Particle acceleration in galactic sources

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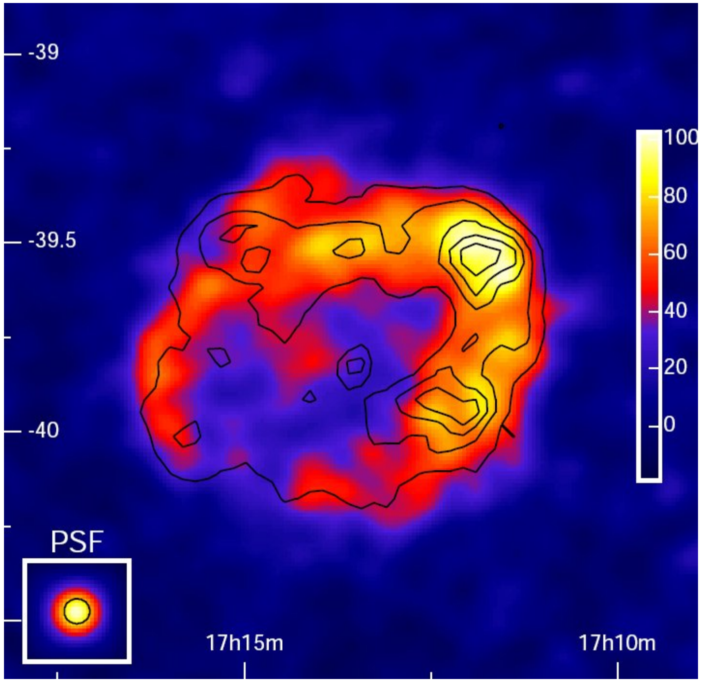
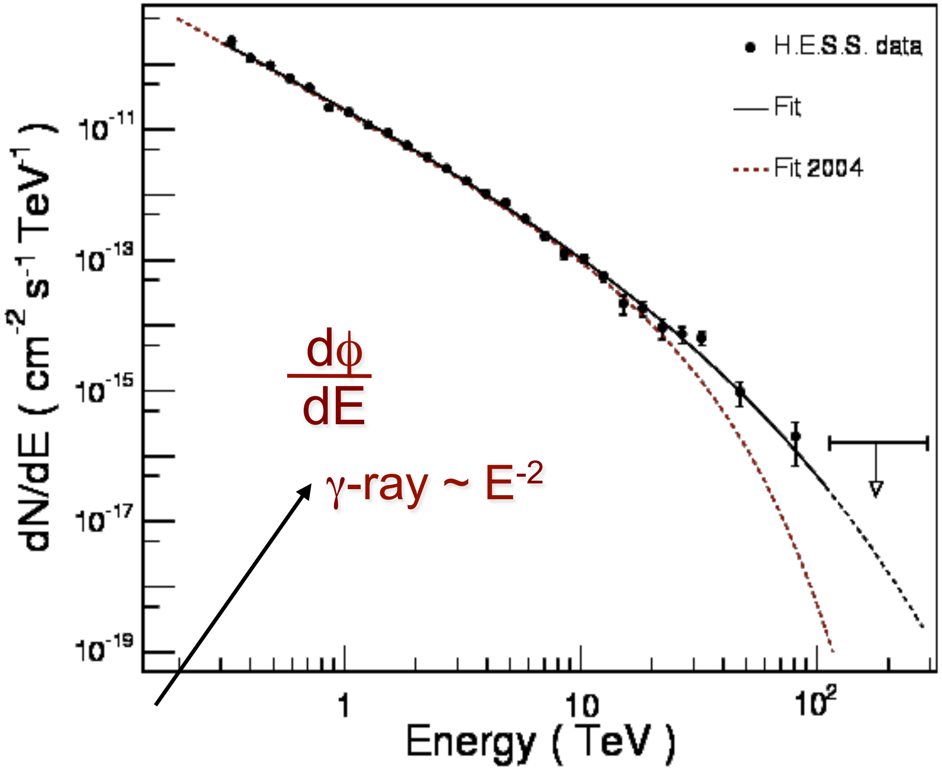
TeV gamma rays from RXJ1713.7-3946

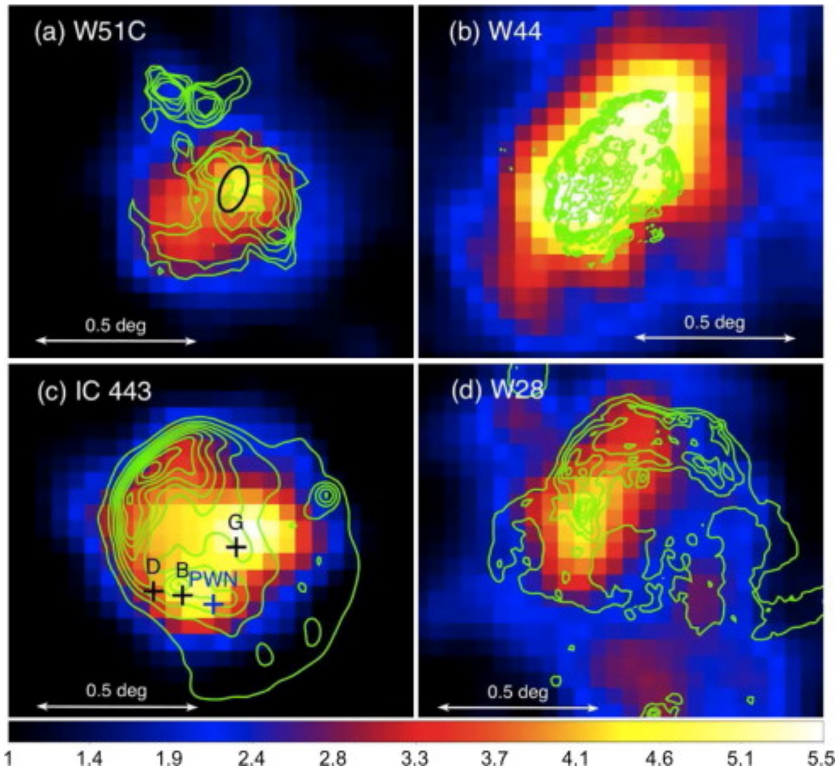


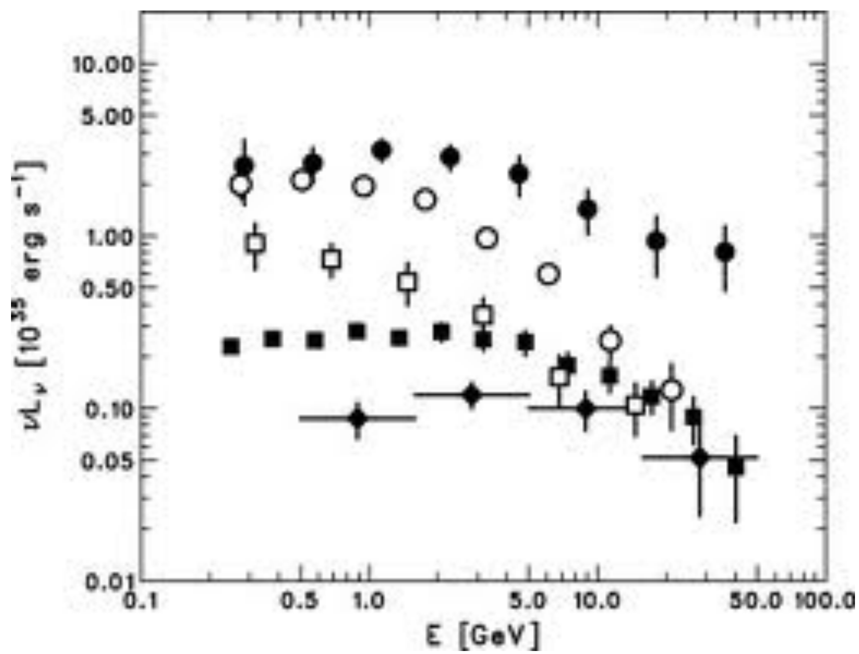
RXJ1713.7-3946 (HESS)

F.Aharonian+, *Astron.Astrophys.* **464**, 235 (2007)



Fermi images of young SNRs



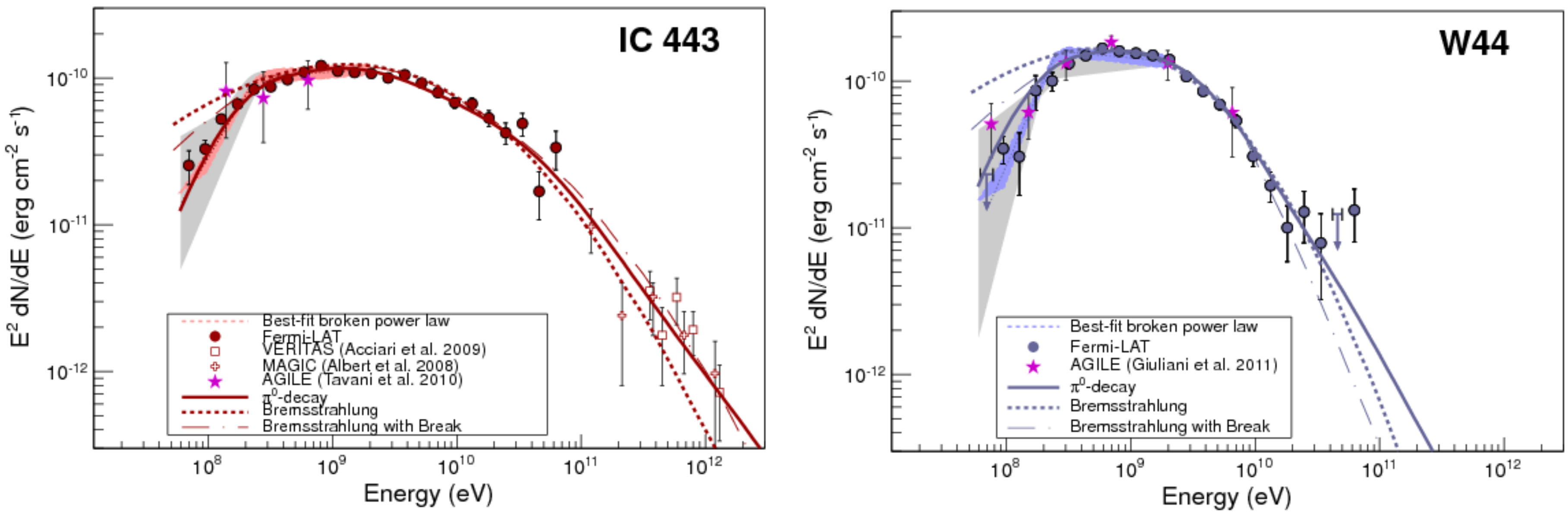


$$L_\gamma \sim 10^{34} - 10^{36} erg / s$$

W51C (filled circles) W44 (open circles);
IC 443 (filled rectangles); W28 (open rectangles)
Cassiopeia A (filled diamonds).

Thompson Baldini Uchiyama 2012

SNR in Molecular Clouds

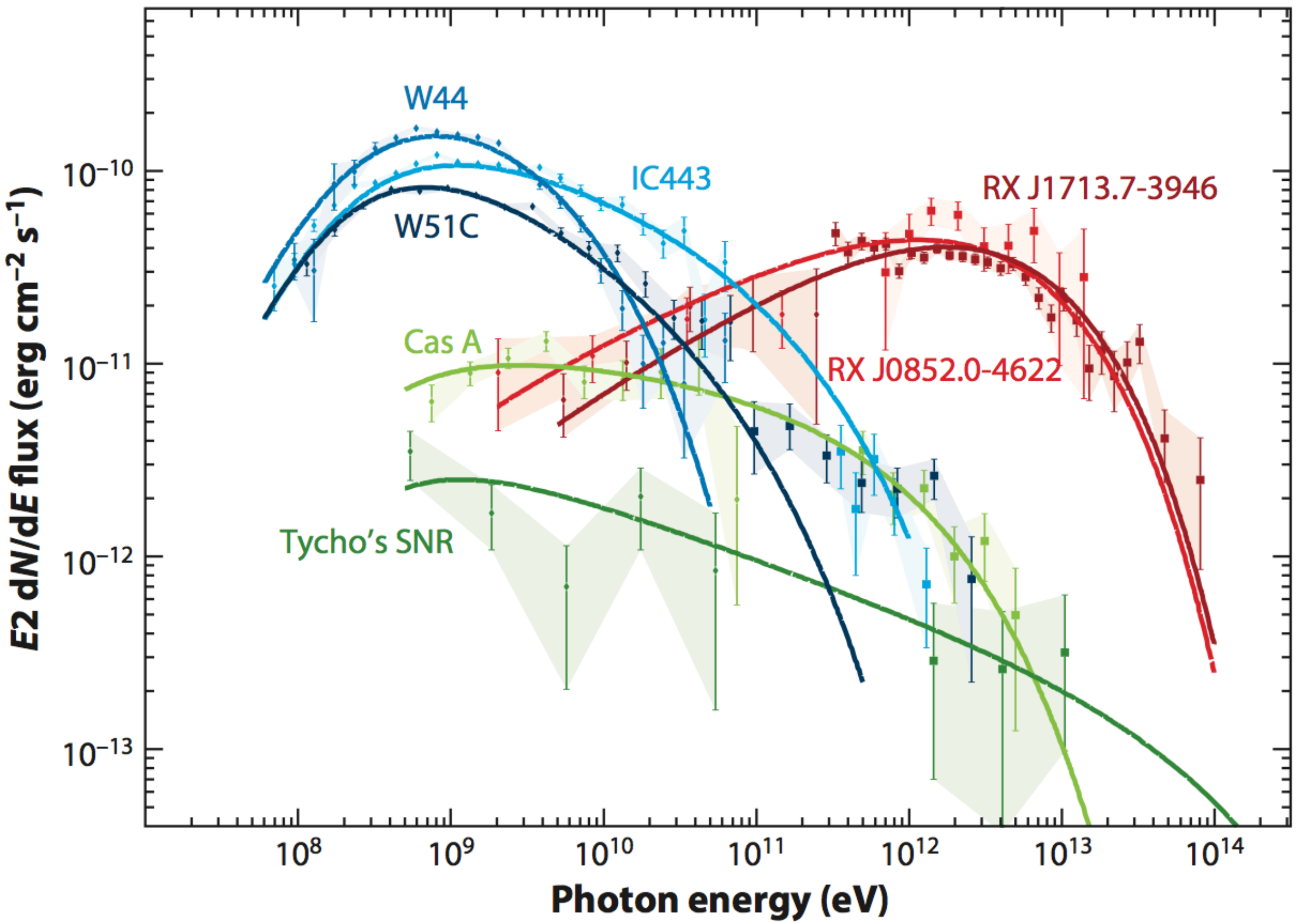


M.Ackermann 2013

Pion-Decay Signatures

see: Tavani + 2010, Uchiyama+ 2010, Giuliani+ 2011, Ackermann+ 2013, Cardillo+ 2014

