

# **Supernovae in stellar clusters as CR pevatrons**

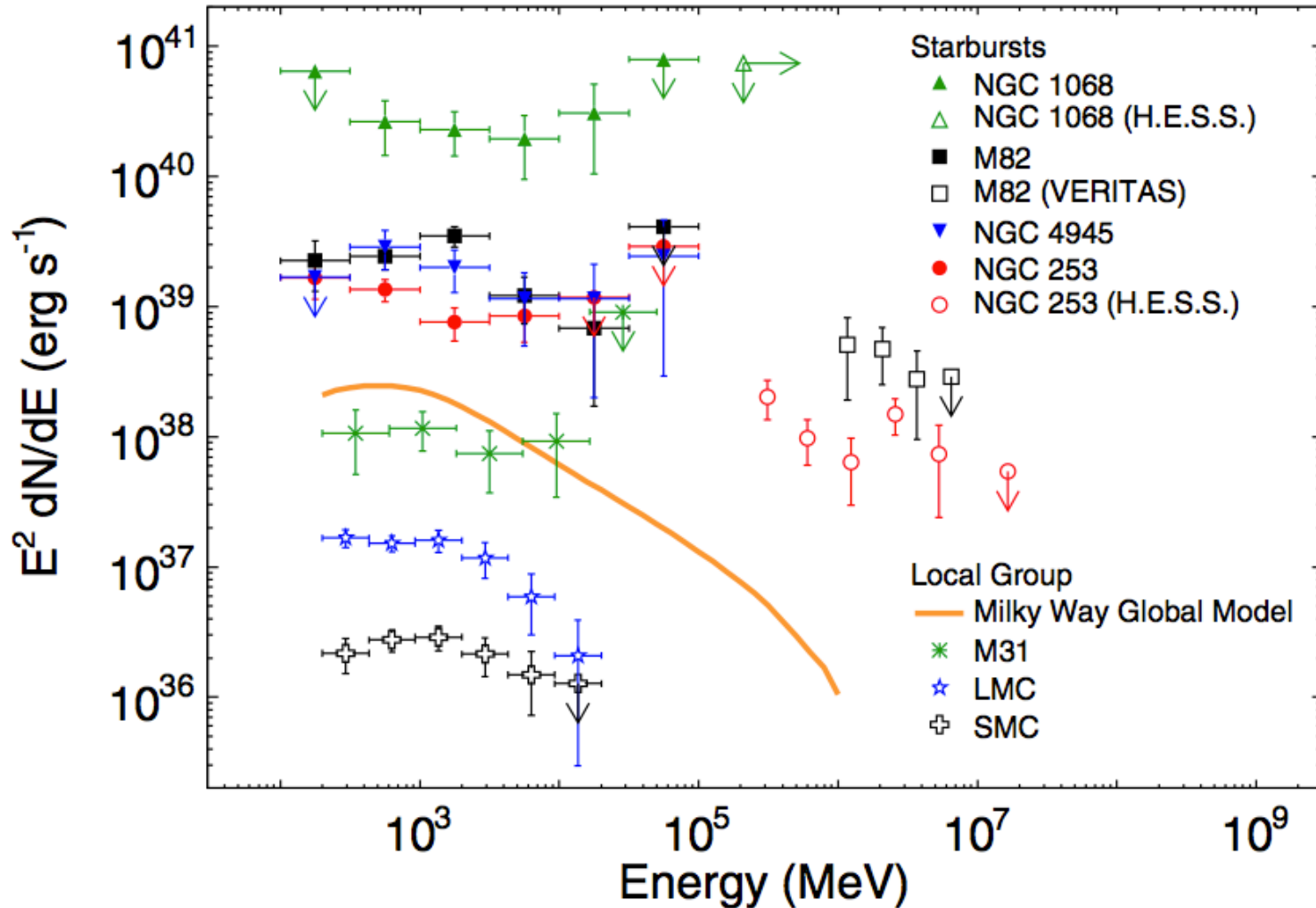
**A.M. Bykov**

**High Energy Astrophysics**

**Ioffe Institute, St.Petersburg, Russian Federation**

**Collaborators: D.C.Ellison, P.E.Gladilin, S.M. Osipov**

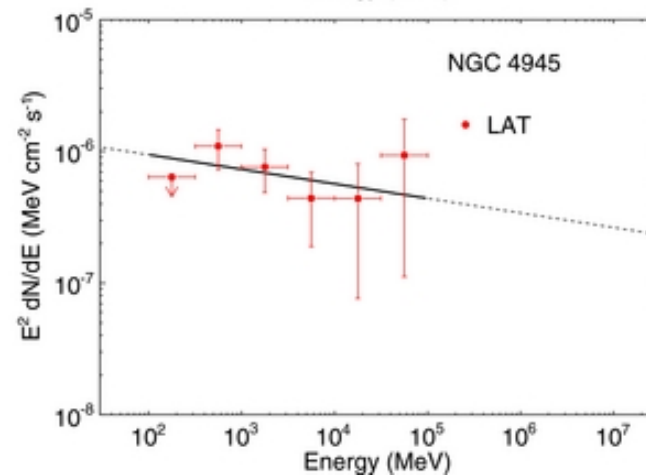
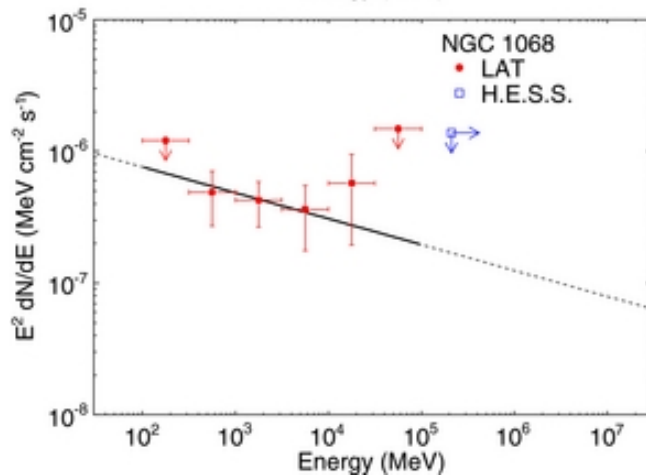
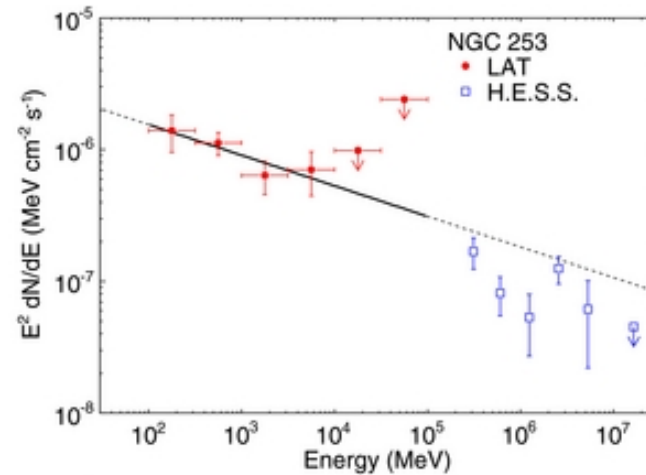
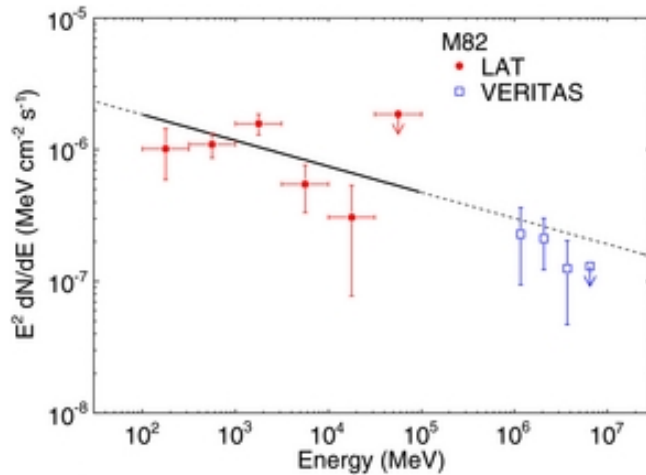
# Gamma Ray Spectral Energy Distribution: Starburst galaxies



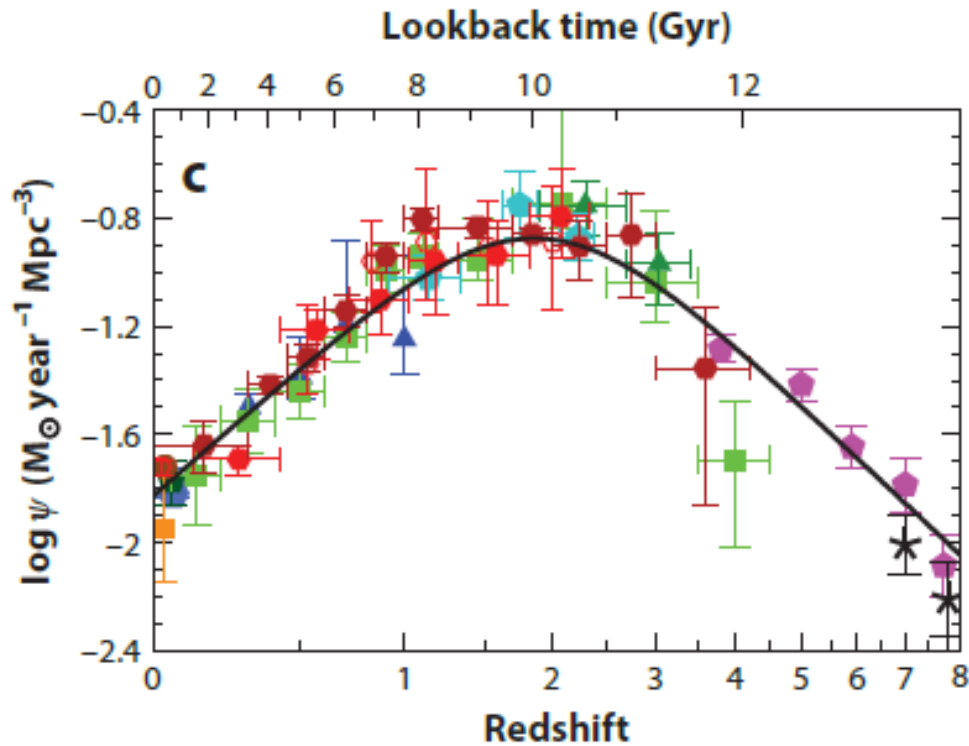
A&ARv v.22, p.54, 2014

S.Ohm, CRePhy, v.17, p. 585, 2016

# Gamma Ray Spectral Energy Distribution: Starburst galaxies

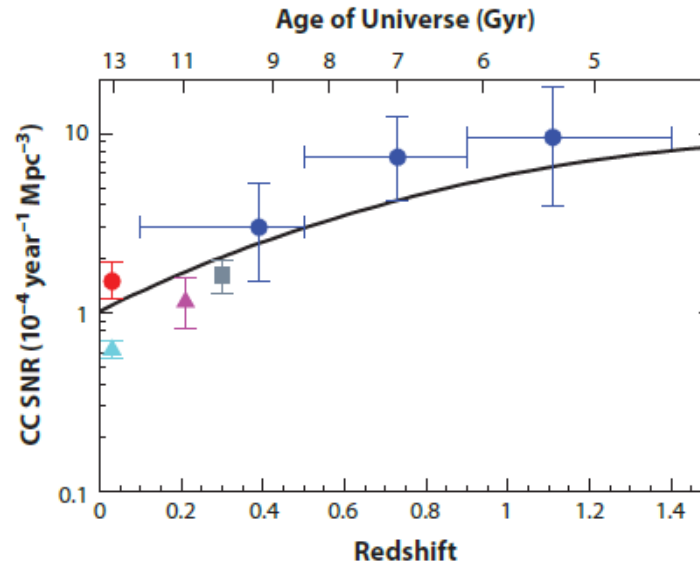


# SFR from FUV+IR



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

# Core-collapse - SN rate



**Figure 10**

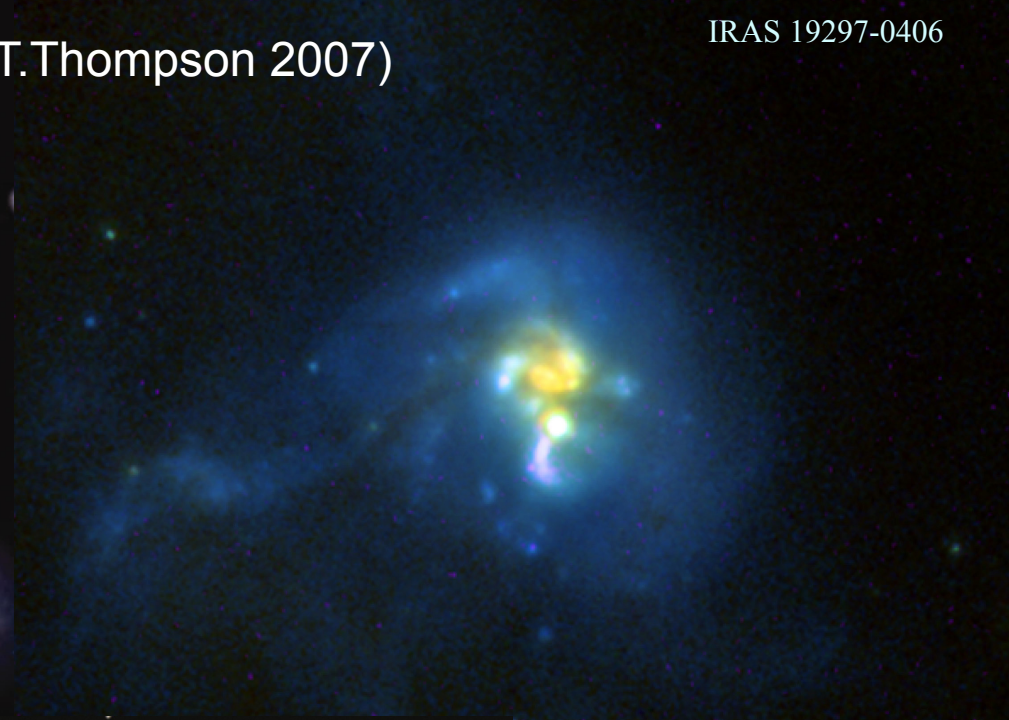
The cosmic core-collapse supernova (SN) rate. The data points are taken from Li et al. (2011) (*cyan triangle*), Mattila et al. (2012) (*red dot*), Botticella et al. (2008) (*magenta triangle*), Bazin et al. (2009) (*gray square*), and Dahlen et al. (2012) (*blue dots*). The solid line shows the rates 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).

