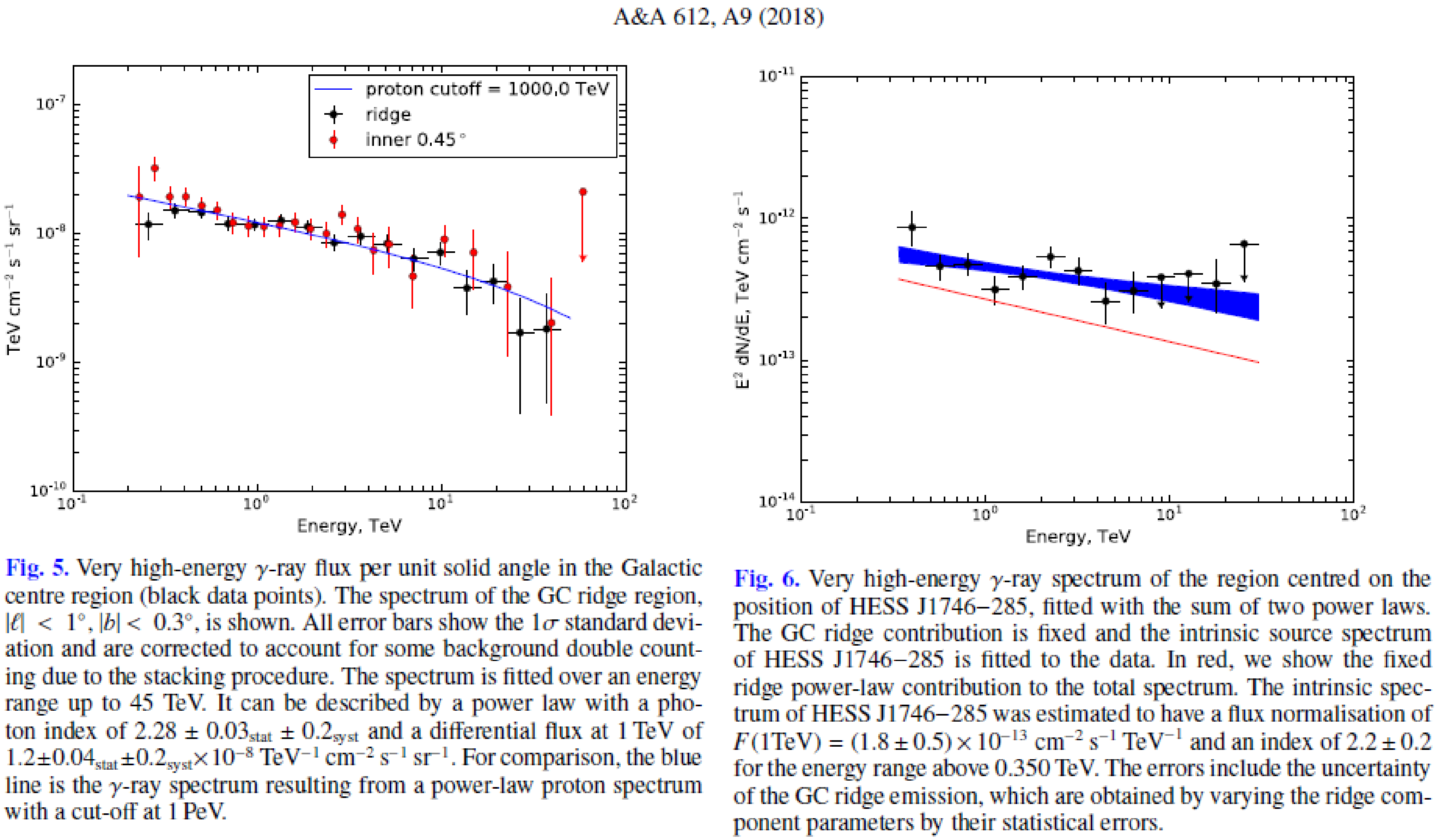
Cao, Aharonian et al Nature, Volume 594, Issue 7861, p.33, 2021

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



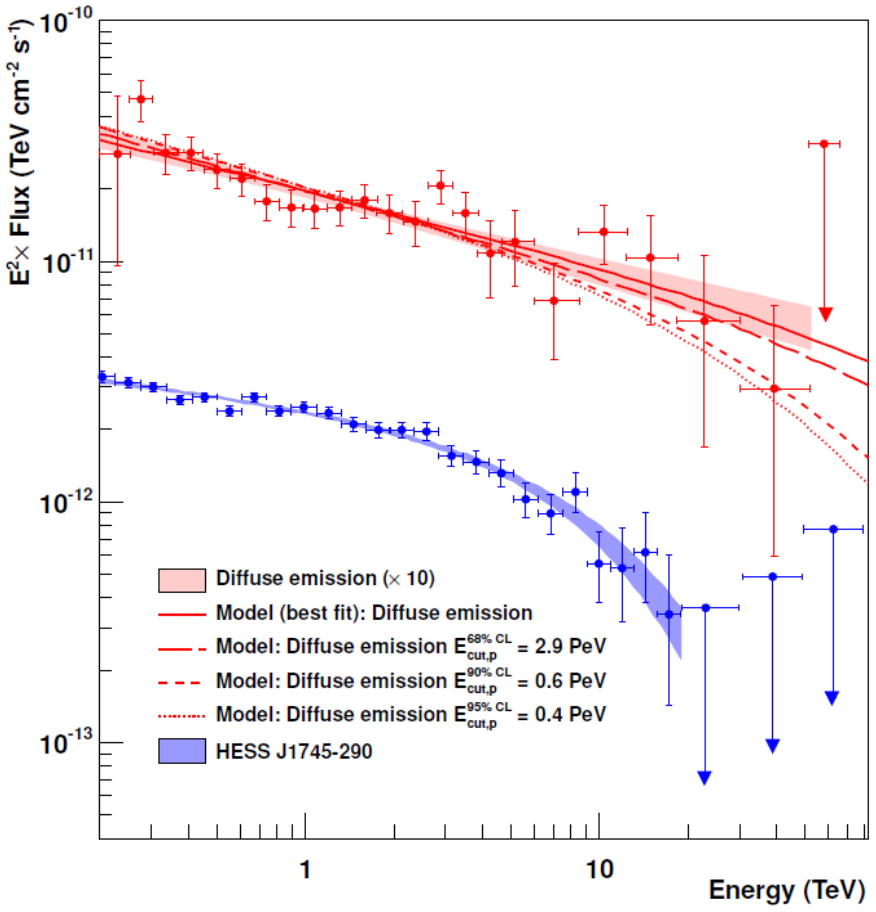
A&A 612, A9 (2018)

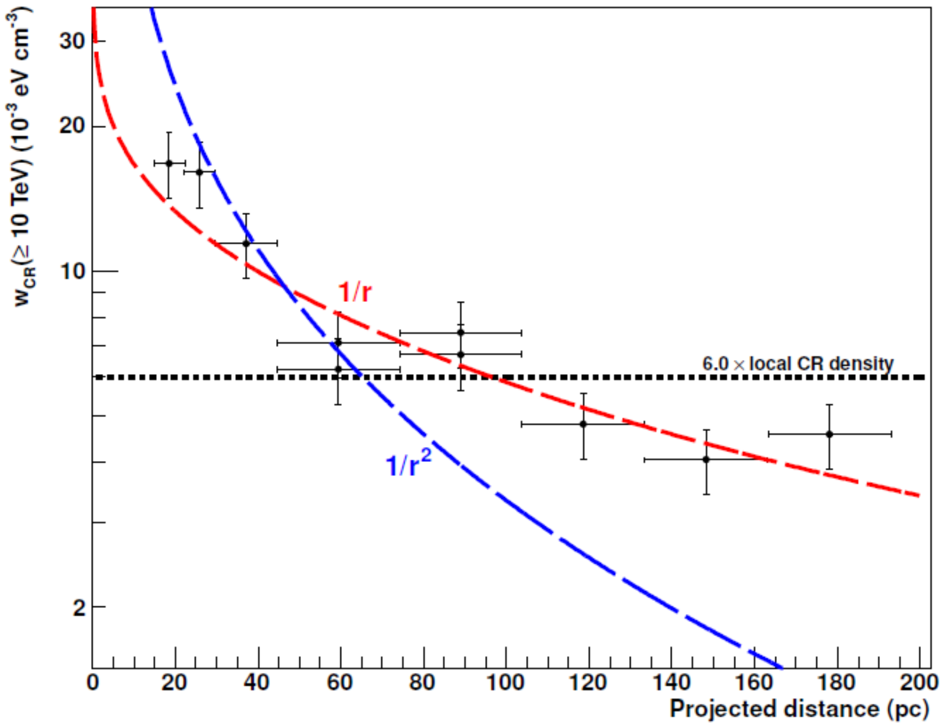
Fig. 5. Very high-energy γ-ray flux per unit solid angle in the Galactic centre region (black data points). The spectrum of the GC ridge region, $|\ell| < 1°$, $|b| < 0.3°$, is shown. All error bars show the 1σ standard deviation and are corrected to account for some background double counting due to 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 $2.28 \pm 0.03_{\rm stat} \pm 0.2_{\rm syst}$ and a differential flux at 1 TeV of $1.2 \pm 0.04_{\rm stat} \pm 0.2_{\rm syst} \times 10^{-8}$ 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 $F(1\,{\rm TeV}) = (1.8 \pm 0.5) \times 10^{-13}$ 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

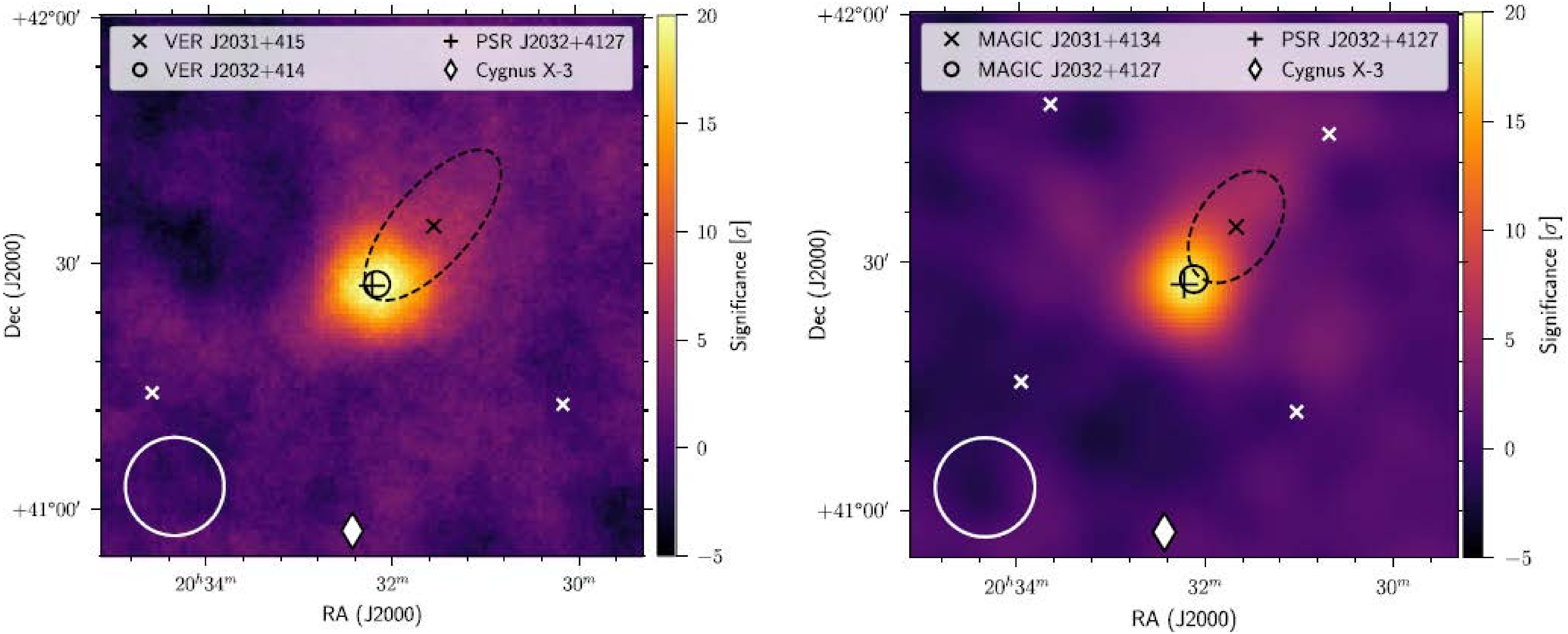
Acceleration of Petaelectronvolt protons in the Galactic Centre





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

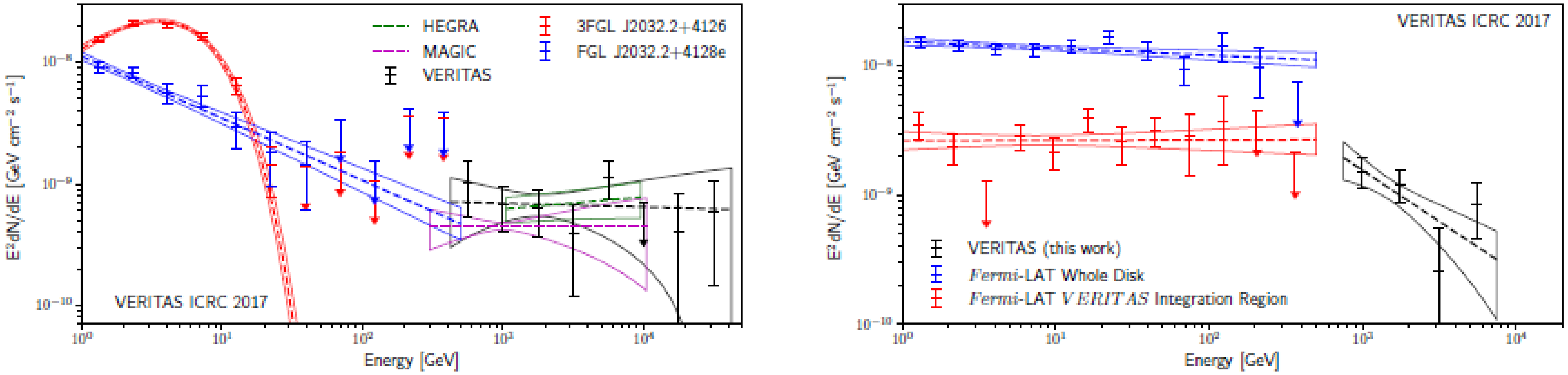
VERITAS MAGIC maps of a crowded region in Cygnus



VERITAS & MAGIC teams The Astrophysical Journal Letters, 867:L19, 2018

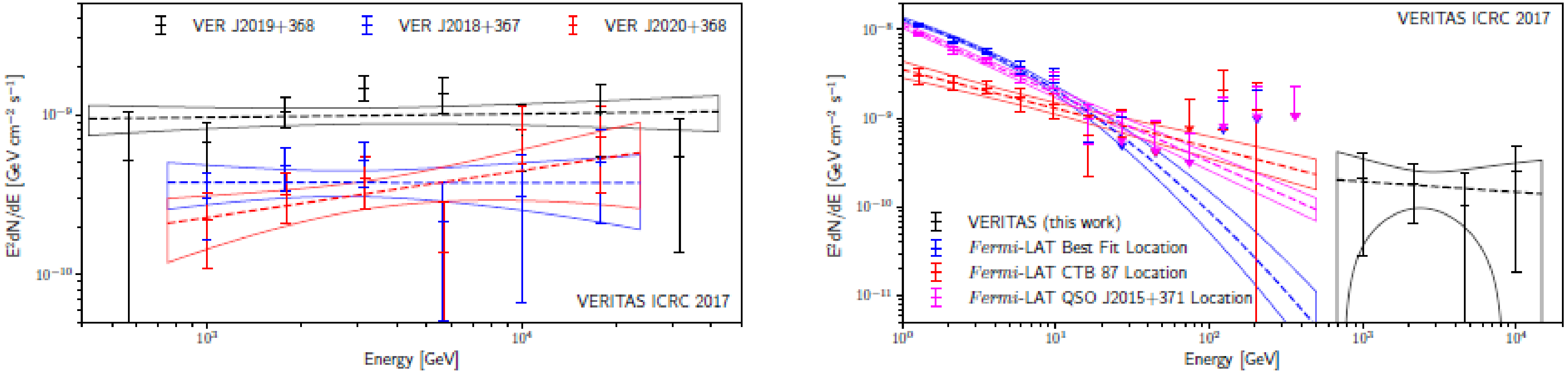
VERITAS spectra of some sources in Cygnus

VERITAS observations of the Cygnus Region Ralph Bird



(a) TeV J2032+4130 region.

(b) Gamma Cygni region.

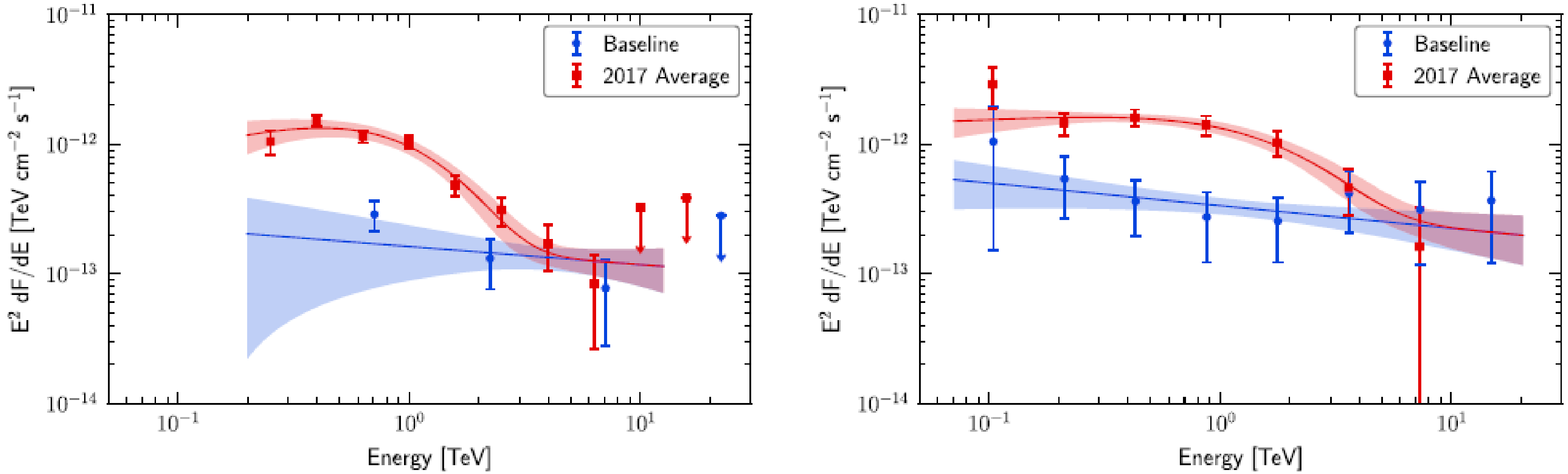


(c) MGRO J2019+37 region.

(d) CTB 87 region.