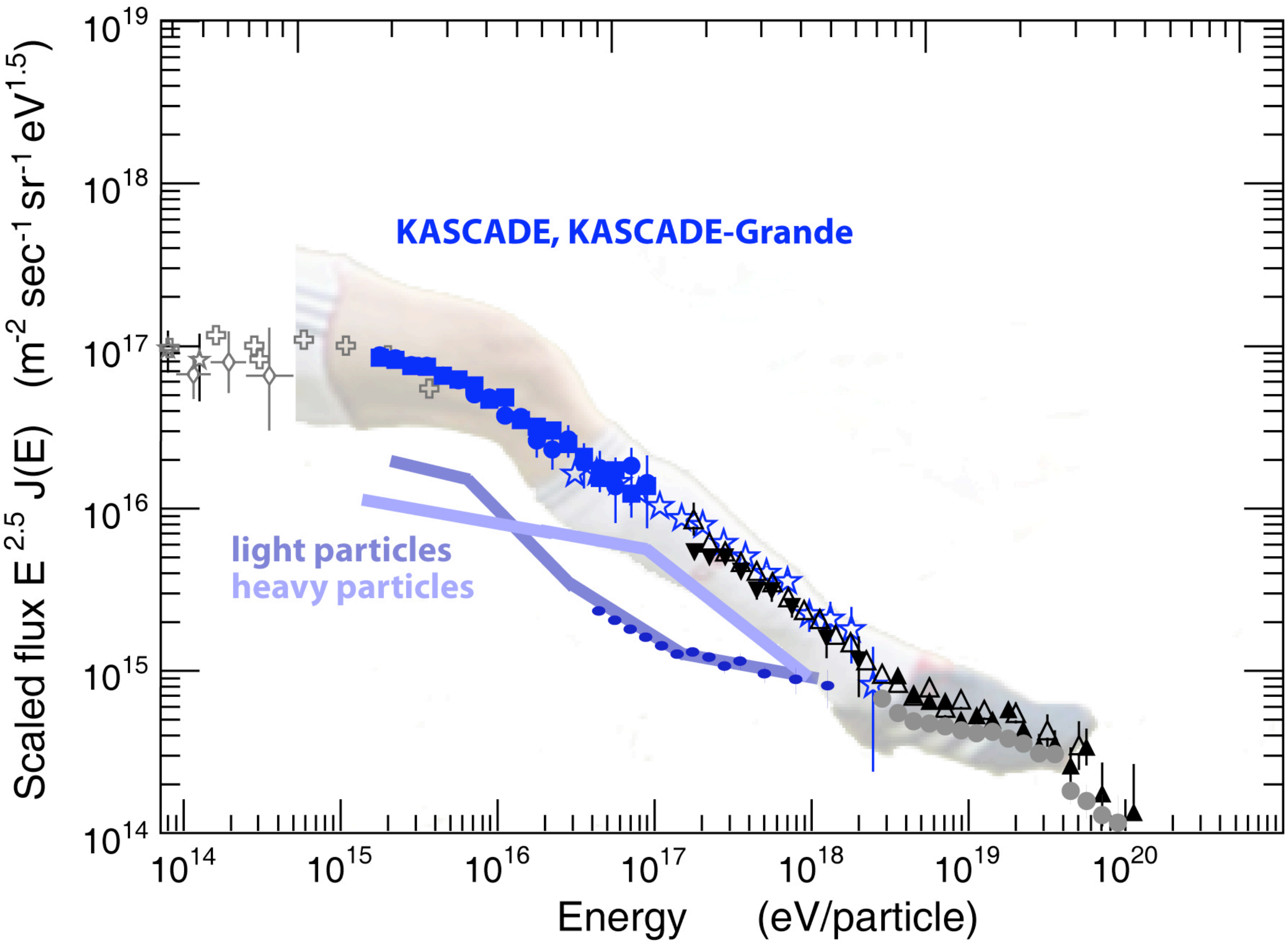
Observed gamma-ray spectra of SNRs



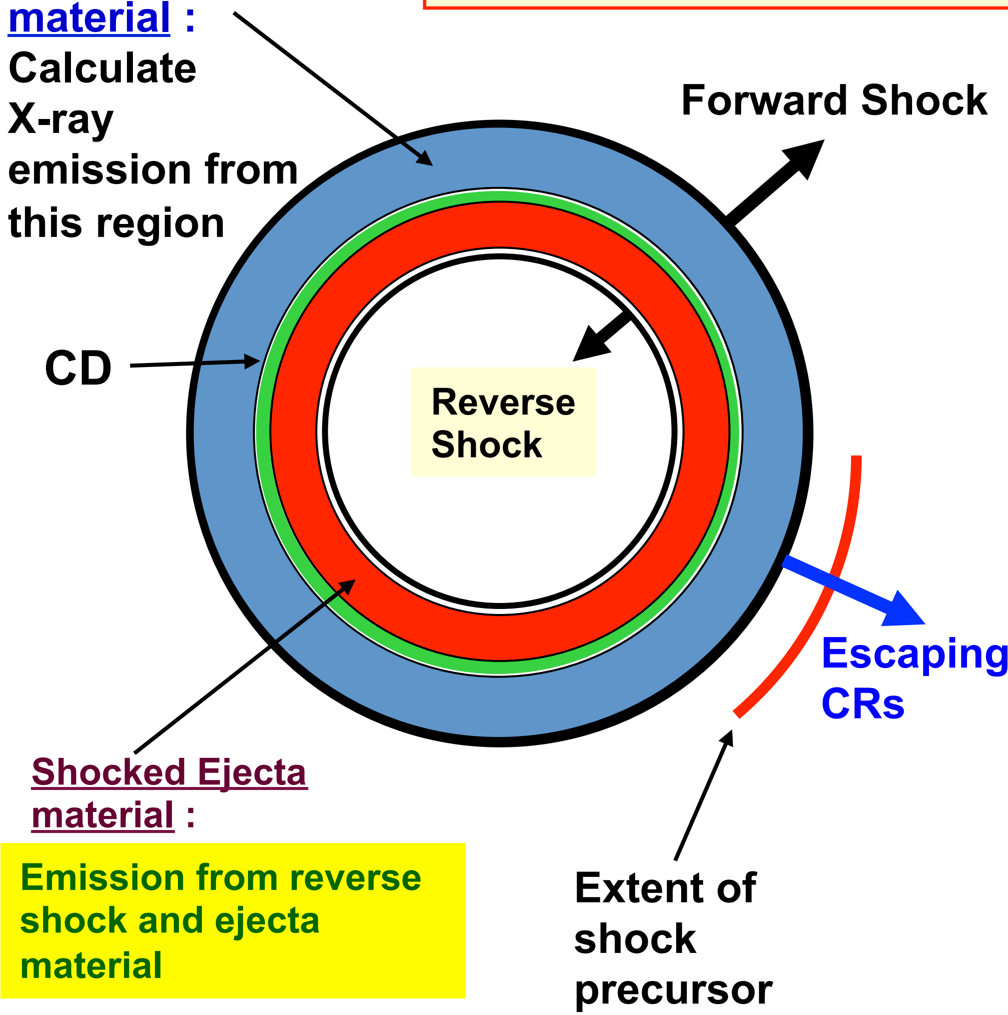
S. Funk 2015

•However what are the sources of PeV regime CRs?

PeV CRs are likely accelerated in the Galaxy



Core-collapse model: Pre-SN wind density: $\rho \propto 1/r^2$



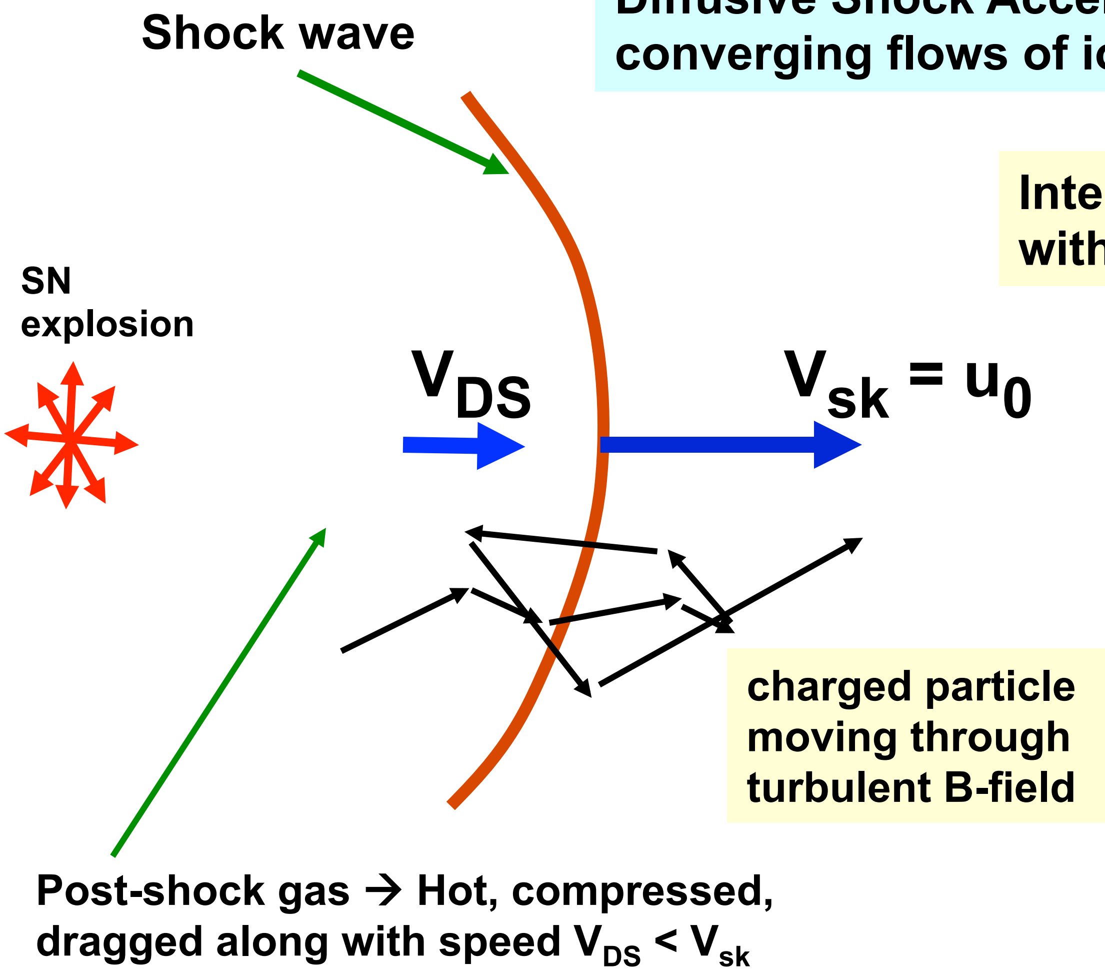
1) CR electrons and ions accelerated at FS
   a) Protons give pion-decay γ-rays
   b) Electrons give synchrotron, IC, & non-thermal brems.
   c) High-energy CRs escape from shock precursor & interact with external mass

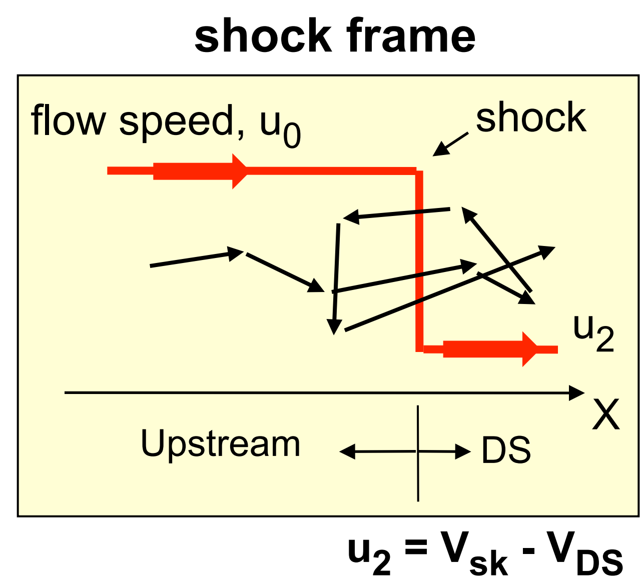
3) Follow evolution of shock-heated plasma between FS and contact discontinuity (CD)
   a) Calculate electron temperature, density, charge states of heavy elements, and X-ray line emission
   b) Include adiabatic losses & radiation losses

Spherically symmetric: We do not model clumpy structure

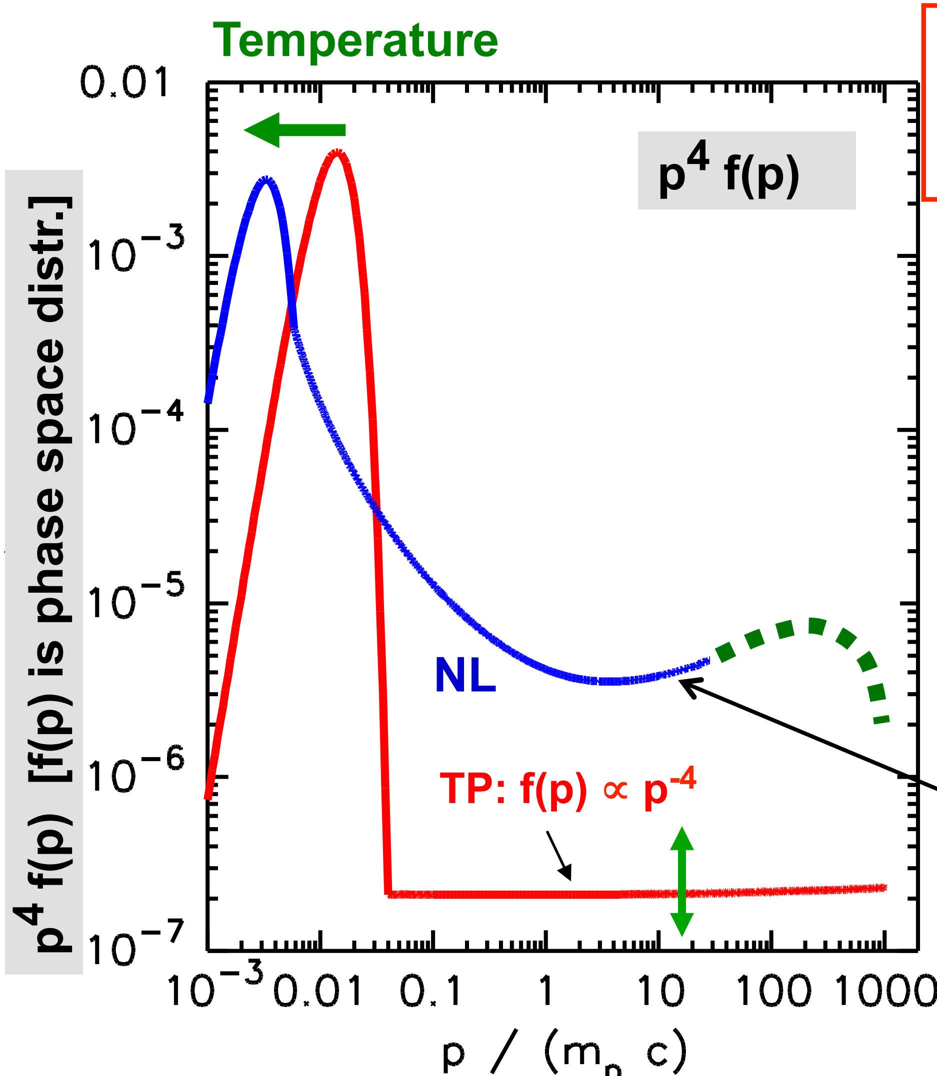
Diffusive Shock Acceleration: Shocks set up converging flows of ionized plasma

Interstellar medium (ISM), cool with speed $V_{ISM} \sim 0$

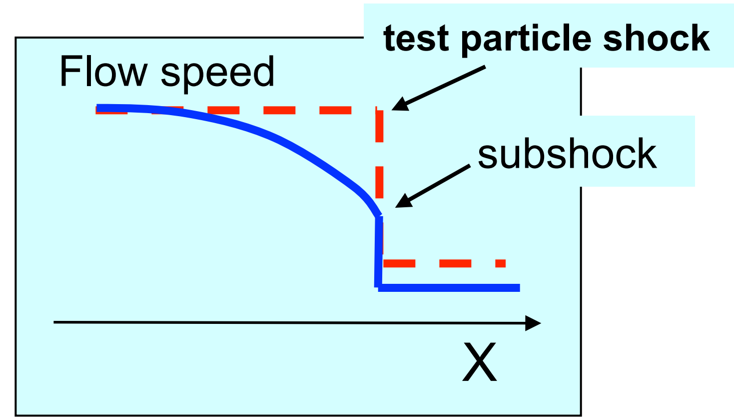




Particles make nearly elastic collisions with background plasma ➔ gain energy when cross shock ➔ bulk kinetic energy of converging flows put into individual particle energy ➔ some small fraction of thermal particles turned into (approximate) power law