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

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

# Starbursts (T.Thompson 2007)

M82



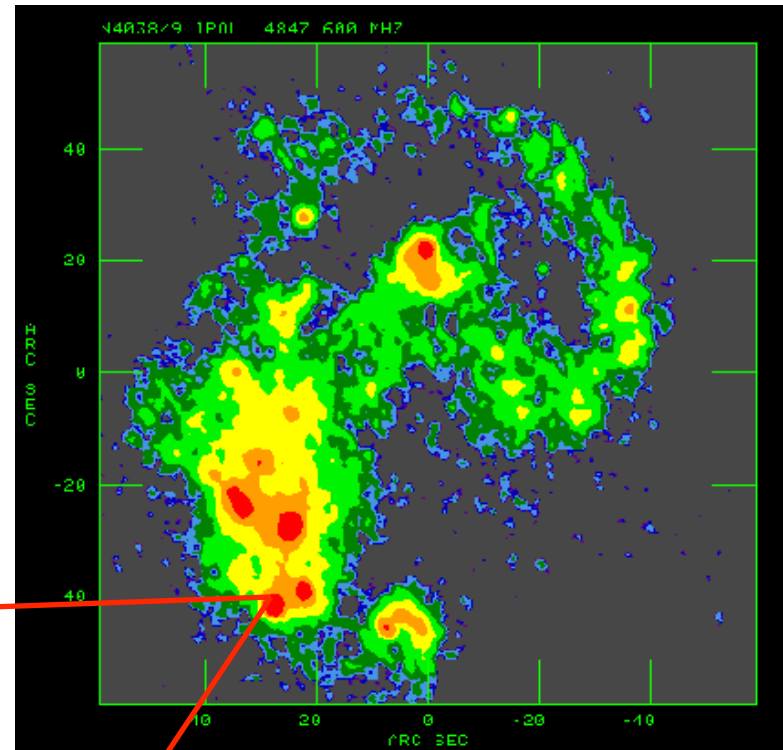
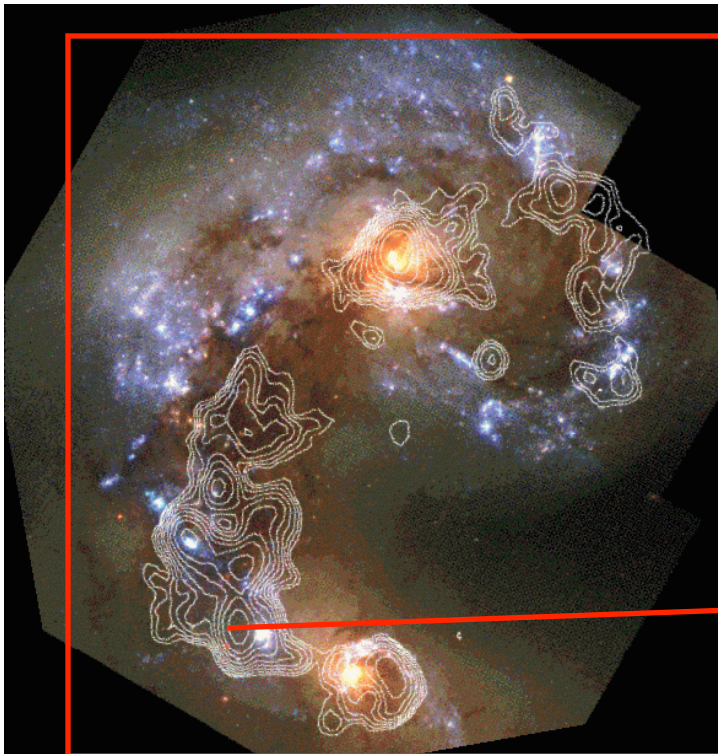
NGC 253



Arp 220

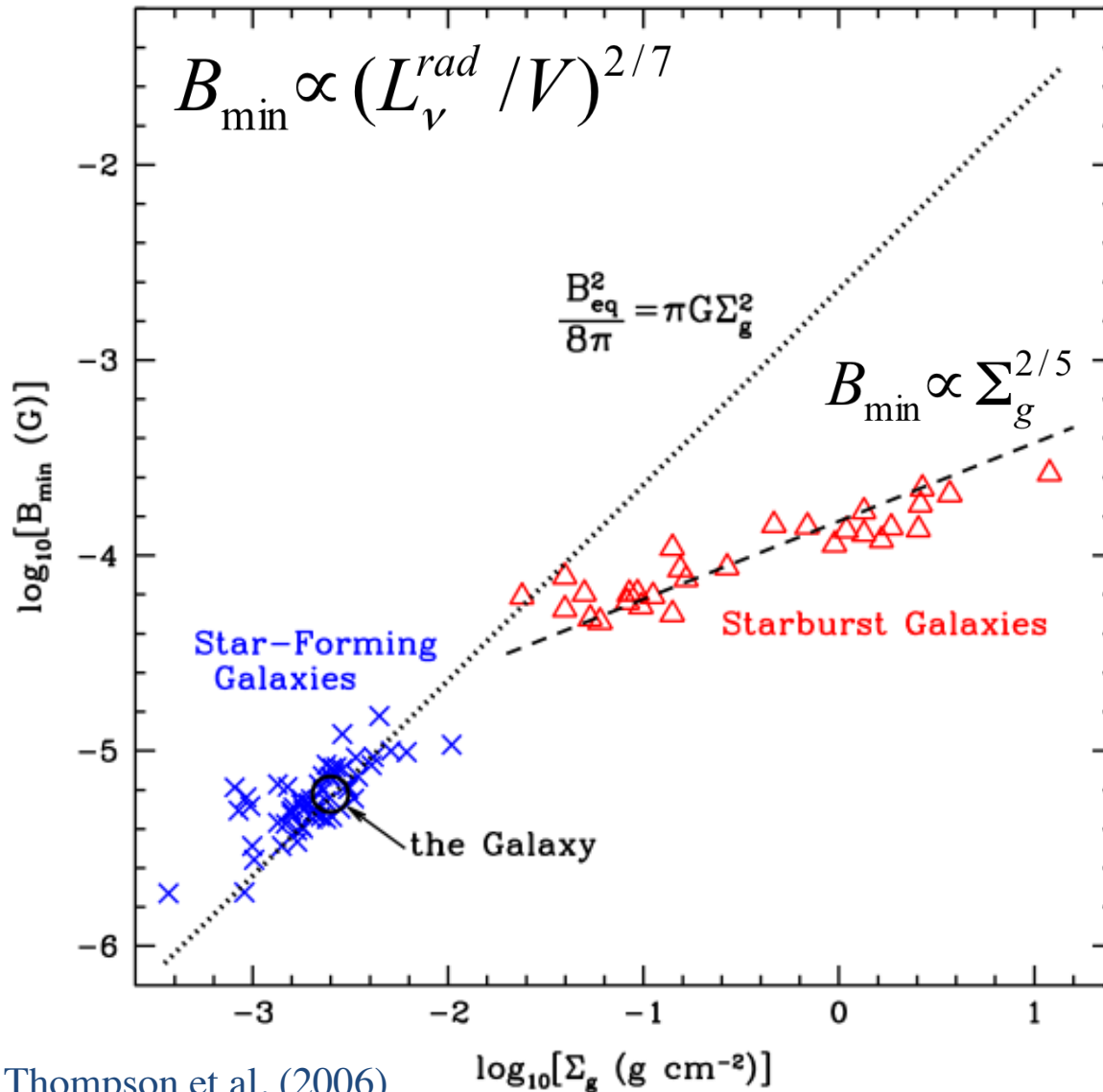
# Nearest Merger—The “Antennae”

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



5 mJy  $\approx$  30,000 O7-equivalent stars

# Magnetic Fields in starbursts from radio observations

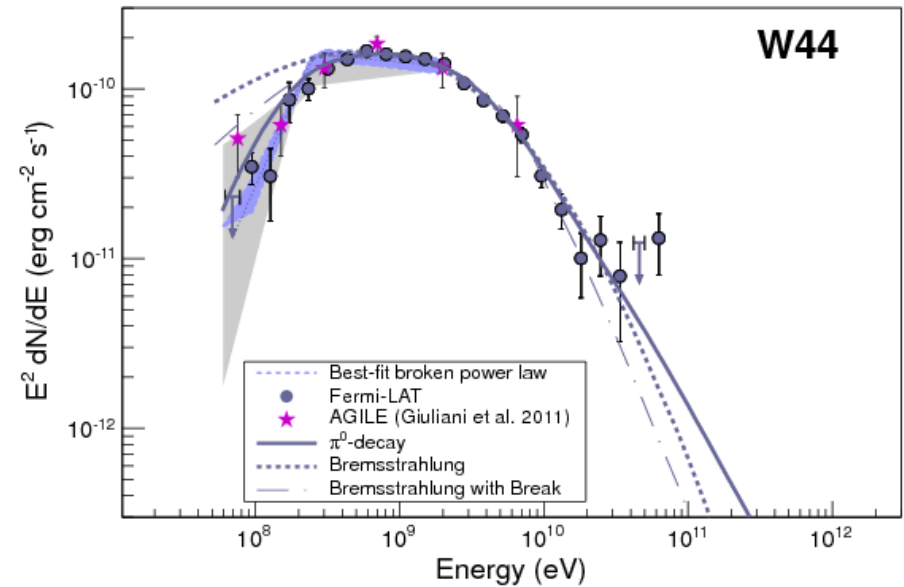
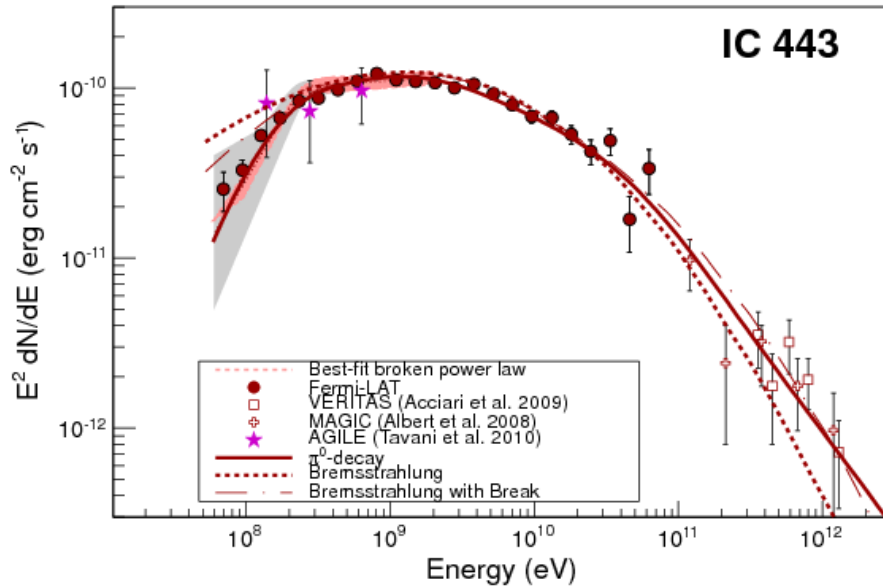


If a fraction  $\sim 1\%$  of  $10^{51}$  ergs per SN goes to CR electrons, **and they cool rapidly**, the observed trend is reproduced.