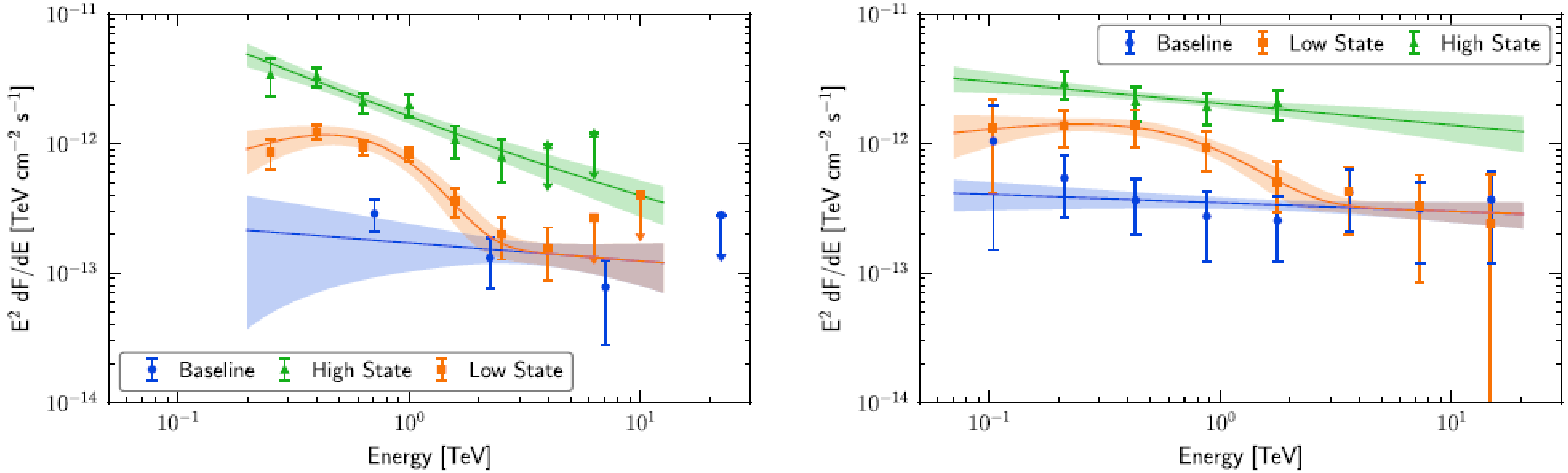
VERITAS ICRC 17

VERITAS MAGIC spectra at different phases PSR 2032



(a) VERITAS 2017 fall average

(b) MAGIC 2017 fall average

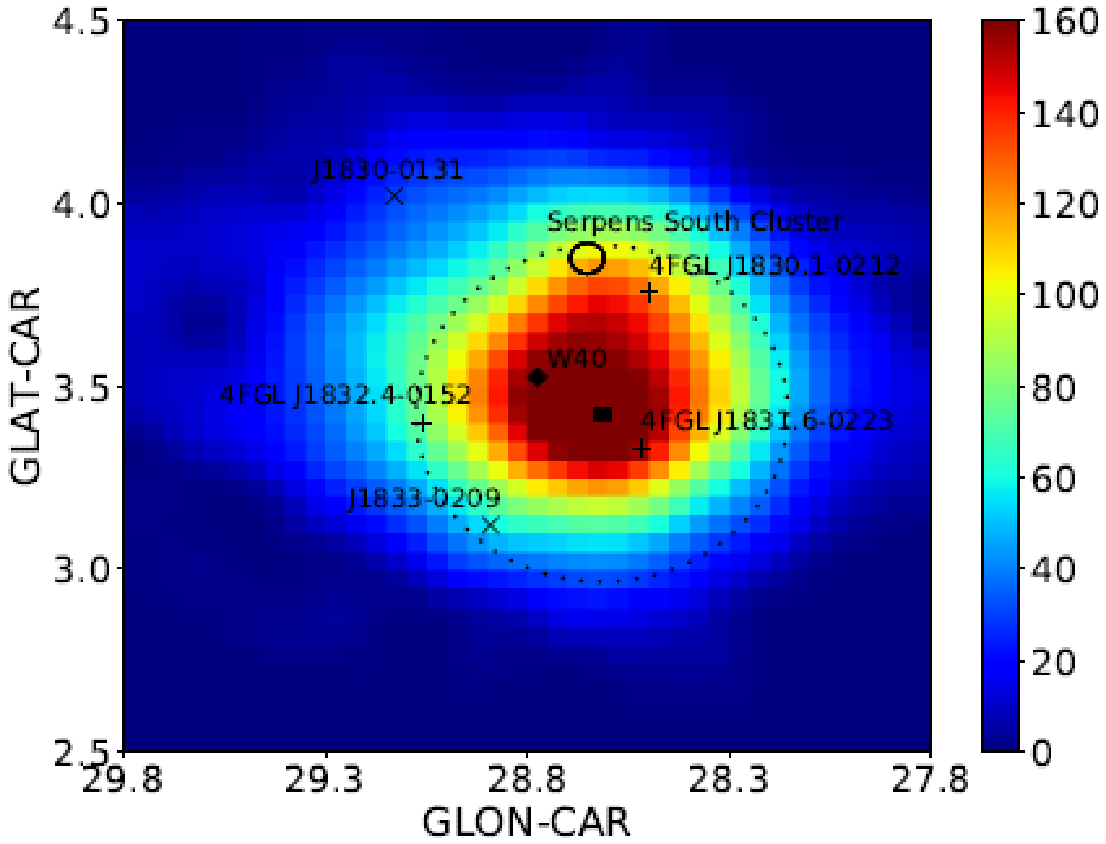


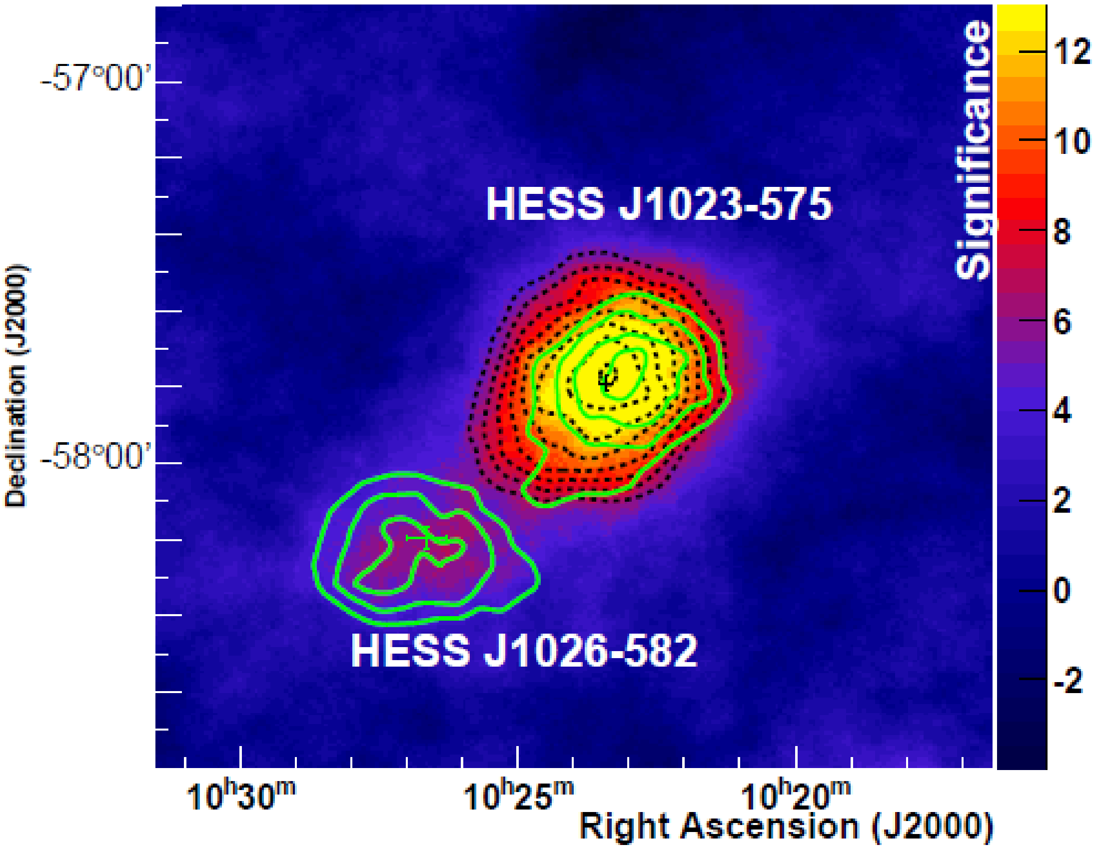
(c) VERITAS high & low states

(d) MAGIC high & low states

VERITAS & MAGIC teams The Astrophysical Journal Letters, 867:L19, 2018

Gamma-ray images of young stellar clusters

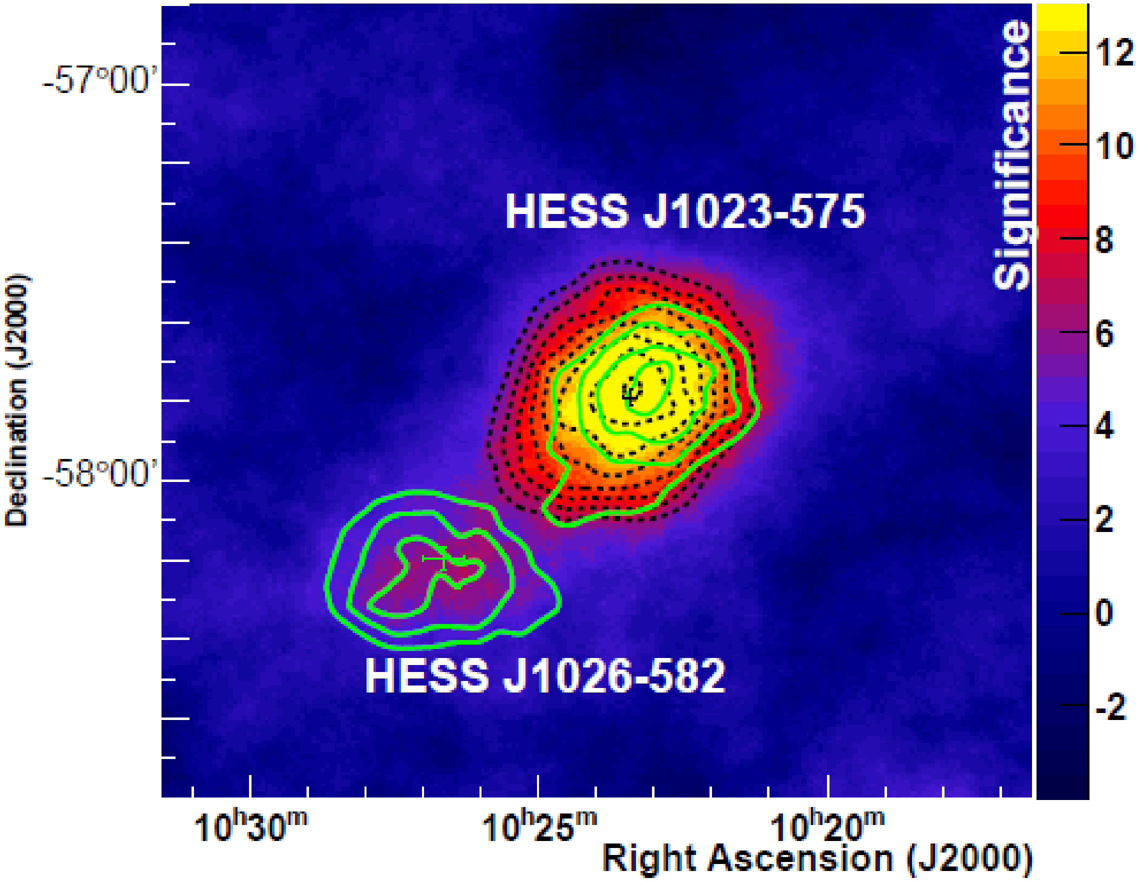




Fermi image W40
Sun + A&A v.639, 2020

H.E.S.S. image Westerlund 2
A&A v. 525, A46, 2011
See also E.Mestre + 2021 arxiv

H.E.S.S. studies of Westerlund 2 field



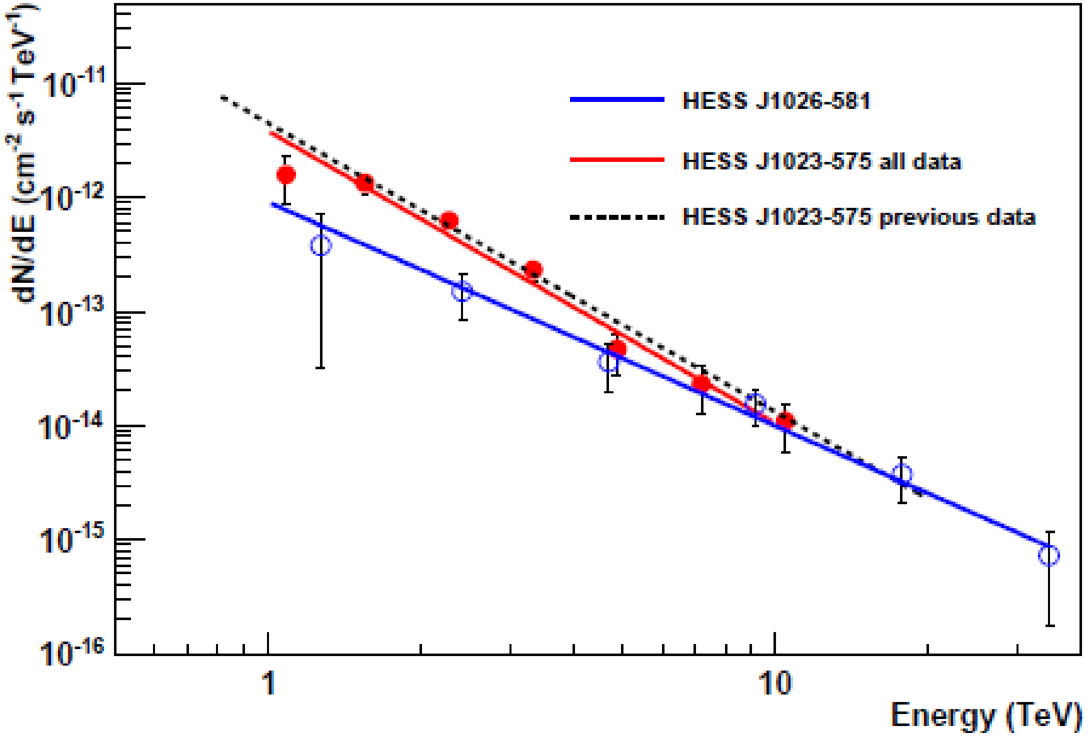
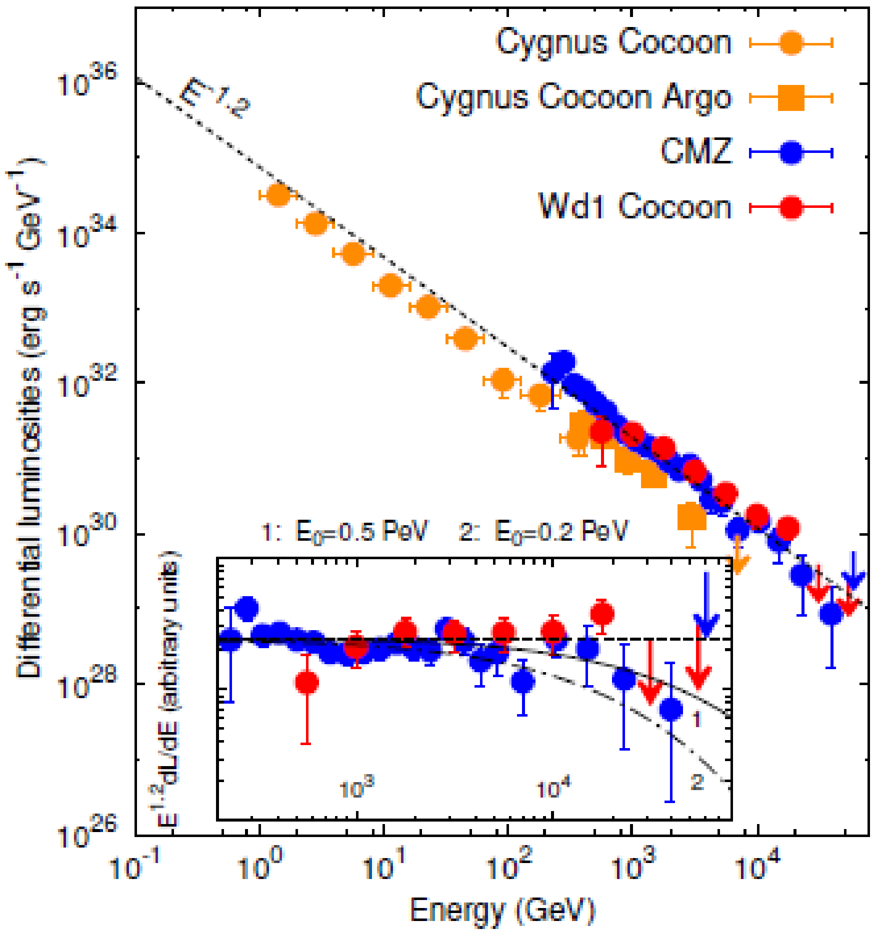
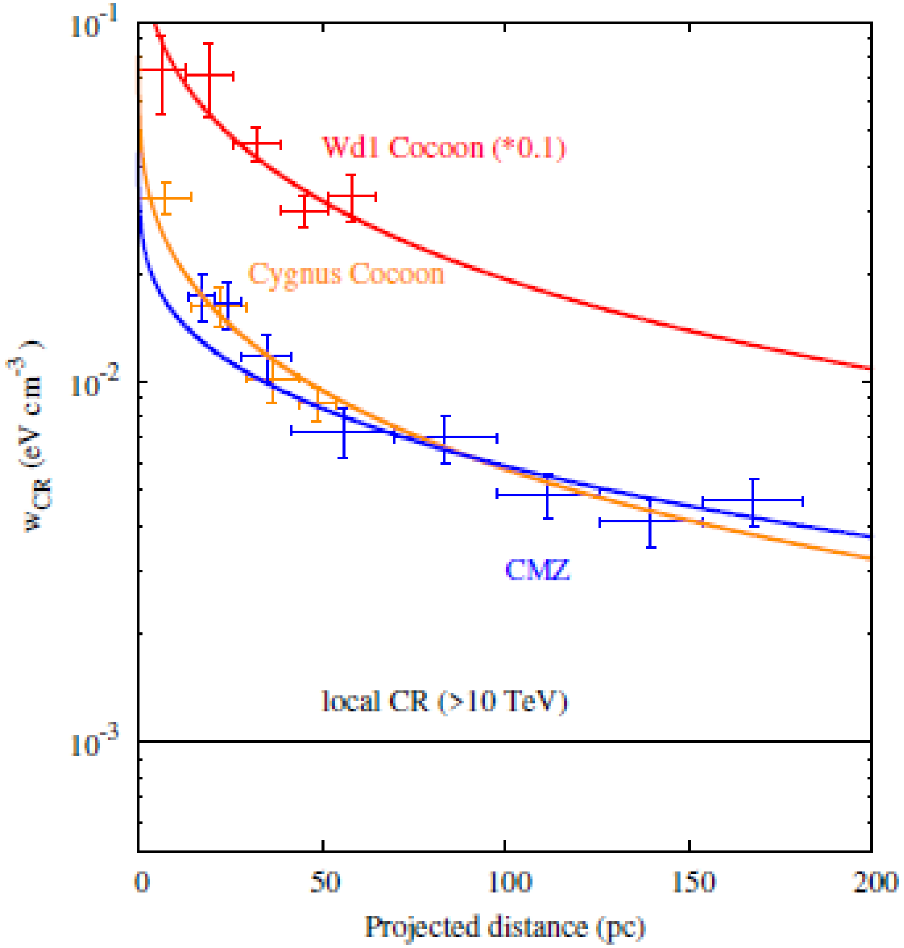


Fig. 4: Differential energy spectra of HESS J1023–575 (red filled circles) and dashed black line for the previous detection and HESS J1026–582 (Aharonian et al. 2007a) (blue open circles).

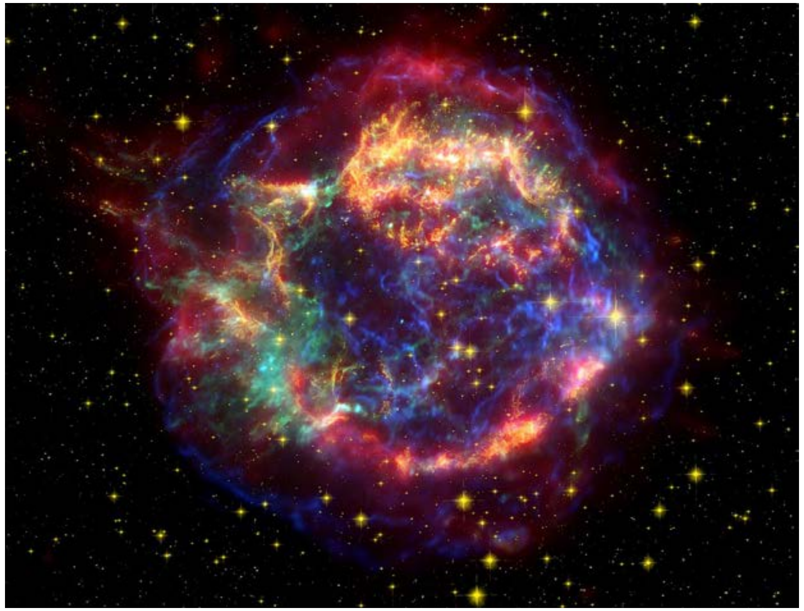
Astron. Astroph. v.525, A46, 2010

Cosmic ray factories

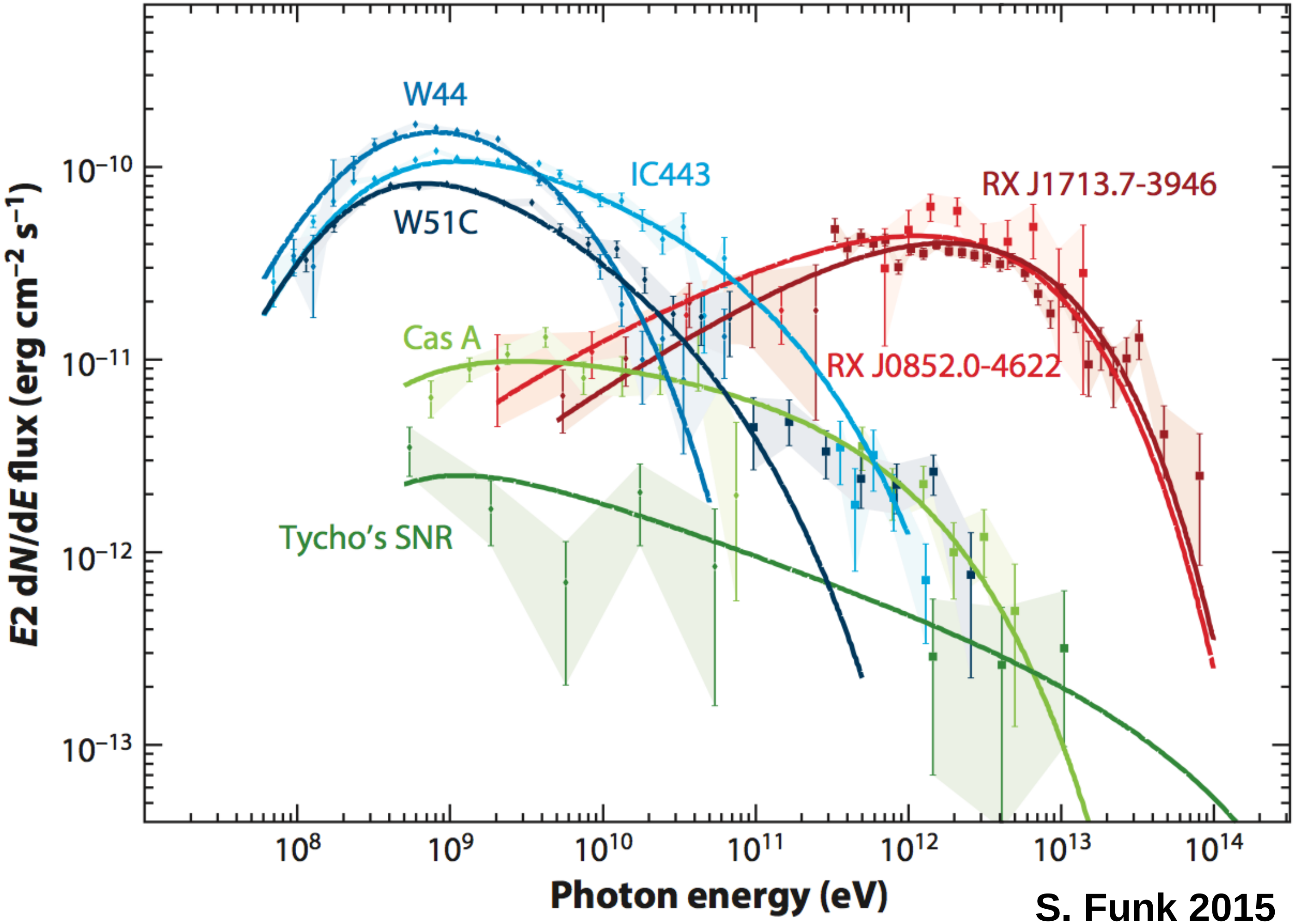




Aharonian, Ona Wilhelmi. Yang Nat. Astron. V.3, p.561, (2019)



Observed gamma-ray spectra of young SNRs

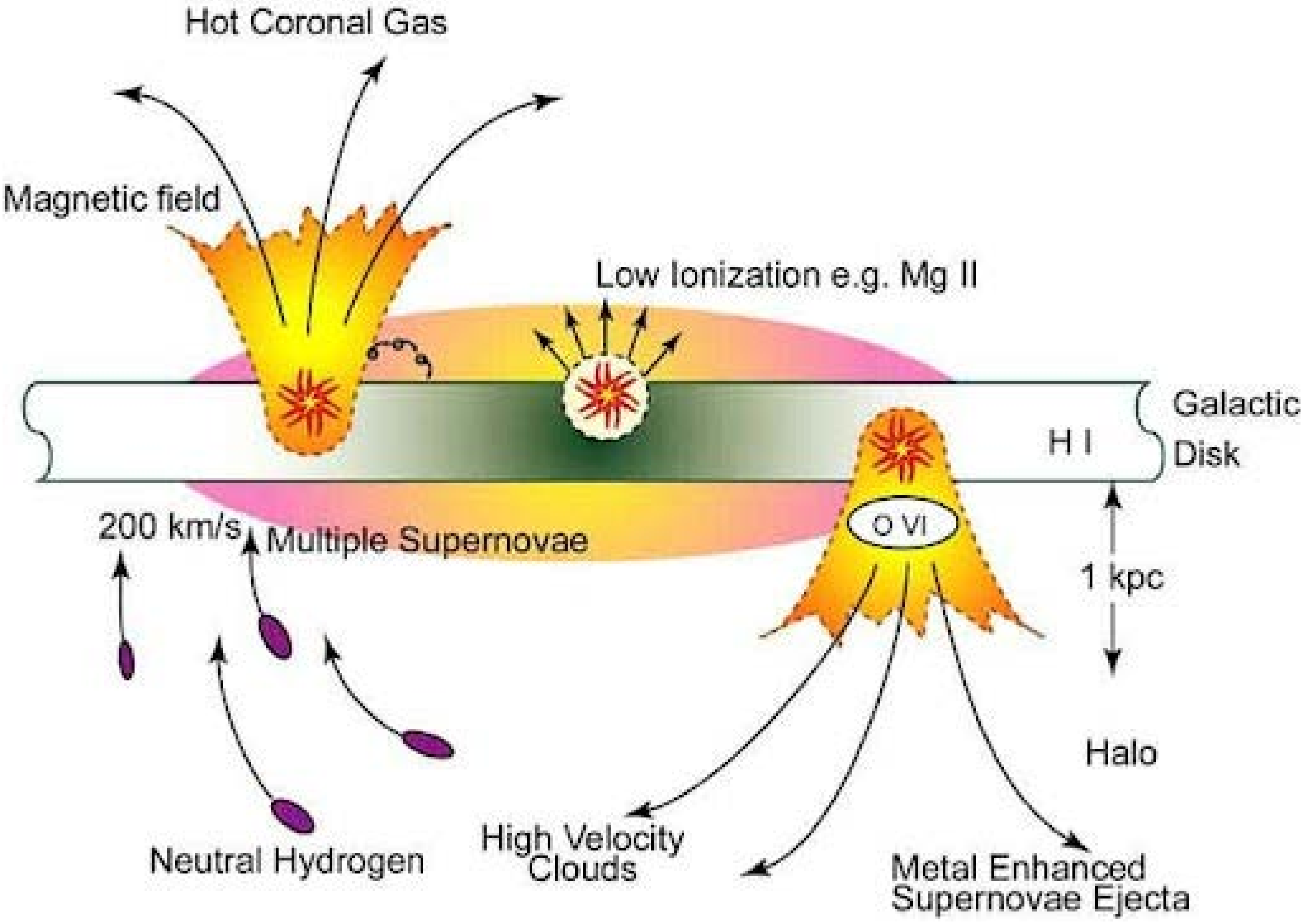


S. Funk 2015

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

We discuss here some limited class of
pevatrons relevant to current
gamma-ray astronomy data.
The extragalactic VHE-UHECR
as neutrino sources sources were
discussed
by A.Bell, M.Lemoine, E.Waxman
and others