If acceleration is efficient, shock becomes smooth from backpressure of CRs

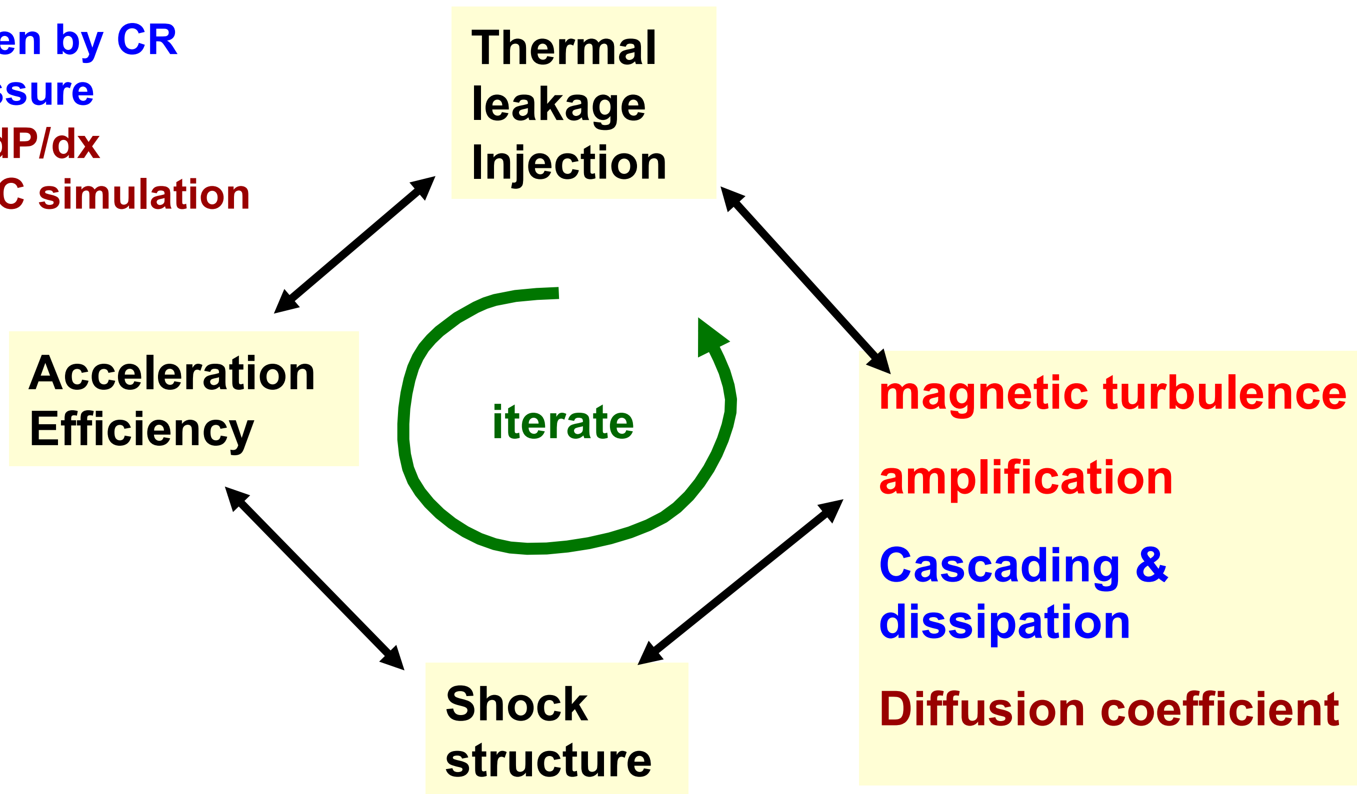


- ► **Concave spectrum**
- ► **Compression ratio, $r_{tot} > 4$**
- ► **Low shocked temp. $r_{sub} < 4$**

B-field effects may reduce curvature

In efficient acceleration, <u>entire particle spectrum</u> must be described consistently, including escaping particles ➔ much harder mathematically BUT, connects thermal emission to radio & GeV-TeV emission

Plasma theory gives instability growth rates & and diffusion coefficient
Instabilities driven by CR current and pressure gradient. J_{CR} & dP/dx determined in MC simulation



If acceleration is efficient, all elements feedback on all others

Kinetic models: Bell, Krymskiy; Eichler; Kang Jones; Berezhko; Ptuskin Zirakashvili, AB+

Semi-analytic non-linear models: Malkov; Blasi, Amato & Caprioli

Non-linear Monte Carlo model with resonant , non-resonant Bell and long-wavelength instabilities: AB, Ellison, Vladimirov +

PiC models: Spitkovsky, Sironi, Caprioli et al

Monte Carlo modeling of DSA Magnetic Field Amplification (simplified models to study non-linear coupling effects)

Conservation laws in MC modeling

$$\rho(x)u(x) = \rho_0 u_0$$ - mass

$$\rho(x)u^2(x) + P_{th}(x) + P_{cr}(x) + P_w(x) = \Phi_{P0}$$ - momentum

$$\frac{\rho(x)u^3(x)}{2} + F_{th}(x) + F_{cr}(x) + F_w(x) + Q_{esc} = \Phi_{E0}$$ - energy

Energy flux background plasma

$$F_{th}(x) = u(x)\frac{\gamma_g P_{th}(x)}{\gamma_g - 1}$$

Energy flux and turbulent pressure

$$F_w(x,k) = \frac{3}{2}u(x)W(x,k) \qquad P_w(x,k) = \frac{W(x,k)}{2}$$

Magnetic Fluctuation Spectral Evolution

$$\frac{\partial F_w(x,k)}{\partial x} + \frac{\partial \Pi(x,k)}{\partial x} = u(x)\frac{\partial P_w(x,k)}{\partial x} + \Gamma(x,k)W(x,k) - L(x,k)$$

Energy flux components

$$\frac{dF_w(x)}{dx} = u(x)\frac{dP_w(x)}{dx} + \int_{(k)} \Gamma(x,k)W(x,k)dk - L(x)$$

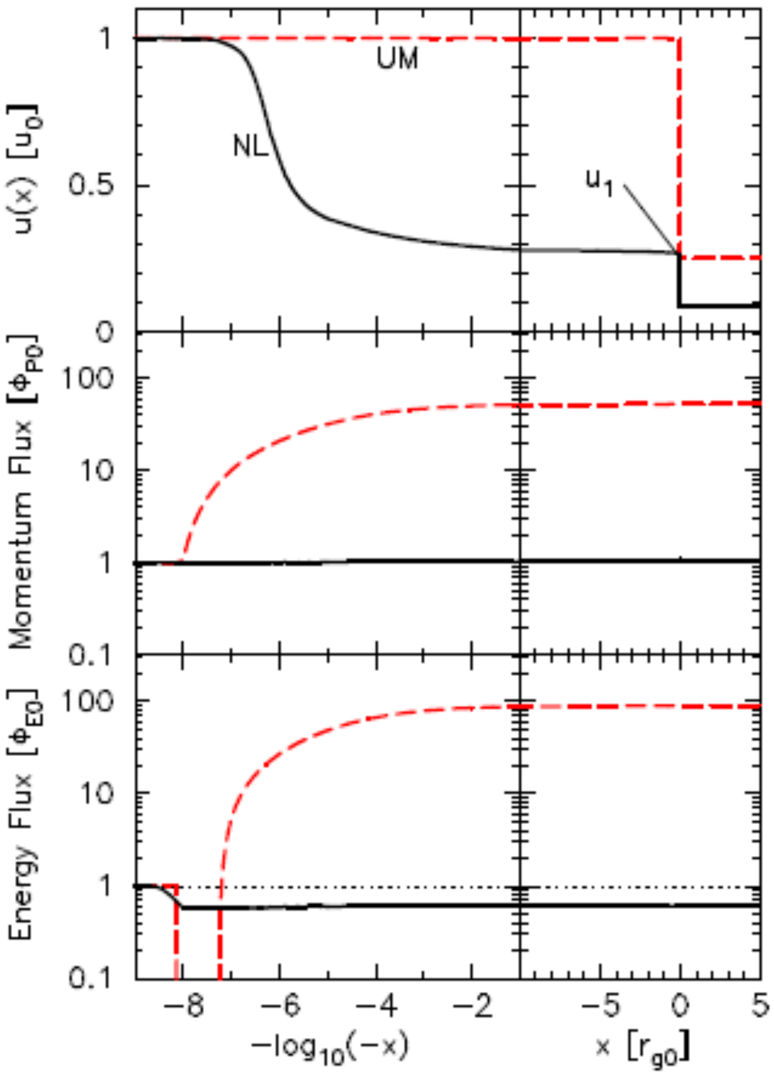
$$\frac{dF_{th}(x)}{dx} = u(x)\frac{dP_{th}(x)}{dx} + L(x)$$

$$\frac{dF_{cr}(x)}{dx} = \left[u(x) + v_{scat}(x)\right]\frac{dP_{cr}}{dx}$$

$$v_{scat}(x) = -\int_{(k)} \Gamma(x,k)W(x,k)dk \Big/ \frac{dP_{cr}}{dx}$$

AB +., ApJ, 789:137, 2014.

Bulk velocity and magnetic field profiles

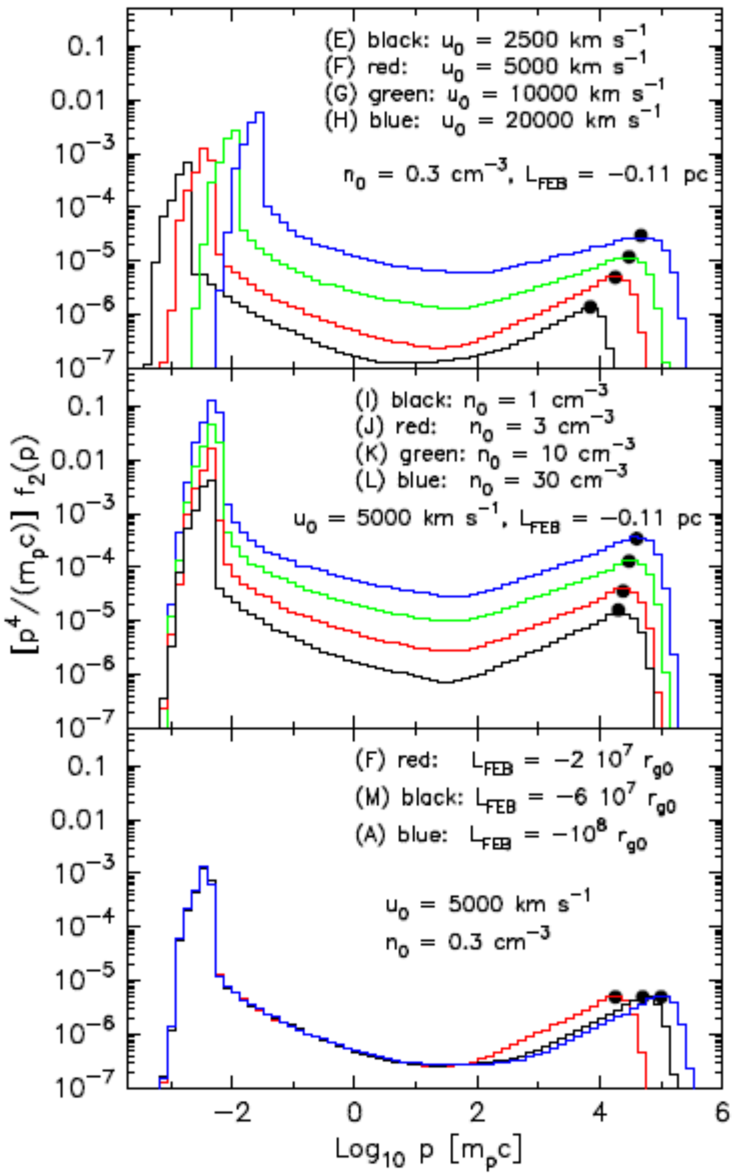


$$r_{g0} = \frac{m_p c u_0}{e B_0}$$

$$n_0 = 0.3\ см^{-3};\ u_0 = 5000\ \frac{км}{c};\ B_0 = 3\ мкГс$$

AB +., ApJ, 789:137, 2014.

CR spectra scalings



Maximal momentum of accelerated CRs

$$p_{\max} \propto n_0^{\delta} u_0 L_{FEB}$$

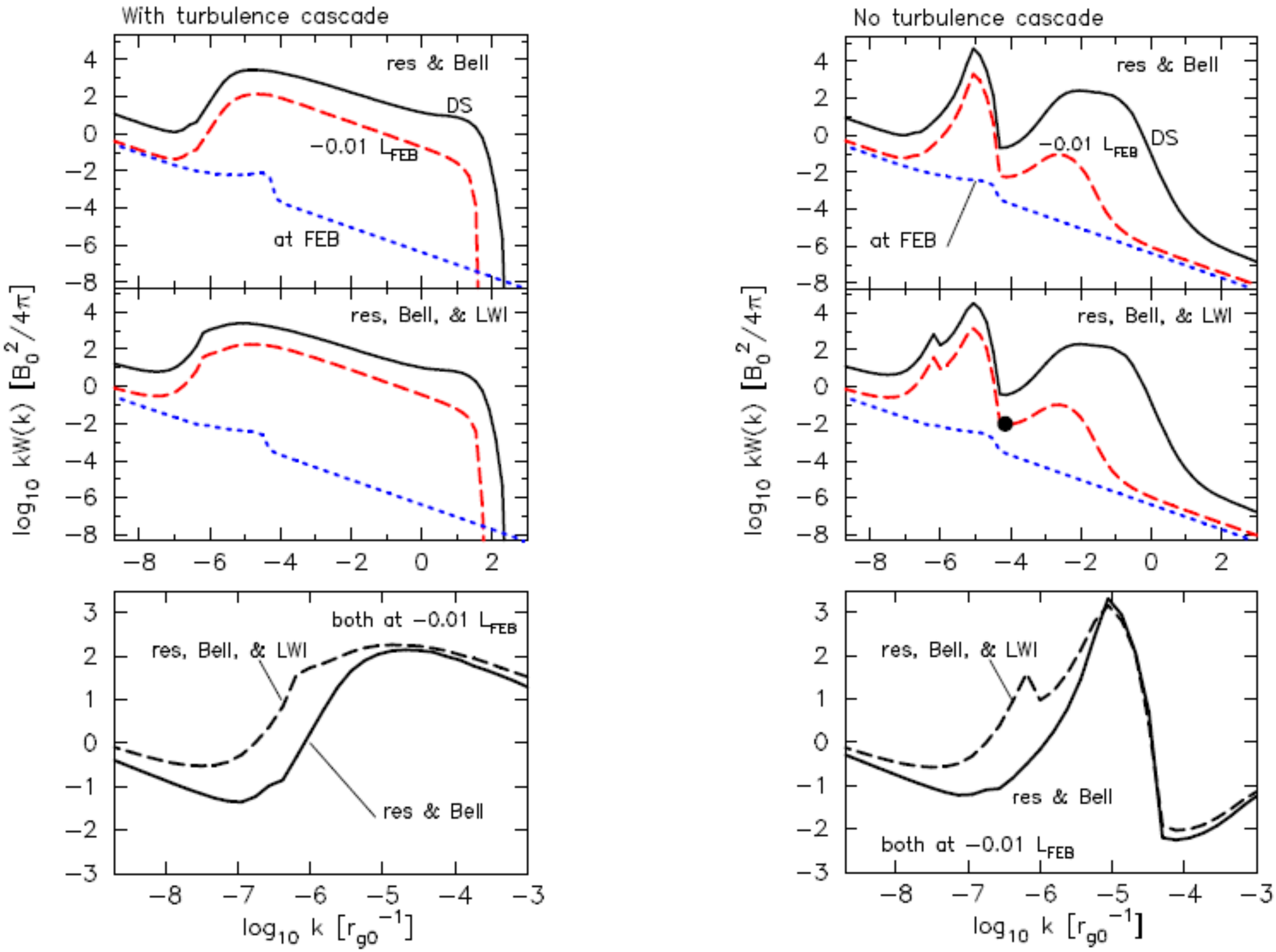
$\delta :\ 0.25$

Efficient acceleration often results in concave spectra

Charge exchange may help for shock speeds below 3,000 km/s Blasi+, Morlino+

ApJ, 789:137, 2014.

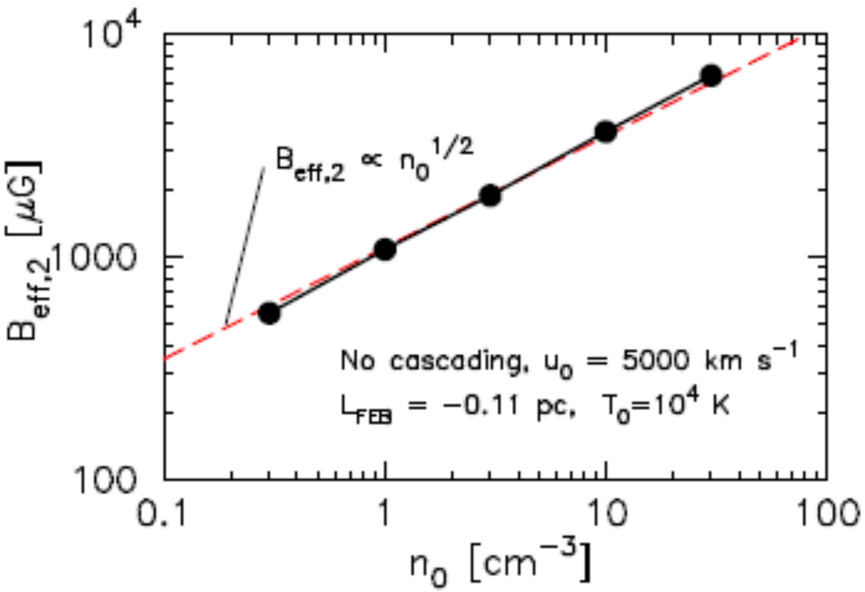
Magnetic turbulence spectra

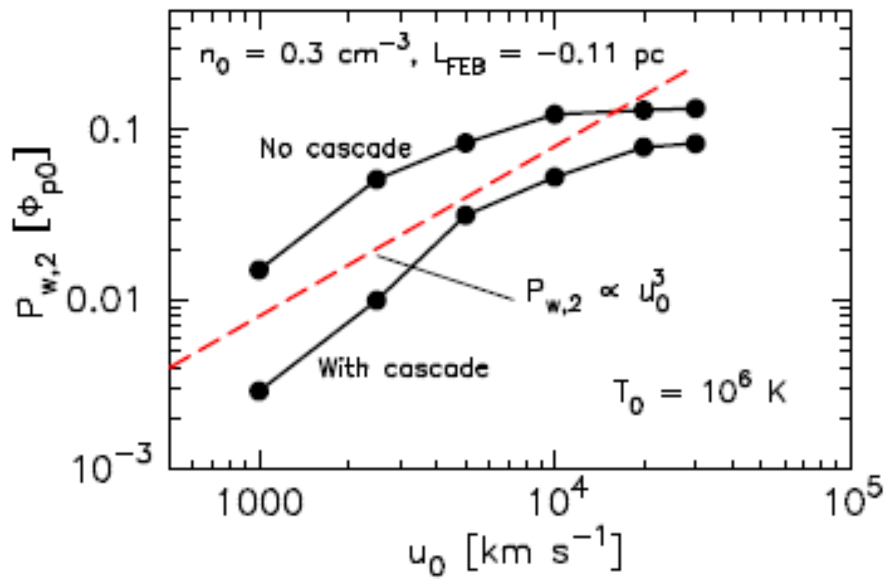


$$n_0 = 0.3\ см^{-3};\ u_0 = 5000\ \frac{км}{c};\ B_0 = 3\ мкГс$$

ApJ, 789:137, 2014.