**What are the HE CR sources in  
starforming / starburst regions?**

# SNR in Molecular Clouds

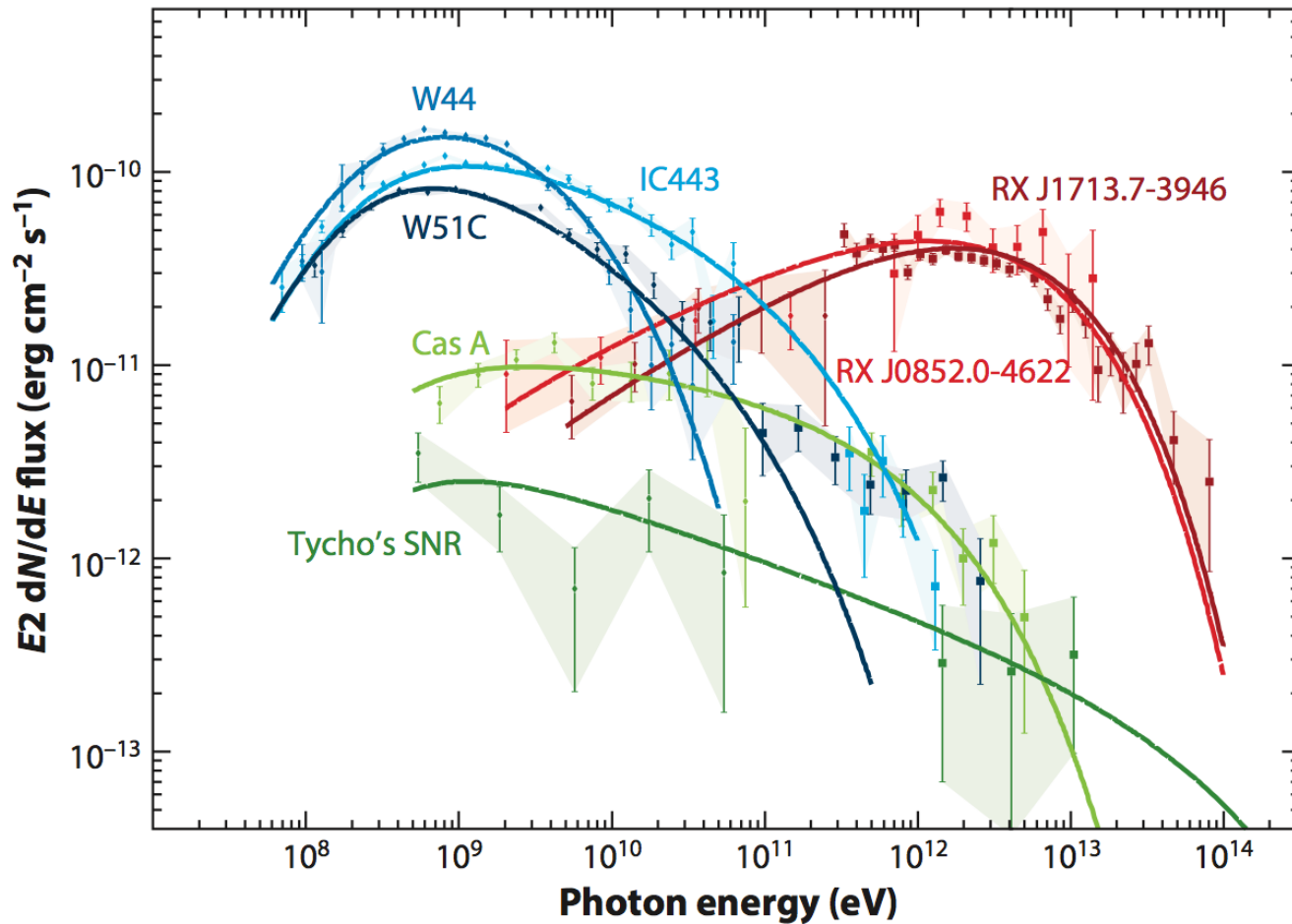


M.Ackermann 2013

## *Pion-Decay Signatures*

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

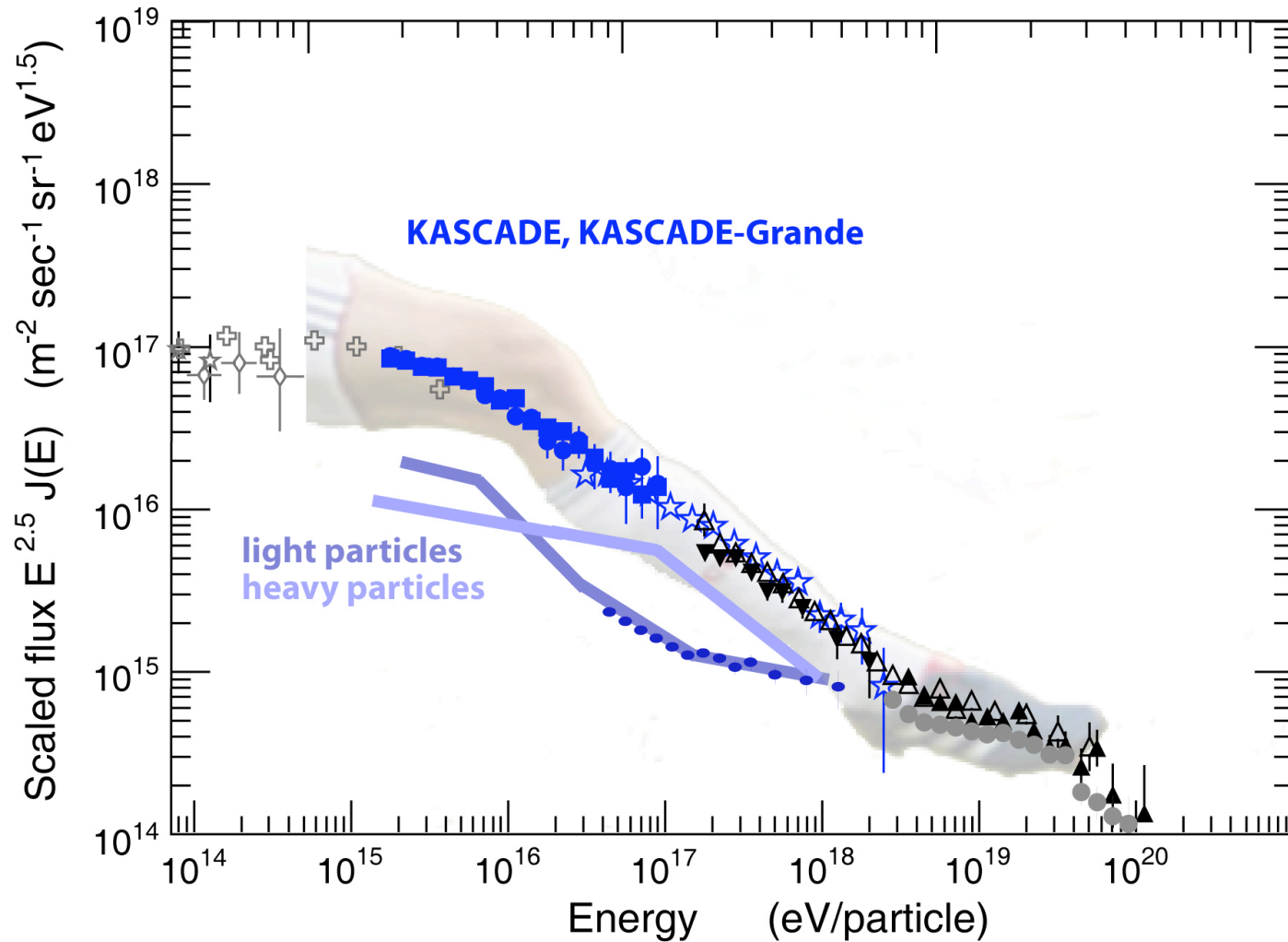
# Observed gamma-ray spectra of SNRs



S. Funk 2015

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

# PeV CRs are likely accelerated in the Galaxy



# How to get PeV energy CRs?

**Rare SNe with a special CSM type II<sub>n</sub>?**

**Rare magnetar-driven SNe?**

**SNR- Stellar/Cluster Wind collision?**

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

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

for a SN in SSC (age 400 yrs)

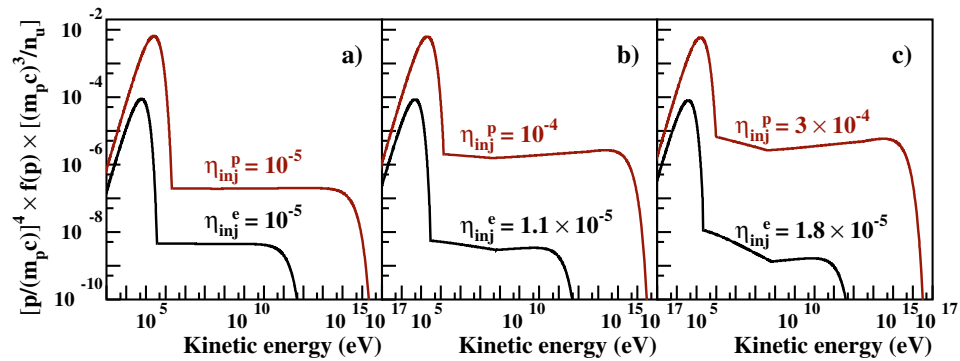
$$L_{\text{kin}} \leq 10^{41} \text{ erg s}^{-1}$$

# PeV proton acceleration in young SNe

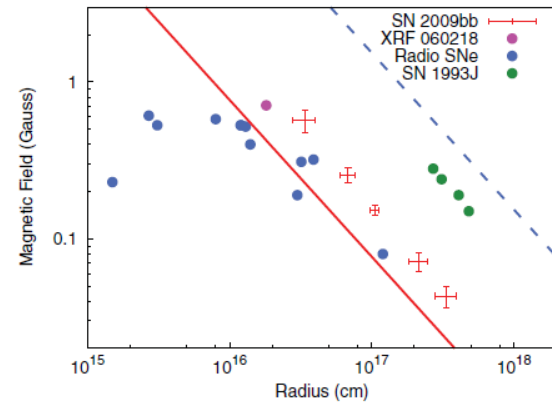
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# CR proton acceleration by radio SNe and trans-relativistic SNRs

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



**V.Tatischeff 2009**



**Figure 1. Hillas Diagram:** Mildly relativistic sources ( $\beta/\Gamma \sim 1$ ) must lie above the *solid line*, to accelerate Iron nuclei to 60 EeV by diffusive shock acceleration, according to  $E_Z \lesssim \beta e Z B R / \Gamma$ . Non-relativistic SNe ( $\beta/\Gamma \sim 0.05$ ) must lie above the *dashed line* to reach the same energies. Radius and magnetic field of SN 2009bb (crosses, at 5 epochs, determined here from radio observations with VLA and GMRT assuming equipartition) and XRF 060218 lie above the solid red line. Other balls denote other radio SNe from Chevalier (1998). For SN 1993J only, the magnetic fields are obtained by Chandra, Ray, & Bhatnagar (2004) without assuming equipartition. All non-relativistic SNe including SN 1993J lie below the dashed line and are unable to produce UHECRs unlike the mildly relativistic SN 2009bb and XRF 060218 which lie above the solid line.

S.Chakraborti, A.Ray, A.Soderberg, A.Loeb, P.Chandra 2011



## CR proton acceleration by SNe type II in with dense pre-SN wind

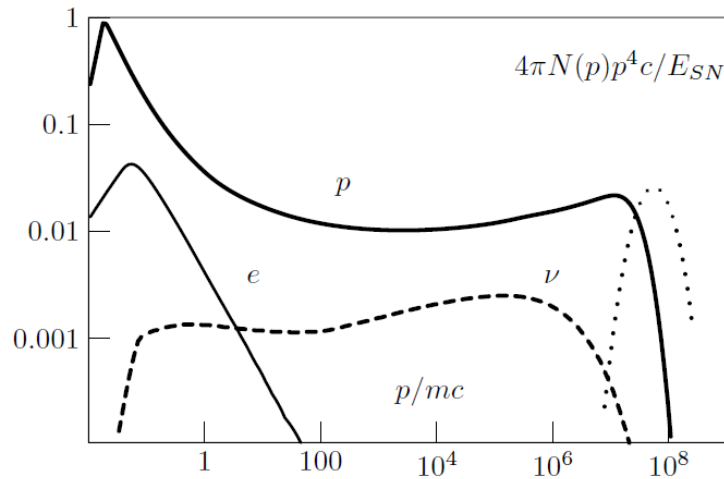
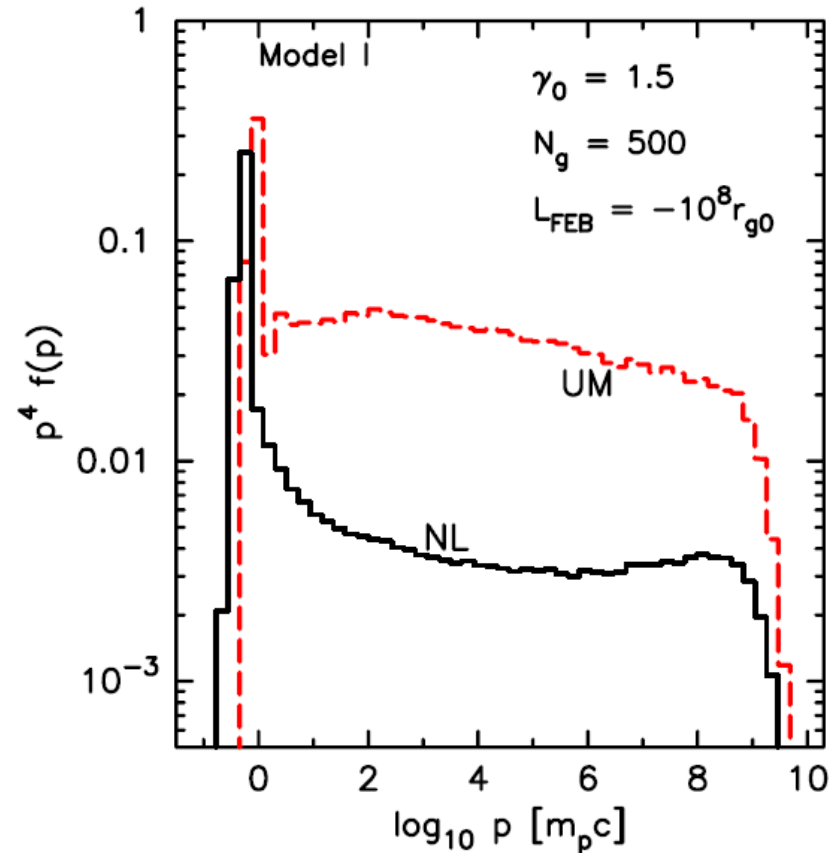


Figure 4: Spectra of particles produced in the supernova remnant during 30 yr after explosion. The spectrum of protons (thick solid line), the spectrum of secondary electrons (multiplied on  $10^3$ , thin solid line), the spectrum of neutrinos (thick dashed line) are shown.

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

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

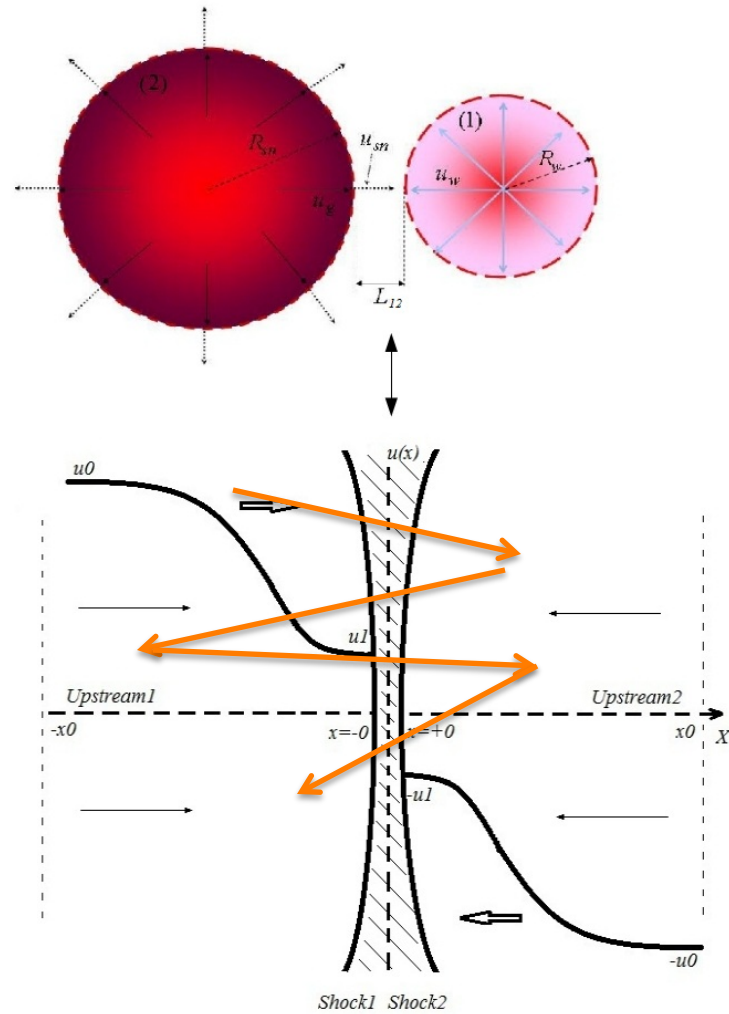


CR proton acceleration by trans-relativistic SNe  $\beta/\Gamma \sim 1$   
Ellison, Warren, AB  
**ApJ v.776, 46, 2013**

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



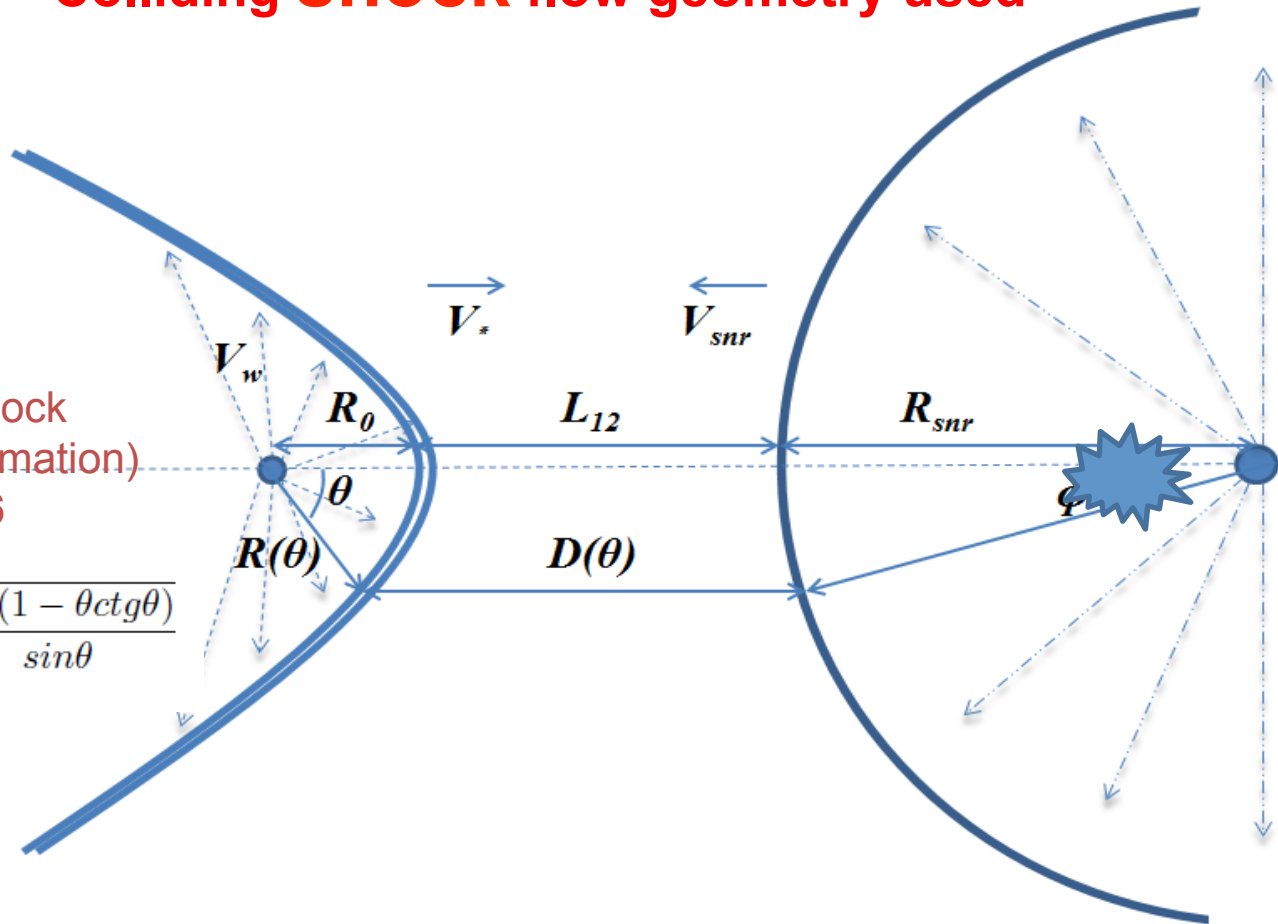
# SNR - cluster wind accelerator



# Colliding shock flow geometry used

Stellar wind shock  
(thin shell approximation)  
Wilkin 1996

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



# SNR-stellar wind accelerator

## Non-linear kinetic model

Transport equation for CR distribution function

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

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

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

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

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

# 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,

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

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

and  $W_0(p) = W(x_0, p)$ .