PeV proton acceleration in superbubbles

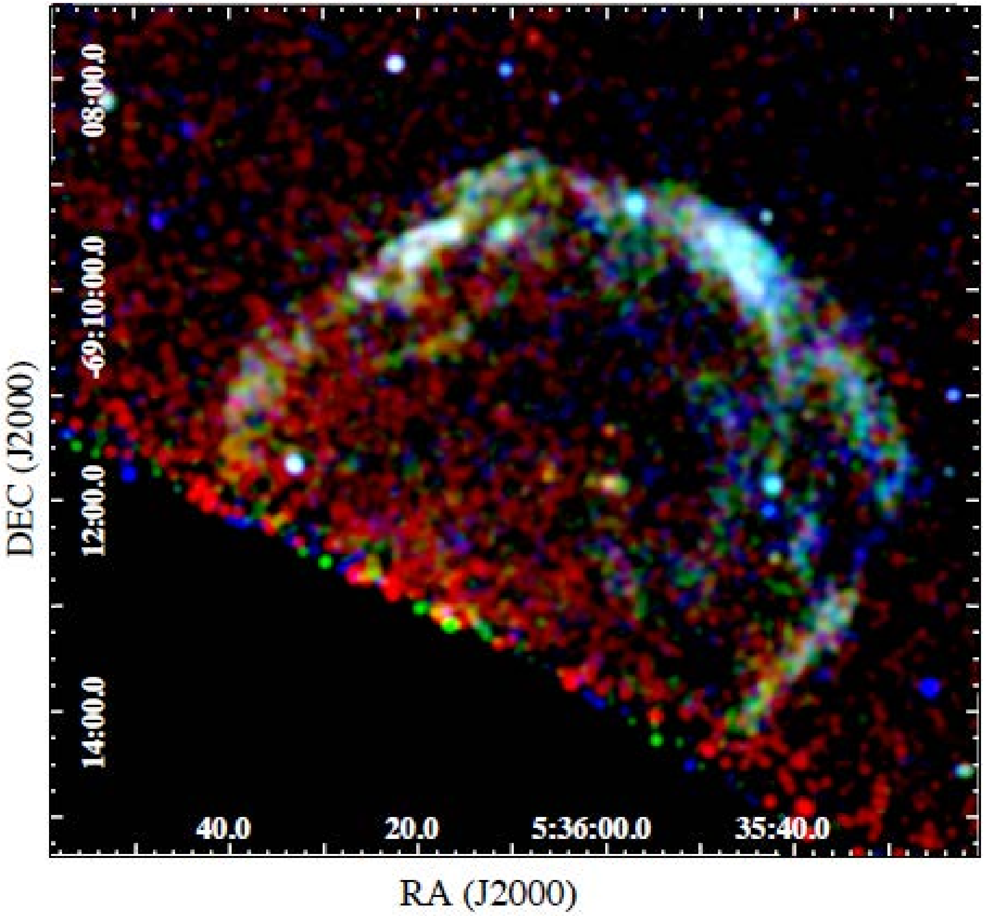


Credit: NASA SSL

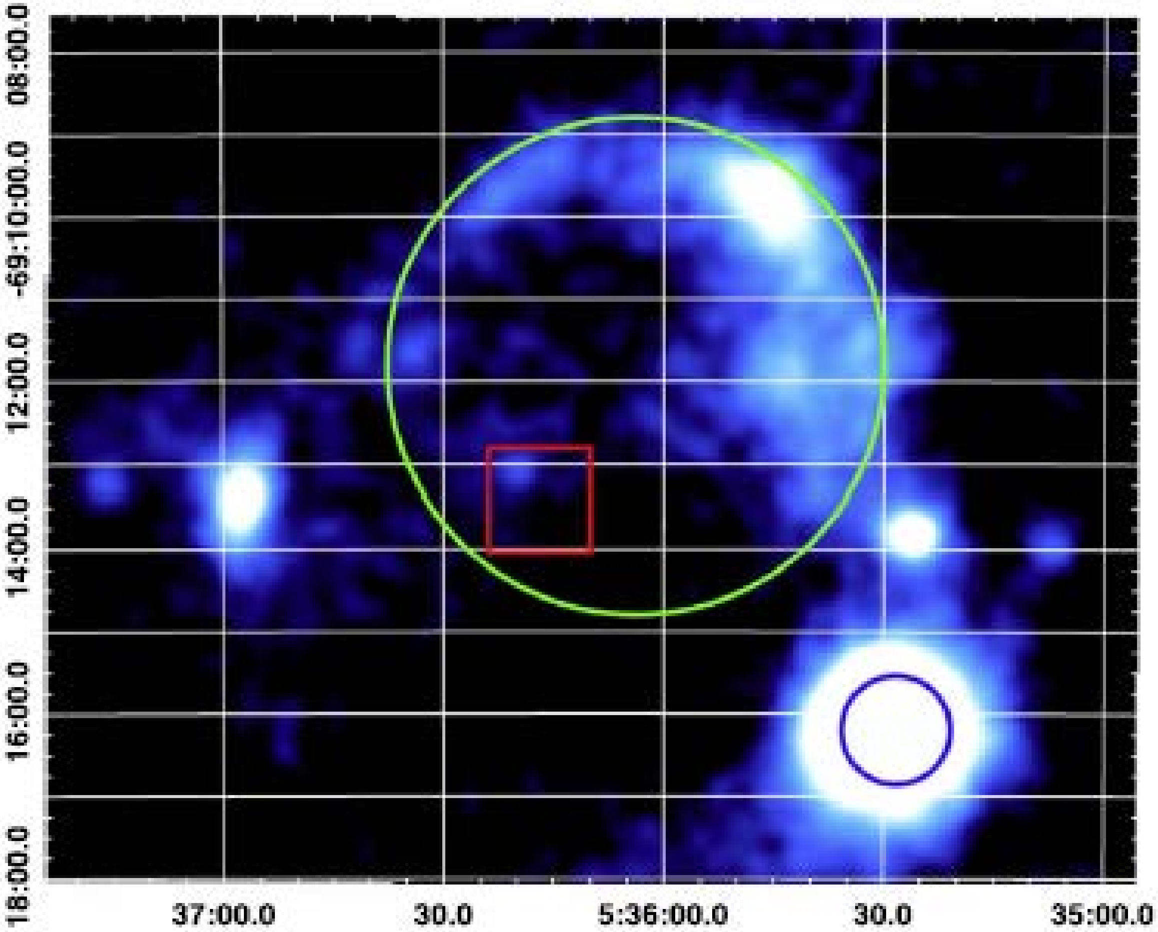
How the clustered young massive stars and SNe would affect galactic CR sources?

A 100 pc superbubble around star cluster NGC 1929 LMC
http://www.solstation.com/x-objects/lmc2sbub.jpg

X-ray images of 30 Dor C superbubble in LMC
Non-thermal is due to synchrotron radiation multi-TeV leptons

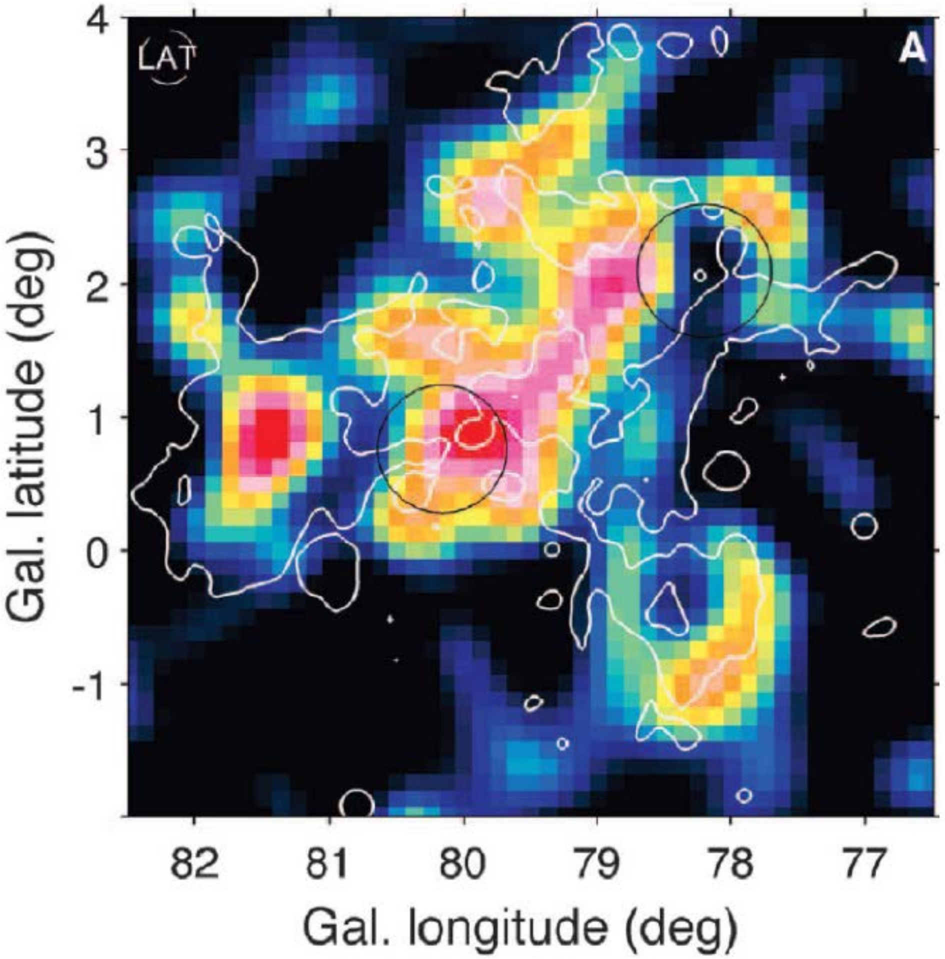


Chandra image
Kavanagh + A&A 2019

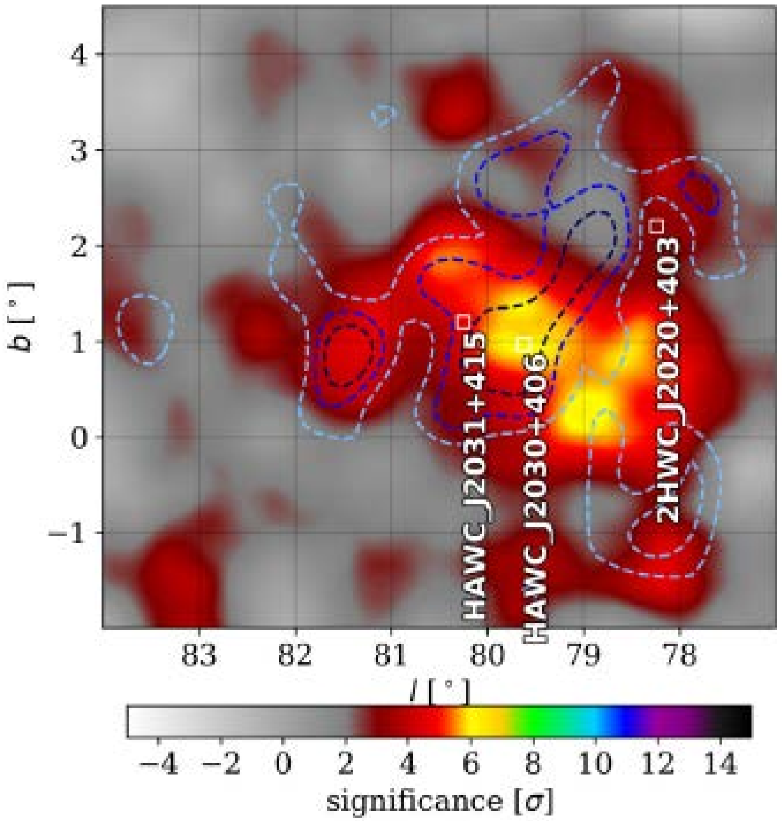


NuSTAR image
L.Lopez + ApJ 2020

Gamma-ray images of Cygnus Cocoon



Ackermann + Fermi team 2011

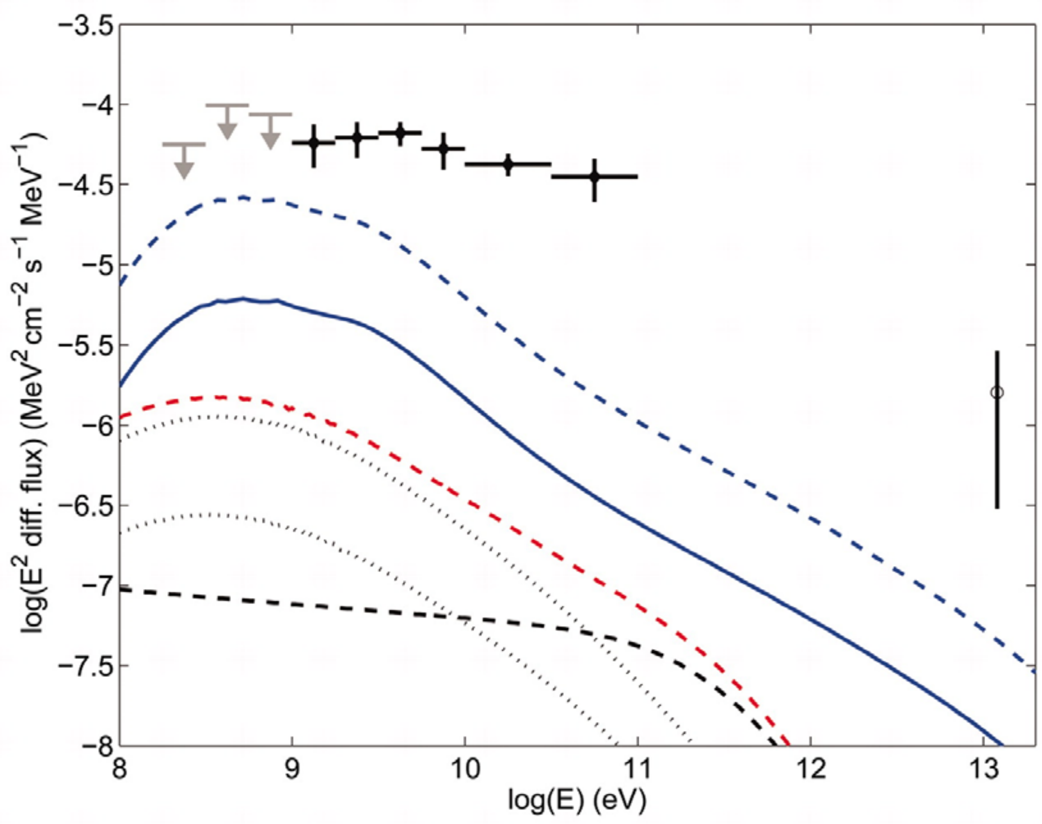


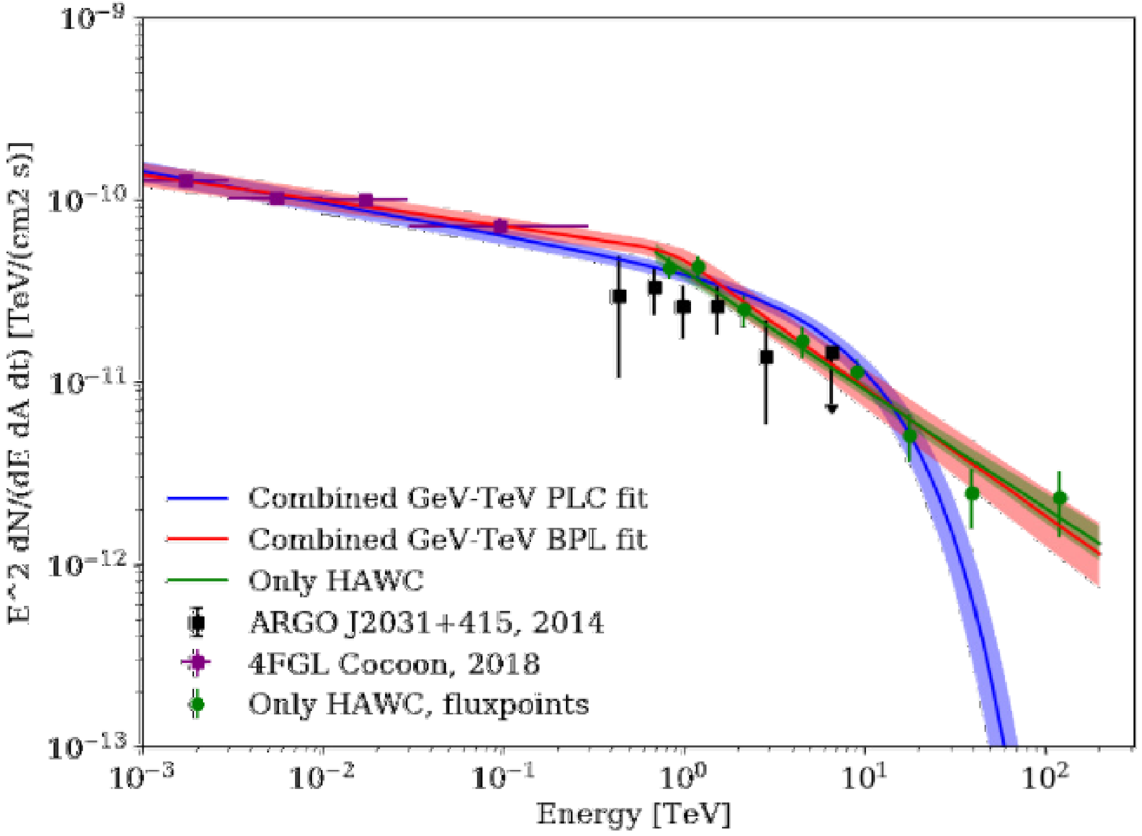
B.Hona HAWC 2020

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

Cygnus X is about 1.7 kpc away. Contain a number of young star clusters and several OB associations. Cygnus OB2 association contains ~ 120 O stars (Knodlseder 2000) and more than 1000 B stars within a region of ~ 10 pc. There is a young supernova remnant Gamma-Cygni and a few gamma-pulsars.

Cygnus Cocoon Fermi, ARGO, HAWC data





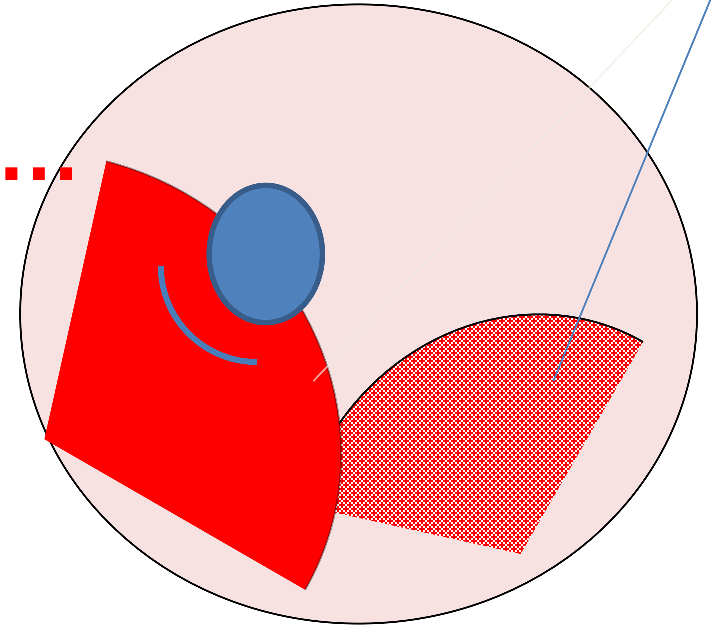
B. Hona + 2020

Ackermann + 2011

Particle acceleration at different stages
of superbubble evolution

Primary SN shocks and
rarefactions

Multiscale, highly intermittent problem…

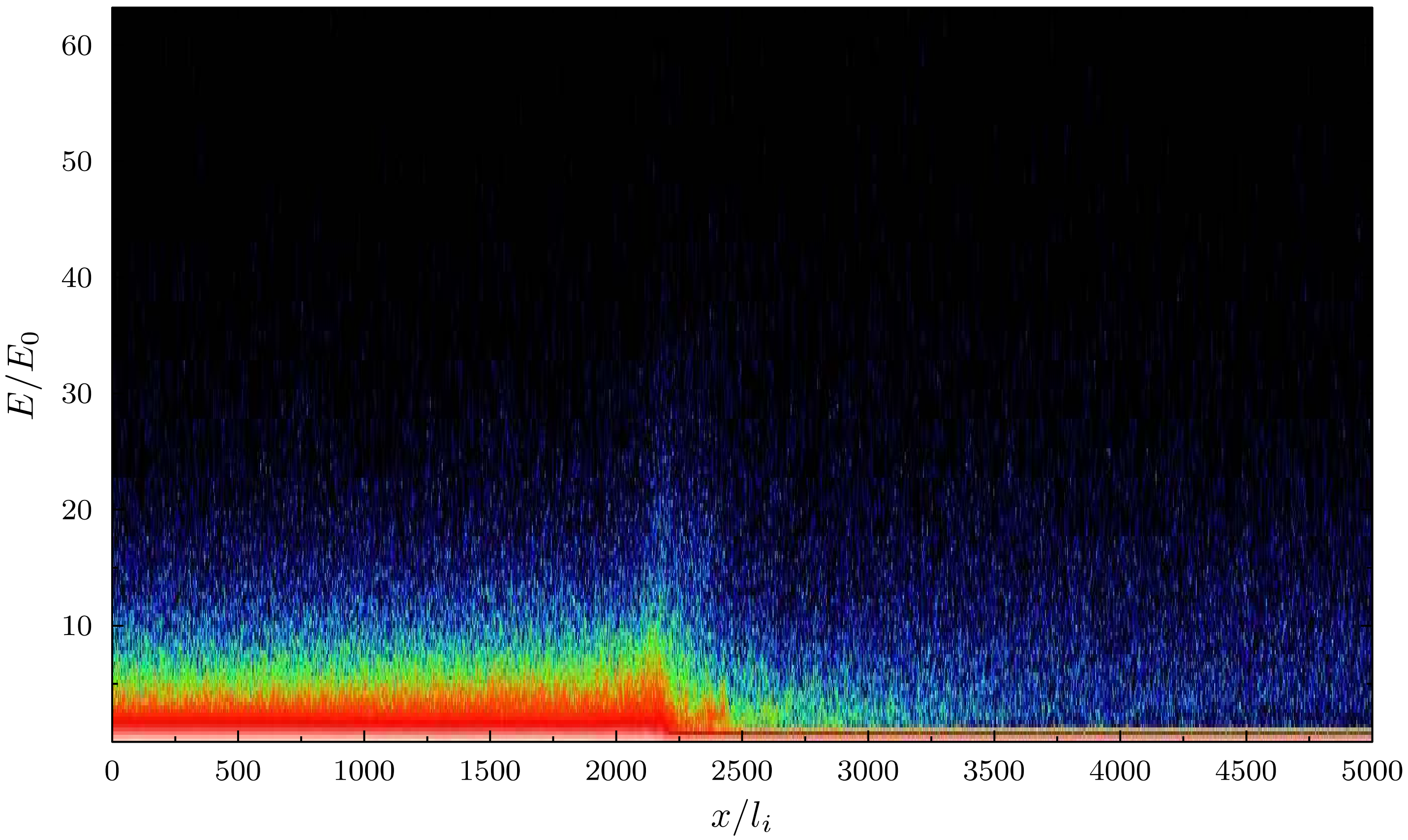


Microscopic scale of collisionless shock structure is ~ 100 km while the macroscopic scale size of the shocks is ~ 10s of pcs…

Microscopic scale

Ion heating vs injection in a moderate Mach number plasma shock

$\beta = 20$



Space Sci Rev . V.215, 14. 2019

Kinetic approach to model CR spectra.

Quasi-linear theory is not good for strong fluctuations

How to deal with the strong intermittency at marcoscopic scales?

To connect the local distribution Fi(r,p,t) at i-th SW
to the mean distribution function in between the SWs - N(r,p,t)

$$F_{\rm i}({\rm r},p,t) = \theta(z_{\rm i})\Phi_{\rm i} + \theta(-z_{\rm i})[\Phi_{\rm i}\exp\left(\Delta u_{\rm i} z_{\rm i}/\chi_{\rm i} z_{\rm i}\right) + N(z_{\rm i},p)]$$

$$\Phi_{\rm i}({\rm r},p,t) = (2+\gamma_{\rm i})p^{-(2+\gamma_{\rm i})}\int_0^p {\rm d}p'\, p'^{(\gamma_{\rm i}+1)}N(p').$$

At a particular i-th shock we are using the local DSA solution
by W.I.Axford +, G.F.Krymsky, A.R. Bell, R.D. Blandford & J.P.Ostriker…

Then for the mean distribution function N(r,p,t) we get a kinetic equation

Particle acceleration by shock ensemble

(renormalized kinetic equations)

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

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

Fermi II due to large-scale turbulence

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

Shocks

Shock-rarefactions

$$\hat{P} = \frac{p}{3}\,\frac{\partial}{\partial p}\,; \qquad \hat{L} = \frac{1}{3p^2}\,\frac{\partial}{\partial p}\,p^{3-\gamma}\int_0^p \mathrm{d}p'\,p'^{\gamma}\,\frac{\partial}{\partial p'}\,.$$

AB Space Sci. Rev. v.99, p.317, 2001; Astron. Astrophys. Rev (2014) 22:77

Renormalized kinetic coefficients for CR transport by strong turbulence

$$\chi = \kappa + \frac{1}{3}\int \frac{d^3k\, d\omega}{(2\pi)^4}\left[\frac{2T+S}{i\omega+\chi k^2} - \frac{2k^2\chi S}{(i\omega+\chi k^2)^2}\right]$$

$$D = \frac{\chi}{9}\int \frac{d^3k\, d\omega}{(2\pi)^4}\frac{S(k,\omega)}{\omega^2+\chi^2k^4}$$

$$\kappa(p) = \frac{v}{3}\cdot l_{\rm corr}\cdot\left[\frac{R_H(p)}{l_{\rm corr}}\right]^{2-\nu}$$

$$A = \chi\int \frac{d^3k\, d\omega}{(2\pi)^4}\frac{k^4\varphi(k,\omega)}{\omega^2+\chi^2k^4}$$

$$B = \chi\int \frac{d^3k\, d\omega}{(2\pi)^4}\frac{k^4\mu(k,\omega)}{\omega^2+\chi^2k^4}$$

$$G = (B + 1/\tau_{sh})$$

AB Space Sci. Rev. v.99, p.317, 2001; Astron. Astrophys. Rev (2014) 22:77

Renormalized kinetic coefficients

$$\chi = \kappa + \frac{1}{3}\int \frac{d^3k\, d\omega}{(2\pi)^4}\left[\frac{2T+S}{i\omega+\chi k^2} - \frac{2k^2\chi S}{(i\omega+\chi k^2)^2}\right]$$

$$D = \frac{\chi}{9}\int \frac{d^3k\, d\omega}{(2\pi)^4}\,\frac{S(k,\omega)}{\omega^2+\chi^2 k^4}$$

$$\kappa(p) = \frac{\mathrm{v}}{3}\cdot l_{\mathrm{corr}}\cdot\left[\frac{R_H(p)}{l_{\mathrm{corr}}}\right]^{2-\nu}$$