Fluctuating magnetic field and magnetic pressure scalings





$$B_{eff,2} \propto \sqrt{n_0}\, u_0^{\theta}$$

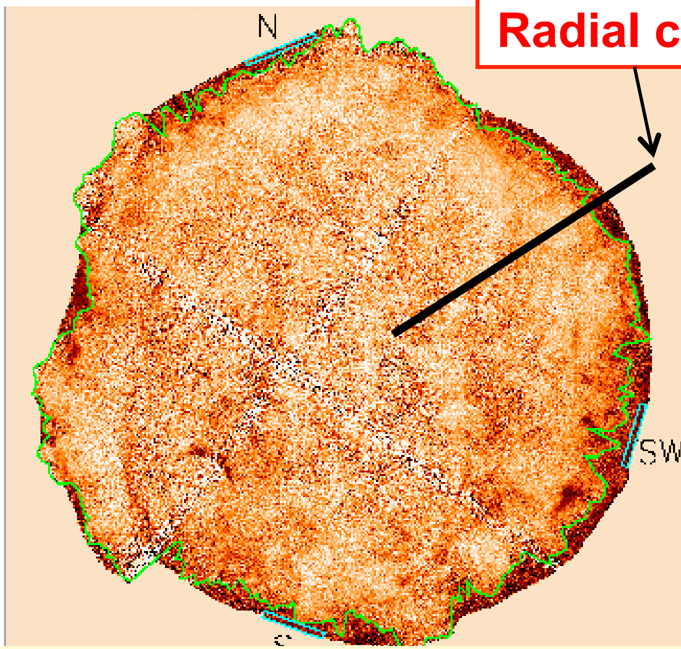
$$\frac{B_{eff,2}^2}{n_0} \propto u_0^3 \rightarrow \theta : \; 1.5$$

, ApJ, 789:137, 2014.

Evidence for High (amplified) B-fields in SNRs

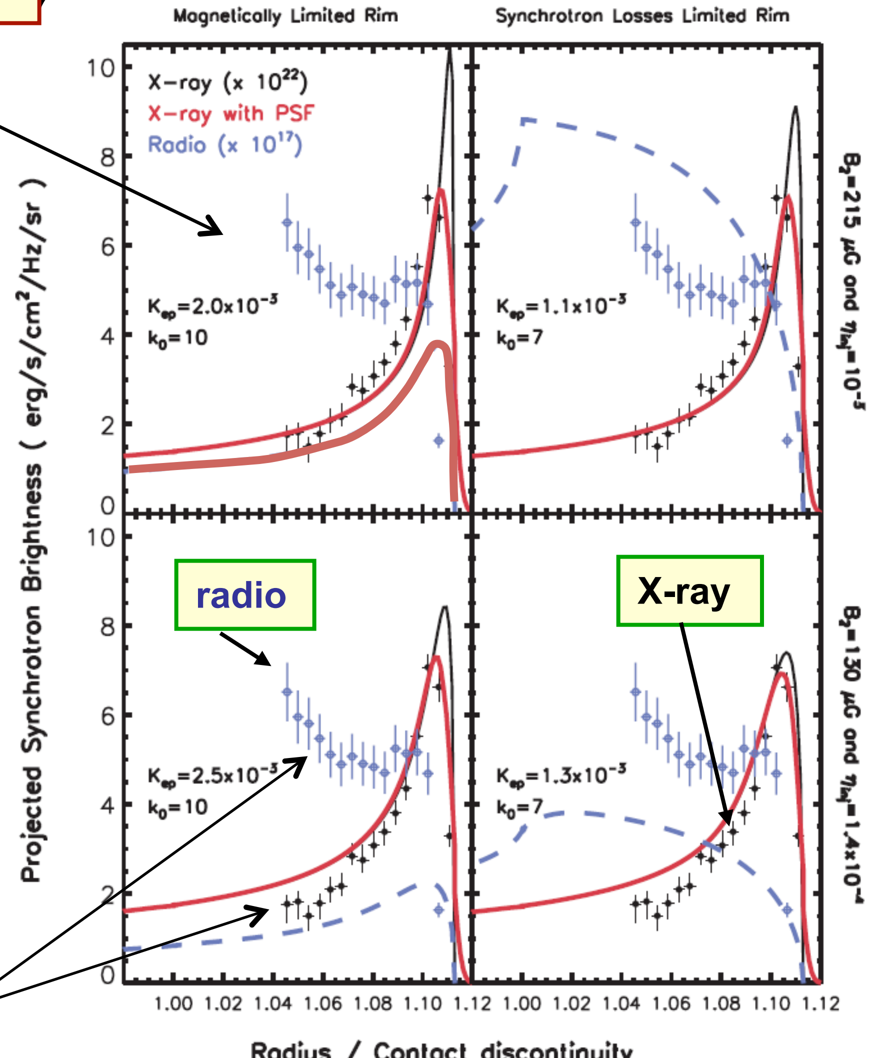
Sharp synch. X-ray edges

Radial cuts



Chandra observations of Tycho's SNR
(Warren et al. 2005)

Cassam-Chenai et al.



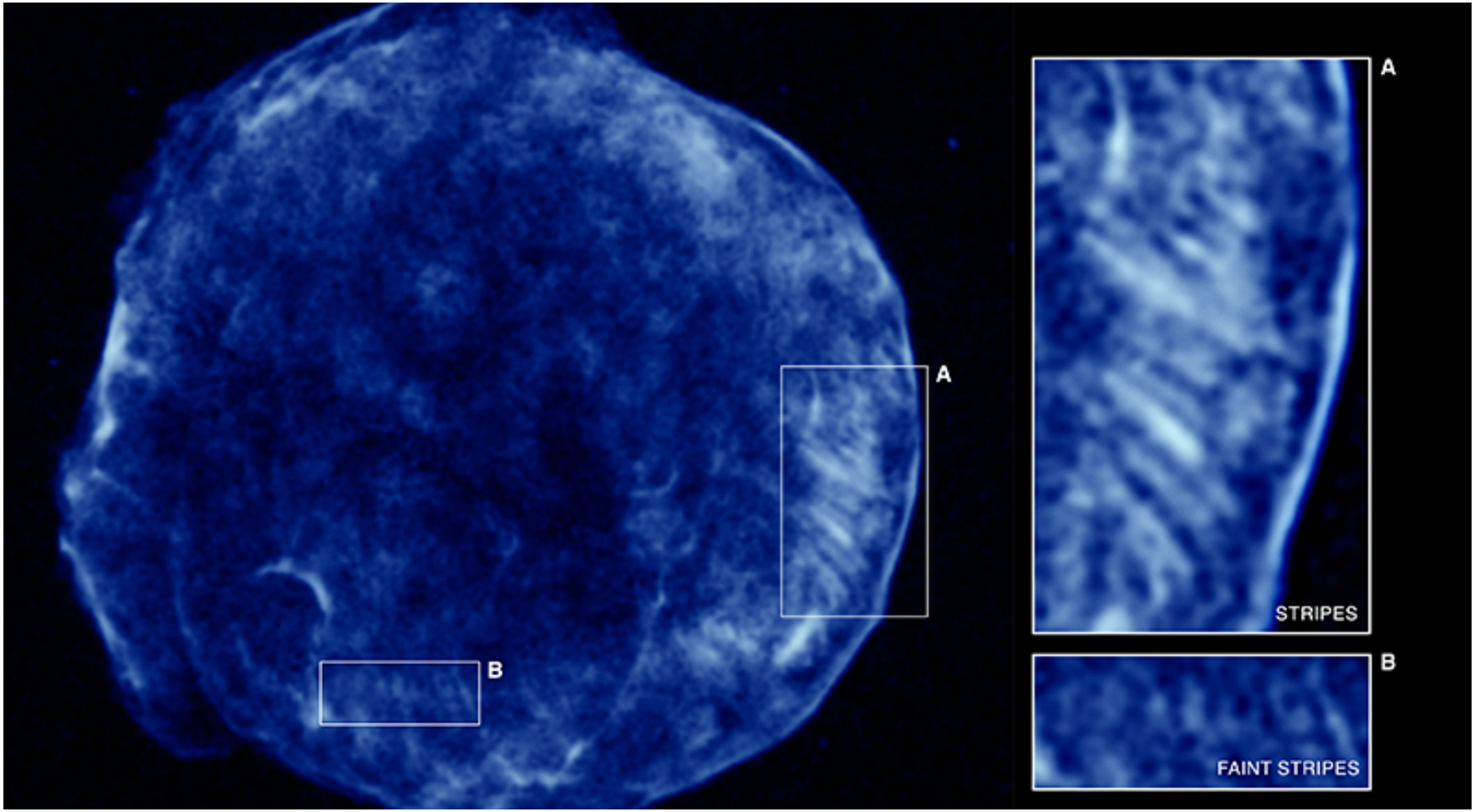
radio

X-ray

If drop from B-field decay instead of radiation losses, expect synch radio and synch X-rays to fall off together.

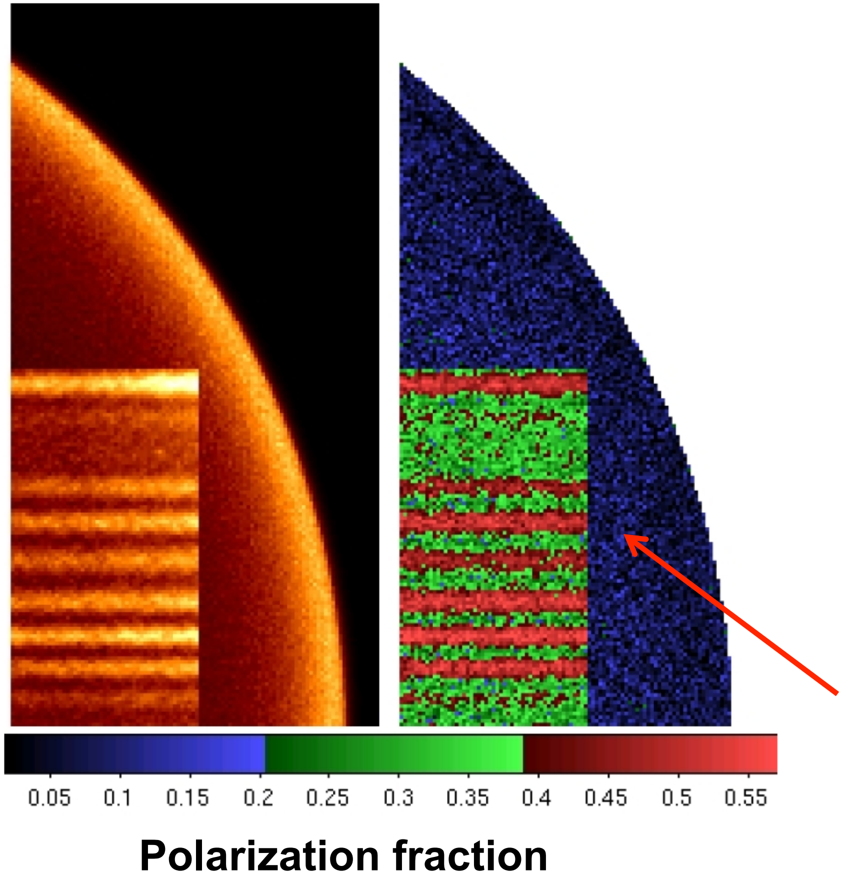
Good evidence for radiation losses and, therefore, large, amplified magnetic field.
On order of 10 times higher than expected

Chandra 4-6 keV Image of Tycho's SNR



Eriksen + 2011

AB+ ApJL v735, L40, 2011



DSA is a possible explanation of strips

➔ Some shock and turbulence properties must come together to produce coherent structure on this scale. Transverse part of the shock, anisotropic cascade, high Pmax

Strong predictions:
Quasi-perpendicular upstream B-field

Strong linear polarization in strips

How to get PeV energy CRs?

Rare SNe with a special CSM type IIn?

Rare magnetar-driven SNe?

SNe- Stellar/Custer Wind collision in young compact stellar clusters?

Rare types of SNe

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

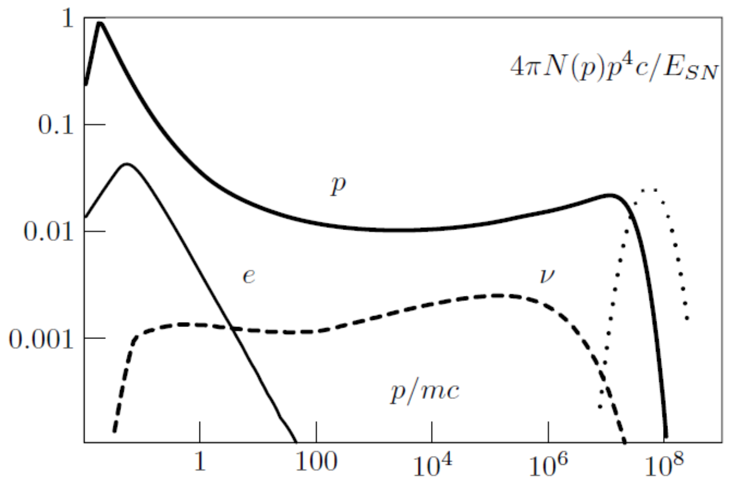
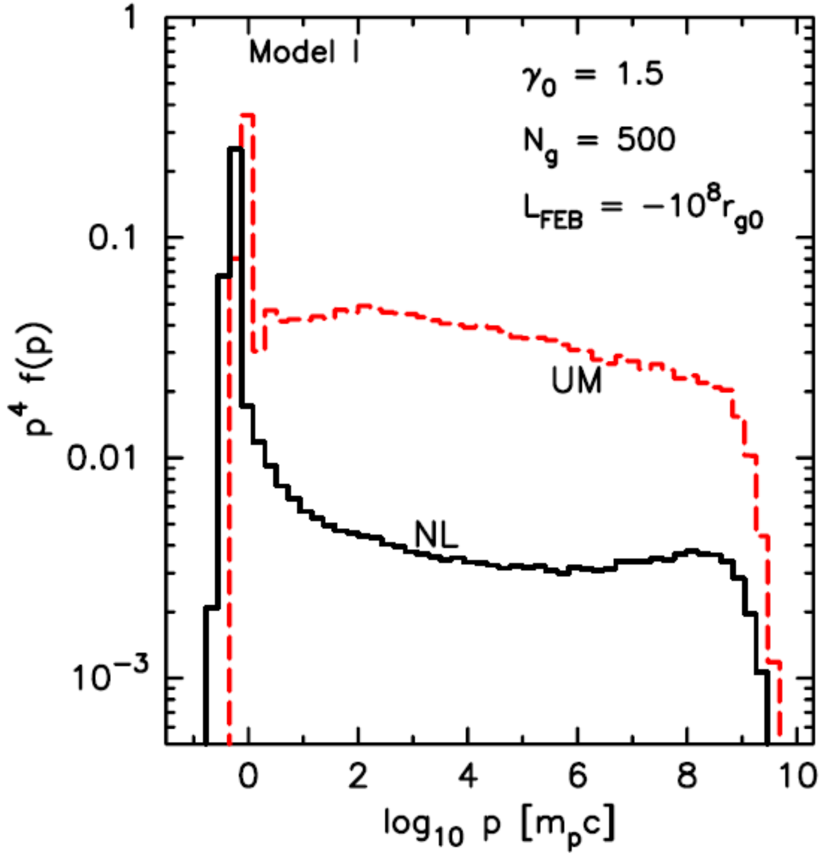


Figure 4: Spectra of particles produced in the supernova remnant during 30 yr after explosion. The spectrum of protons (thick solid line), the spectrum of secondary electrons (multiplied on 10^3, thin solid line), the spectrum of neutrinos (thick dashed line) are shown.