cf Malkov' 97; Amato & Blasi 05; Caprioli + 11

# SNR-stellar wind accelerator

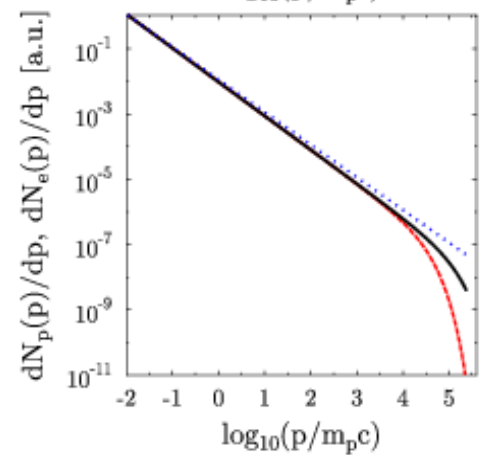
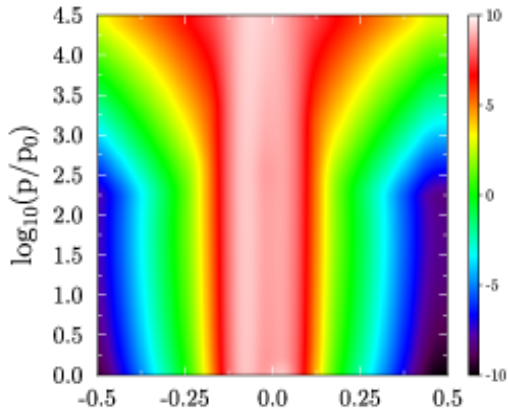
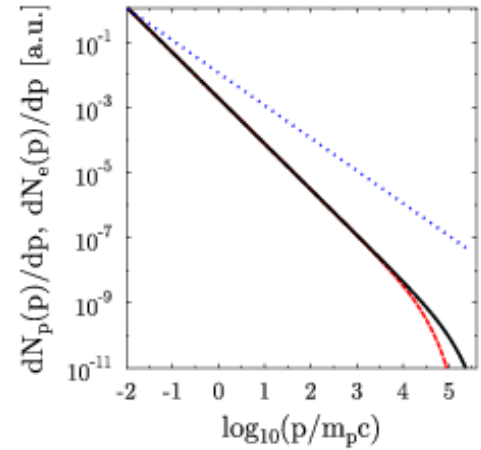
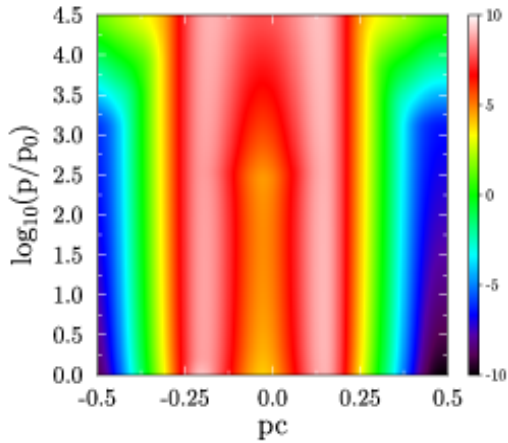
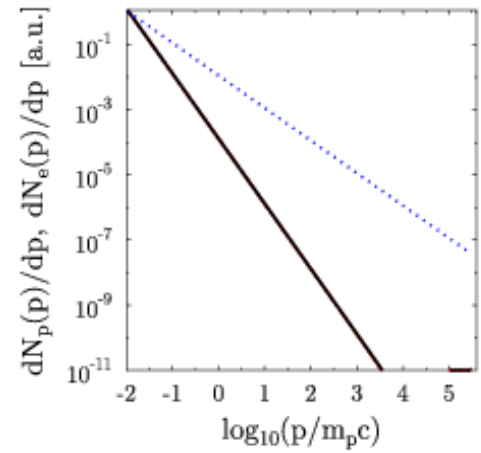
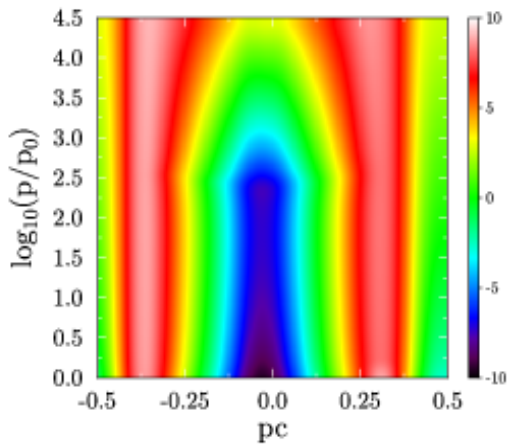
We solve one-dimensional transport equations for the pitch-angle-averaged phase space distribution function of protons,  $f_p(x, p, t)$ , and electrons,  $f_e(x, p, t)$ , given by

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

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

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

# SNR-stellar wind accelerator





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

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

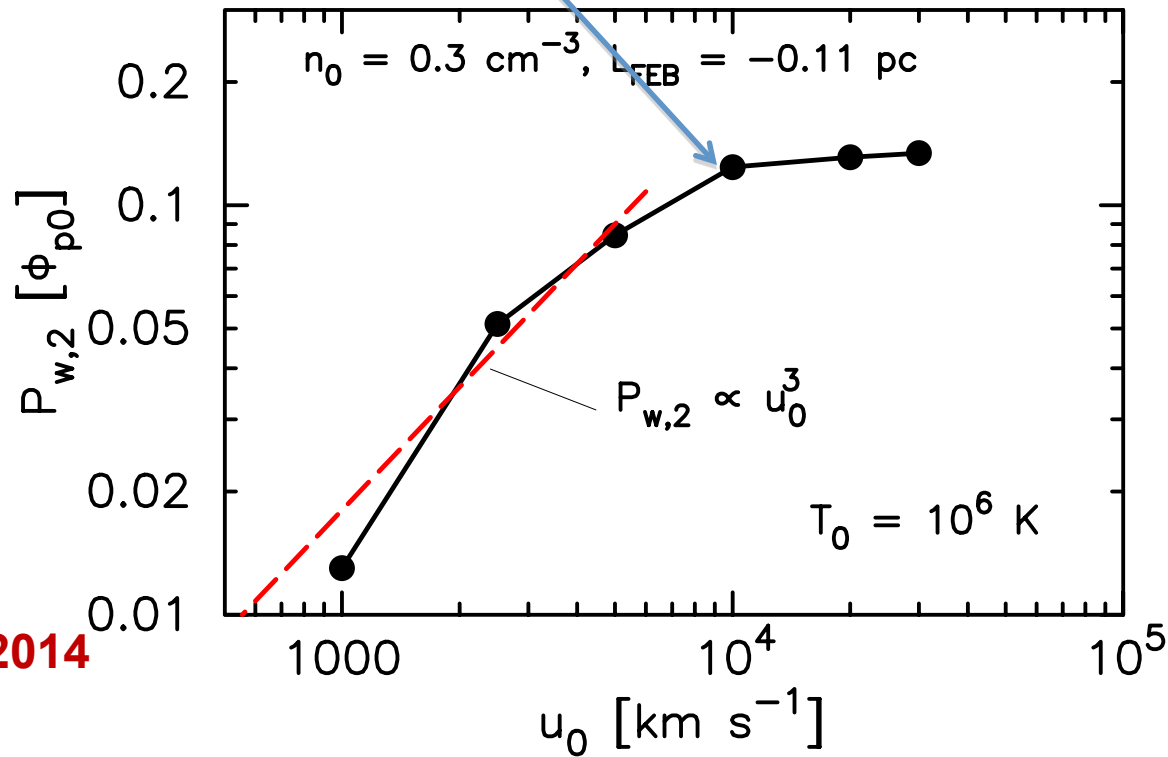
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## Acceleration time in the test particle approximation for Bohm diffusion

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

Acceleration time is about 500 yrs for 10-40 PeV

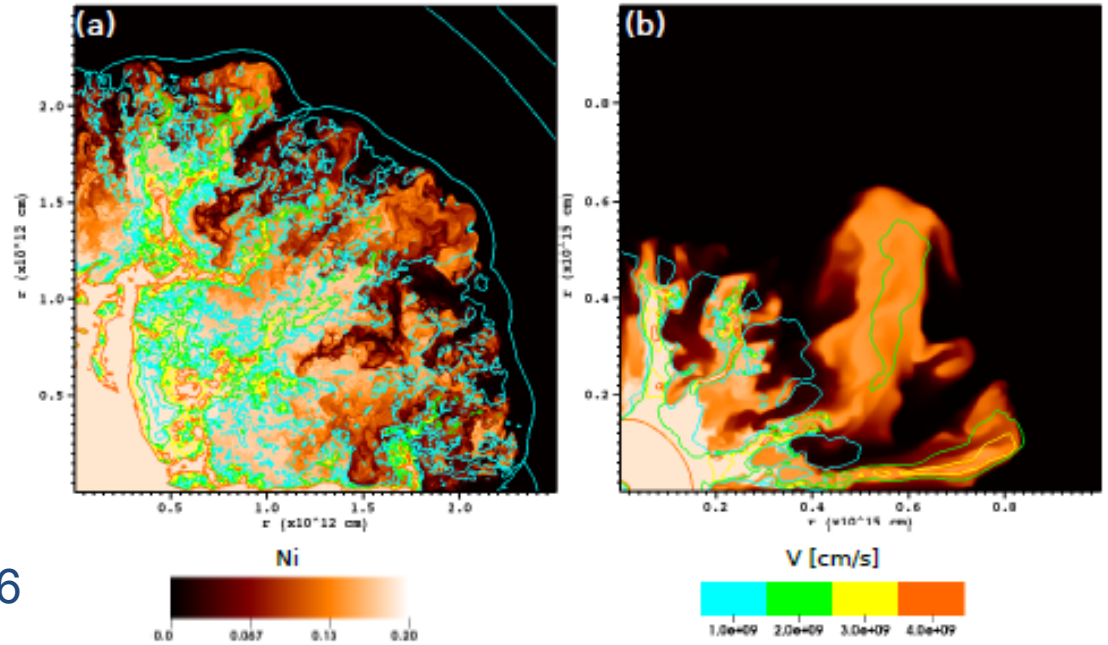
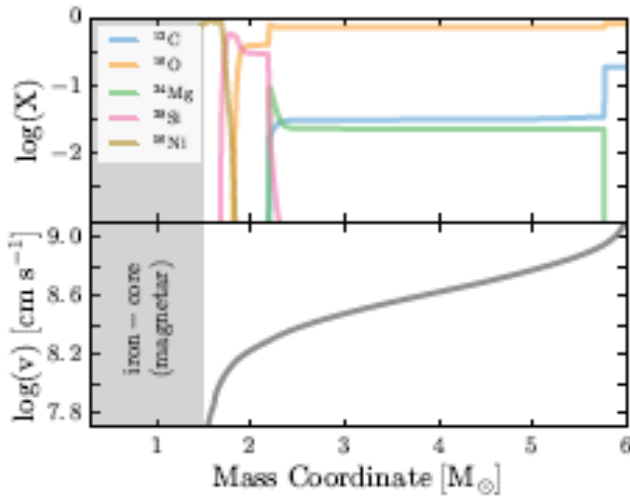
$$\tau_a \approx 2 \cdot 10^{10} \mathcal{E}_{\text{PeV}} (\eta_b n)^{-0.5} u_{s3}^{-2} u_{w3}^{-1} \text{ (s)}$$



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

**ApJ v.789, 137, 2014**

# MAGNETAR-POWERED SUPERNOVAE IN TWO DIMENSIONS. SUPERLUMINOUS SUPERNOVAE



Chen, Woosley & Sukhbold 2016

FIG. 12.— 2D  $^{56}\text{Ni}$  and velocity distributions for the 1 ms model (Panel a) and 5 ms model (Panel b) at the last model calculated.  $^{56}\text{Ni}$  is mixed out with velocities of  $1 \times 10^9$   $\text{cm s}^{-1}$ . In Panel a, the entire shell has reached the weak breakout regime and will become optically thin region when the strong breakout occurs. In Panel b, two prominent  $^{56}\text{Ni}$  fingers appear at the breakout phase. The mixing of  $^{56}\text{Ni}$  and other chemical elements may be reflected in the spectrum.