Turbulent advection regime K(p) $\ll \varkappa$

CR diffusion regime K(p) $= \varkappa$

AB Space Sci. Rev. v.99, p.317, 2001; Astron. Astrophys. Rev (2014) 22:77

Turbulence model

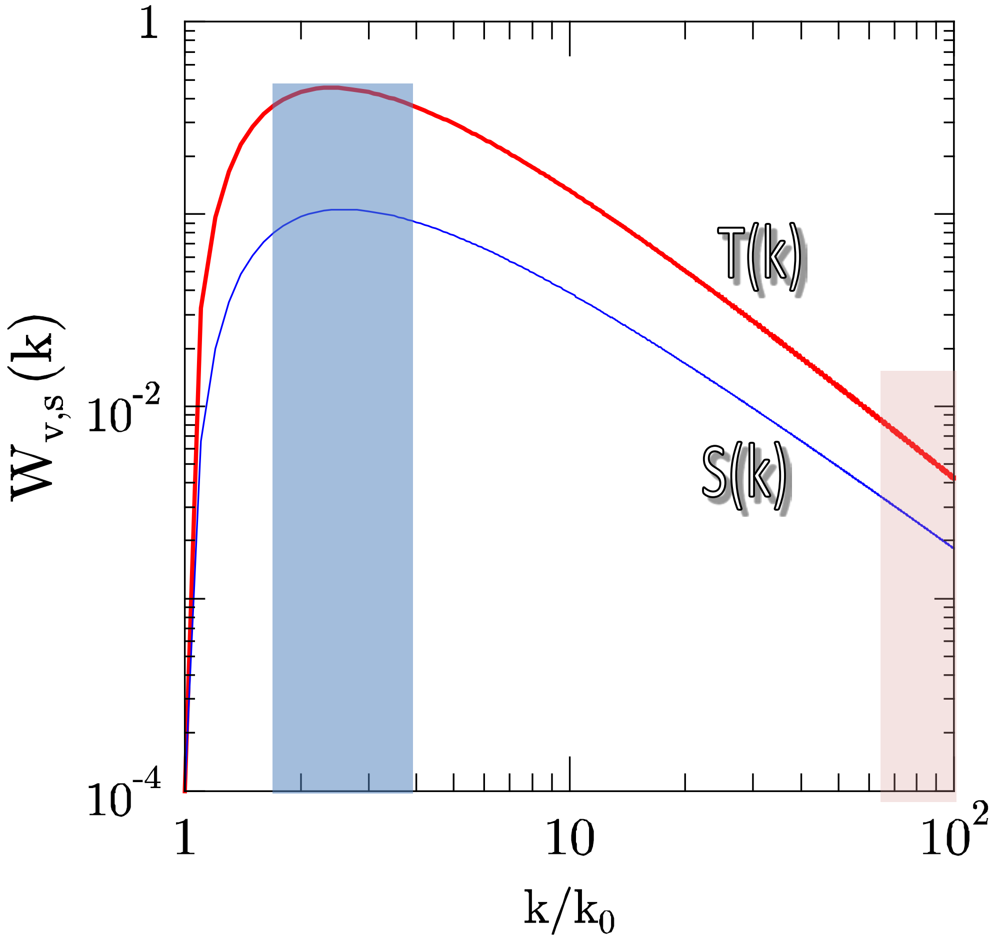
$$\frac{\partial S}{\partial t}+\frac{\partial \Pi^{s}}{\partial k}=\gamma_{vs}T-\gamma_{cr}S-\gamma_{ds}S$$

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

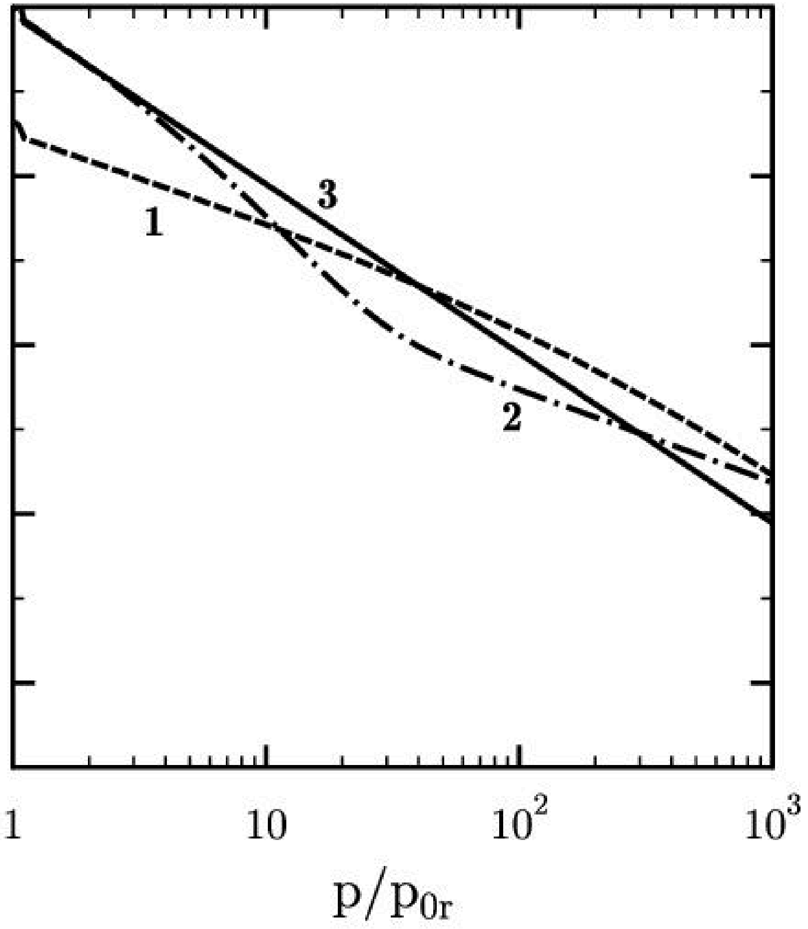
The CR acceleration model is nonlinear since we require the total energy [CRs + turbulence] conservation

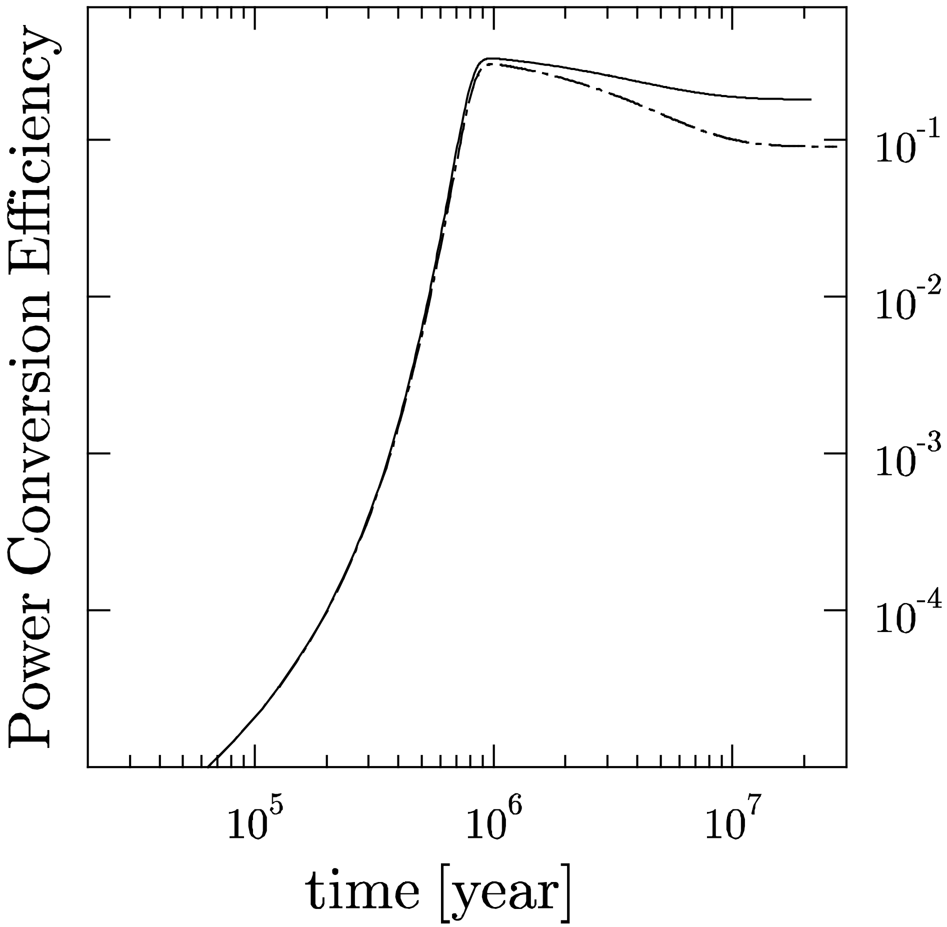
The model is time dependent, but statistically homogeneous

MHD fluctuation spectra



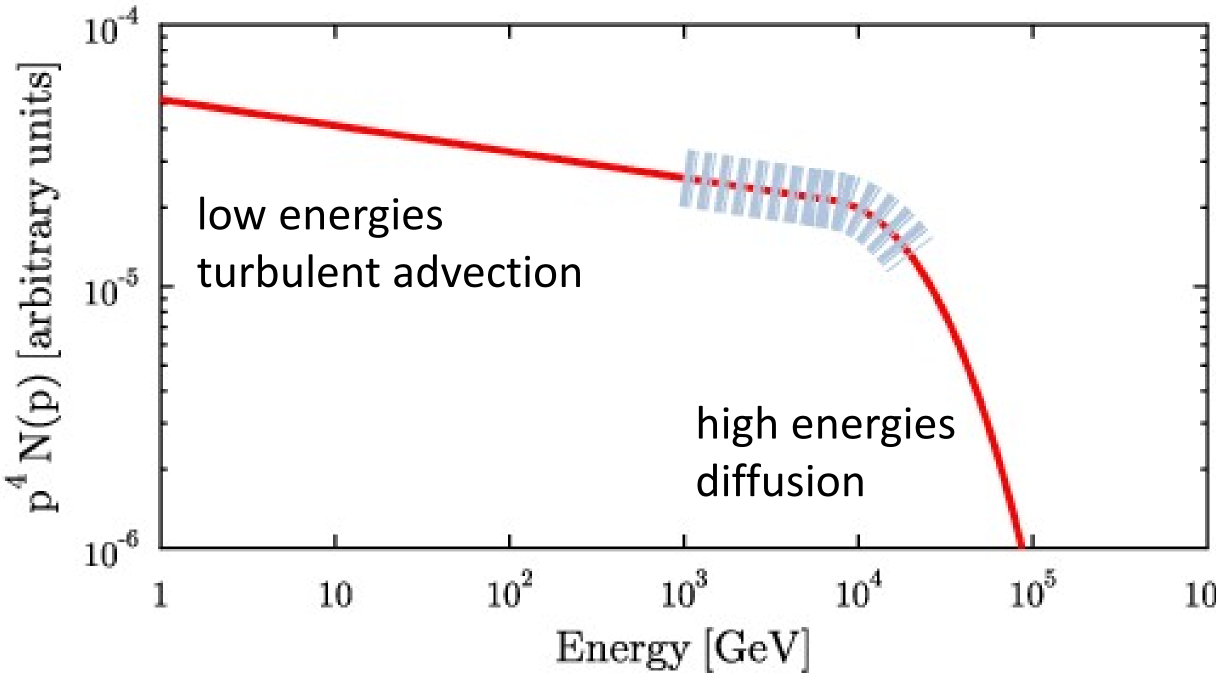
Temporal evolution of low energy CRs in SB (turbulent advection regime)





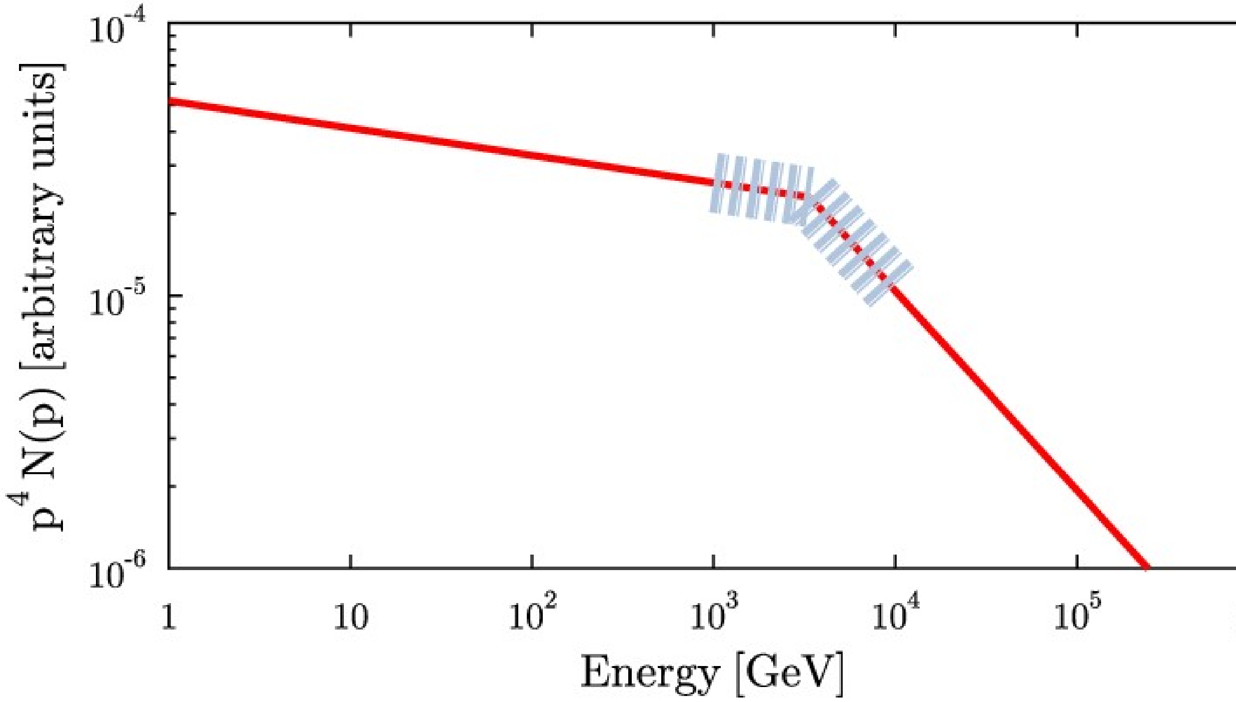
AB   Space Sci. Rev. v.99, p.317, 2001; Astron. Astrophys. Rev (2014) 22:77

Model cosmic ray proton spectra in Cygnus Cocoon



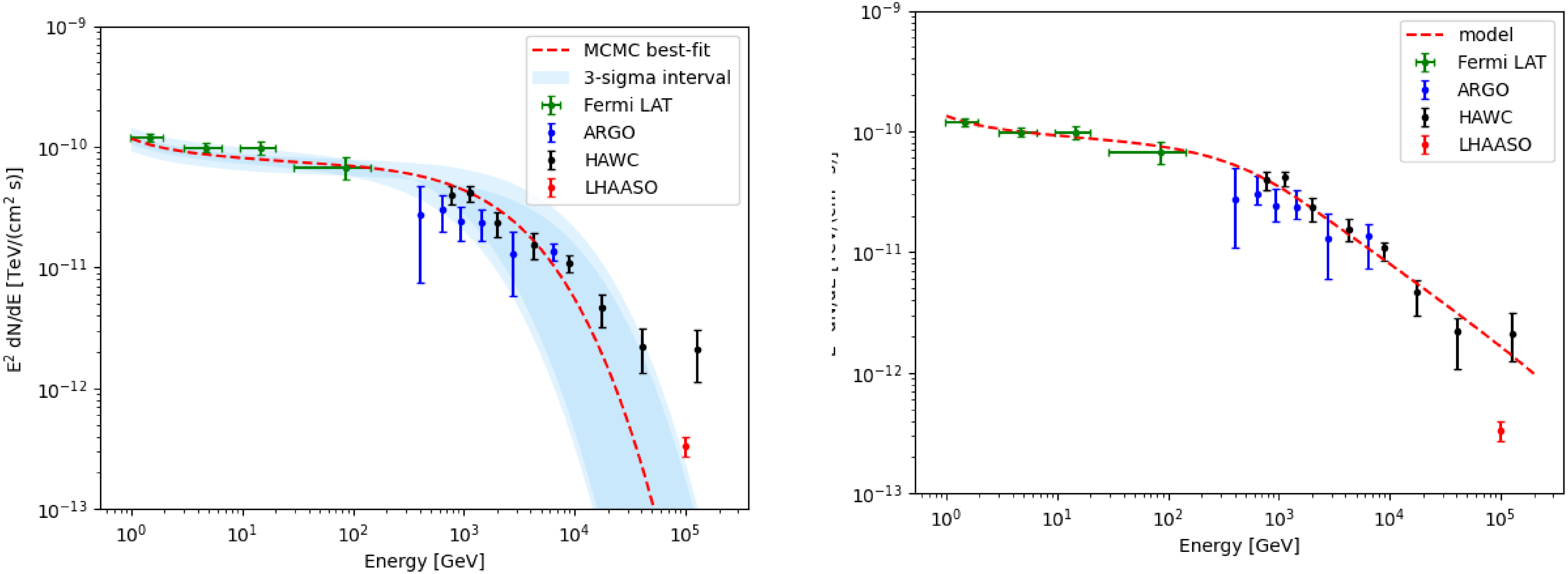
low energies
turbulent advection

high energies
diffusion



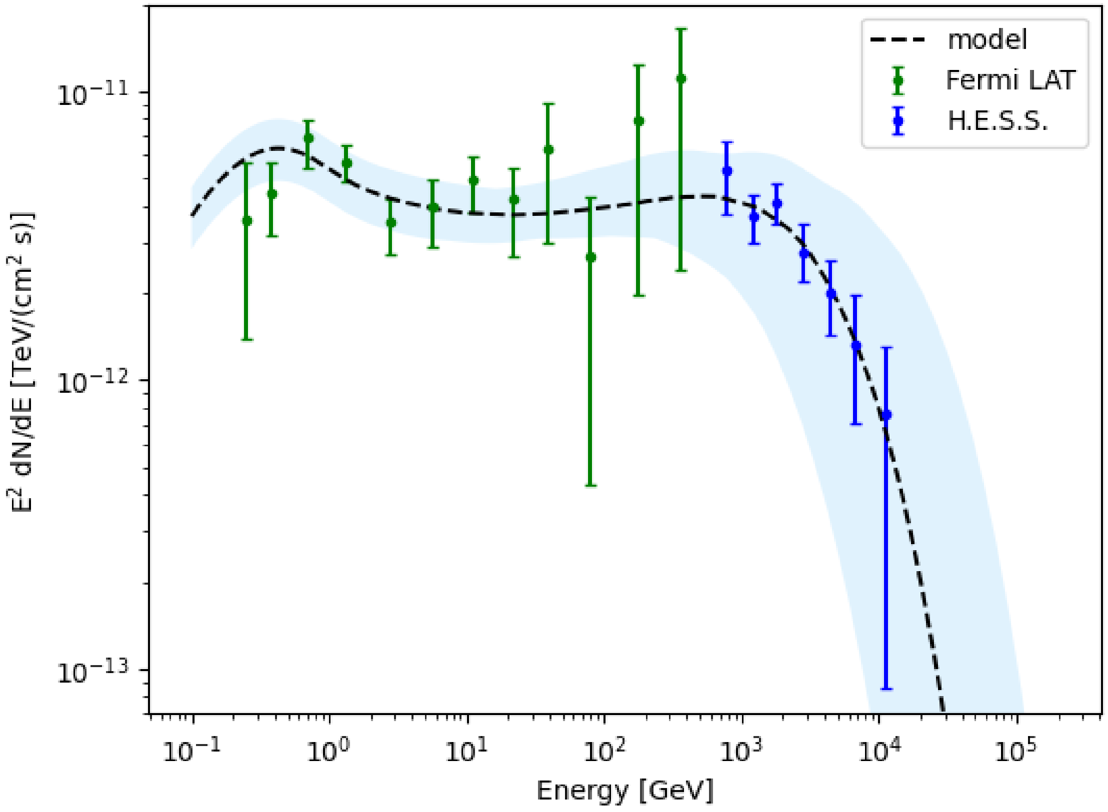
AB Kalyashova ASR 2021

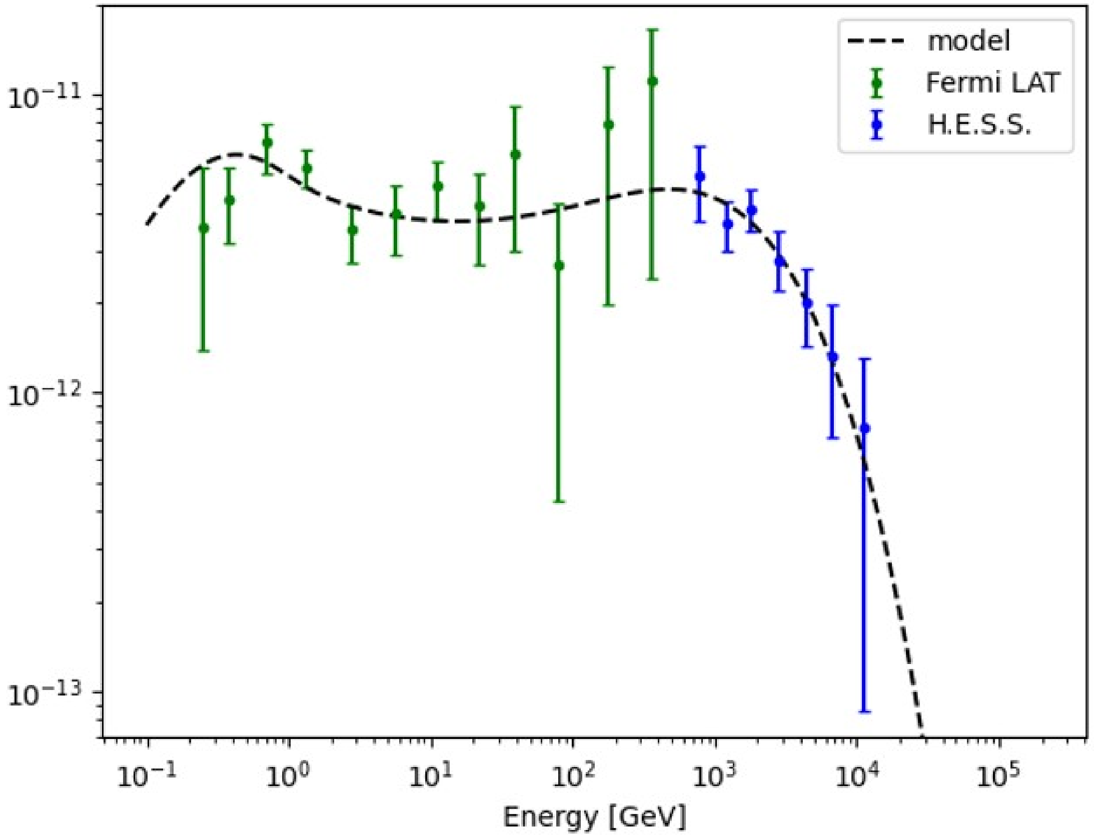
Gamma-ray spectra of Cygnus Cocoon



AB Kalyashova ASR 2021

Gamma-ray spectra of Westerlund 2





AB Kalyashova ASR 2021

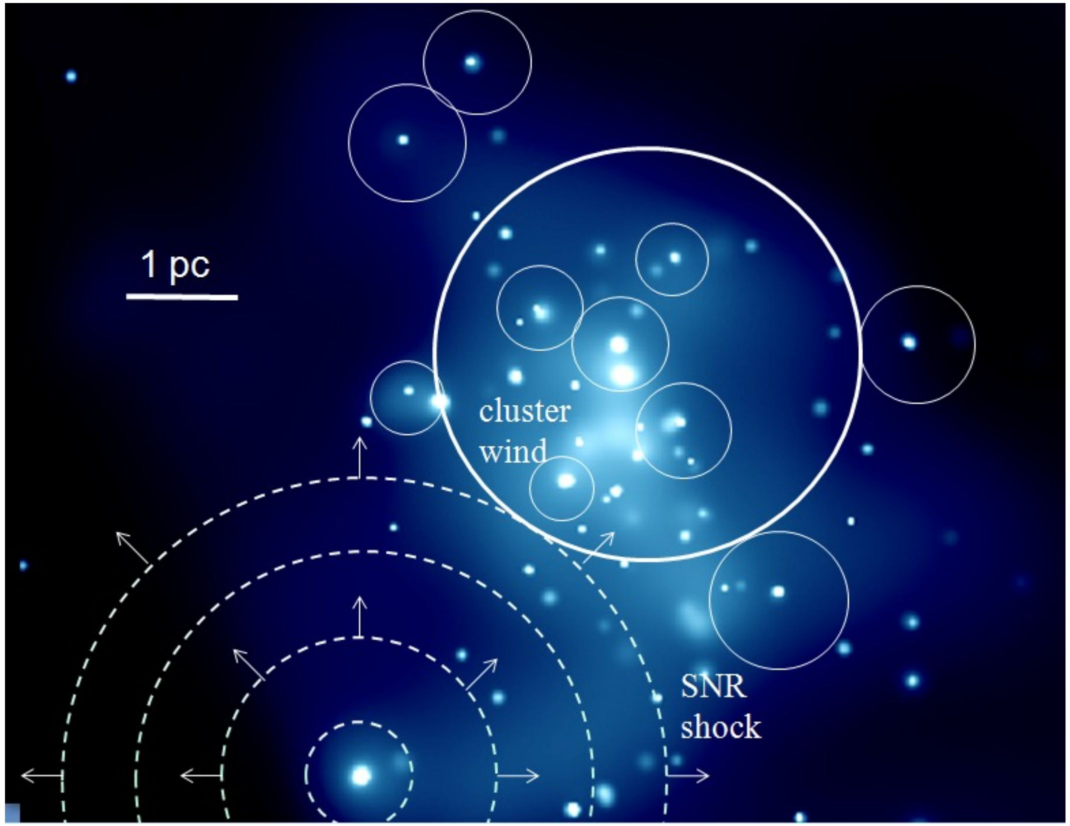
PeV proton acceleration by SNe in young compact stellar clusters & starbursts