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, Warren, Bykov
ApJ v.776, 46, 2013

How to get PeV energy CRs?

Rare Sne

Diffusive shock acceleration is the Fermi acceleration in a converging plasma flow

SNe- Stellar/Custer Wind collision in young compact stellar clusters?

CR acceleration in the colliding shock flow is the most efficient Fermi acceleration…

- **From a general constraint on the CR acceleration rate the "luminosity" of NR MHD flow should exceed:**

$$L_{\rm tot} > 6 \times 10^{40}\, Z^{-2} \beta_{\rm sh}^{-1}\, \Theta^2\, \mathcal{E}_{18}^{2}\ {\rm erg\,s^{-1}}$$

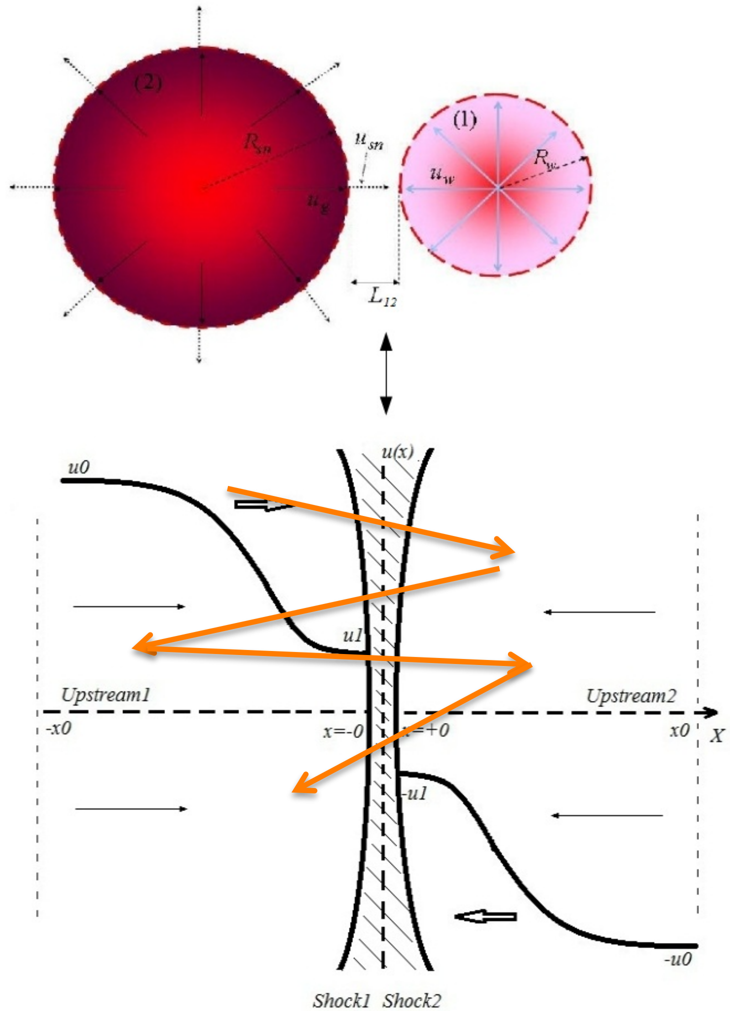
$$\text{for a SN in SSC (age 400 yrs)}$$

$$L_{\rm kin} \le 10^{41}\ {\rm erg\,s^{-1}}$$

cf F.Aharonian, M.Lemoine, E.Waxman …

CR acceleration in colliding shock flows SNe in a compact young star cluster

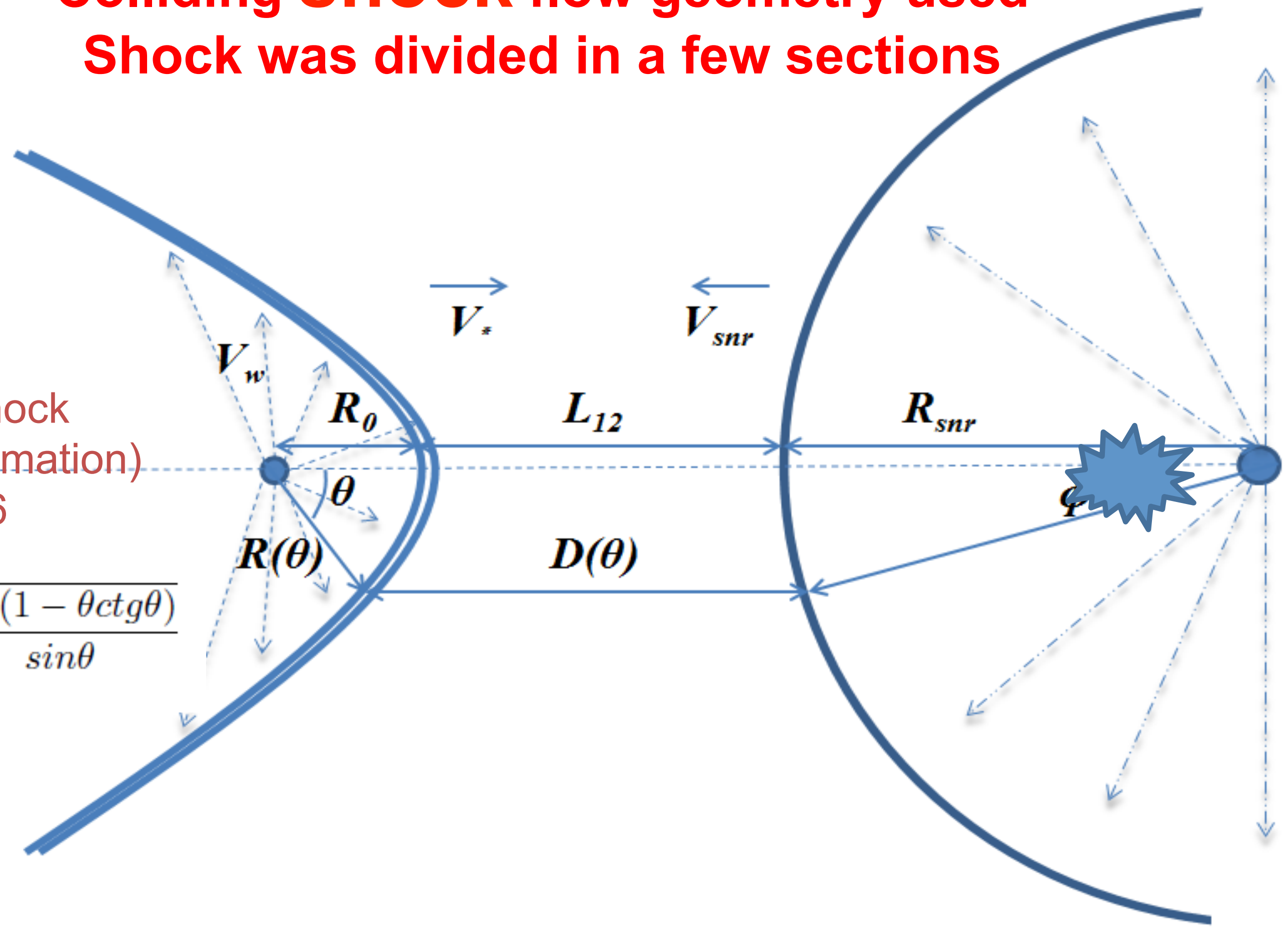
SNR - cluster wind collision



MNRAS V. 429, 2755, 2013

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

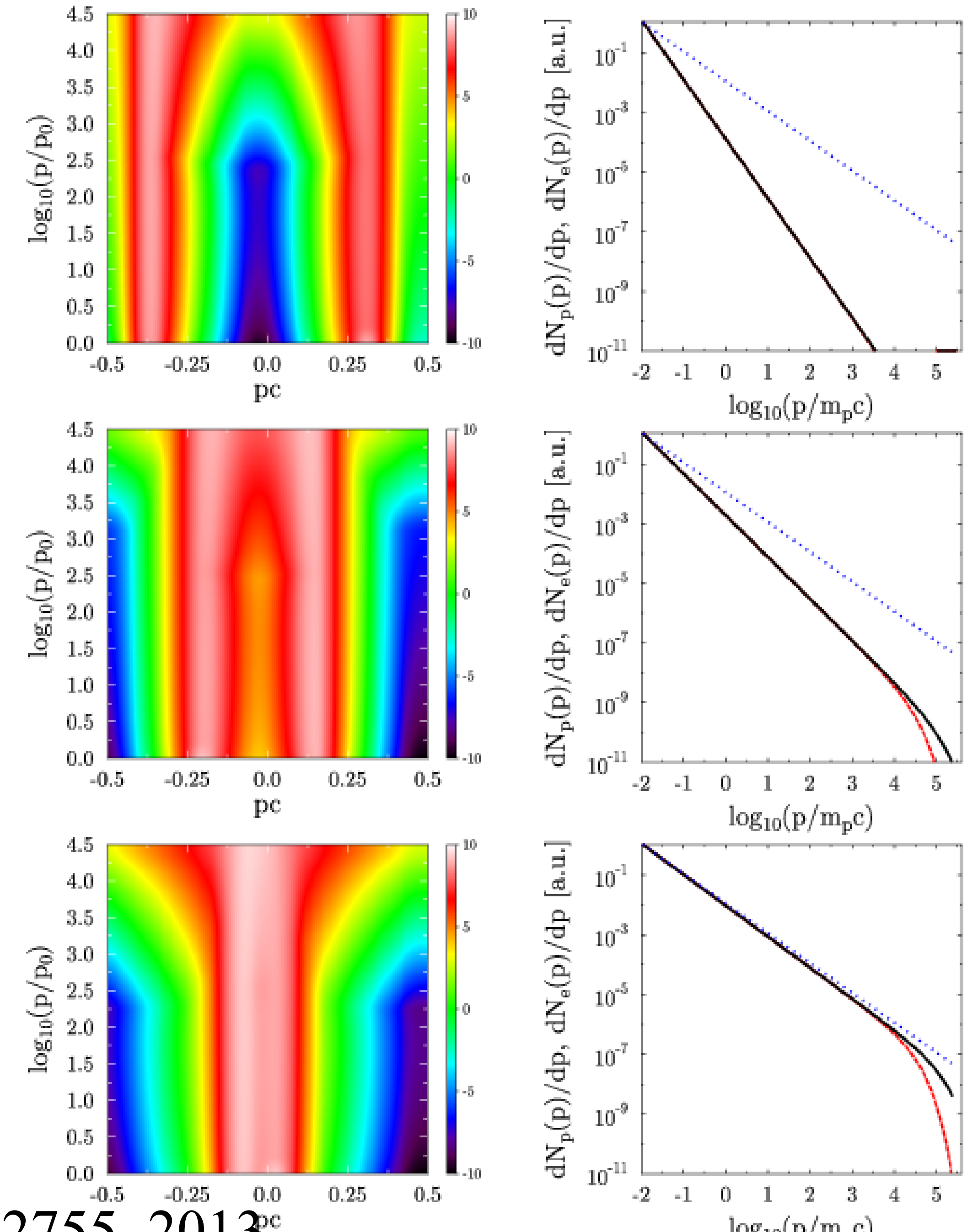
Colliding shock flow geometry used
Shock was divided in a few sections



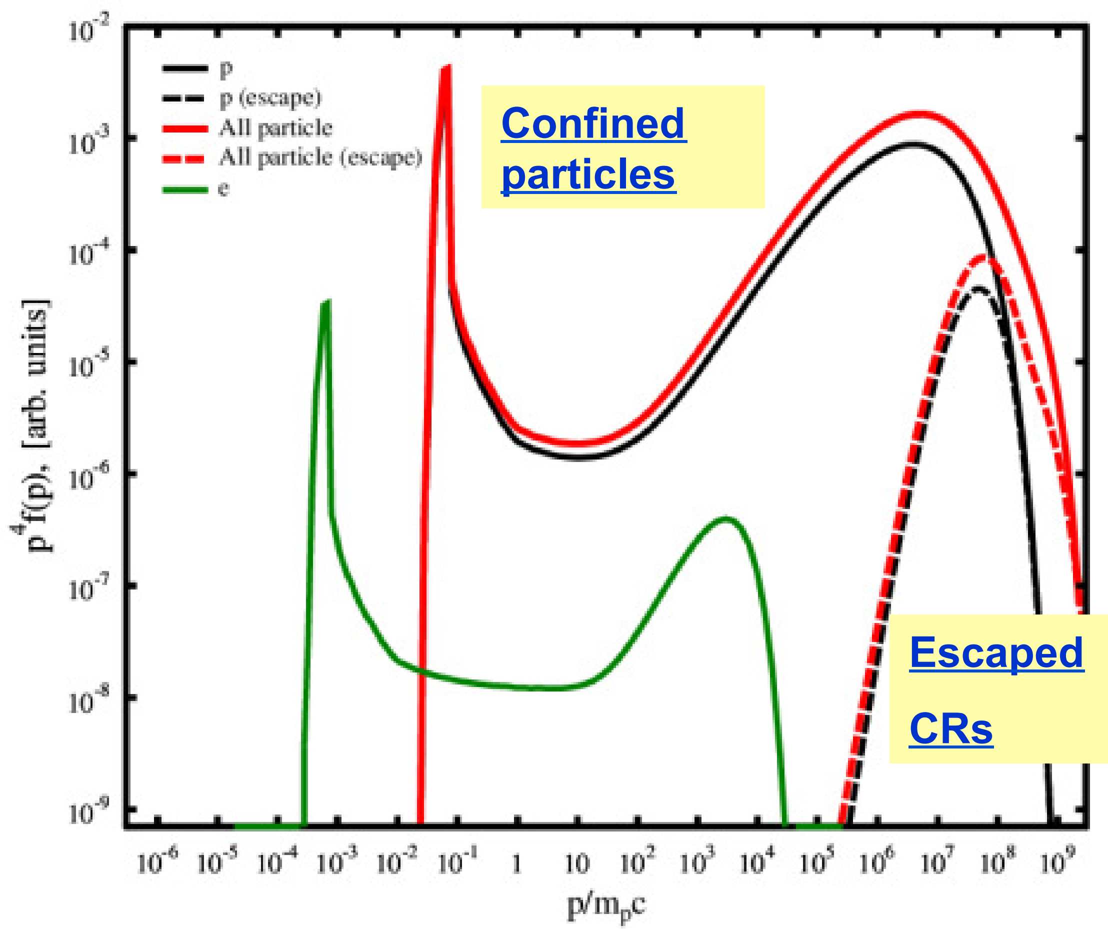
Stellar wind shock
(thin shell approximation)
Wilkin 1996

$$R(\theta) = \sqrt{\frac{\dot{m}V_w}{4\pi\rho_a V_*^2}} \cdot \frac{\sqrt{3(1-\theta ctg\theta)}}{sin\theta}$$

SNR-stellar wind accelerator



AB+ MNRAS v. 429, 2755, 2013



p
p (escape)
All particle
All particle (escape)
e
Confined particles
Escaped CRs
$p^4 f(p)$, [arb. units]
p/m_pc