## SNe in COMPACT CLUSTER of YOUNG MASSIVE STARS

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

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

# A Galactic Super Star Cluster



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

2MASS Atlas Image from M.Muno

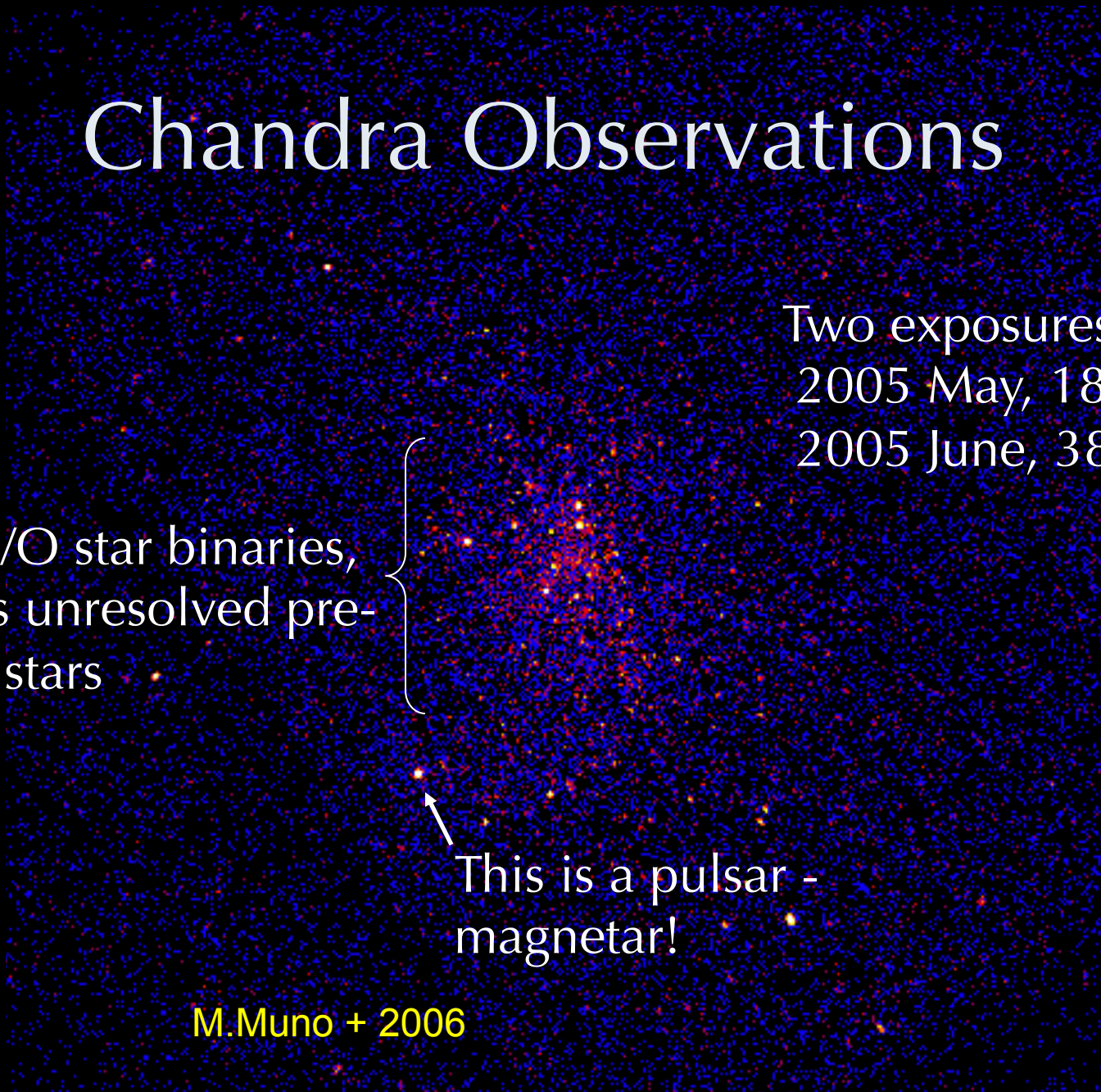
# Chandra Observations

Two exposures:  
2005 May, 18 ks  
2005 June, 38 ks

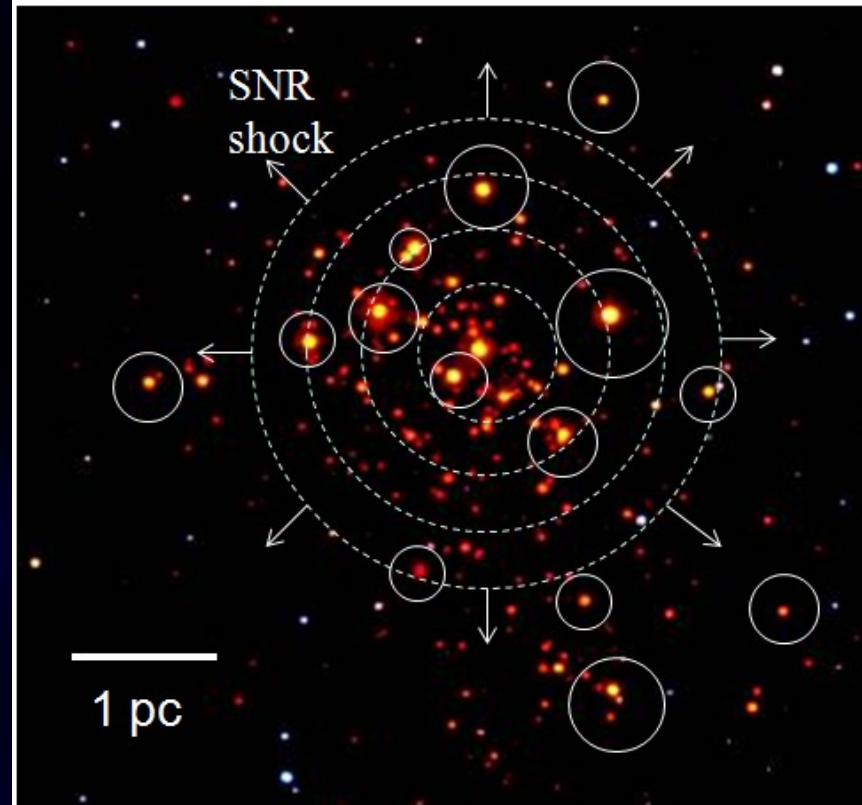
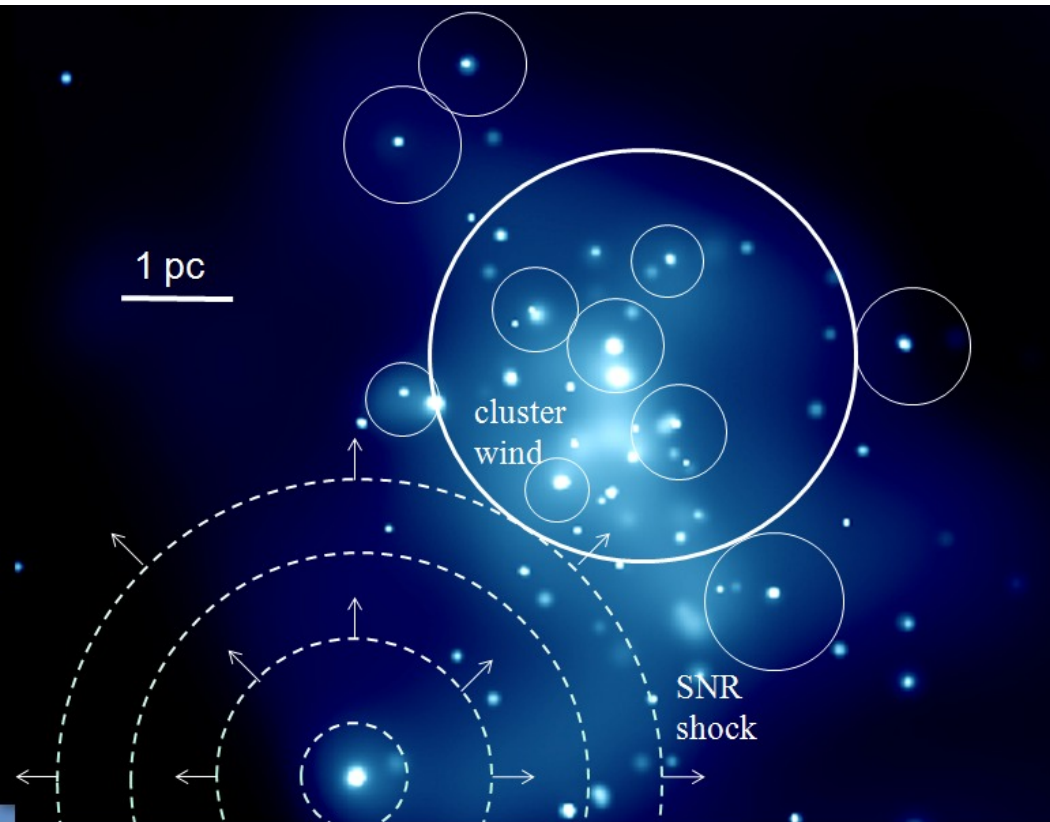
WR/O star binaries,  
plus unresolved pre-  
MS stars

This is a pulsar -  
magnetar!

M.Muno + 2006

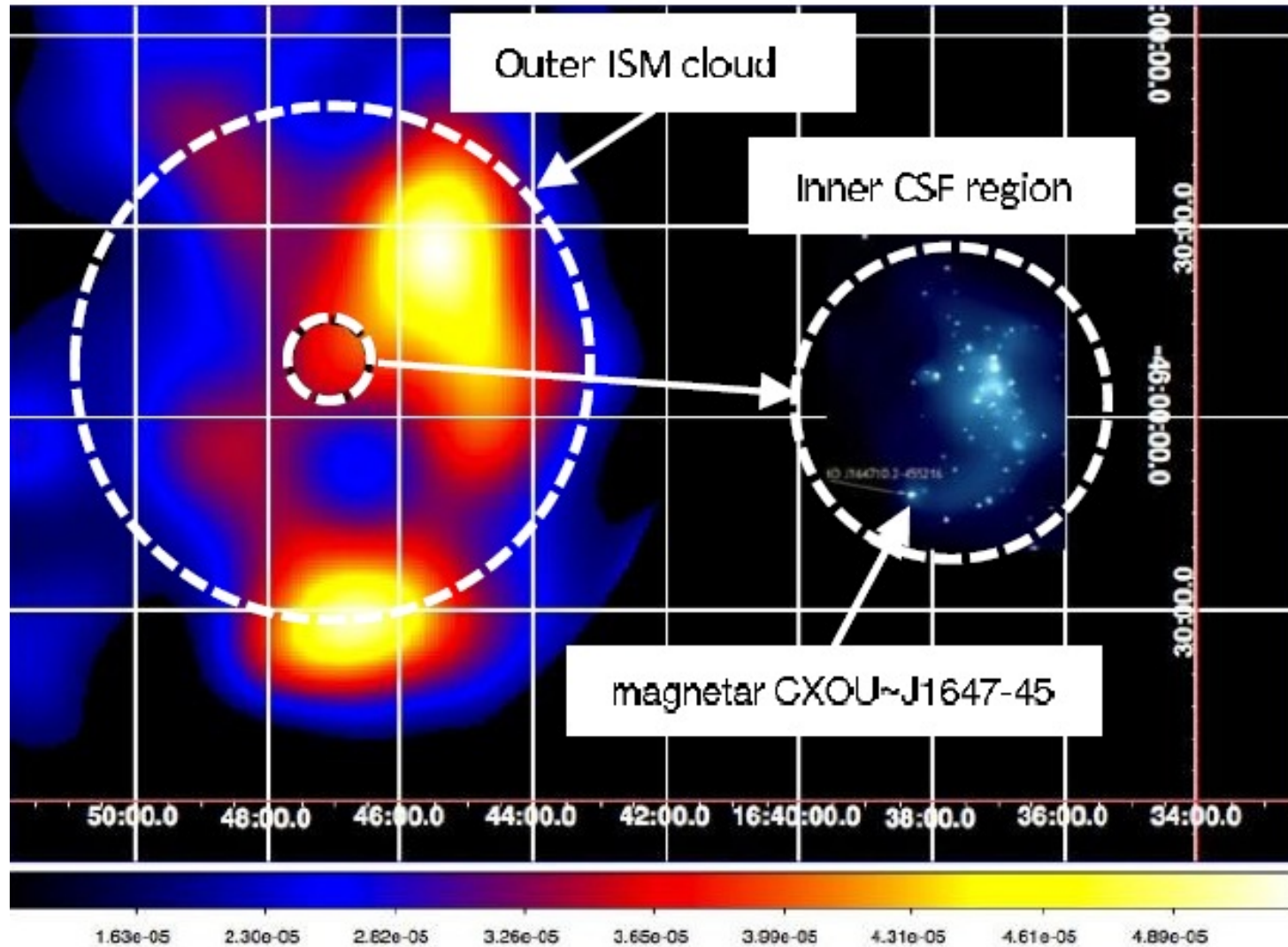


# Westerlund 1





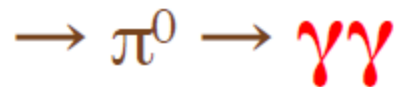
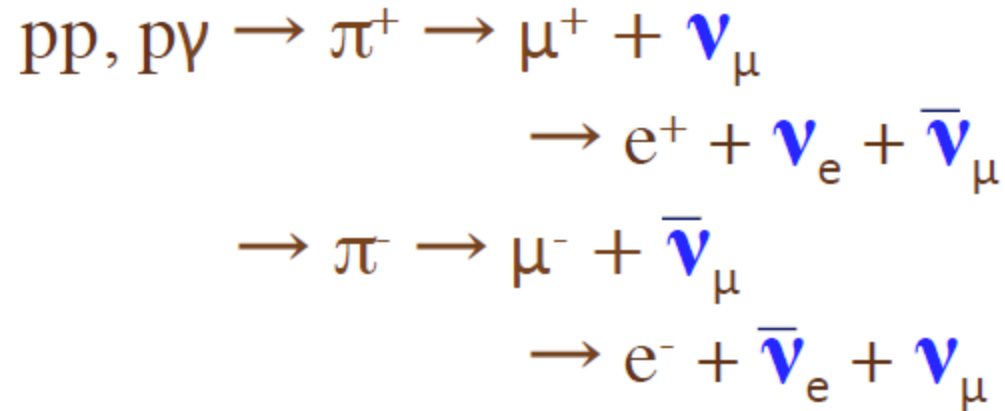
# H.E.S.S. image of Westerlund I



# Gamma Rays and Neutrinos

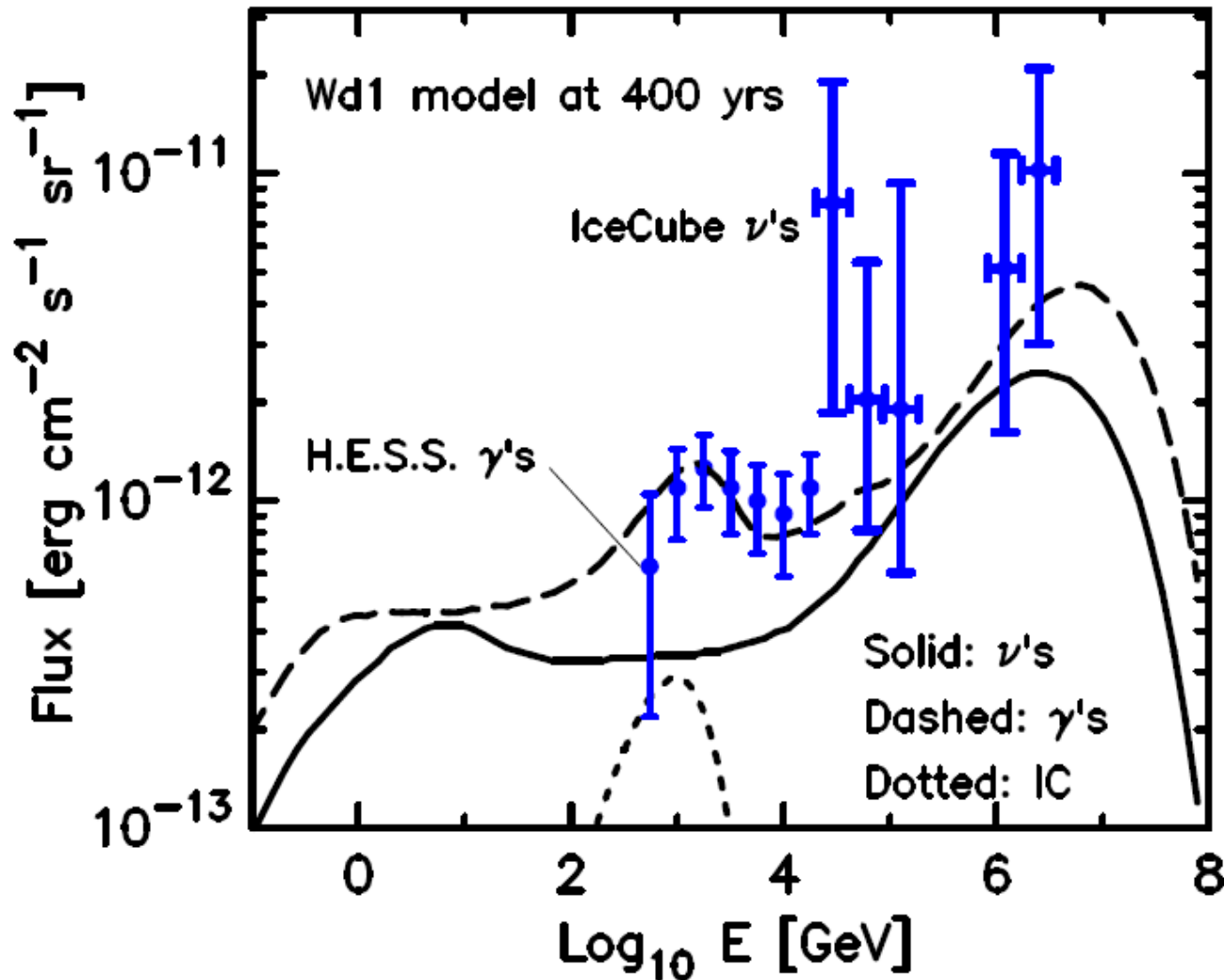
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gamma-rays and high-energy  
neutrinos :