A Galactic Super Star Cluster

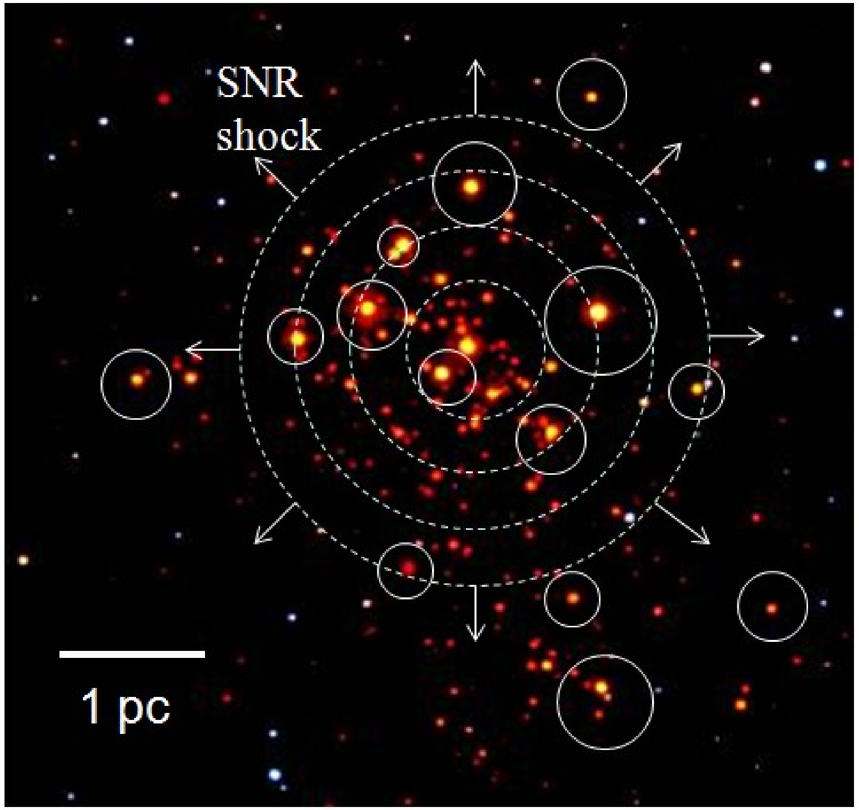
2MASS Atlas Image from M.Muno

- Distance: 2.5-3.5 kpc
- 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

Westerlund 1

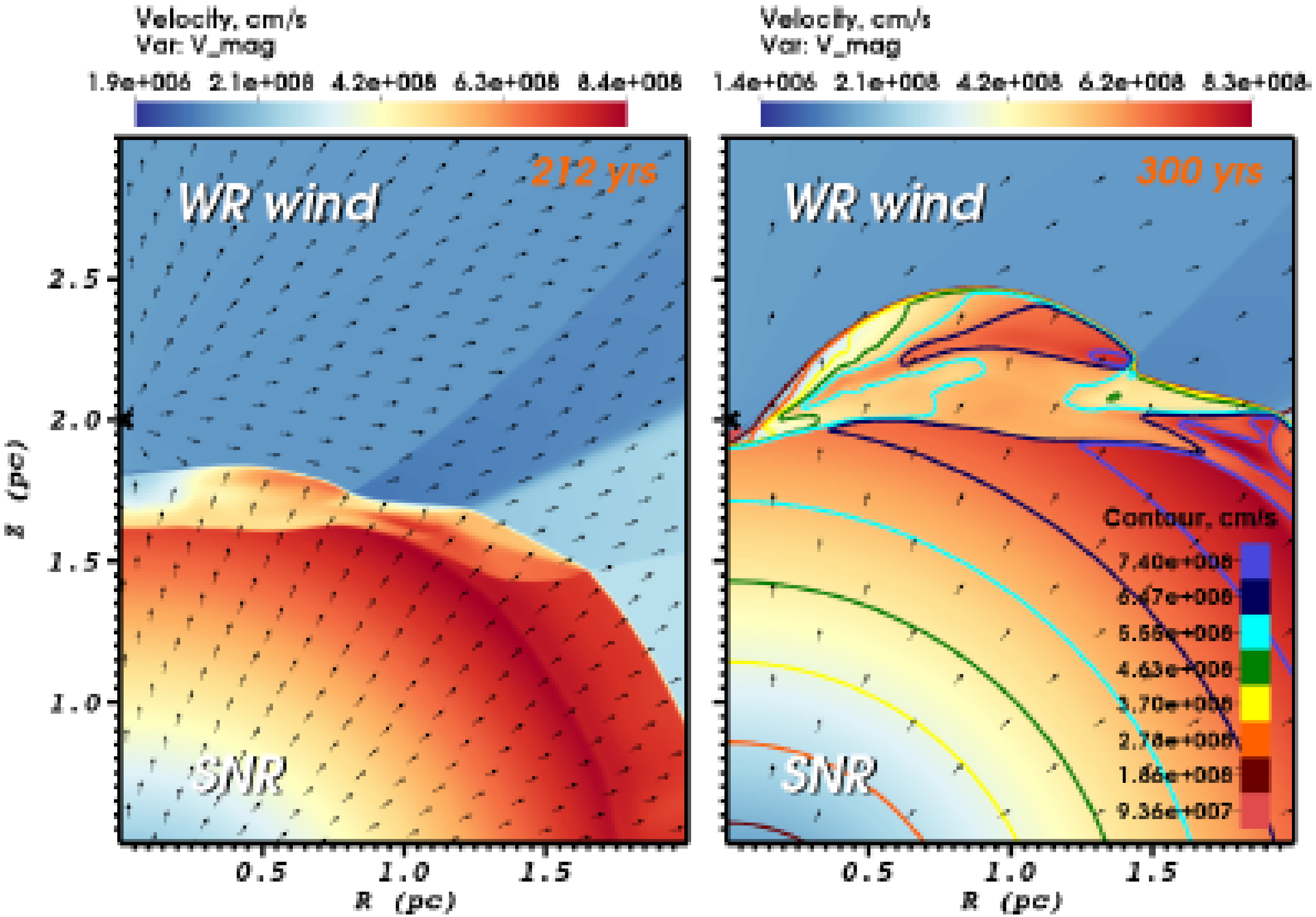


Muno+ 05



Clark+ 05

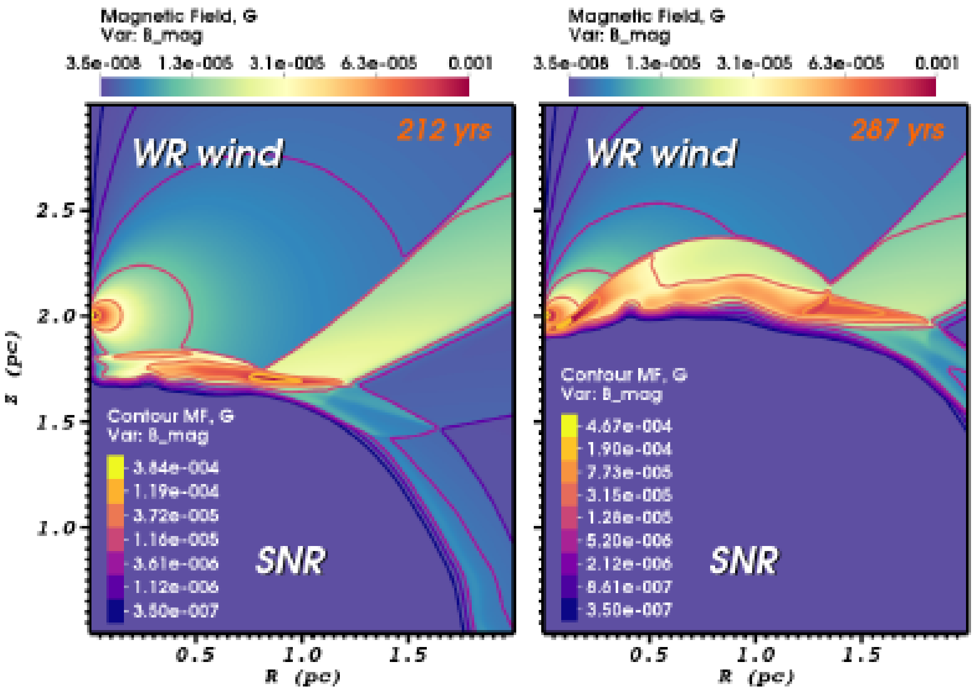
Supernova – Stellar Wind Interaction MHD model



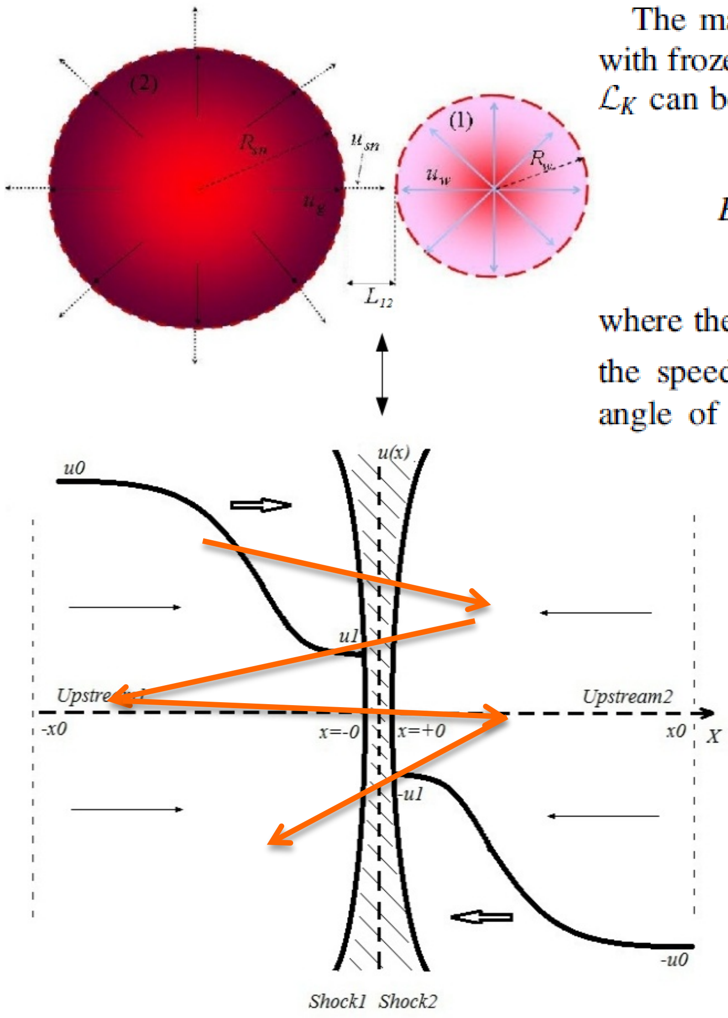
Badmaev AB 2019

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

Fermi I: SNR - cluster wind accelerator



Badmaev AB 2019



The maximum energies of protons accelerated by outflows with frozen-in magnetic fields of a kinetic/magnetic luminosity $\mathcal{L}_K$ can be estimated from the equation:

$$E_{\max} \approx \frac{f(\beta_{\rm f})}{\Gamma_{\rm f}\Omega}\left(\frac{\mathcal{L}_K}{5\times10^{34}\ \mathrm{erg\ s^{-1}}}\right)^{1/2}\ \mathrm{PeV}, \qquad (1)$$

where the dimensionless velocity of the flow is $\beta_{\rm f} = u_f/c$, c is the speed of light, $\Gamma_{\rm f} = 1/\sqrt{1-\beta_{\rm f}^2}$, and Ω is the opening angle of the outflow (see, e.g., Lemoine & Waxman 2009;

$\mathrm{Lk} > 10^{38}\ \mathrm{erg\ s}^{-1}$

$\beta f \sim 0.01$

AB+ MNRAS V. 429, 2755, 2013

The high efficiency of Fermi I
CR acceleration in colliding flows may
suggest a non-linear feedback effects…

Toy models can be considered

SNR-stellar wind accelerator
Non-linear kinetic model

Transport equation for CR distribution function

$$u(x)\frac{\partial f(x,p)}{\partial x} - \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial}{\partial x}f(x,p)\right] = \\ = \frac{p}{3}\,\frac{du(x)}{dx}\,\frac{\partial f(x,p)}{\partial p} + Q(x,p)\delta(x). \qquad (1)$$

The momentum conservation equation, normalized to $\rho_0 u_0^2$ reads

$$U(x) + P_c(x) + P_w(x) + P_g(x) = 1 + \frac{1}{\gamma M_0^2}\,,$$

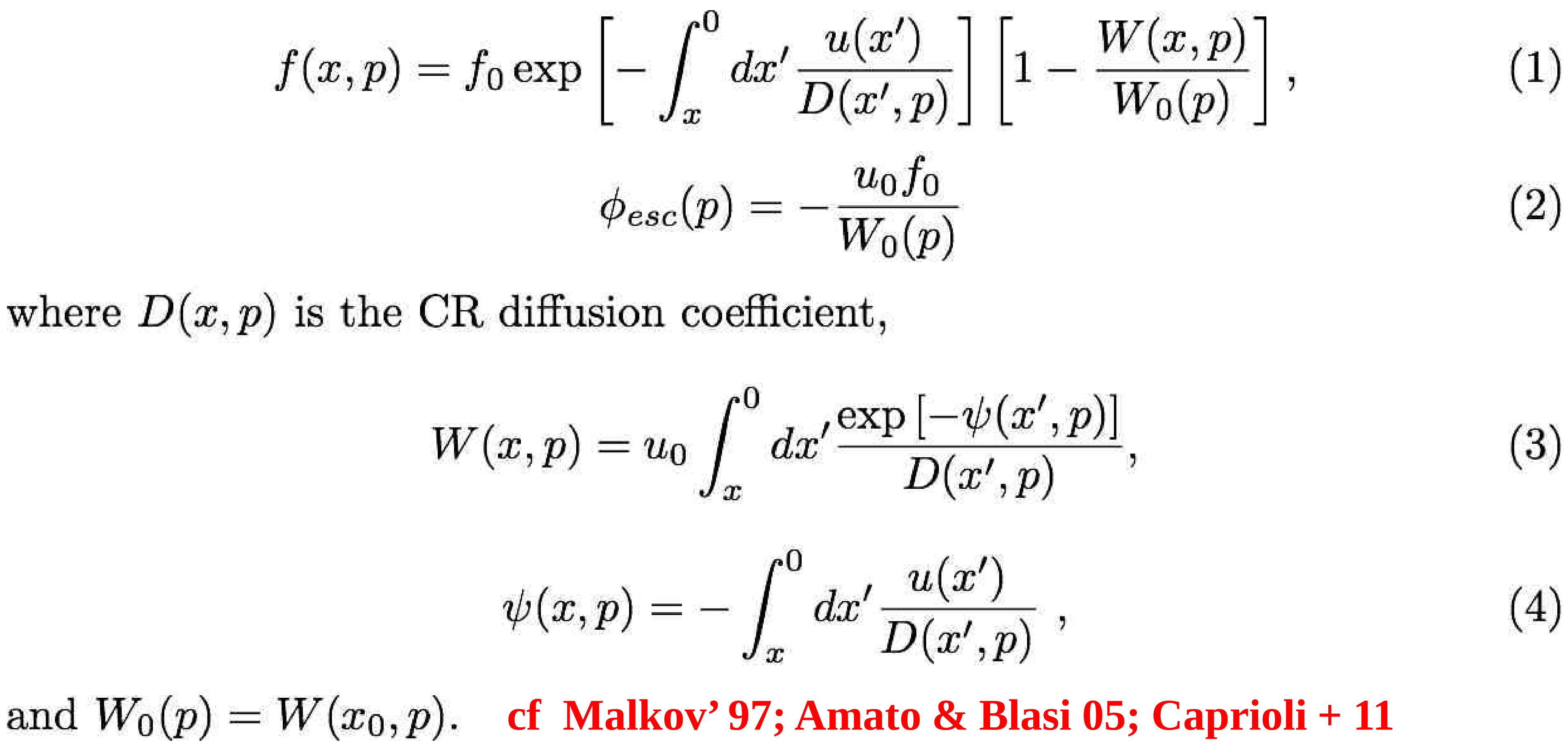
[redacted]

where M_0 is the Mach number of the unperturbed flow. The normalized cosmic ray pressure

$$P_c(x) = \frac{4\pi}{3\rho_0 u_0^2}\int_{p_{inj}}^{\infty} dp\; p^3\; v(p)\; f(x,p)\,, \qquad (2)$$

MNRAS V. 429, 2755, 2013

SNR-stellar wind accelerator



$$f(x,p) = f_0 \exp\left[-\int_x^0 dx' \frac{u(x')}{D(x',p)}\right]\left[1 - \frac{W(x,p)}{W_0(p)}\right], \quad (1)$$

$$\phi_{esc}(p) = -\frac{u_0 f_0}{W_0(p)} \quad (2)$$

where $D(x,p)$ is the CR diffusion coefficient,

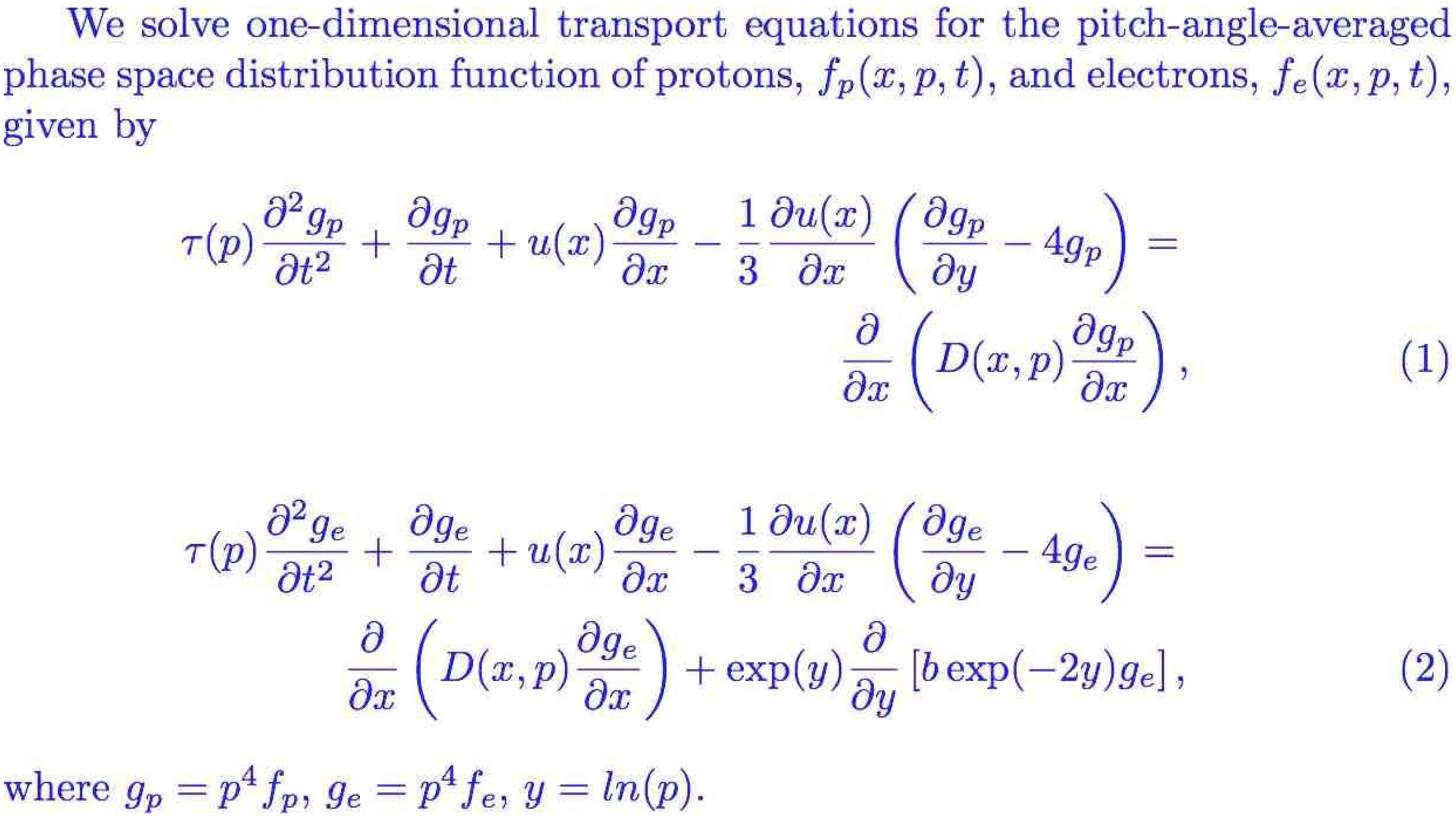
$$W(x,p) = u_0 \int_x^0 dx' \frac{\exp\left[-\psi(x',p)\right]}{D(x',p)}, \quad (3)$$

$$\psi(x,p) = -\int_x^0 dx' \frac{u(x')}{D(x',p)}\ , \quad (4)$$

and $W_0(p) = W(x_0,p)$. **cf Malkov' 97; Amato & Blasi 05; Caprioli + 11**

AB+ MNRAS V. 429, 2755, 2013

SNR-stellar wind accelerator



We solve one-dimensional transport equations for the pitch-angle-averaged phase space distribution function of protons, $f_p(x,p,t)$, and electrons, $f_e(x,p,t)$, given by

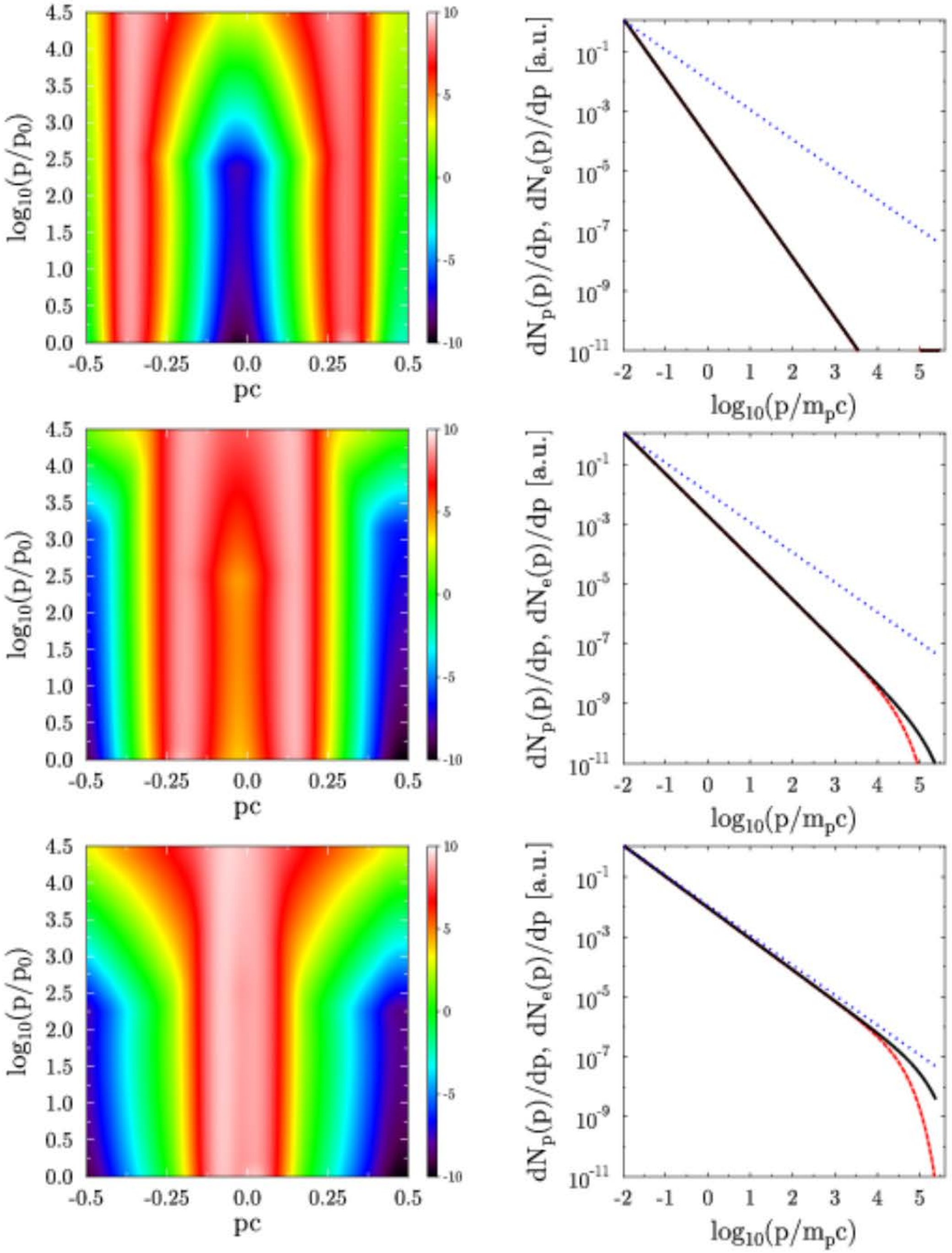
$$\tau(p)\frac{\partial^2 g_p}{\partial t^2} + \frac{\partial g_p}{\partial t} + u(x)\frac{\partial g_p}{\partial x} - \frac{1}{3}\frac{\partial u(x)}{\partial x}\left(\frac{\partial g_p}{\partial y} - 4g_p\right) = \frac{\partial}{\partial x}\left(D(x,p)\frac{\partial g_p}{\partial x}\right), \qquad (1)$$

$$\tau(p)\frac{\partial^2 g_e}{\partial t^2} + \frac{\partial g_e}{\partial t} + u(x)\frac{\partial g_e}{\partial x} - \frac{1}{3}\frac{\partial u(x)}{\partial x}\left(\frac{\partial g_e}{\partial y} - 4g_e\right) = \frac{\partial}{\partial x}\left(D(x,p)\frac{\partial g_e}{\partial x}\right) + \exp(y)\frac{\partial}{\partial y}\left[b\exp(-2y)g_e\right], \qquad (2)$$

where $g_p = p^4 f_p$, $g_e = p^4 f_e$, $y = ln(p)$.