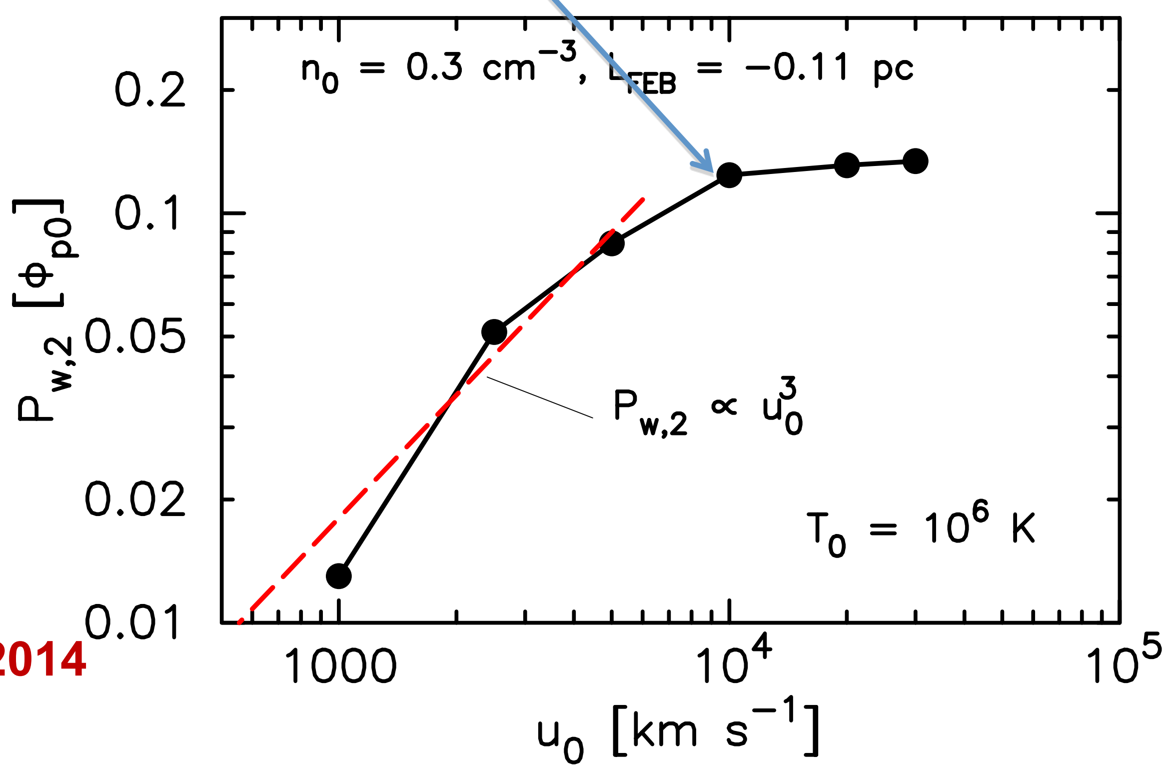
Particle acceleration in colliding flows is the most plausible scenario for SNe in young compact stellar clusters & starbursts

Acceleration time in the test particle approximation for Bohm diffusion

$$\tau_a \approx \frac{cR_g(p)}{u_s\, u_w}.$$

Acceleration time is about 500 yrs for 10-40 PeV

$$\tau_a \approx 2 \cdot 10^{10}\, \mathcal{E}_{\rm PeV}\, (\eta_b n)^{-0.5}\, u_{s3}^{-2}\, u_{w3}^{-1}\, ({\rm s})$$