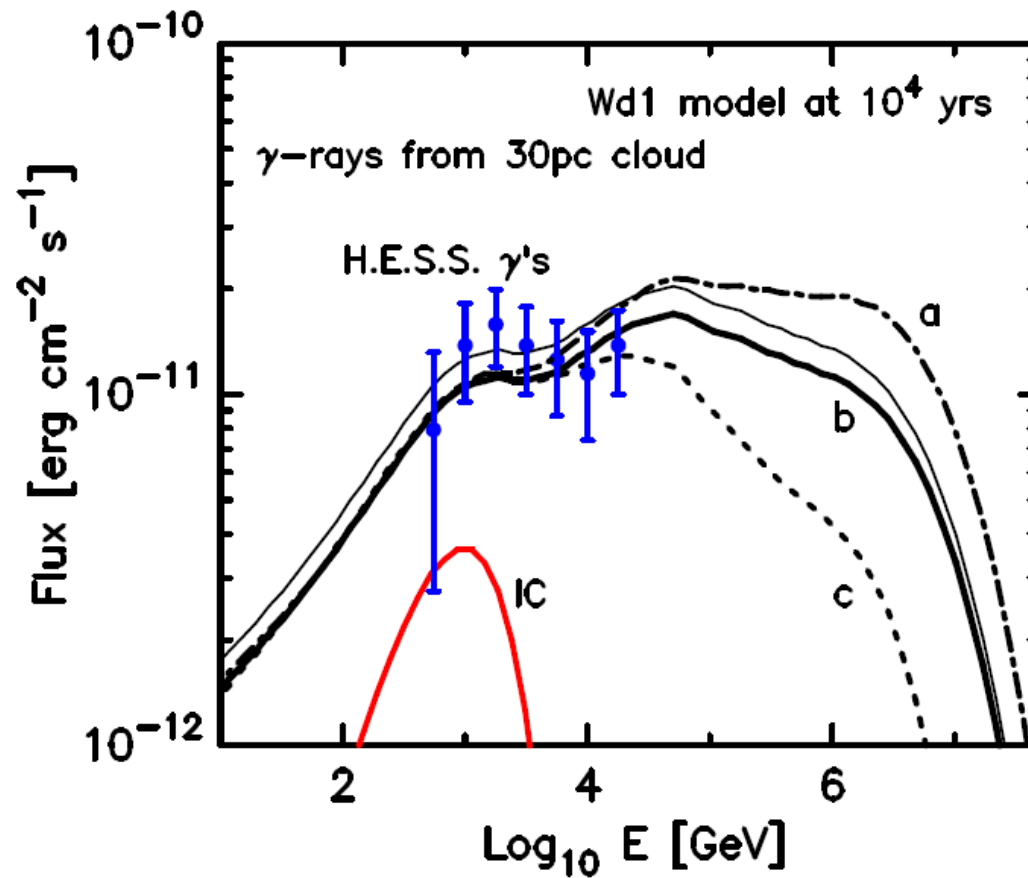


gamma rays  
we also get  $\gamma$ 's from electrons  
(NB, inverse Compton)

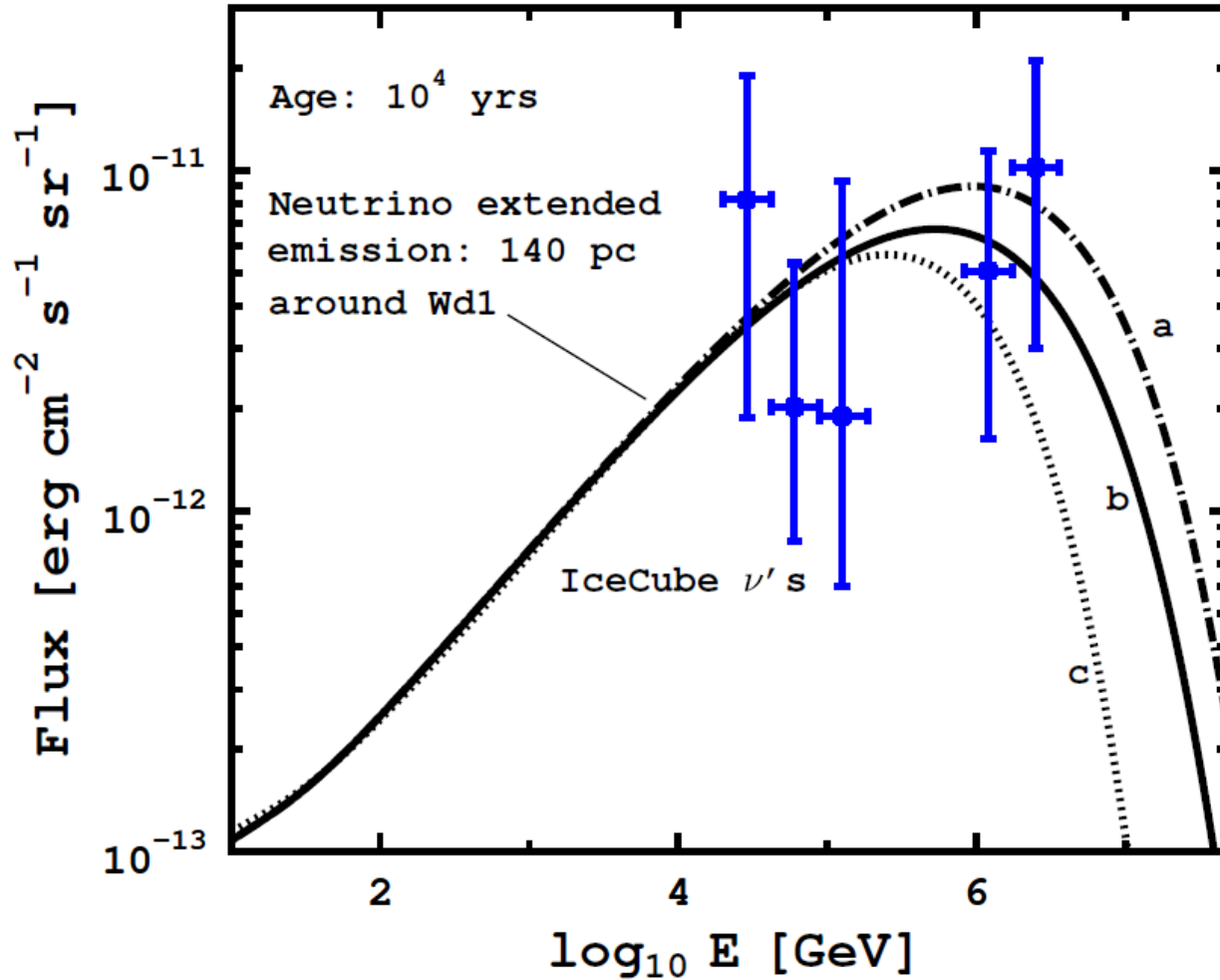
# Gamma-rays from a Pevatron



# Gamma-rays from a Pevatron

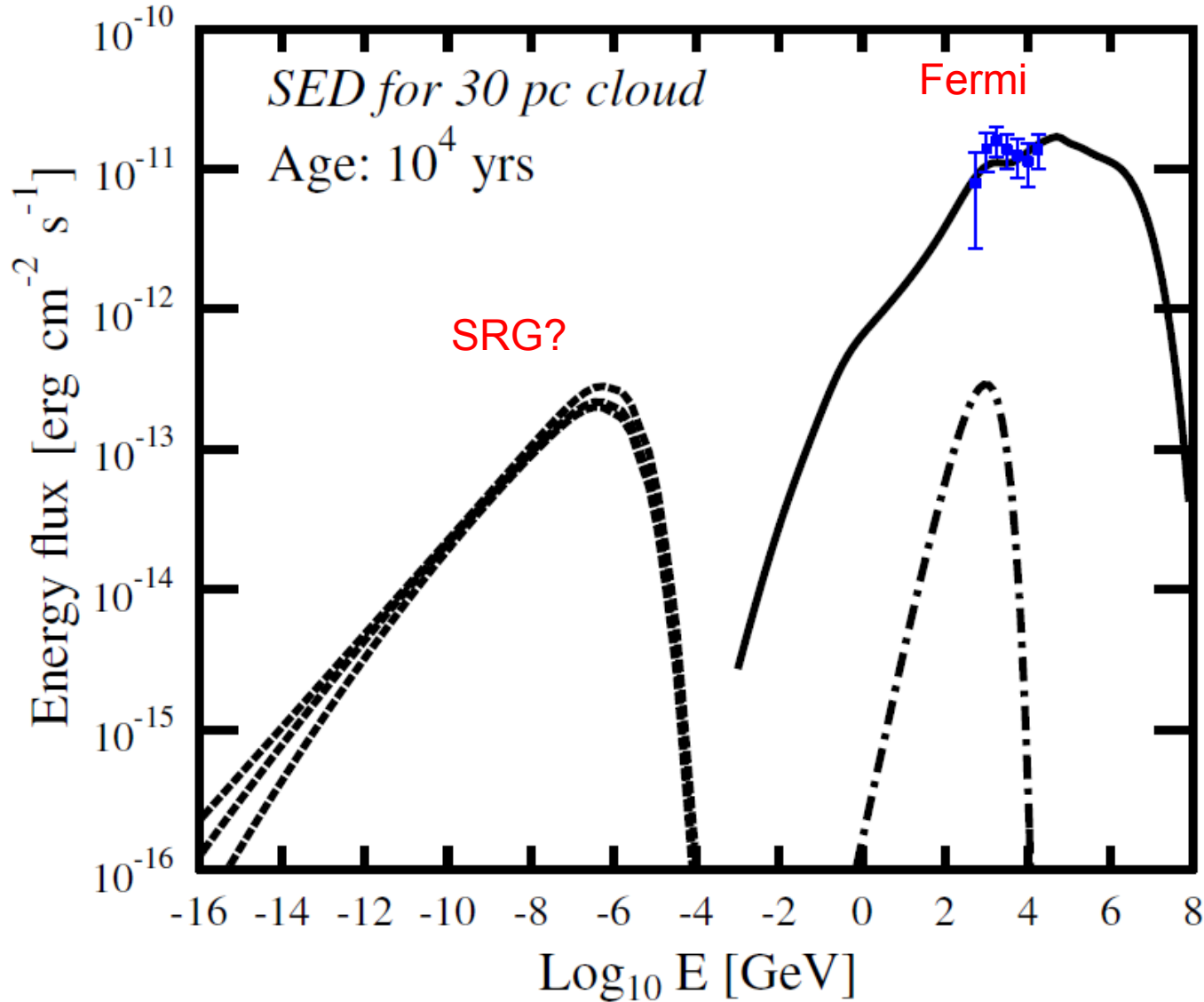


# Neutrinos from a Pevatron



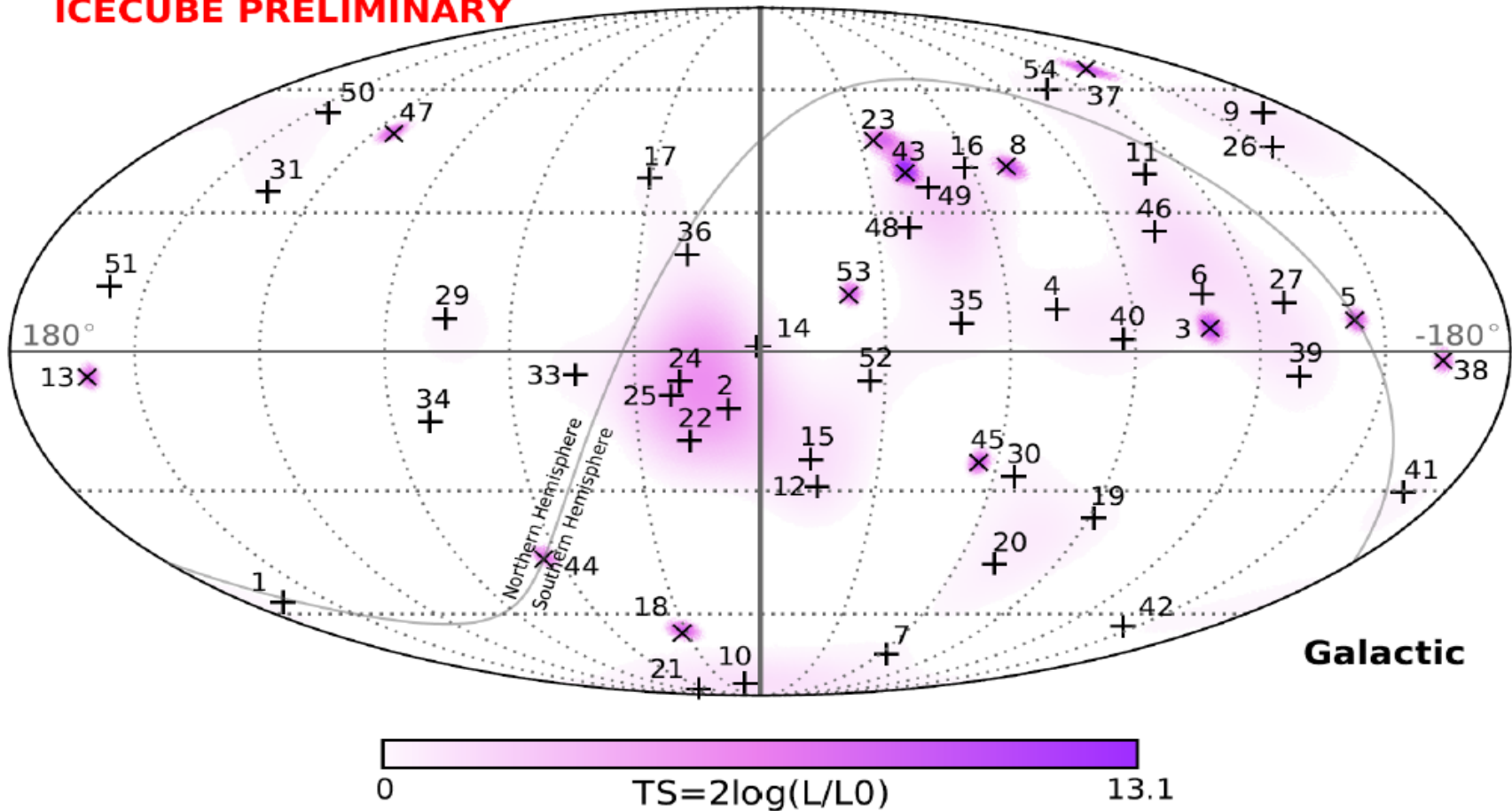
# Secondary pairs synchrotron X-ray counterpart to the Pevatron