MNRAS v. 429, 2755, 2013

SNR-stellar wind accelerator

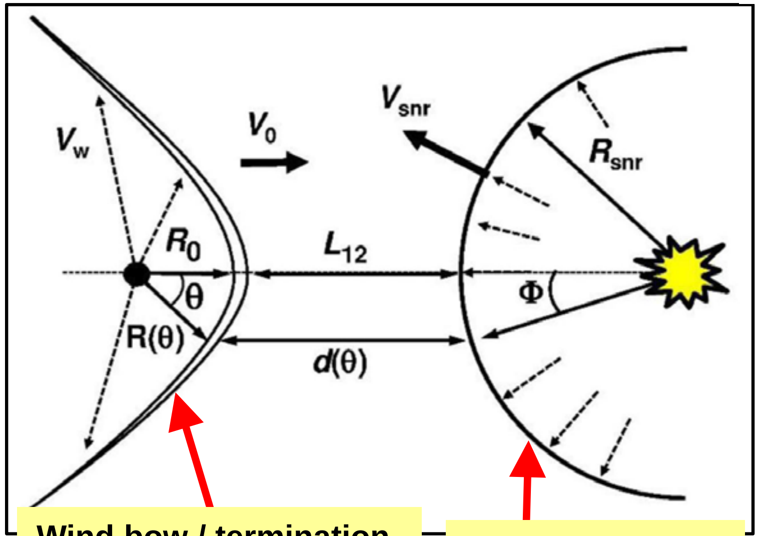


A toy 1D plane model to estimate the nonlinear feedback of accelerated CR pressure on the MHD flow…
However an accurate CR transport model
Is certainly needed

Another question is to study the effect of flow geometry in
Monte Carlo simulations

AB+ MNRAS v. 429, 2755, 2013

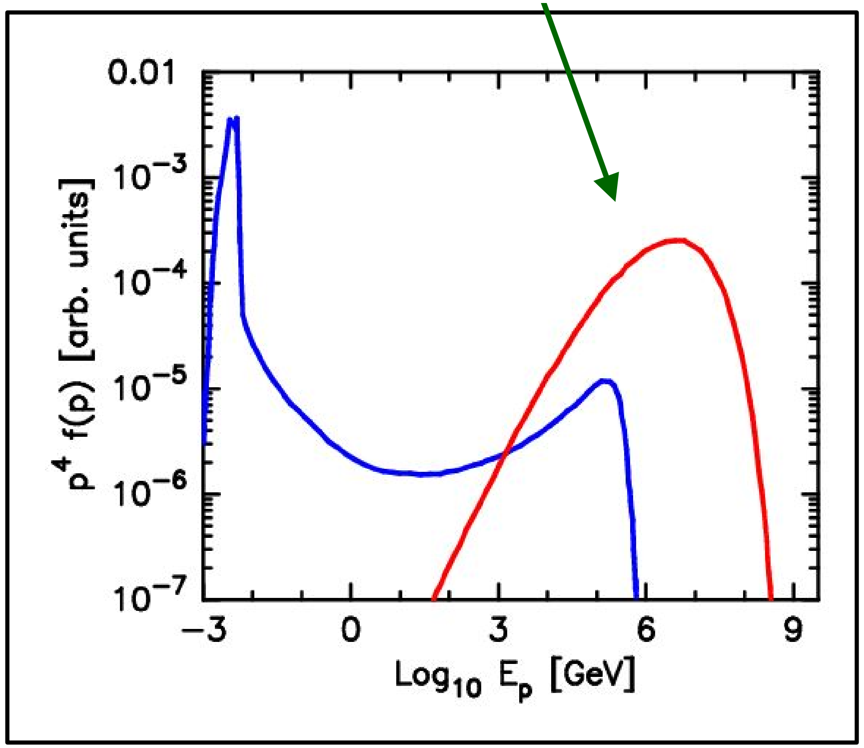
Enhanced acceleration as CRs bounce between shock and wind



Wind bow / termination shock from young star

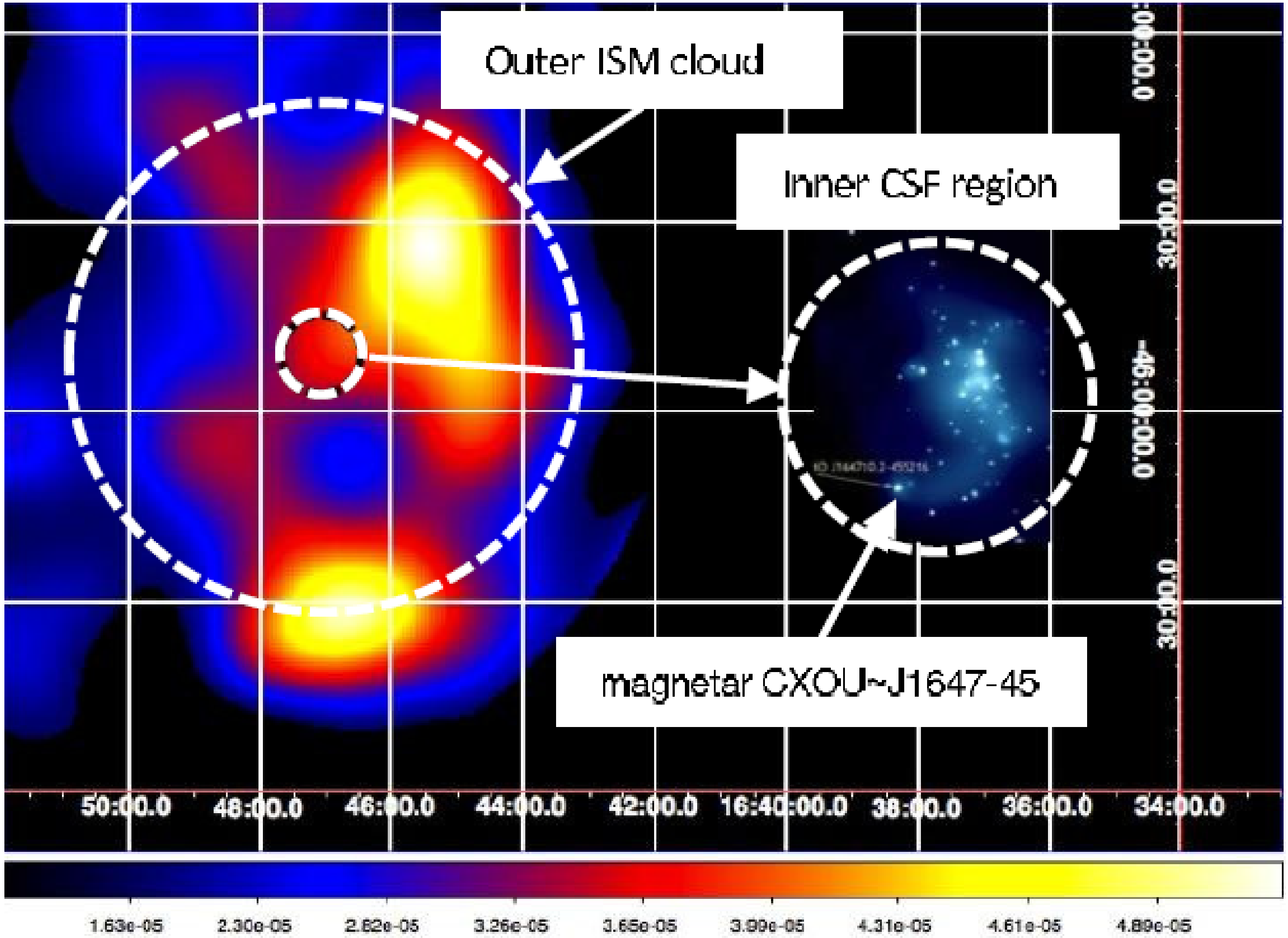
SNR blast wave

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



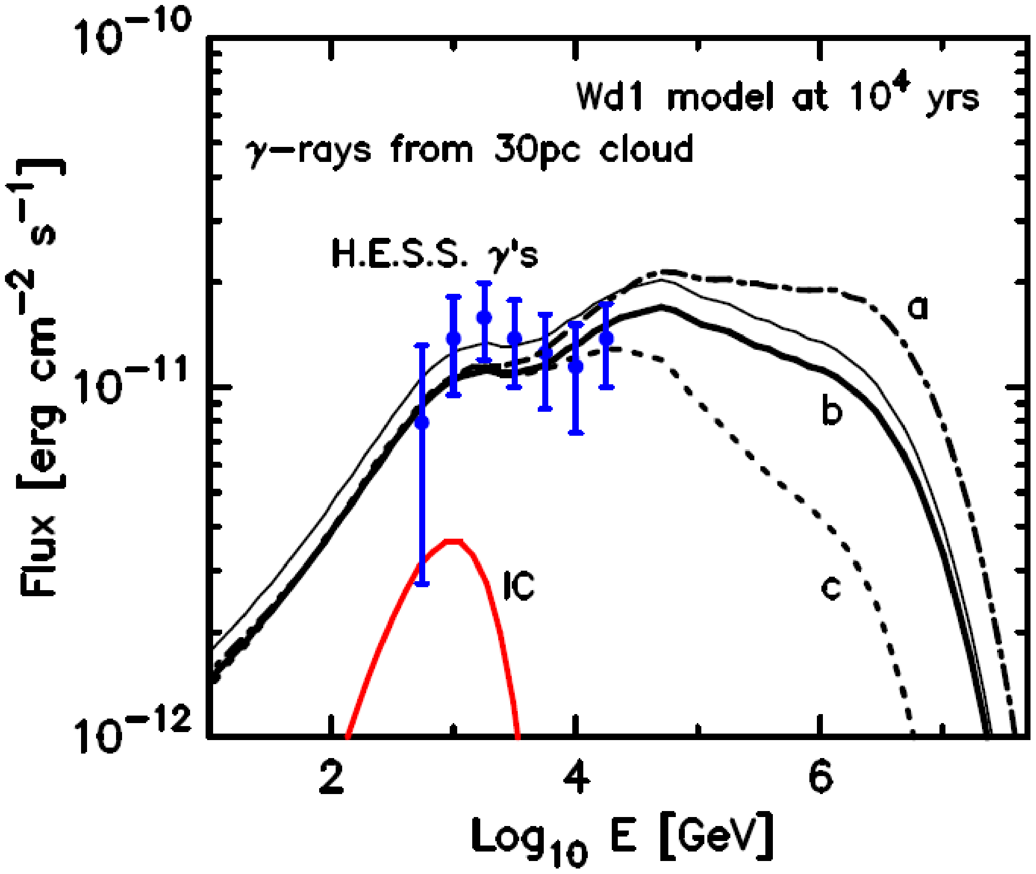
AB, Ellison et al, v 453, p.113, 2015

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



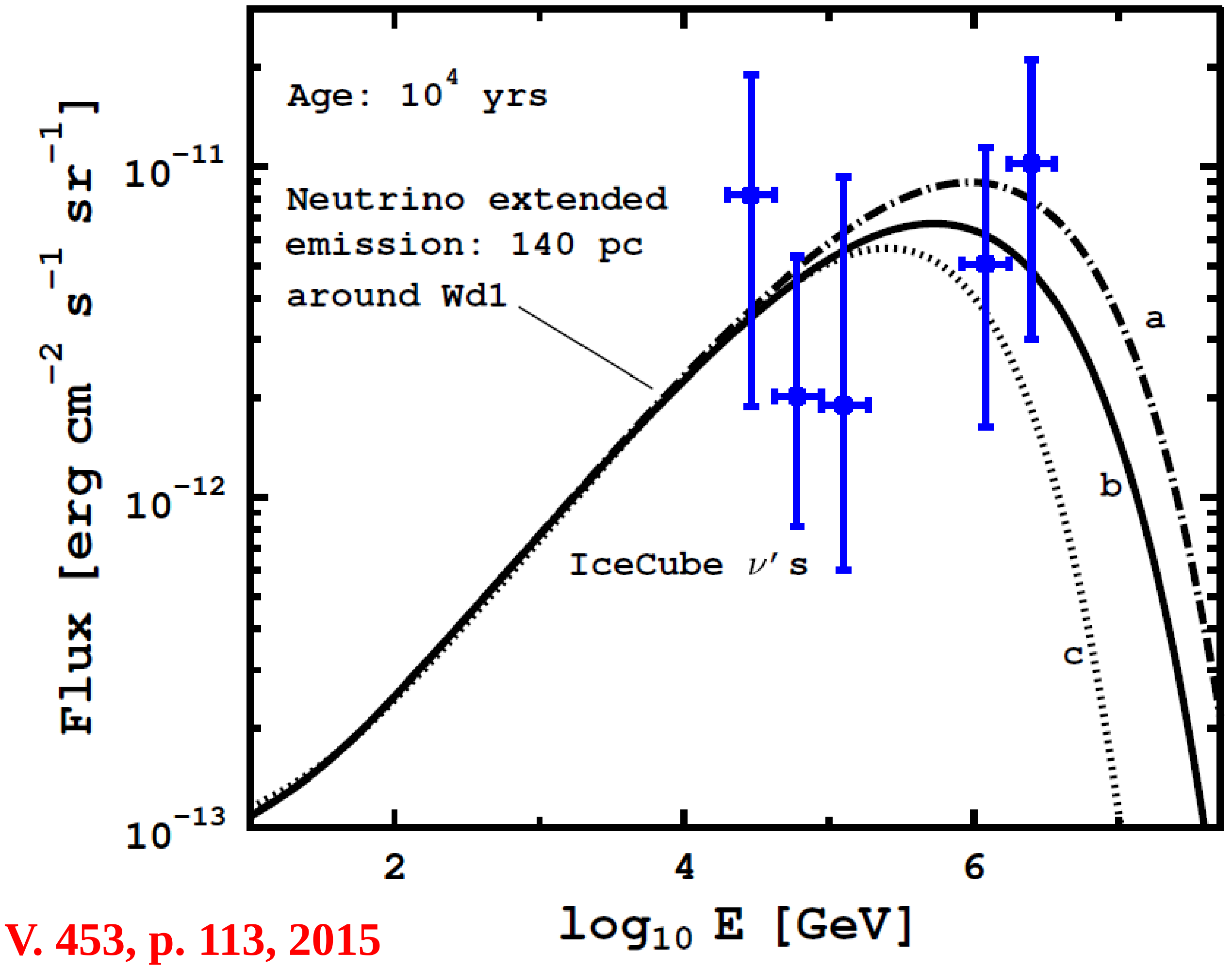
MNRAS v. 453, p. 113, 2015

Gamma-rays from a Pevatron



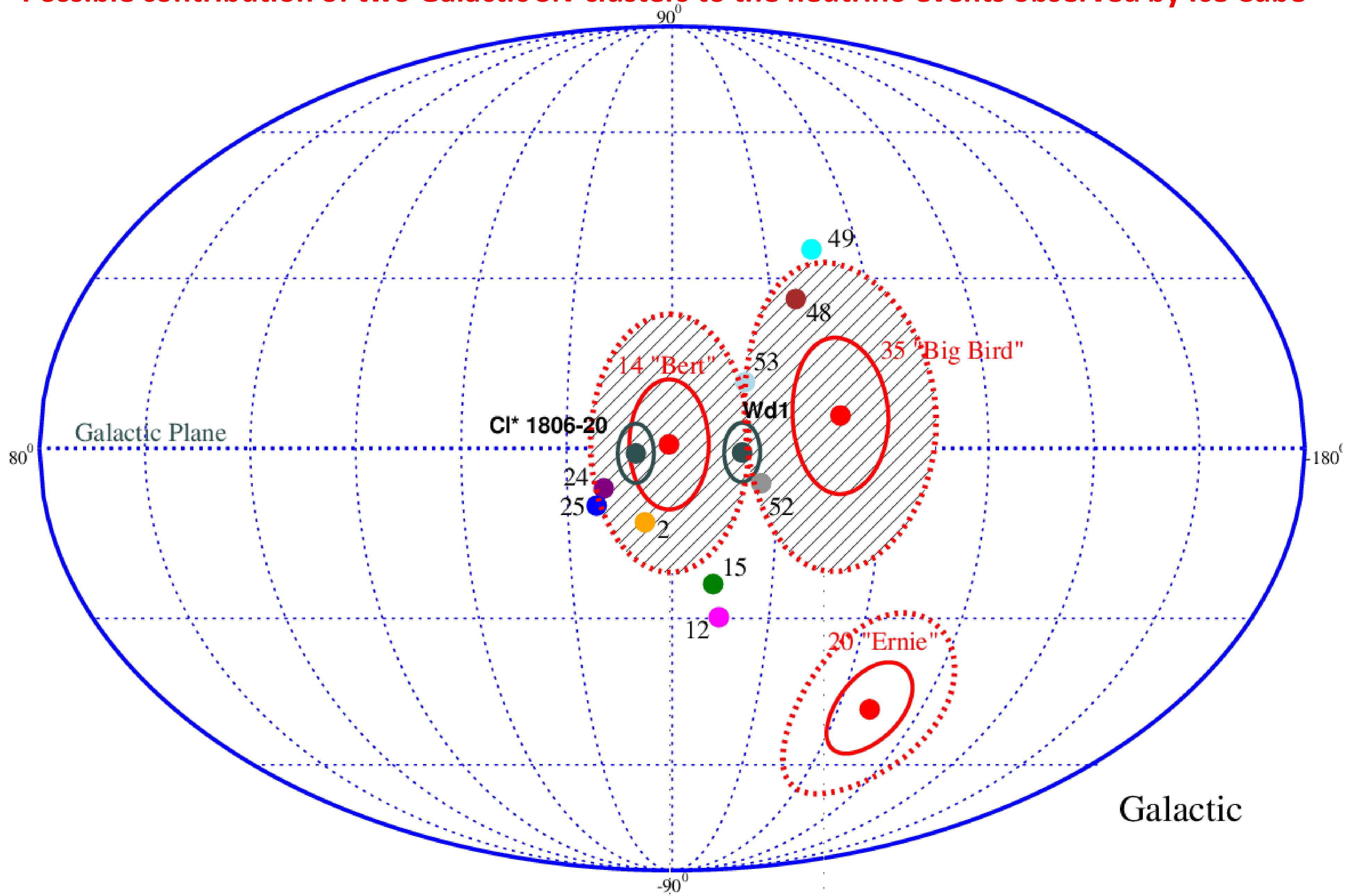
MNRAS V. 453, p. 113, 2015

Neutrinos from a 140 pc vicinity of a Westerlund I like Pevatron



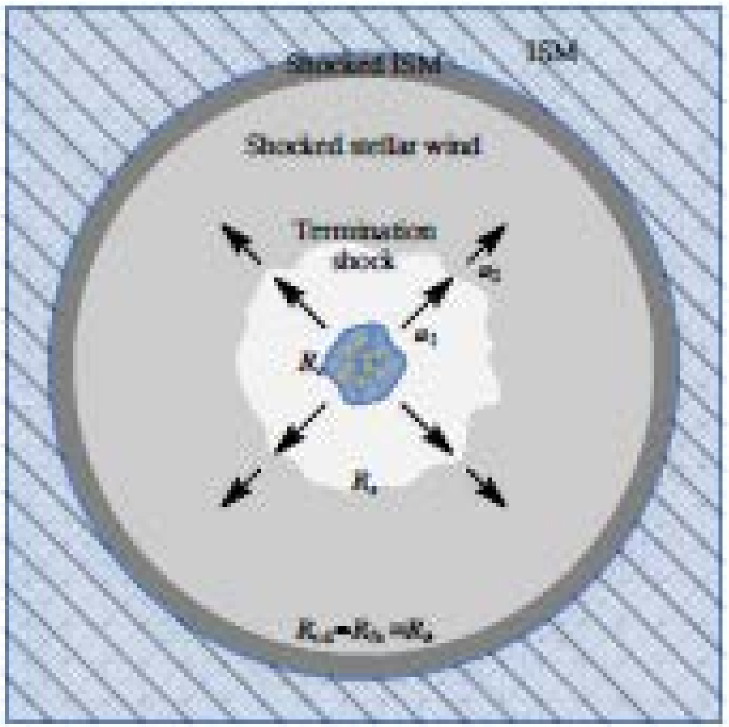
MNRAS V. 453, p. 113, 2015

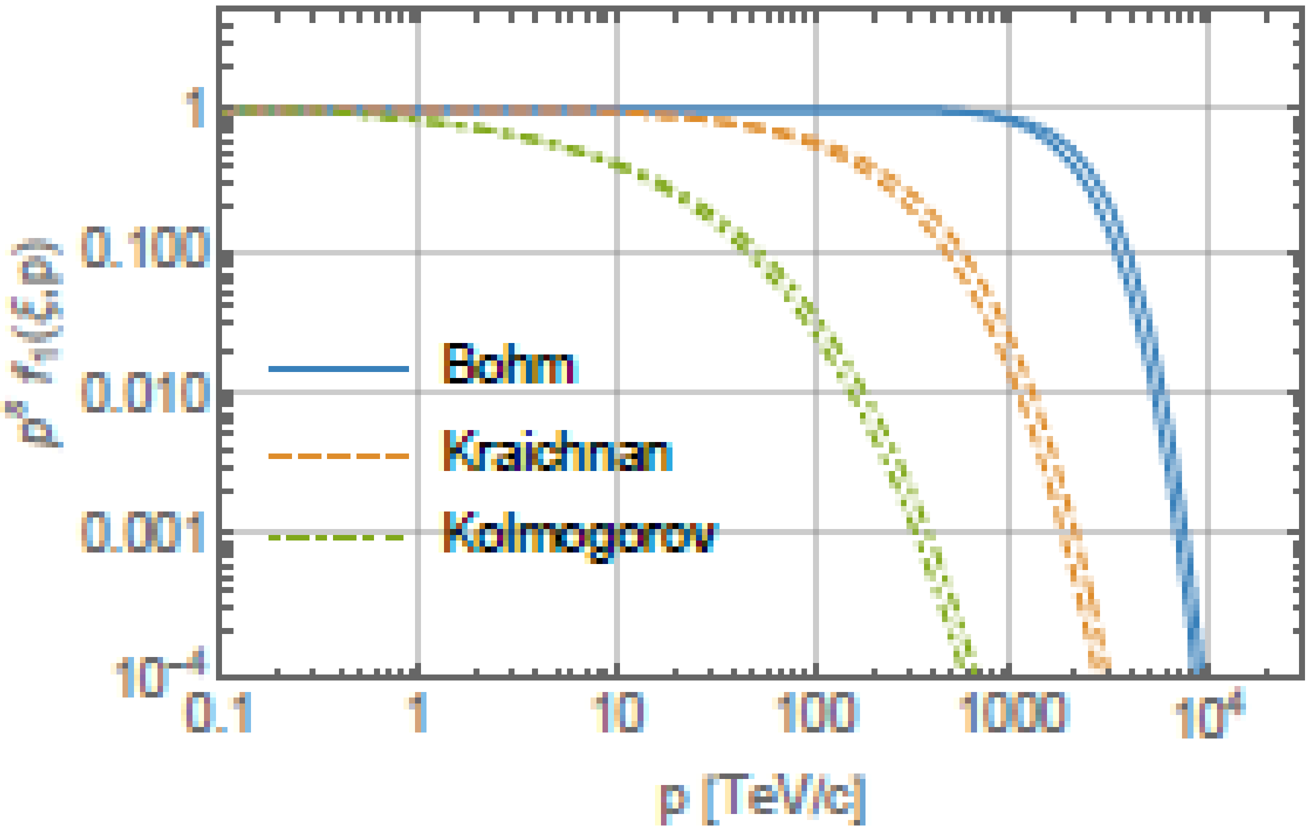
Possible contribution of two Galactic SN-clusters to the neutrino events observed by Ice Cube