Magnetic field amplification by CR current driven instabilities: Bell's and LW

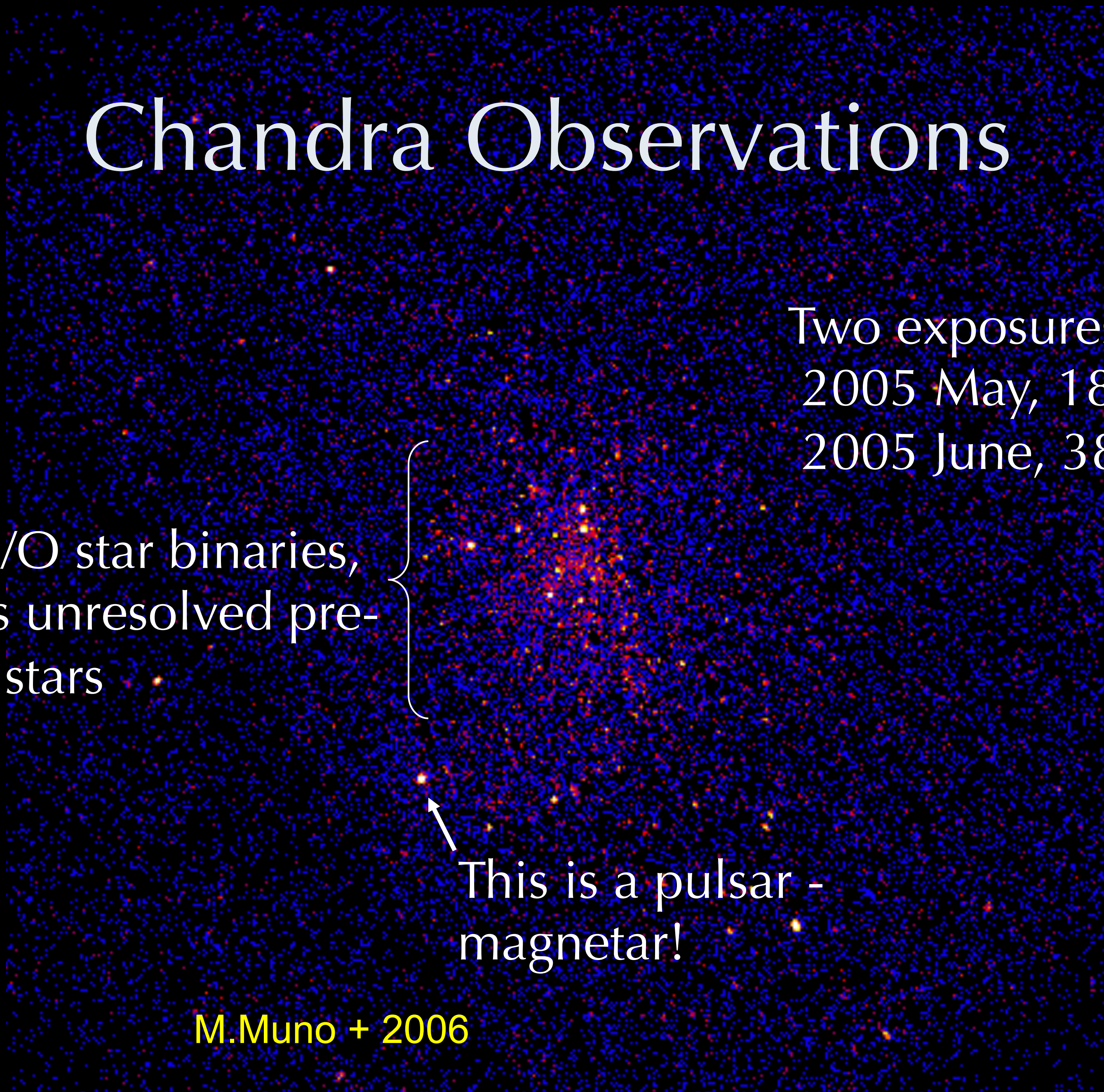
ApJ v.789, 137, 2014

A Galactic Super Star Cluster

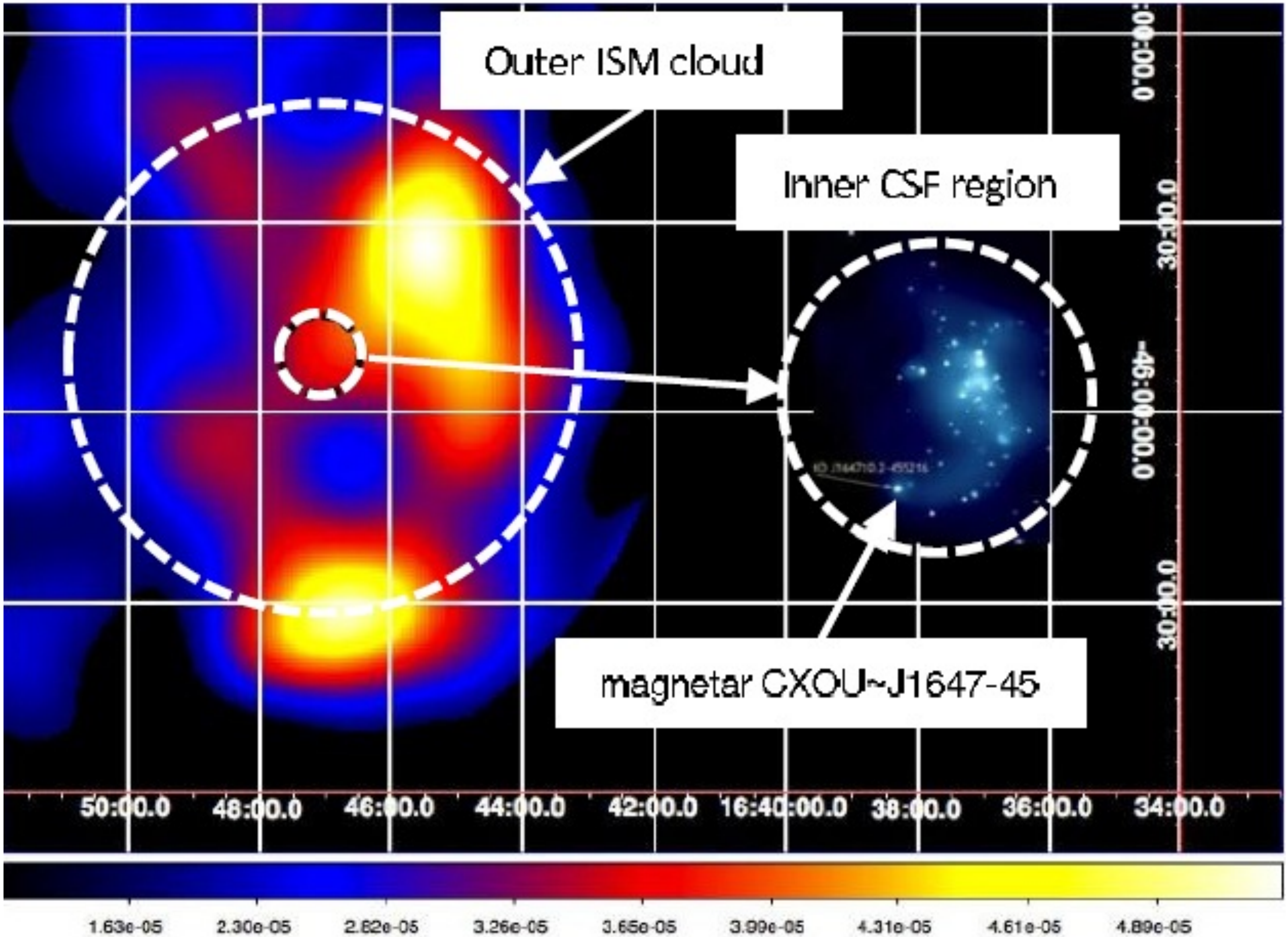
2MASS Atlas Image from M.Muno

- 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

Chandra Observations

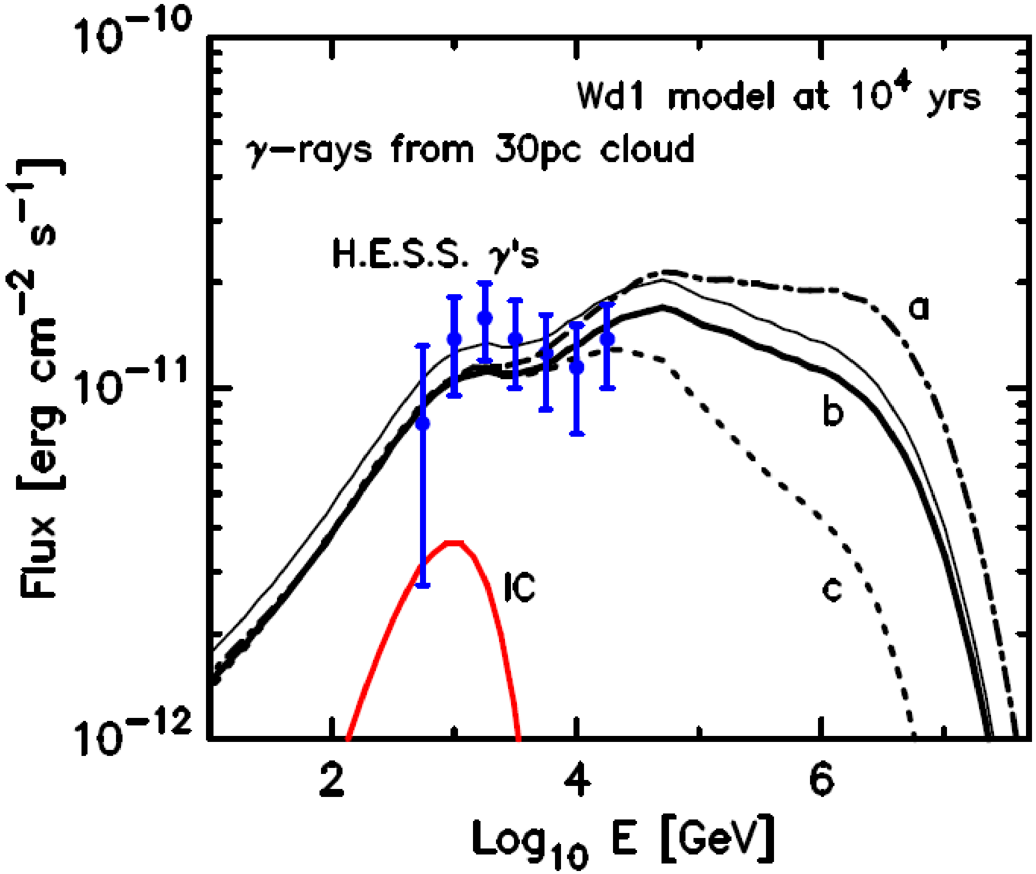


H.E.S.S. image of Westerlund I



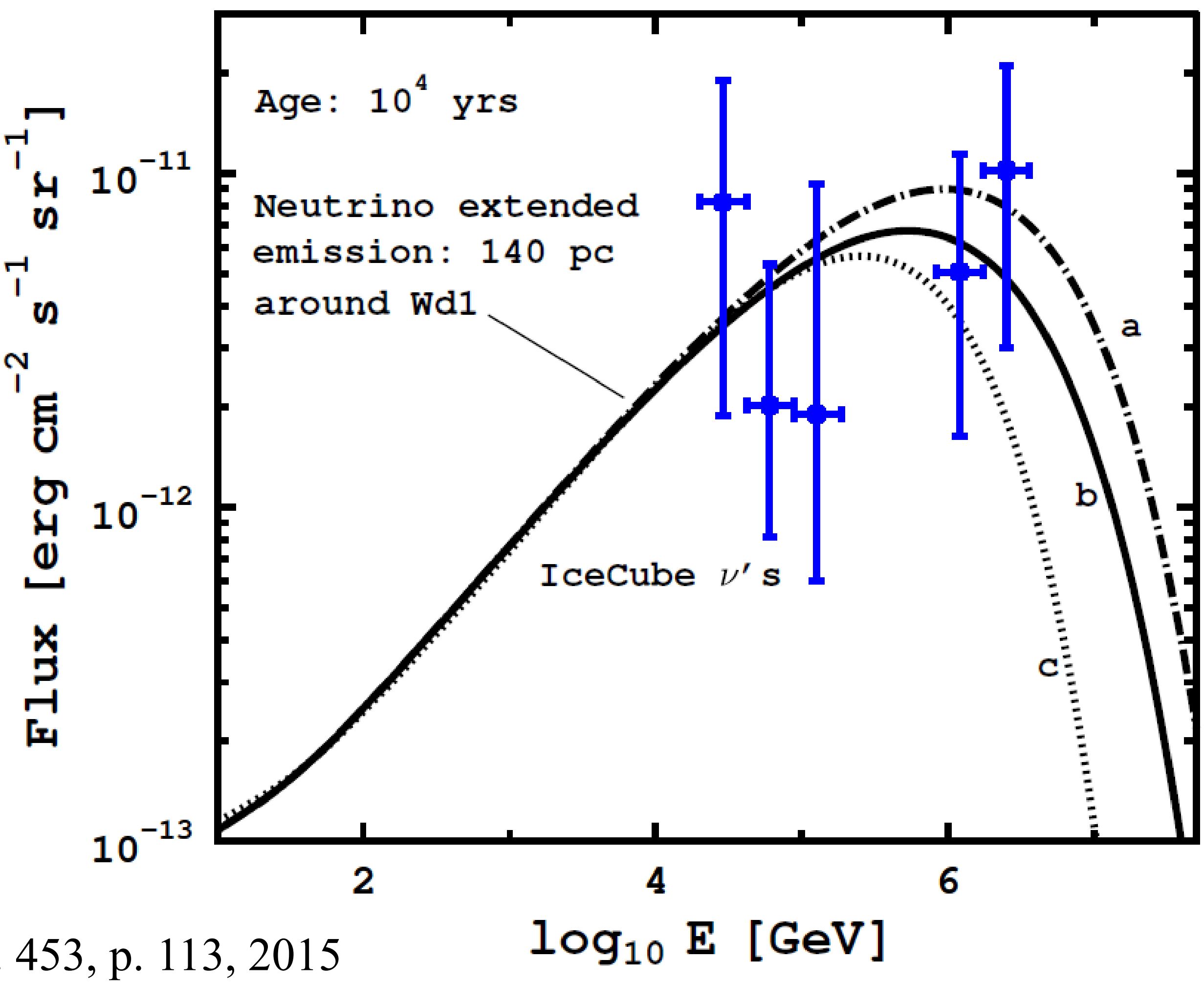
MNRAS v. 453, p. 113, 2015

Gamma-rays from a Pevatron



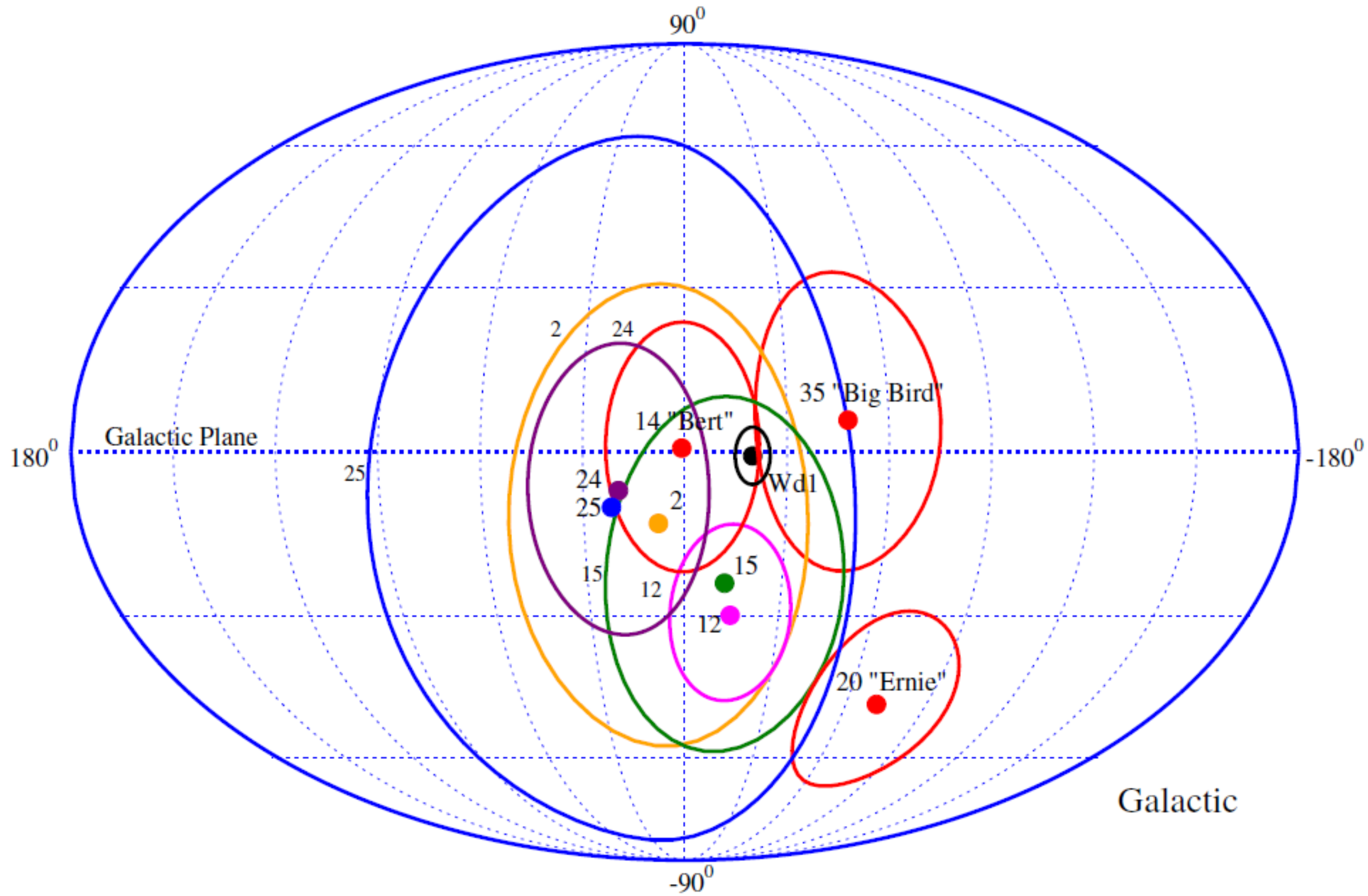
MNRAS V. 453, p. 113, 2015

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



MNRAS V. 453, p. 113, 2015

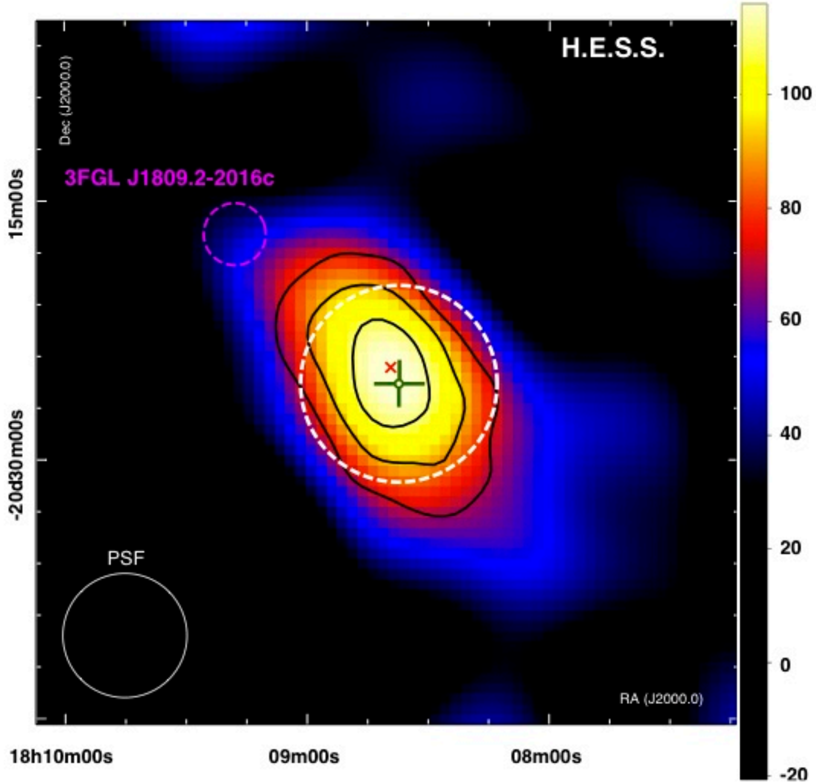
IceCube events in the vicinity of Wd I



A.B. + 2015

MNRAS V. 453, p. 113, 2015

H.E.S.S. J1808-204



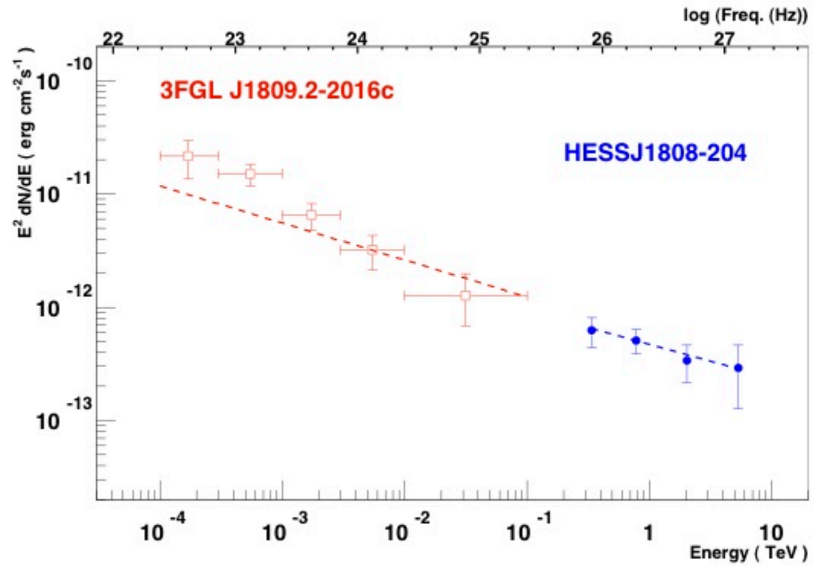


Fig. 2. Energy fluxes, 1 σ statistical errors, and fitted pure power-law fits for HESS J1808−204 (blue solid points and blue dashed line) and the *Fermi-LAT* source 3FGL J1809.2−2016c (red open squares and red dashed line) from Acero et al. (2015).

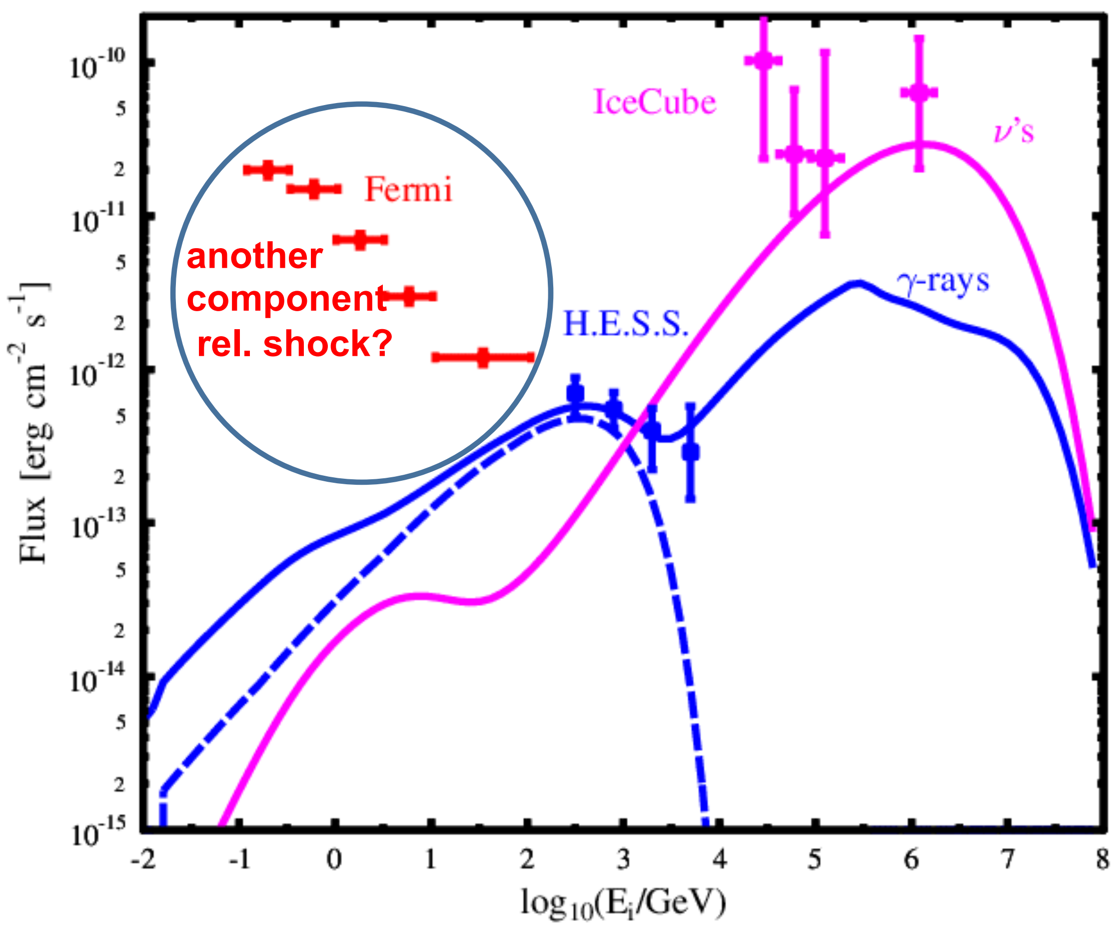
power-law photon index of 2.3 ± 0.2stat ± 0.3sys
Lvhe ~ 1.6 × 10^(34)[D/8.7 kpc]^2 erg/s

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.

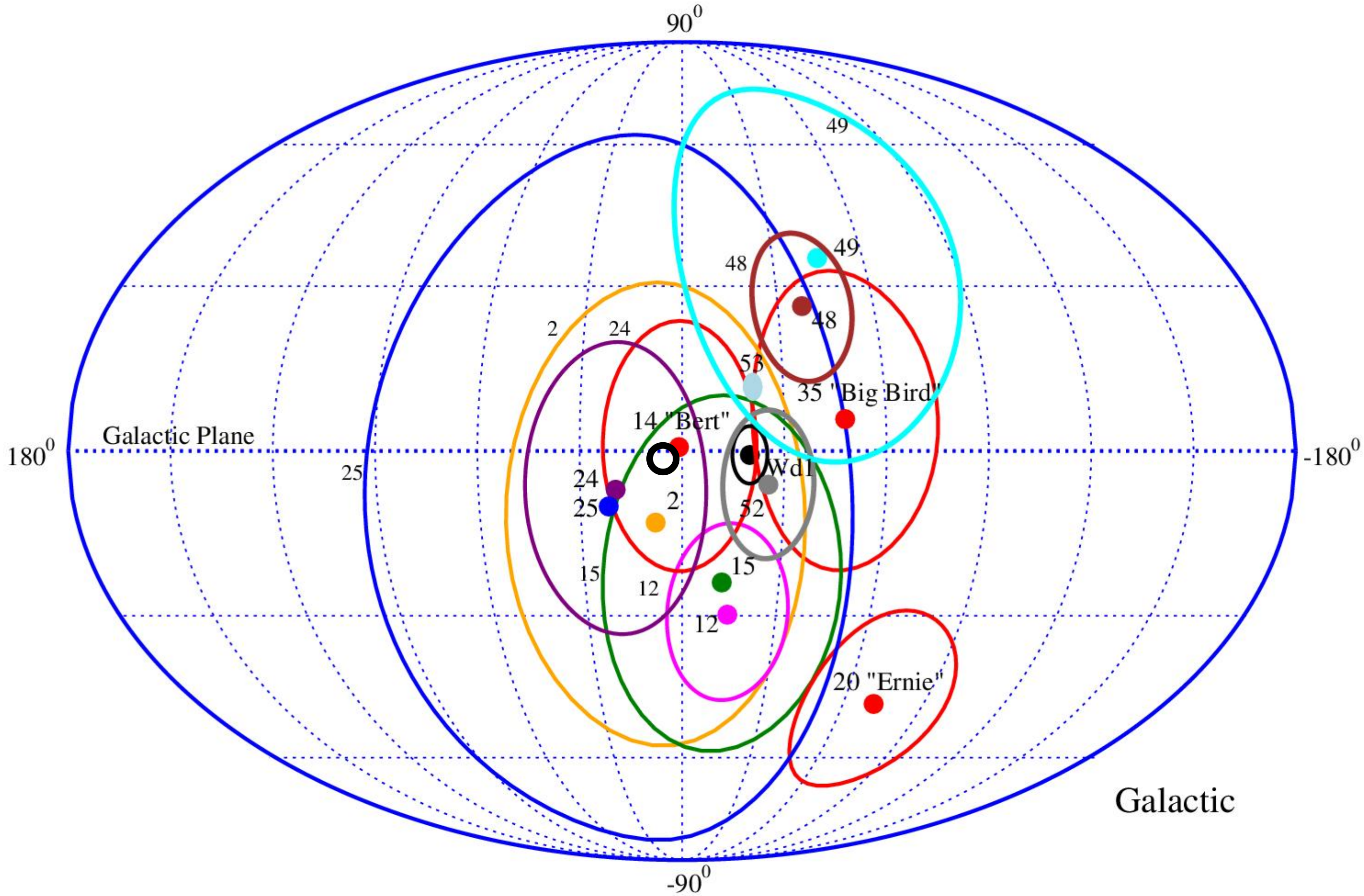
H.E.S.S. collaboration arxiv 1606.05404 2016

H.E.S.S. J1808-204 model

with gamma-rays from the H.E.S.S. imaged region and total "calorimeter" neutrinos (IC flux is for a few "nearby" events only)



Potential IceCube events from the two galactic SNe in young star clusters



Wd I = 339 32 57.6; b = -00 24 15.0 (black filled circle)
SGR1806 l=09 58 42.0; b=-00 14 33.3 (black open circle)

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

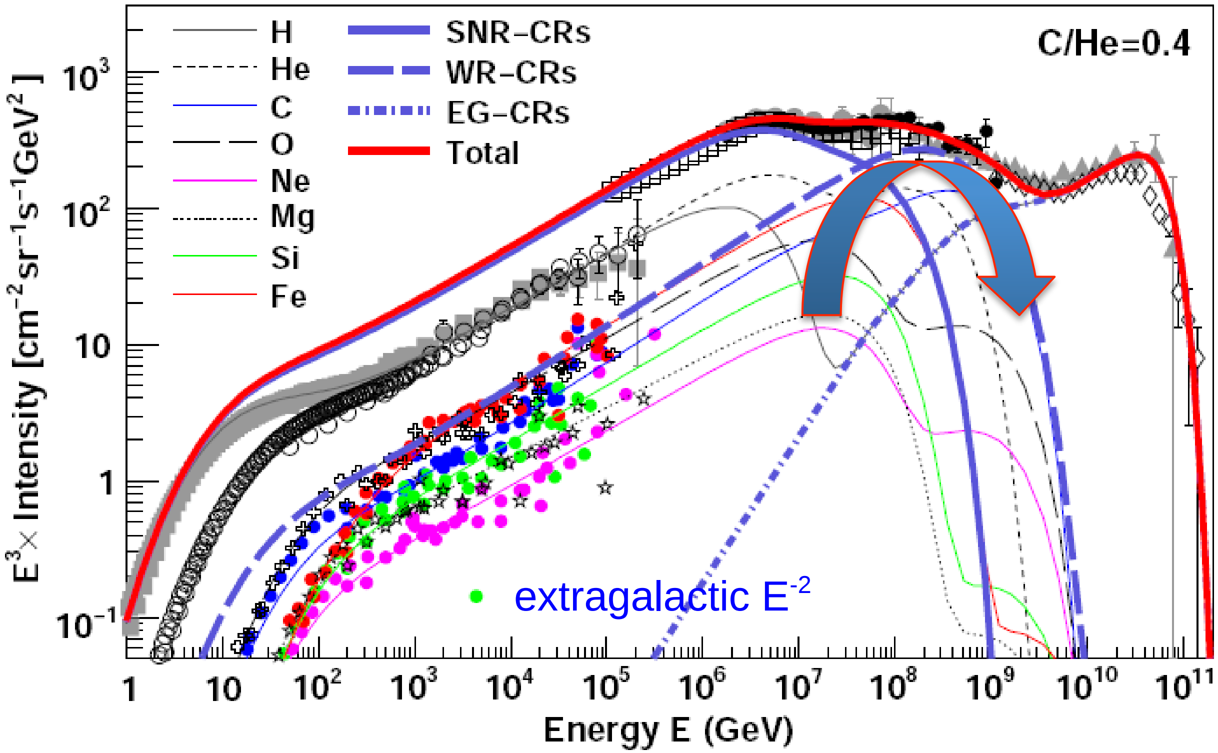


Fig. 6. Model prediction for the all-particle spectrum using the Wolf-Rayet stars model. *Top*: C/He = 0.1. *Bottom*: C/He = 0.4. The thick solid blue line represents the total SNR-CRs, the thick dashed line represents WR-CRs, the thick dotted-dashed line represents EG-CRs, and the thick solid red line 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

Currently **the expected amount of PeV sources like SNe – cluster wind collision in the Milky Way is likely a few**

However, the sources are likely dominated in the starburst galaxies (hundreds of clusters) with the high ISM pressure due to mergers etc.