A cloud nearby: **SRG perspective?**

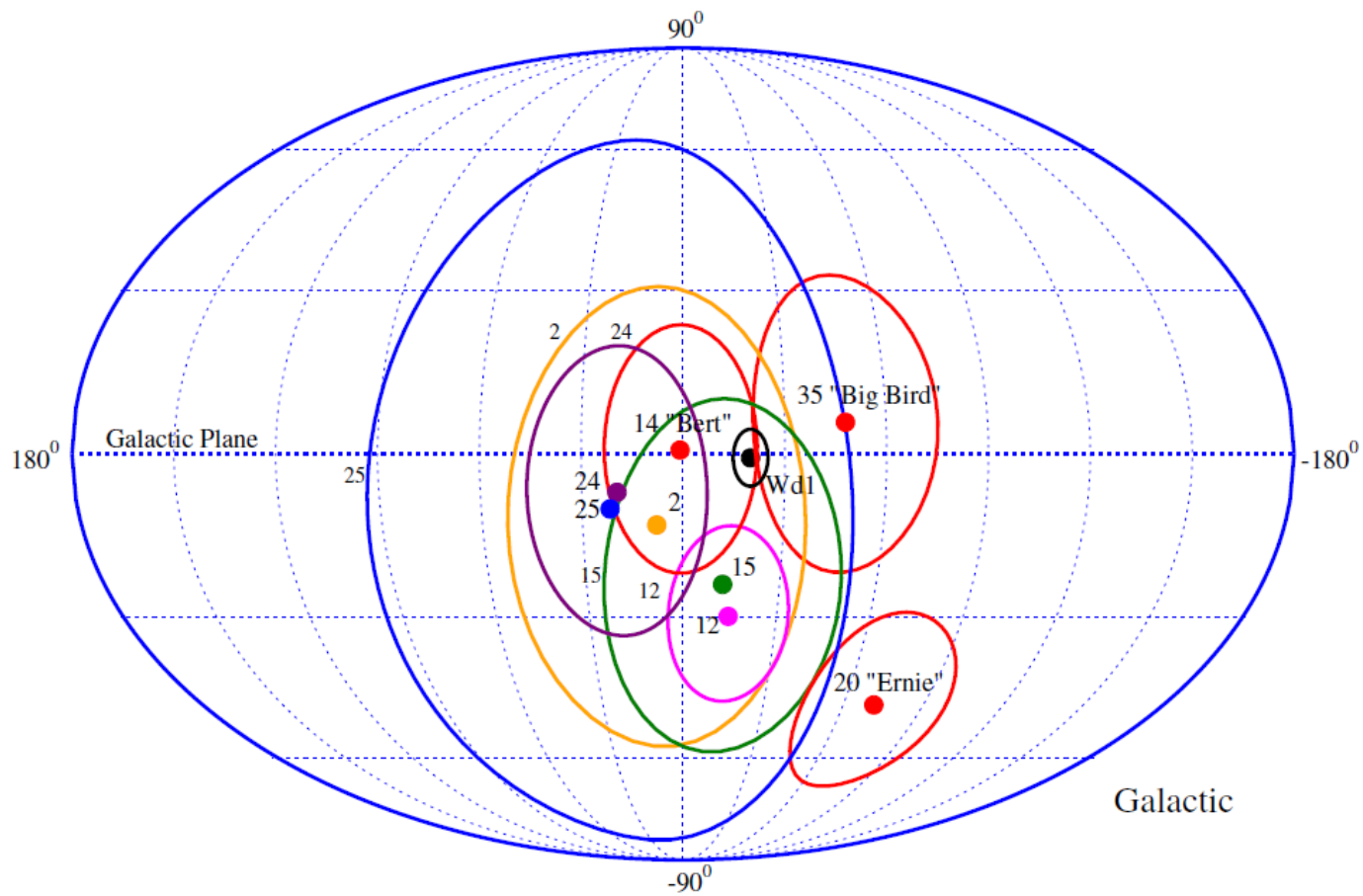


# All Sky Map IceCube 4 years

ICECUBE PRELIMINARY



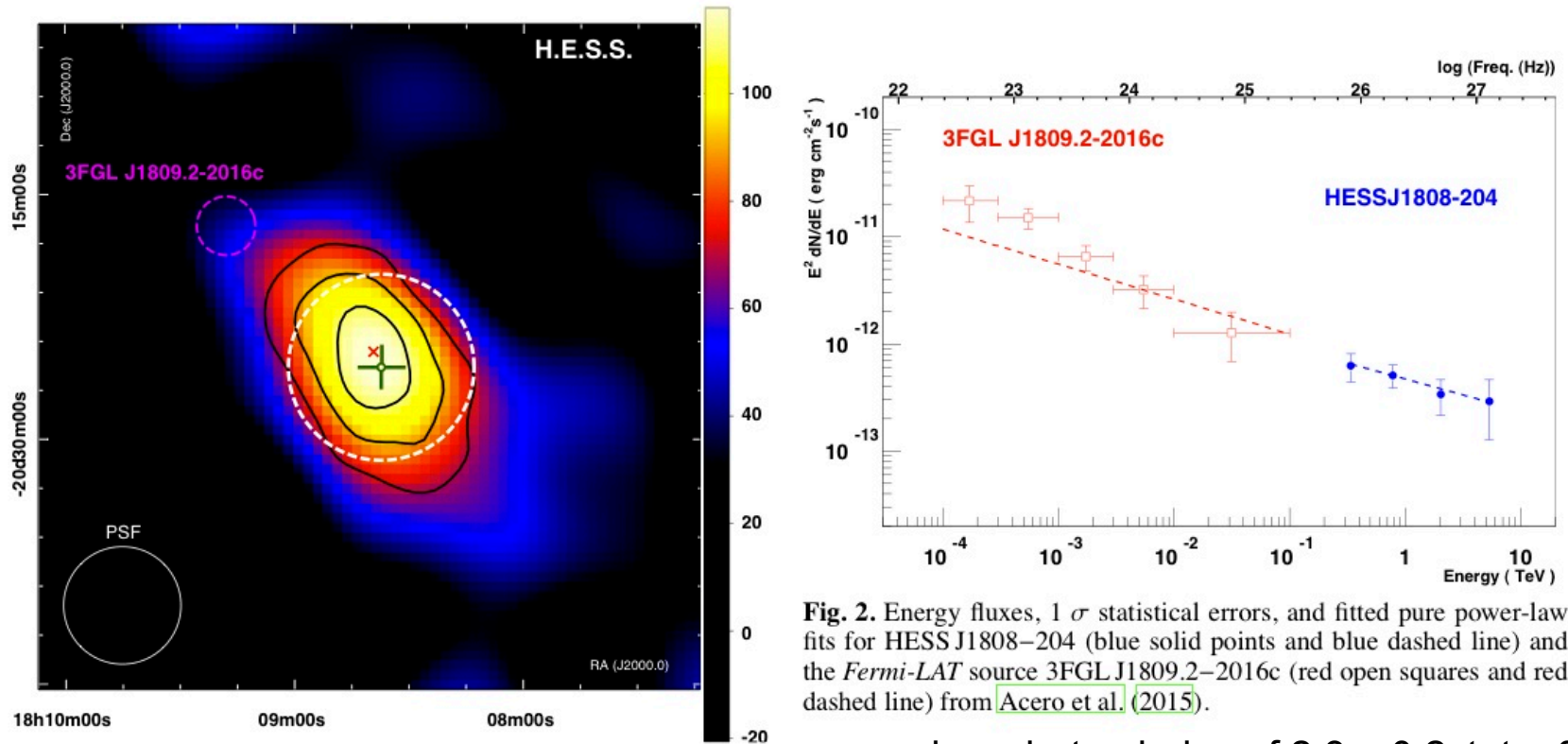
# IceCube events in the vicinity of Wd I



A.B. + 2015



# H.E.S.S. J1808-204



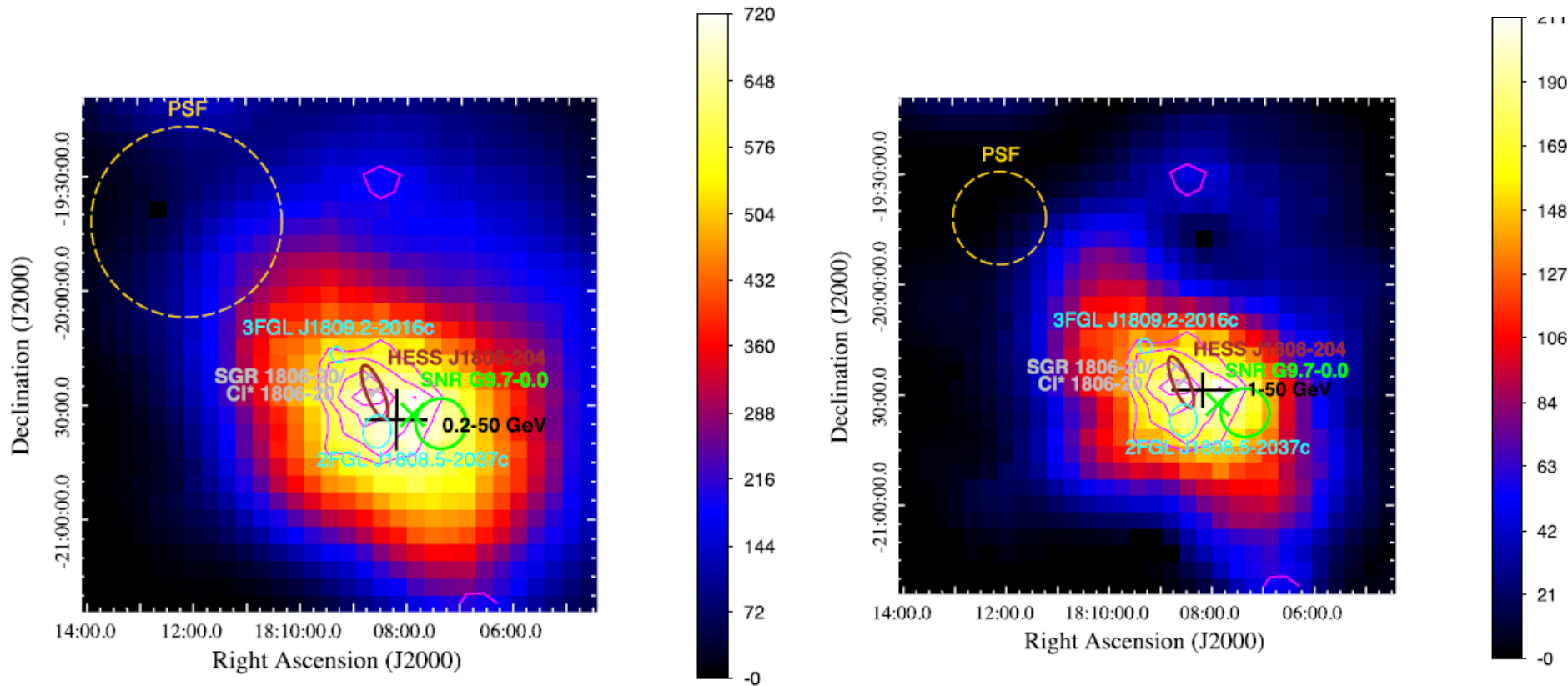
**Fig. 2.** Energy fluxes,  $1\sigma$  statistical errors, and fitted pure power-law fits for HESS J1808–204 (blue solid points and blue dashed line) and the *Fermi*-LAT source 3FGL J1809.2–2016c (red open squares and red dashed line) from [Acero et al. \(2015\)](#).

power-law photon index of  $2.3 \pm 0.2_{\text{stat}} \pm 0.3_{\text{sys}}$   
 $L_{\text{vhe}} \sim 1.6 \times 10^{34} [D/8.7 \text{ kpc}]^2 \text{ erg/s}$