AB+ 2015, 2017

Pevatrons from massive star clusters



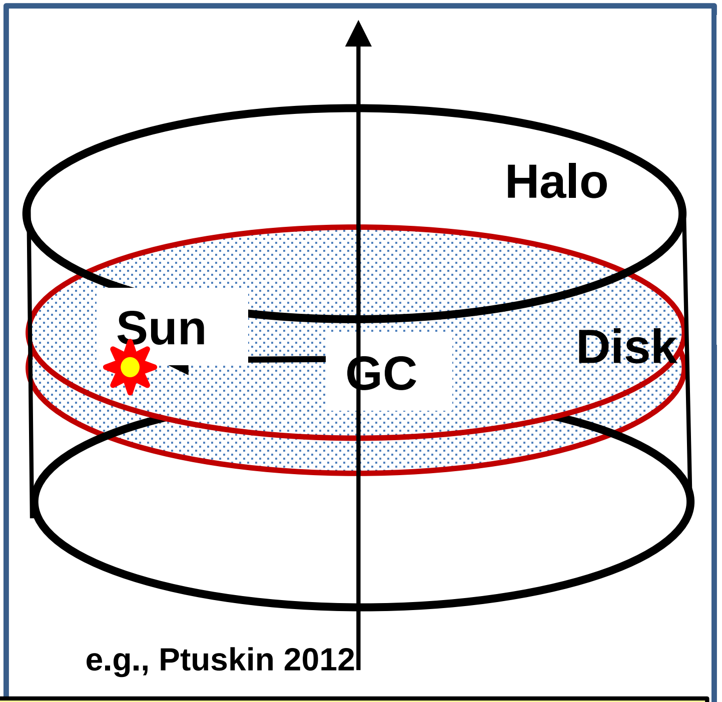


Morlino+ MNRAS v. 504, p.6096, 2021

see for review Amato & Casanova J. Plasma Phys.v 87, id.845870101, 2021

Cristofari Universe, 7, 324, 2021, AB+ Space Sci Rev v.216 (3), 42, 2020

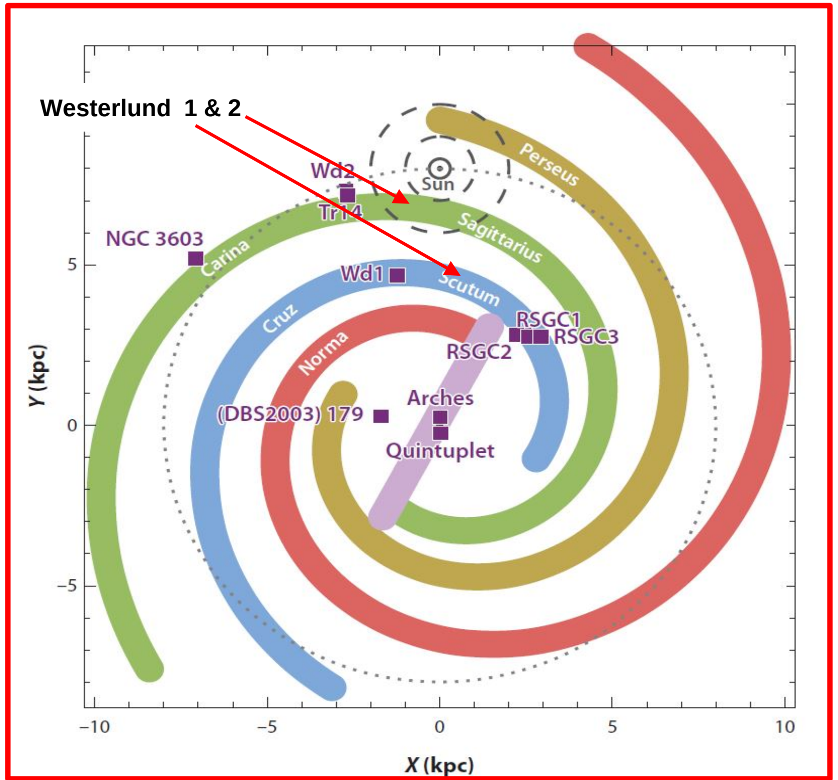
VHE CR propagation from the compact stellar clusters



e.g., Ptuskin 2012

- ➔ 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

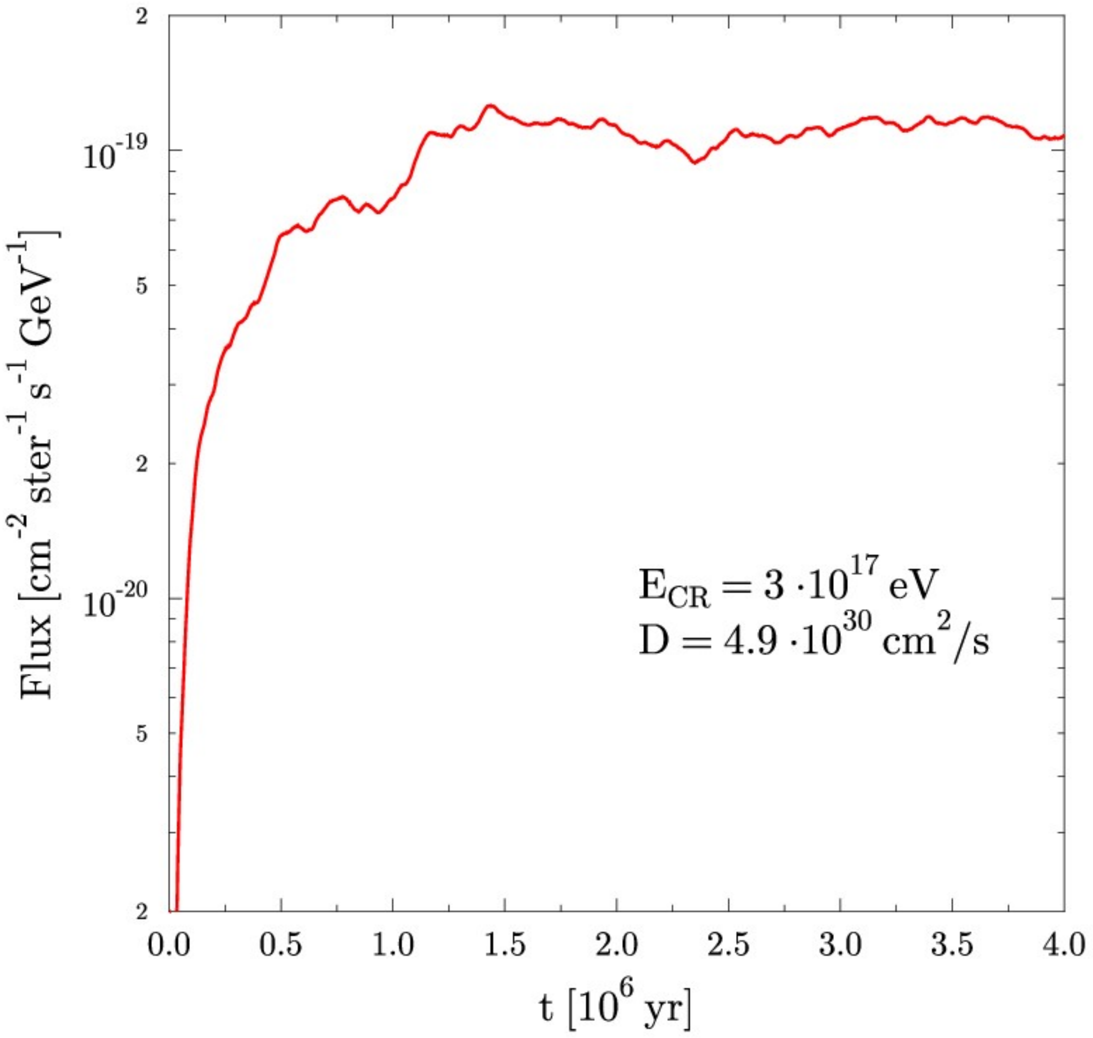


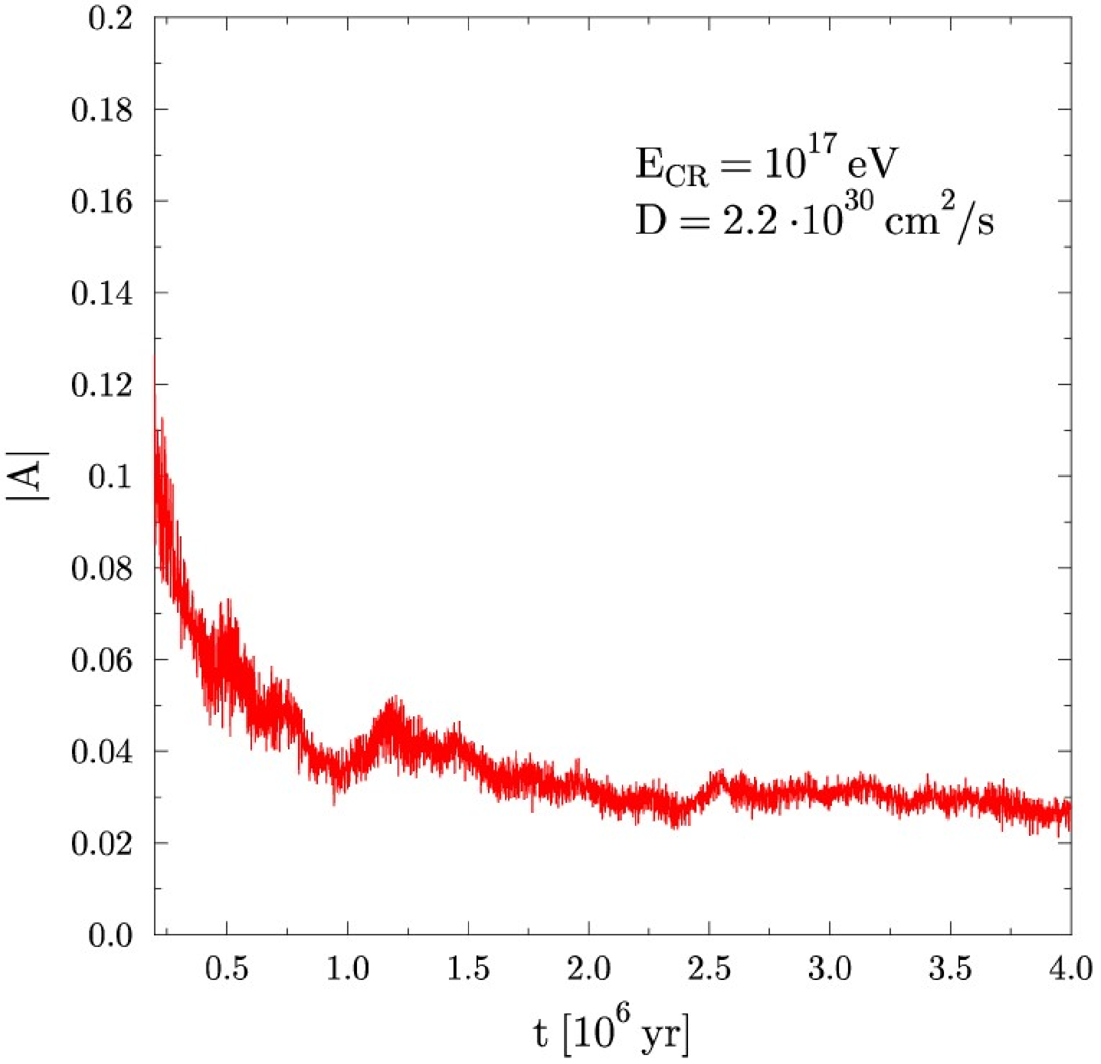
Portegies Zwart et al. 2010

Here we look at simple case: Sources concentrated in the inner Galaxy
➔Good estimate of average flux and average anisotropy at Earth

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

CR propagation from the compact stellar clusters



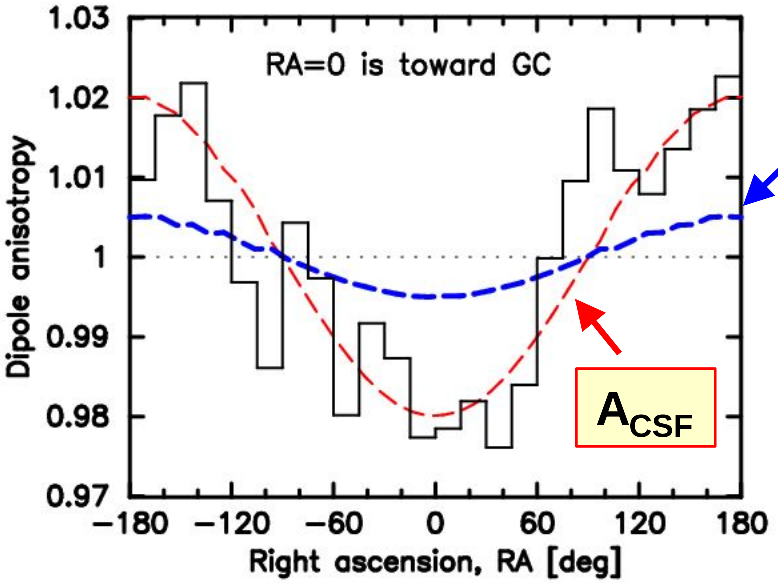


AB+ Advances in Space Research, v. 64,, p. 2439, 2019

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

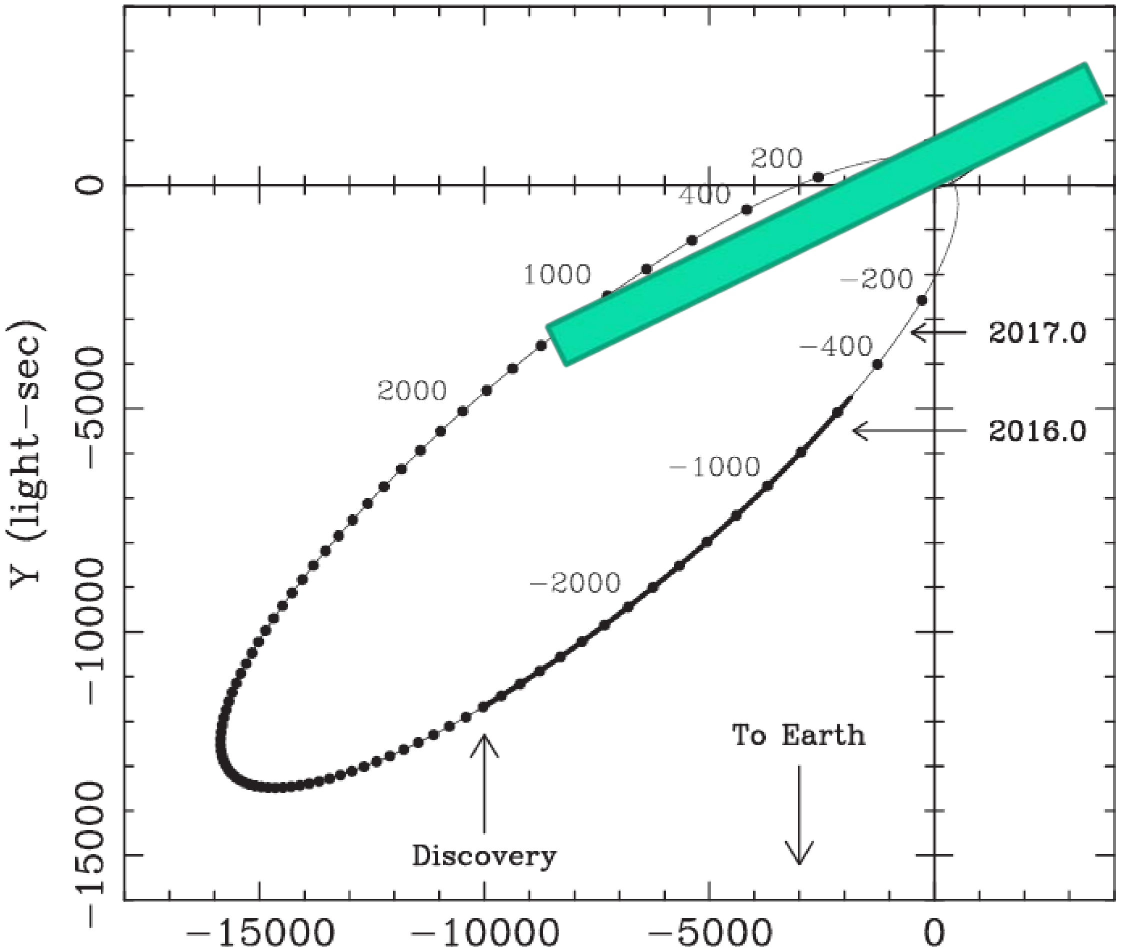
Find ~30% of all 10^{17} eV CRs can be from a galactic source without violating isotropy constraints

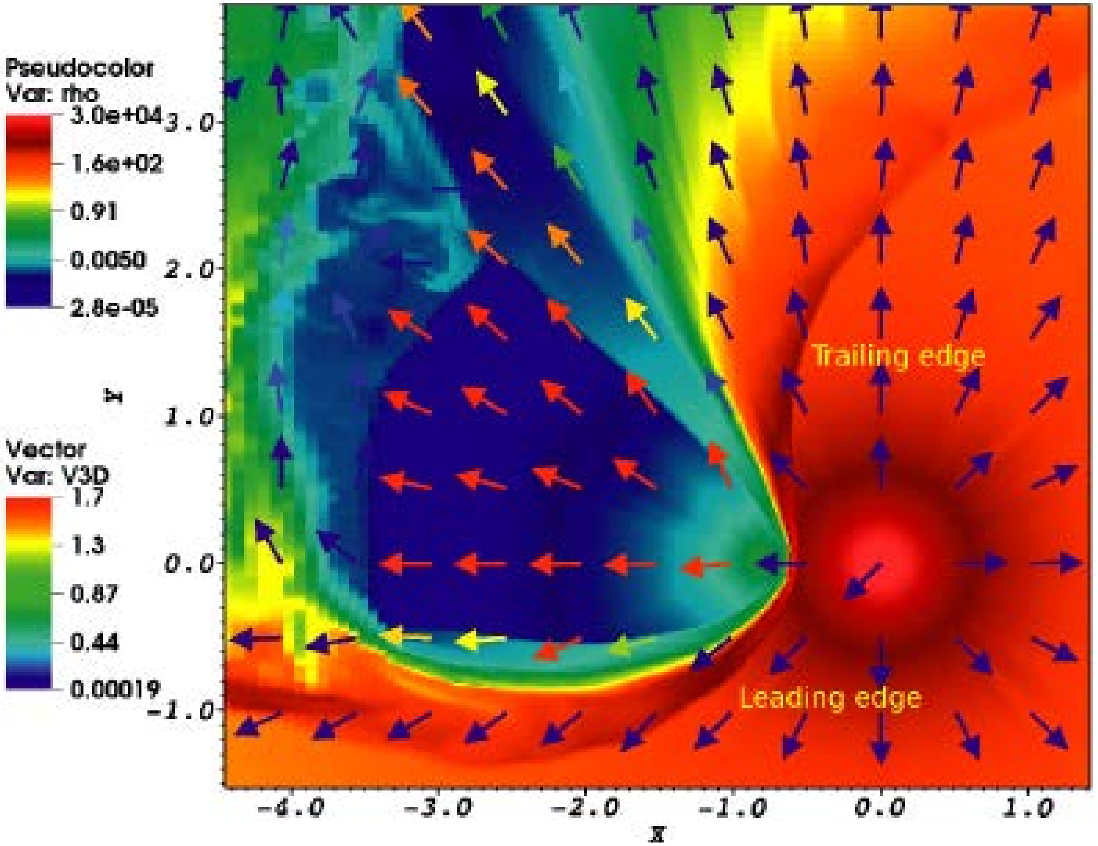
A gamma-ray flare of a few months duration in 2020 at energies above 300 TeV from Cygnus Cocoon direction reported by Carpet-2 (Dzhappuev + Ap.J Lett 916, L22, 2921). It was associated with a 150 TeV neutrino event detected by IceCube (IceCube Collaboration 2020). The gamma-ray flare luminosity at 1.5 kpcs ~ 2 10^{35} erg s^{-1}

PeV gamma ray emission should most likely come from a Galactic source.

PSR J2032+4127 is located at a distance of ∼1.4 kpc and orbits around a massive Be star MT91 213 (B0Vp) with a long period of ∼50 yr (Ho et al. 2017). Its spin-down power ~ 3 10^{35} erg s^{-1} (Camilo et al. 2009). Multi-wavelength observations of PSR J2032+4127 during the periastron passage in 2017 analyzed by Ng + (ApJ v.880, 147, 2019) and Chernyakova et al. (MNRAS v.495, 365, 2020).

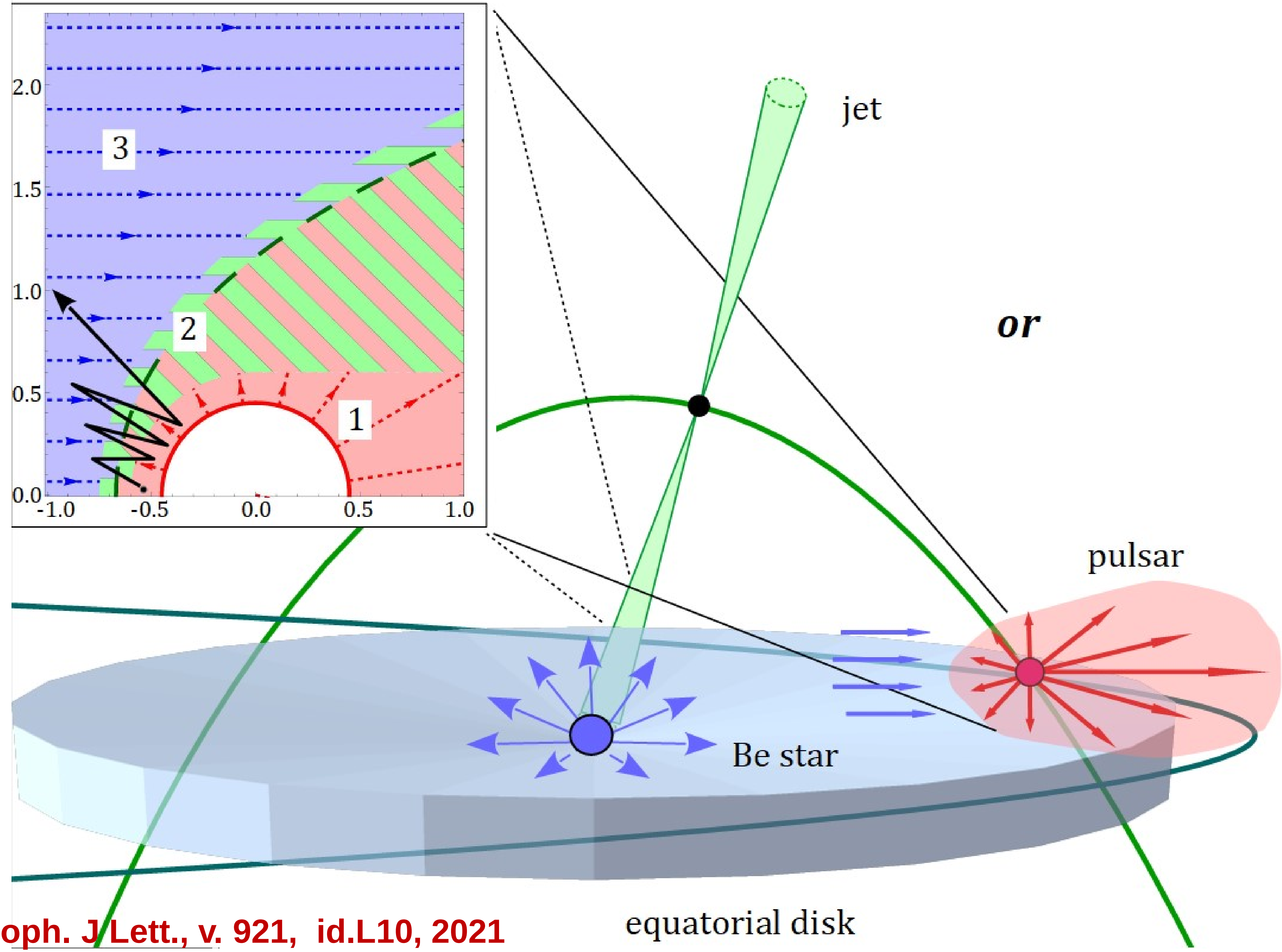
This suggests that if one attribute the flare to PSR J2032+4127 then most of the CWF acceleration source power should be converted into PeV-regime protons.