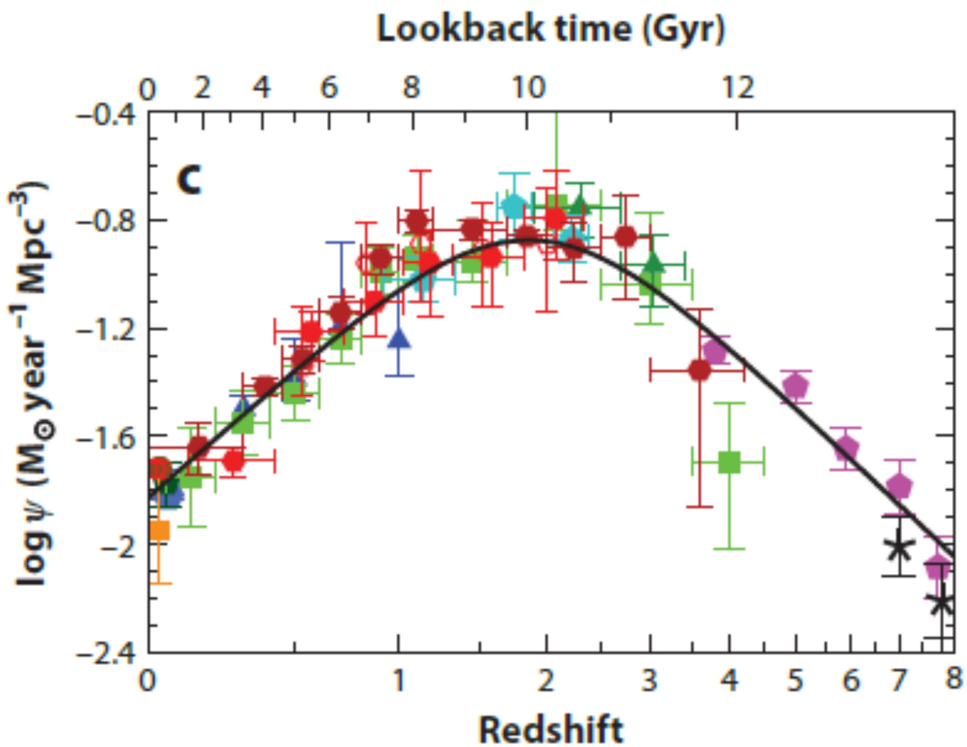
They may be the CR sources for the Waxman-Bahcall starburst calorimeter hypothesis

SNe in COMPACT CLUSTER of YOUNG MASSIVE STARS

$$L_\gamma \approx 10^{34} \left(\frac{\eta_p}{0.1}\right) \left(\frac{L_{\rm kin}}{10^{39} {\rm erg\,s^{-1}}}\right) \left(\frac{n}{\rm cm^{-3}}\right) \left(\frac{\tau_a}{5\times 10^{10}\,{\rm s}}\right) {\rm erg\,s^{-1}},$$

@ GC or starbursts $\mathrm{n} \sim 100\,\mathrm{cm}^{-3}$, $L_\gamma \sim 10^{36}\,\mathrm{erg\,s^{-1}}$

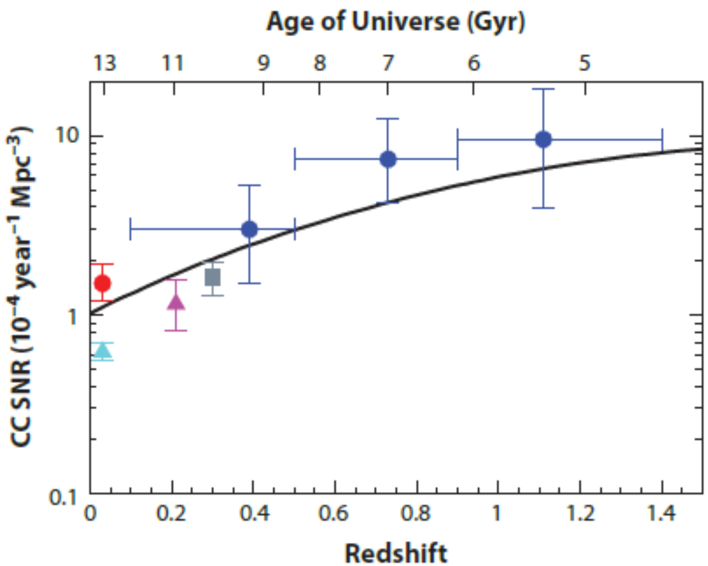
SFR from FUV+IR



$$\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1 + [(1+z)/2.9]^{5.6}} \,M_\odot \,\text{year}^{-1}\,\text{Mpc}^{-3}.$$

Madau & Dickinson, ARAA 2014

Core-collapse - SN rate



What about the cosmological evolution of young stellar clusters?

Figure 10

The cosmic core-collapse supernova (SN) rate. The data points are taken from Li et al. (2011) (*cyan triangle*), Mattila et al. (2012) (*red dot*), Botticella et al. (2008) (*magenta triangle*), Bazin et al. (2009) (*gray square*), and Dahlen et al. (2012) (*blue dots*). The solid line shows the rates predicted from our fit to the cosmic star-formation history. The local overdensity in star formation may boost the local rate within 10–15 Mpc of Mattila et al. (2012).

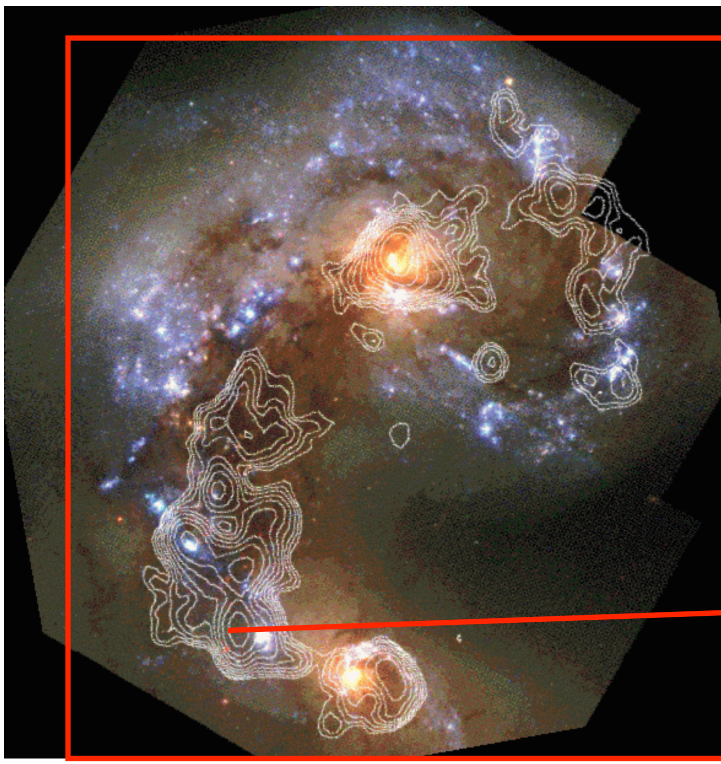
$$R_{\mathrm{CC}}(z) = \psi(z) \times \frac{\int_{m_{\min}}^{m_{\max}} \phi(m)\mathrm{d}m}{\int_{m_l}^{m_u} m\phi(m)\mathrm{d}m} \equiv \psi(z) \times k_{\mathrm{CC}}, \tag{16}$$

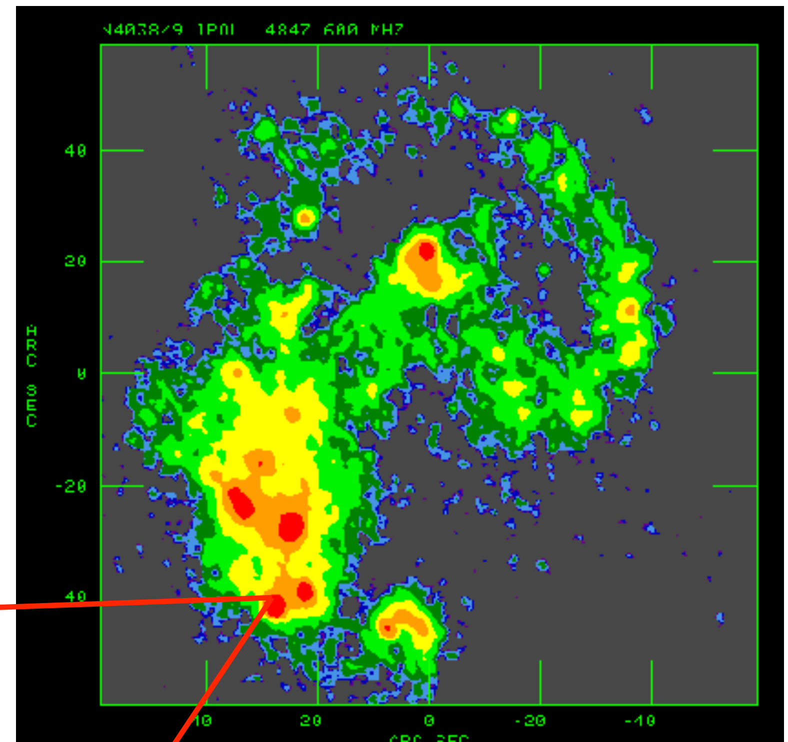
where the number of stars that explode as SNe per unit mass is $k_{\mathrm{CC}} = 0.0068\ \mathrm{M}_\odot^{-1}$ for a Salpeter IMF, $m_{\min} = 8\,\mathrm{M}_\odot$ and $m_{\max} = 40\,\mathrm{M}_\odot$. The predicted cosmic SN rate is shown in **Figure 10**

Madau & Dickinson, ARAA 2014

Nearest Merger—The "Antennae"

- WFPC2, with CO overlay (Whitmore et al. 1999; Wilson et al. 2000)
- VLA 5 GHz image (Neff & Ulvestad 2000)





5 mJy 30,000 O7-equivalent stars

SNe in YMSCs can accelerate CRs well above PeV with a specific hard spectrum of an upturn-type

The efficiency of YMSC formation in starbursts may be ~ 0.4

Then ~ 10^{-5} Mpc^{-3} yr^{-1} of CC SNe are YMSCs in starbursts providing CR power > 10^{44} ergs Mpc^{-3} yr^{-1}

This is consistent with the Waxman-Bahcall starburst calorimeter and the hard spectrum may be useful to avoid a conflict with Fermi gamma-ray diffuse emission flux

Thanks for your attention!

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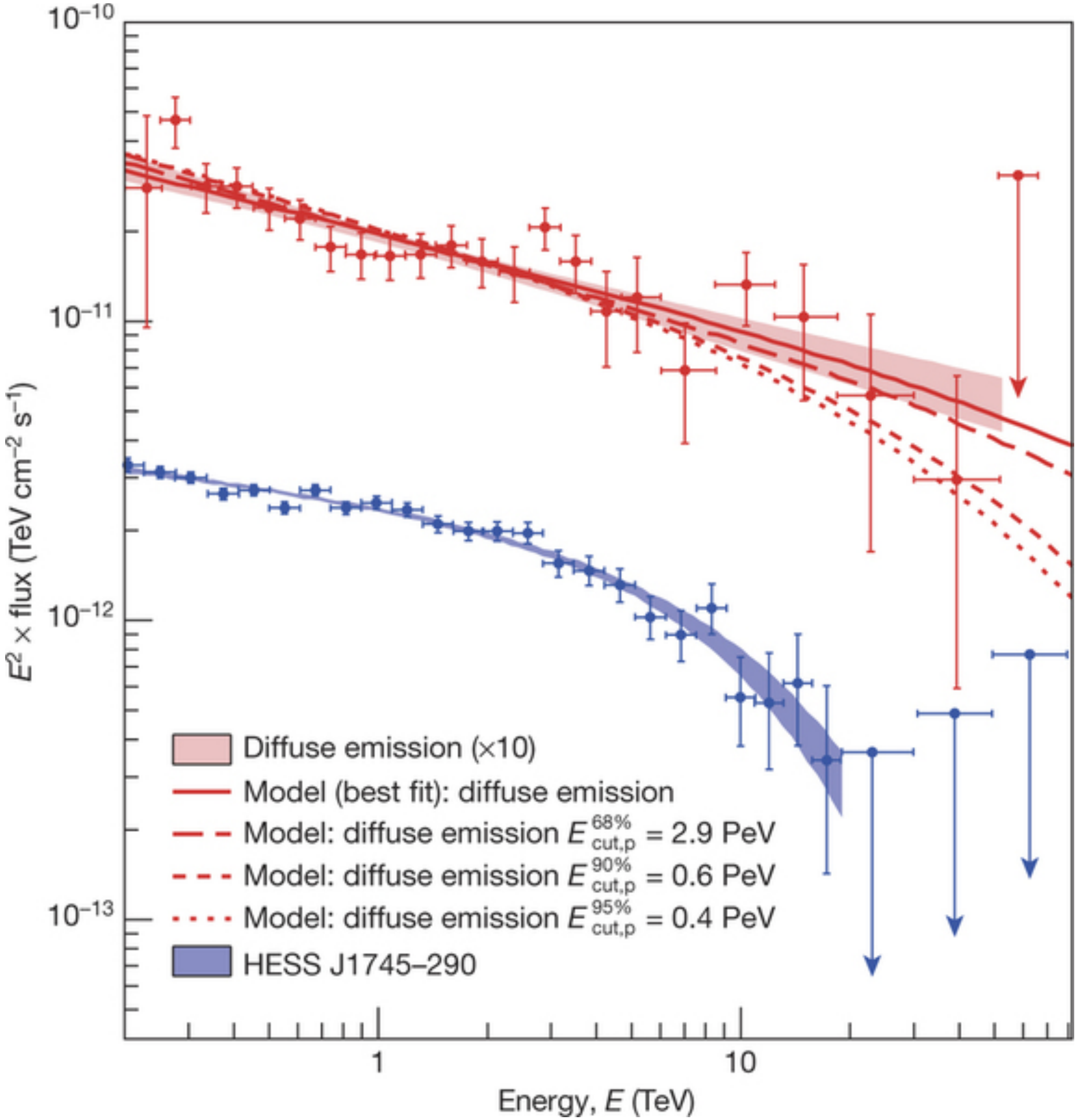
Acceleration of petaelectronvolt protons in the Galactic Centre?



SNR in GC wind?
YMSC wind- Sne?

HESS collaboration Nature 531, 476, 2016