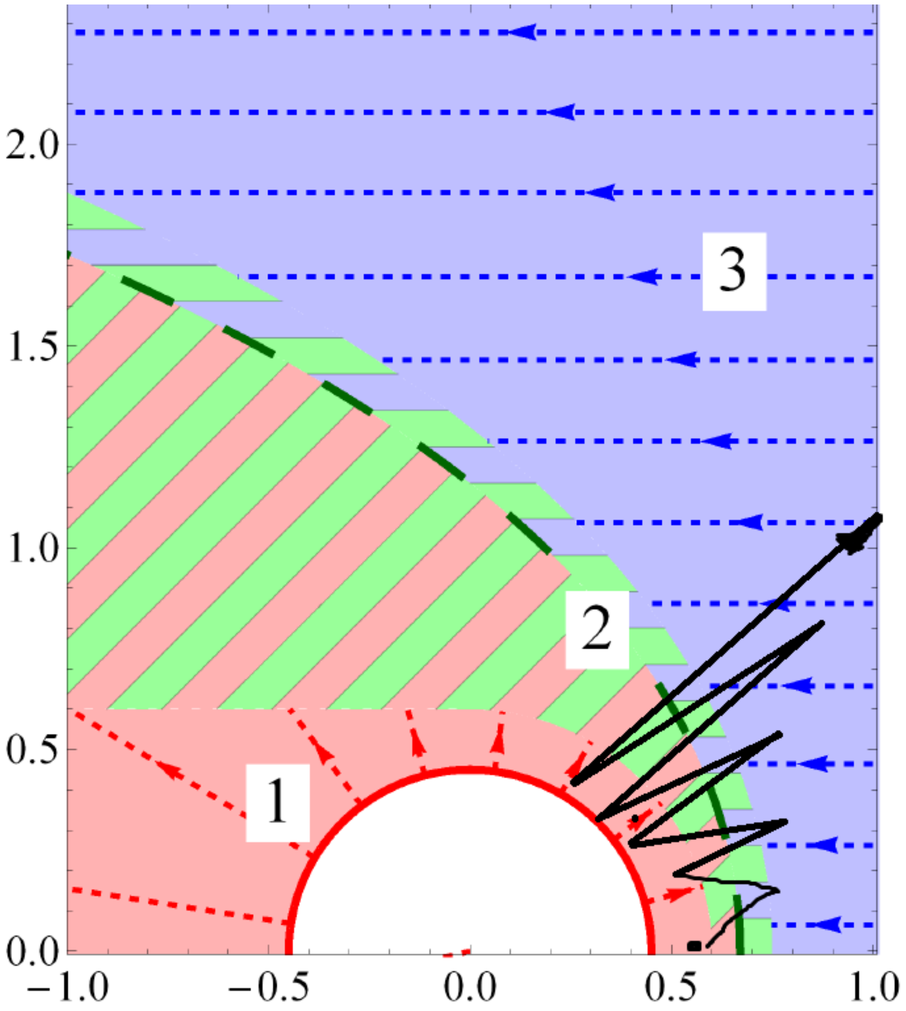
Bosch-Ramon Barkov Perucho A&A 577, A89 (2015)

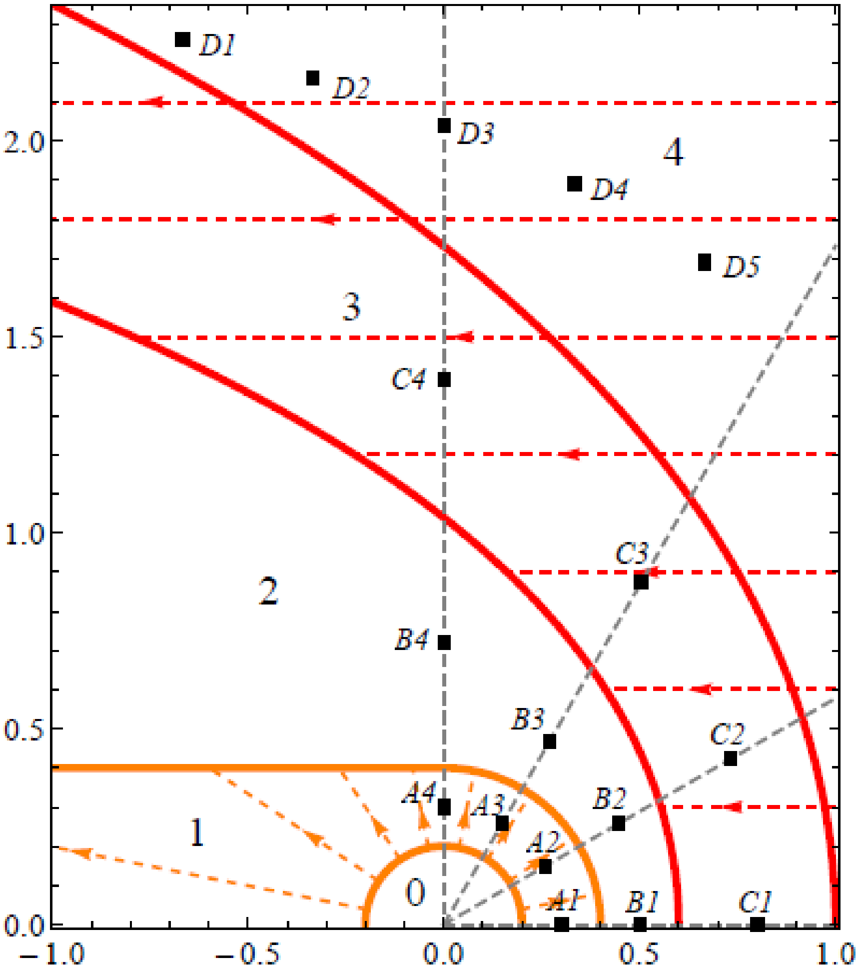
Ho + MNRAS 464, 1211, 2017



AB+ Astroph. J Lett., v. 921, id.L10, 2021

Bow shock PWN geometries for Monte Carlo simulations



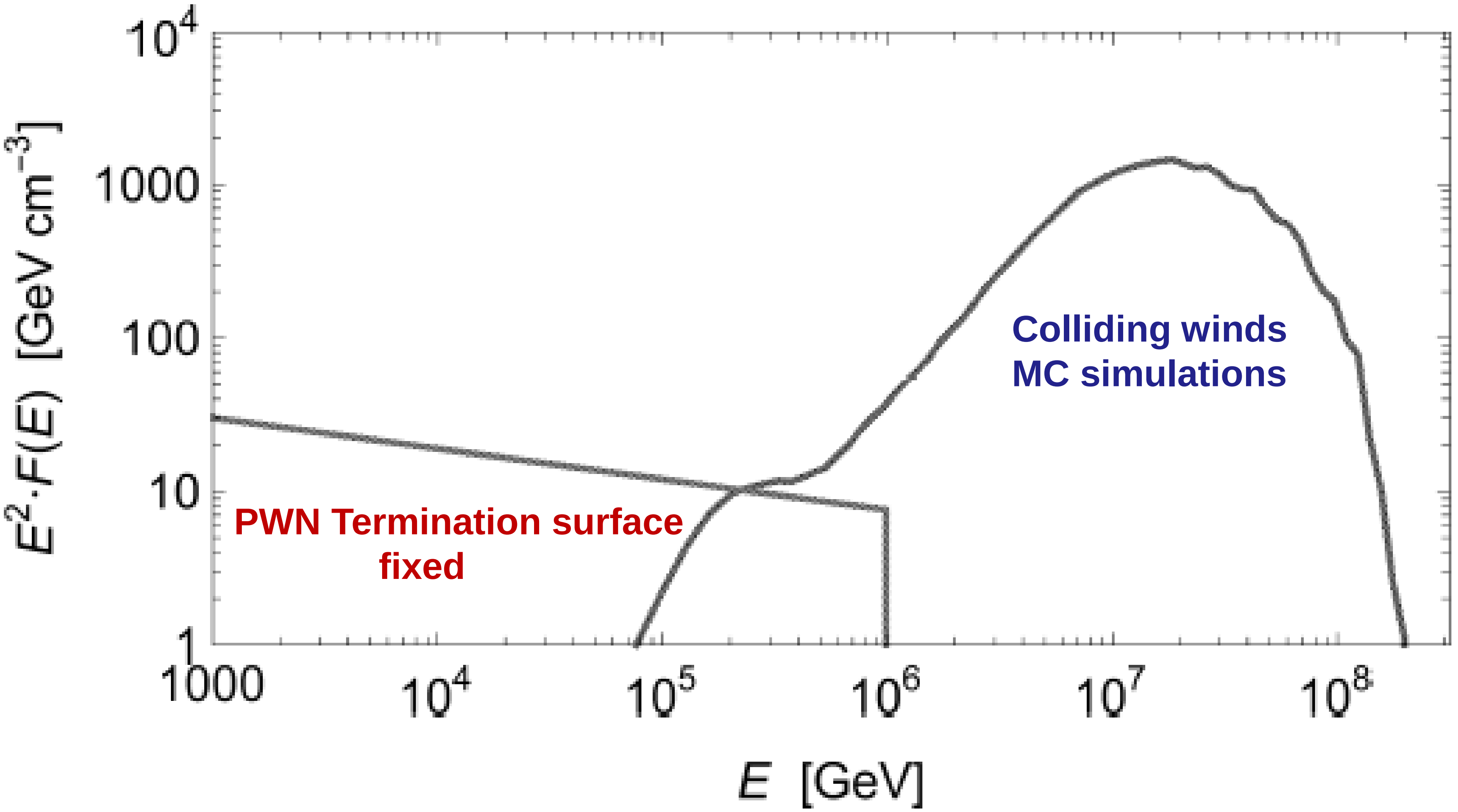


The numbers 1- 3 (for left panel) label the regions with different transport regimes: 1 is the cold PW, 2 is the shocked wind, 3 is the B-star wind.

Astroph. J Lett., v. 921, id.L10, 2021

AB+ Space Sci. Rev v.207 p.235, 2017

Proton spectra in the colliding MHD flows PSR 2032 – Be star winds



AB+ Astroph. J Lett., v. 921, id.L10, 2021

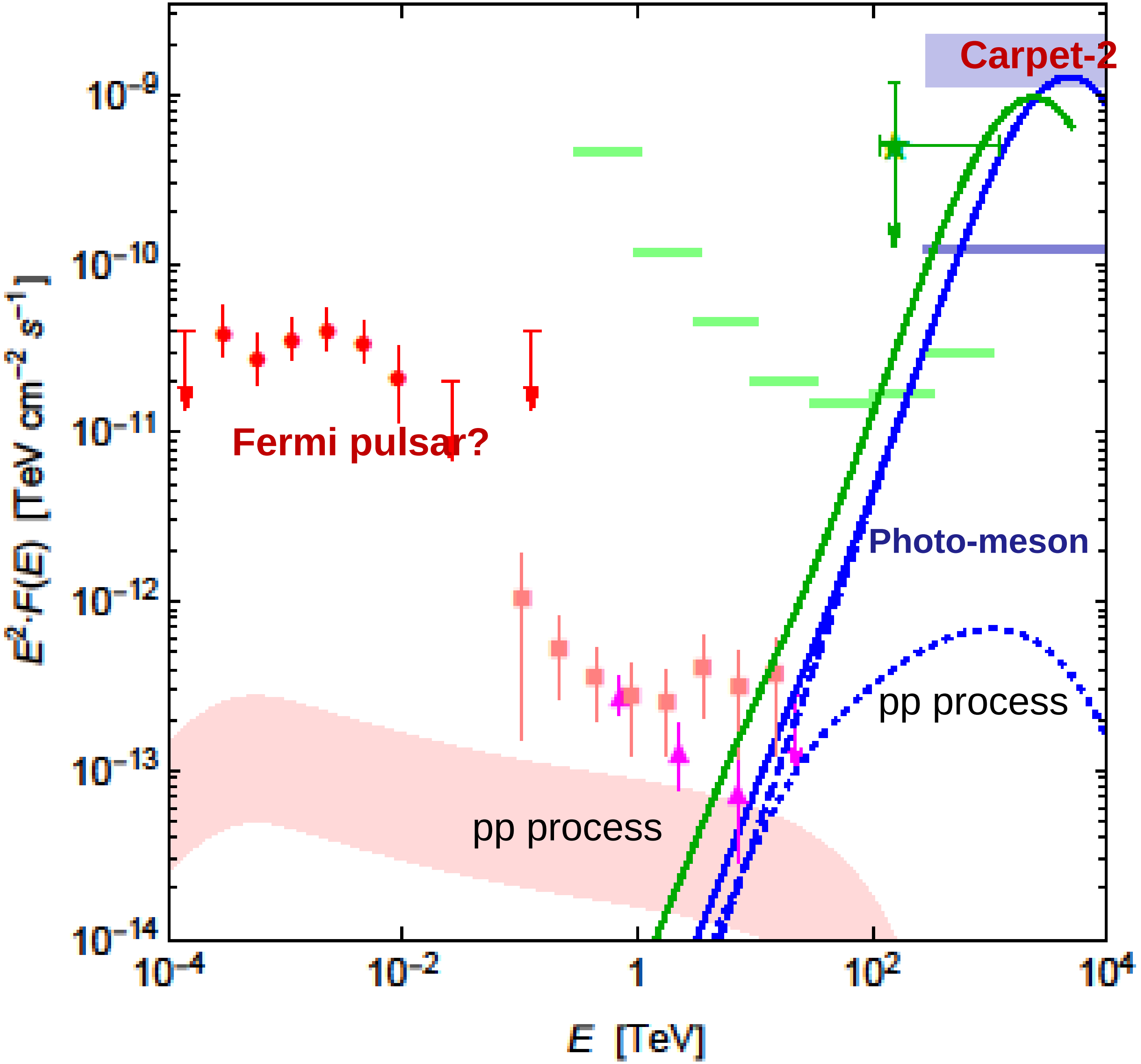
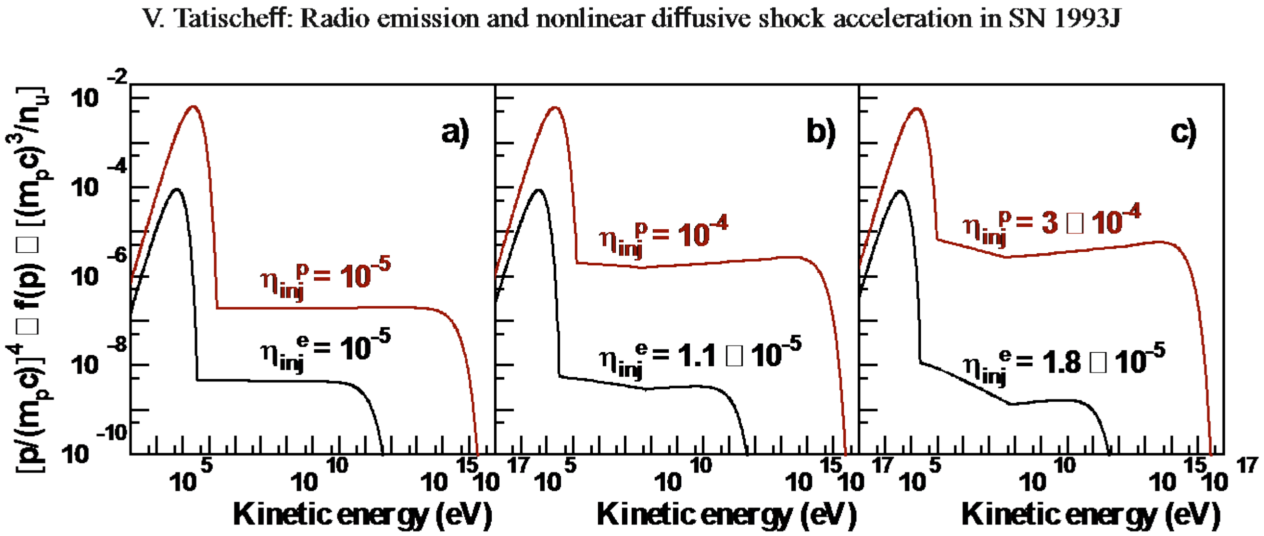


Photo-meson cross-sections are from Kelner Aharonian PhRvD, 78, 034013

AB+ Astroph. J Lett., v. 921, id.L10, 2021

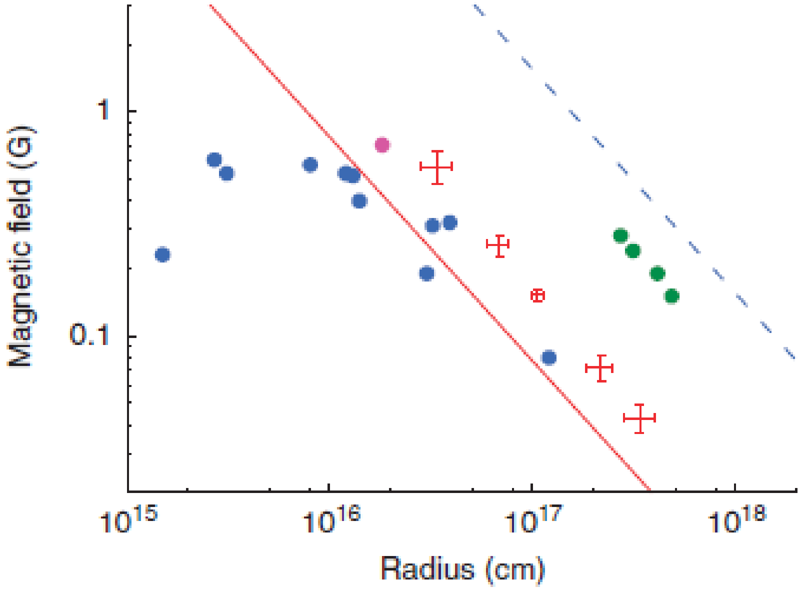
Other possible galactic pevatrons

CR proton acceleration by radio SNe and trans-relativistic SNRs



V.Tatischeff 2009

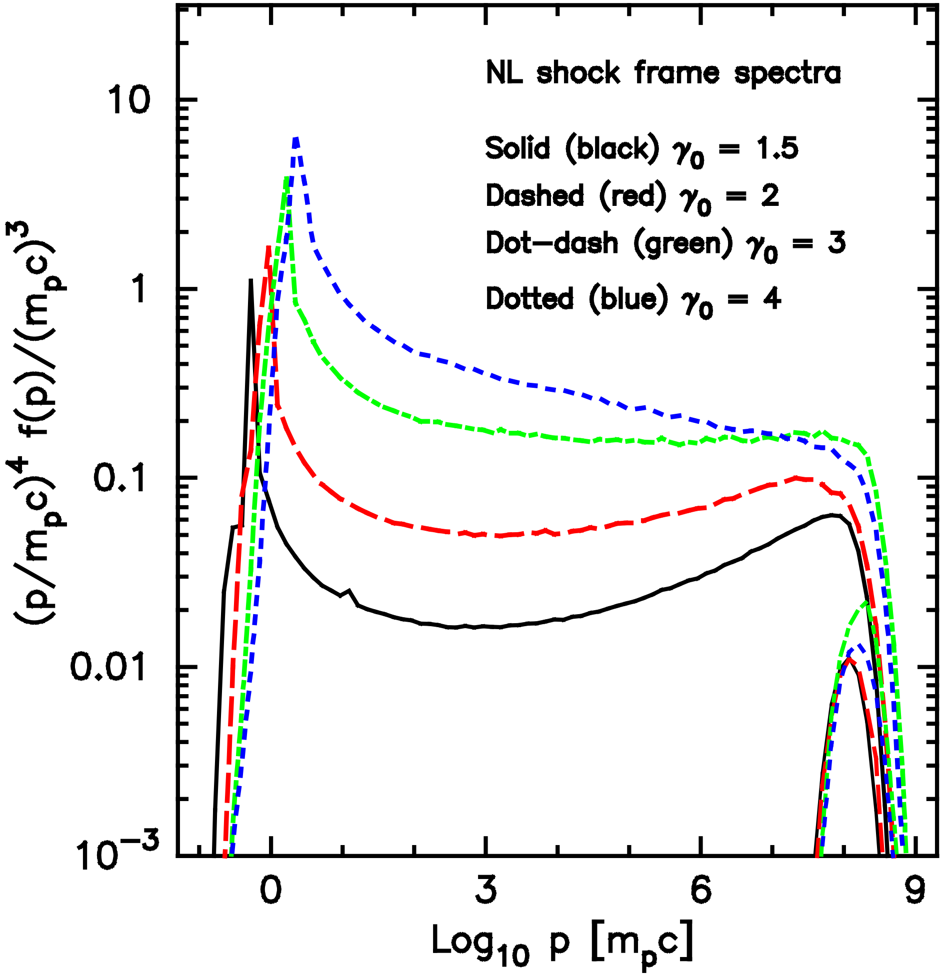
S.Chakraborti, A.Ray, A.Soderberg+ 2011

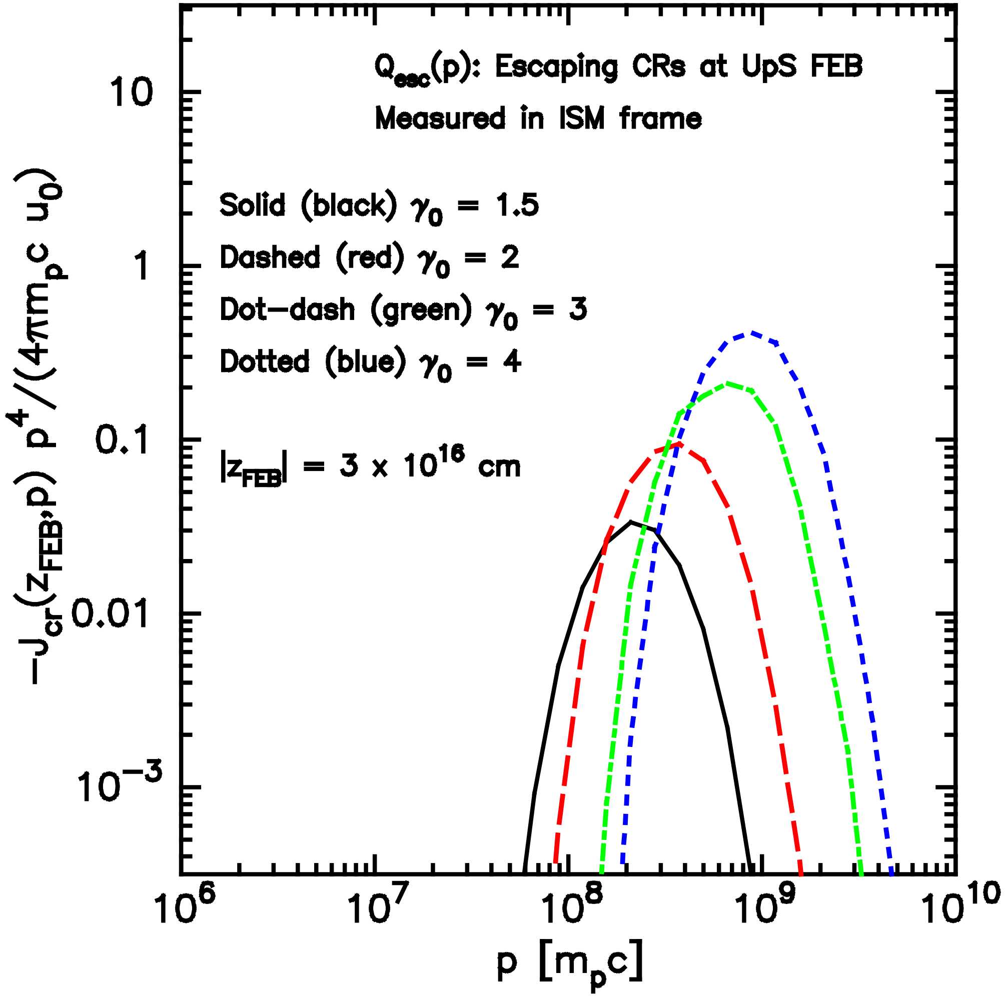


SN 2009bbb Hillas value Emax > EeV

Non-linear Monte Carlo modeling of CR acceleration in relativistic SNe

(with magnetic field amplification)





AB+ Space Sci. Rev. 2018 v,214, 41

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

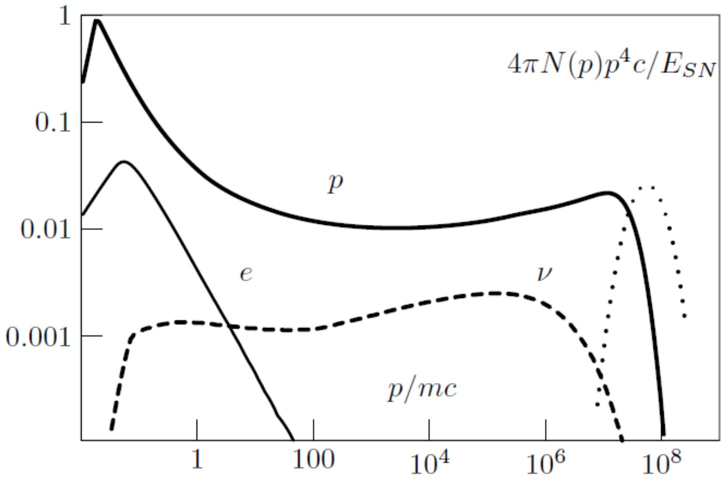
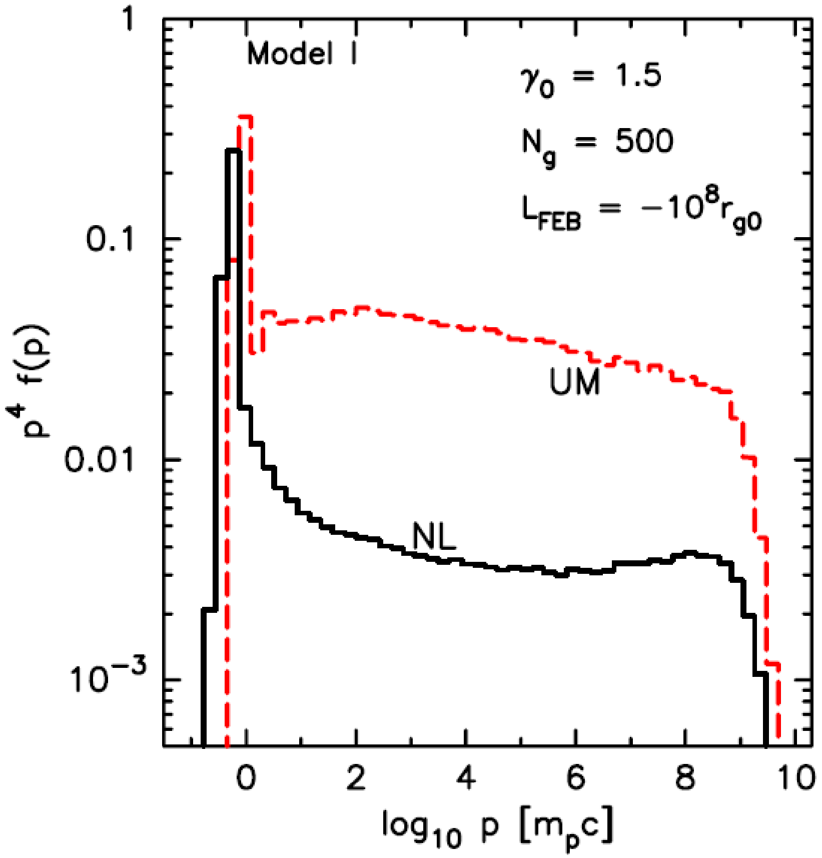


Figure 4: Spectra of particles produced in the supernova remnant during 30 yr after explosion. The spectrum of protons (thick solid line), the spectrum of secondary electrons (multiplied on 10^3, thin solid line), the spectrum of neutrinos (thick dashed line) are shown.

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 β/Γ ~ 1
Ellison, AB
ApJ v.776, 46, 2013

Thanks for your attention!

Supported in part by the RSF grant 21-72-20020