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

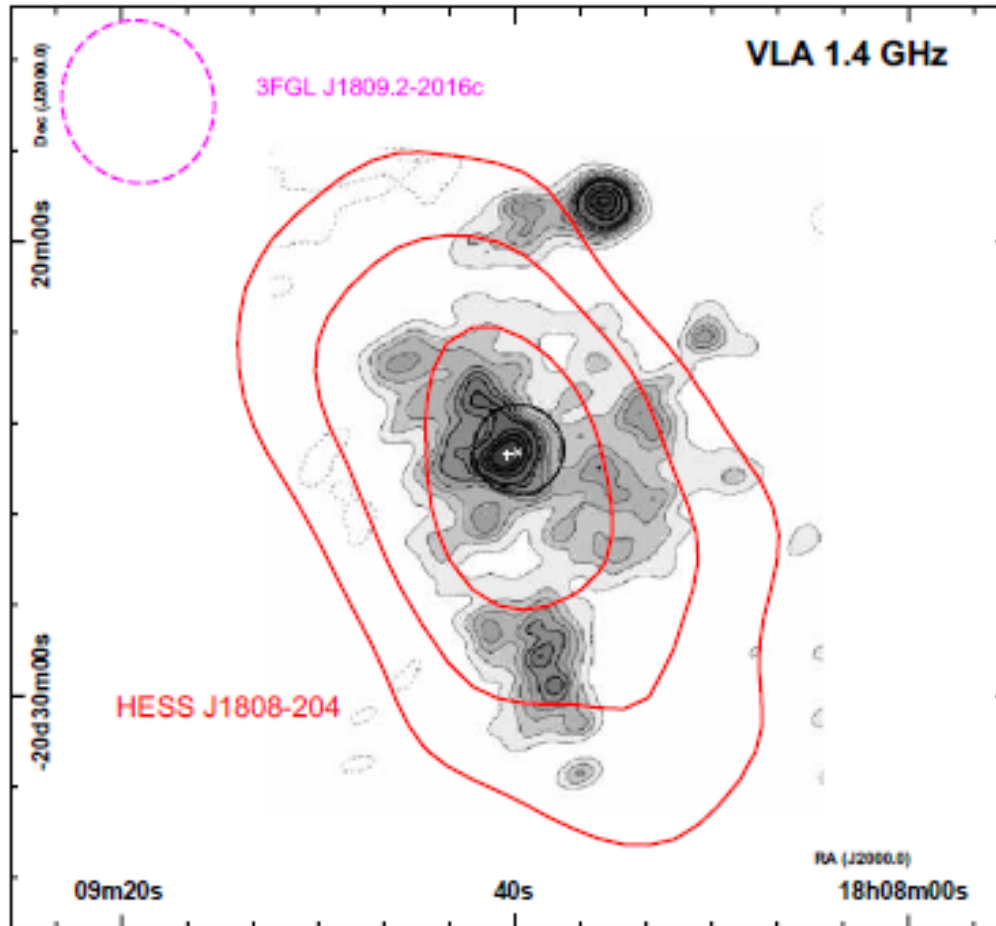
# 3FGL J1809



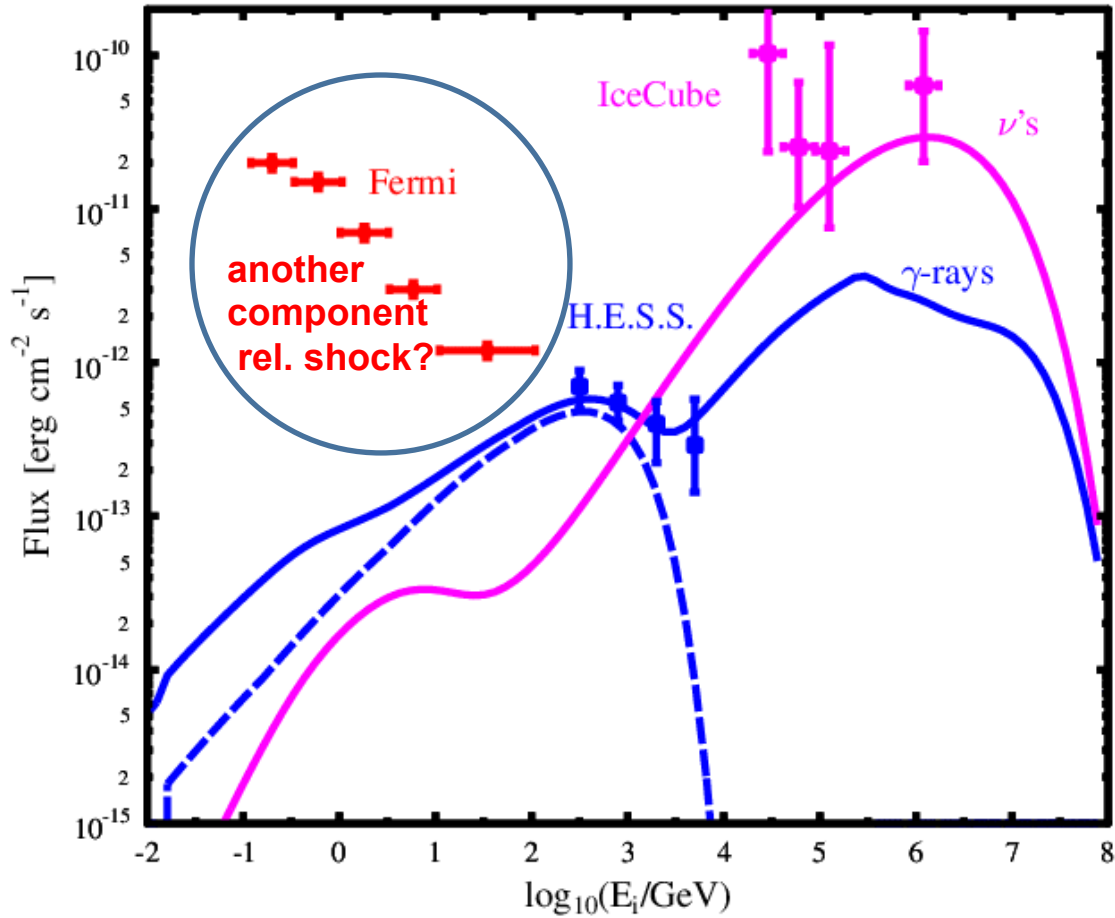
**Figure 1.** TS maps in 0.2–50 GeV (top) and 1–50 GeV (bottom), respectively, where all neighboring 3FGL catalog sources except 3FGL J1809.2-2016c are subtracted. On each map, the 95% confidence region of the centroid is indicated as a black thick cross, and the FWHM of the PSF is illustrated by a golden dashed circle. Both panels are overlaid with the magenta contours of detection significance (4, 4.5, 5, 5.5 $\sigma$ ) determined in 2.5–500 GeV. The position and extents of HESS J1808-204, described as a thick brown ellipse, are taken from Rowell et al. (2012). The position and dimension of SNR G9.7-0.0, described by a green thick circle, are taken from Brogan et al. (2006), and the position of its OH maser, indicated as a green “X”, is taken from Hewitt & Yusef-Zadeh (2009). The position of SGR 1806-20/CI\* 1806-20, indicated as a gray diamond, is taken from Israel et al. (2005).

Yeung + 2016

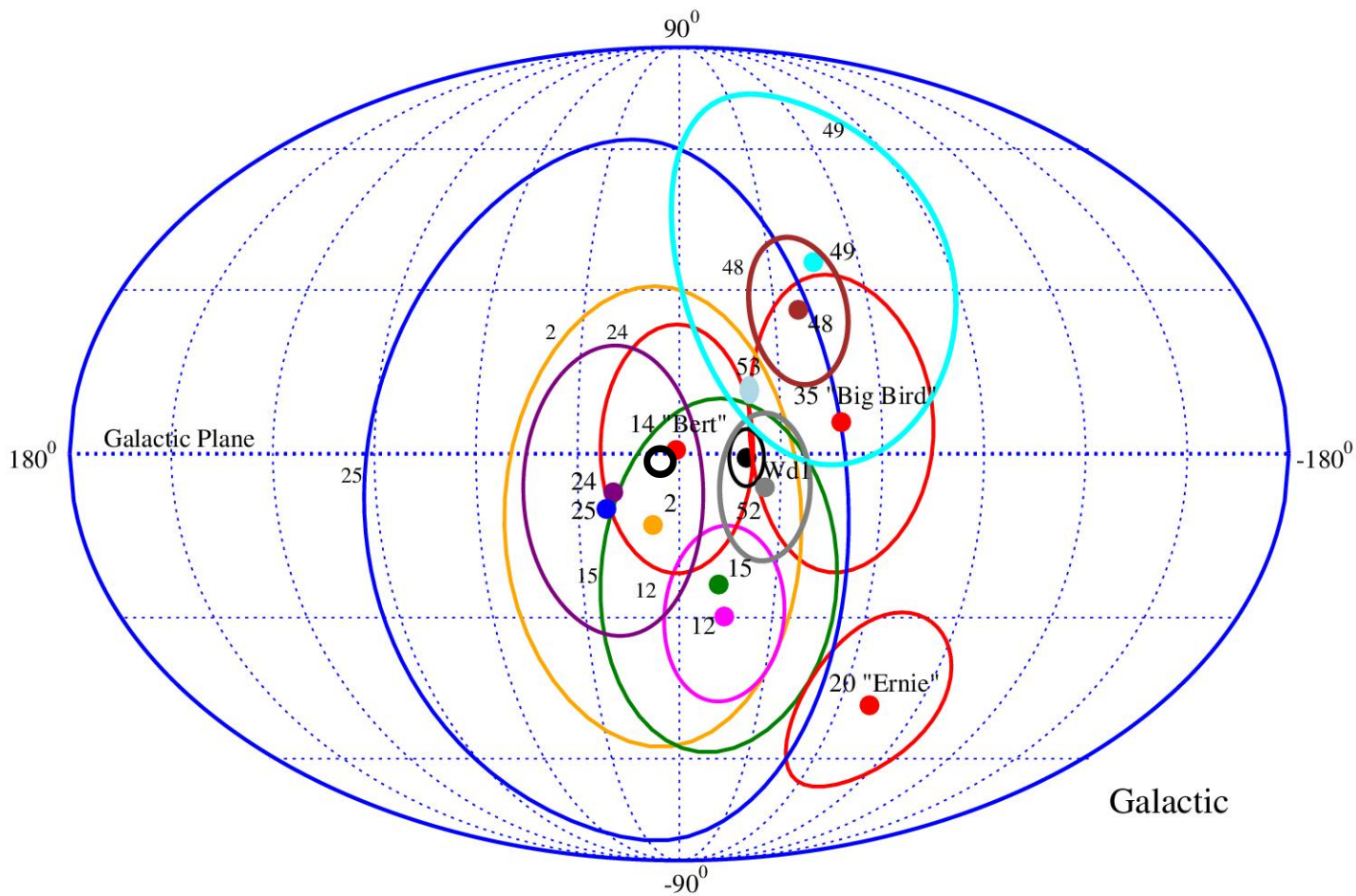
# H.E.S.S. J1808-204



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



# Potential IceCube events from galactic SNe in young star clusters

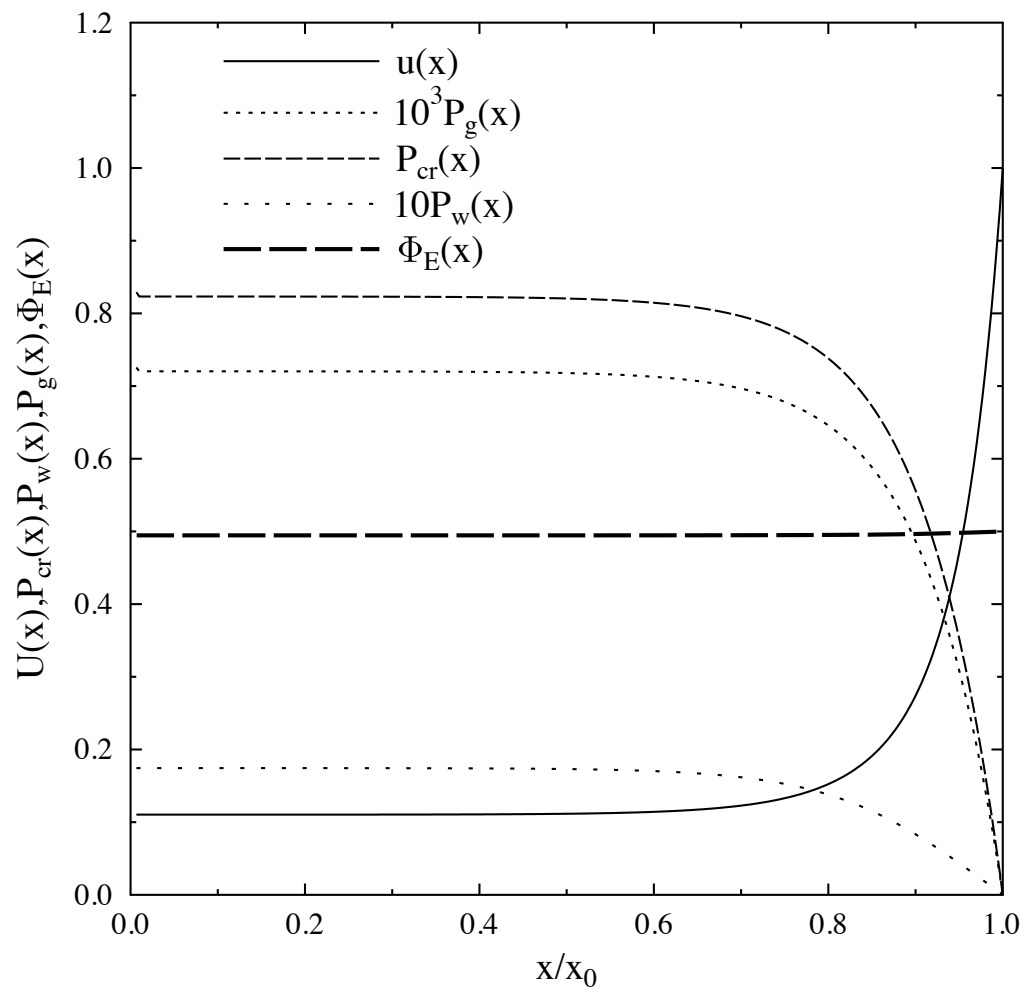


Wd I = 339 32 57.6; b = -00 24 15.0 (black filled circle)

SGR1806 l=09 58 42.0; b=-00 14 33.3 (black open circle)

**Thanks for your attention!**

Acknowledge support from RSF grant 16-12-10225



# Monte Carlo modeling of DSA Magnetic Field Amplification





# Conservation laws in MC modeling

$$\rho(x)u(x) = \rho_0 u_0 \quad - \text{mass}$$

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

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

## Energy flux background plasma

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

## Energy flux and turbulent pressure

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

## 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

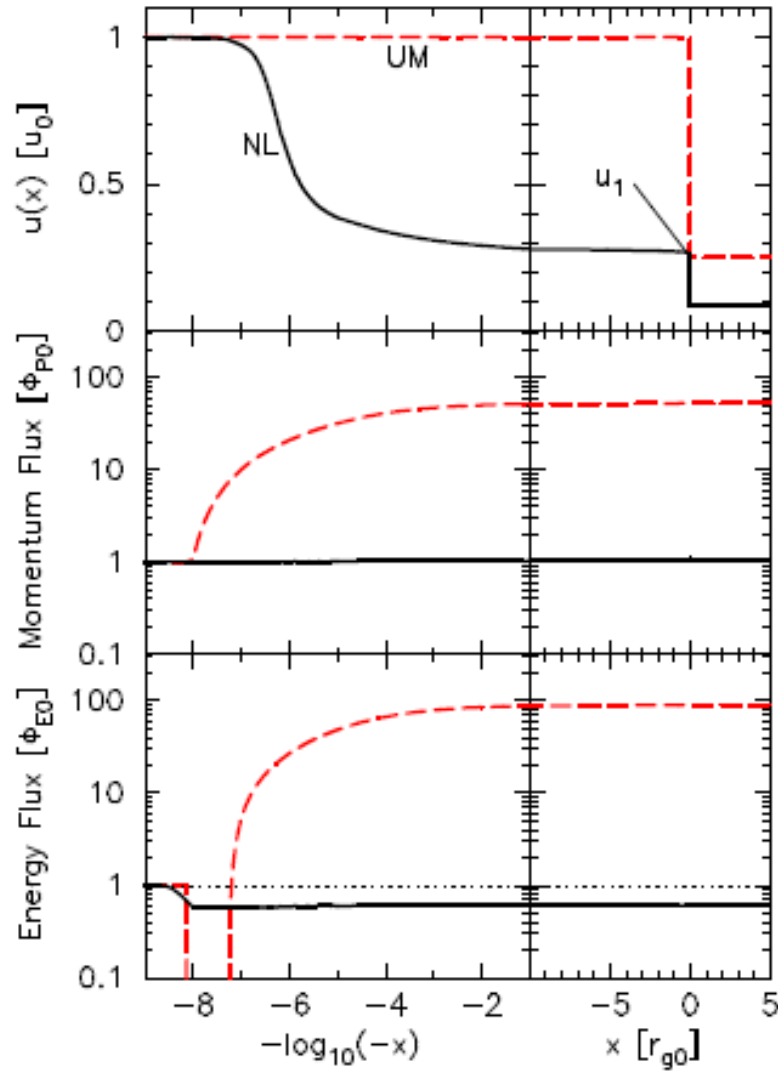
$$\frac{dF_w(x)}{dx} = u(x) \frac{dP_w(x)}{dx} + \int_{(k)} \Gamma(x, k) W(x, k) dk - L(x)$$

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

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

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

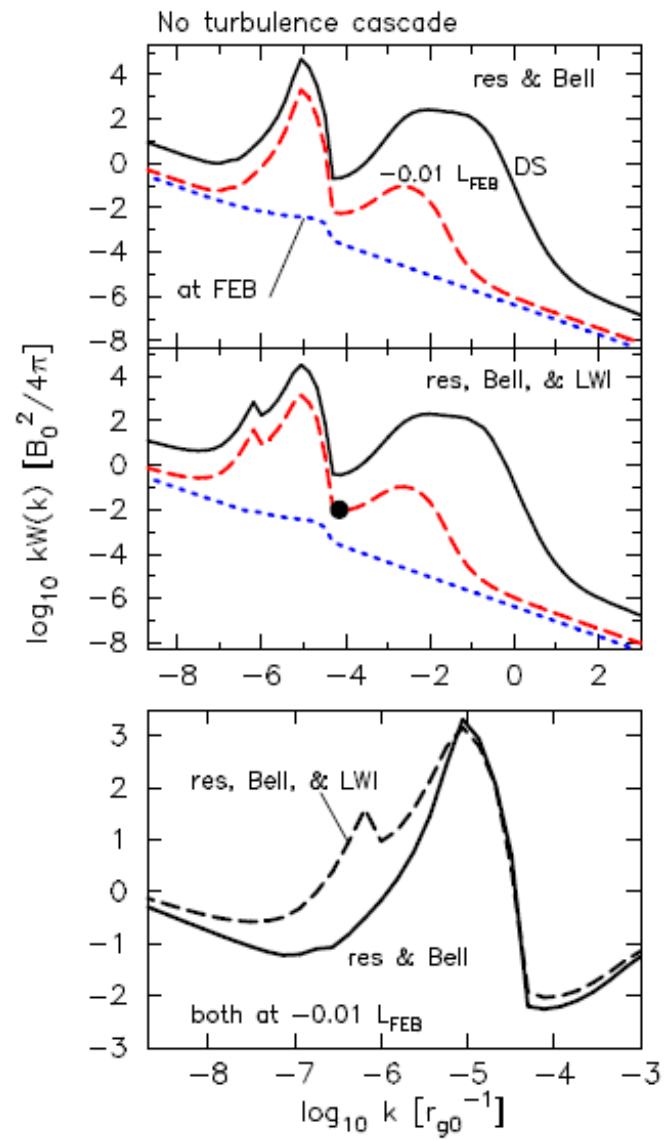
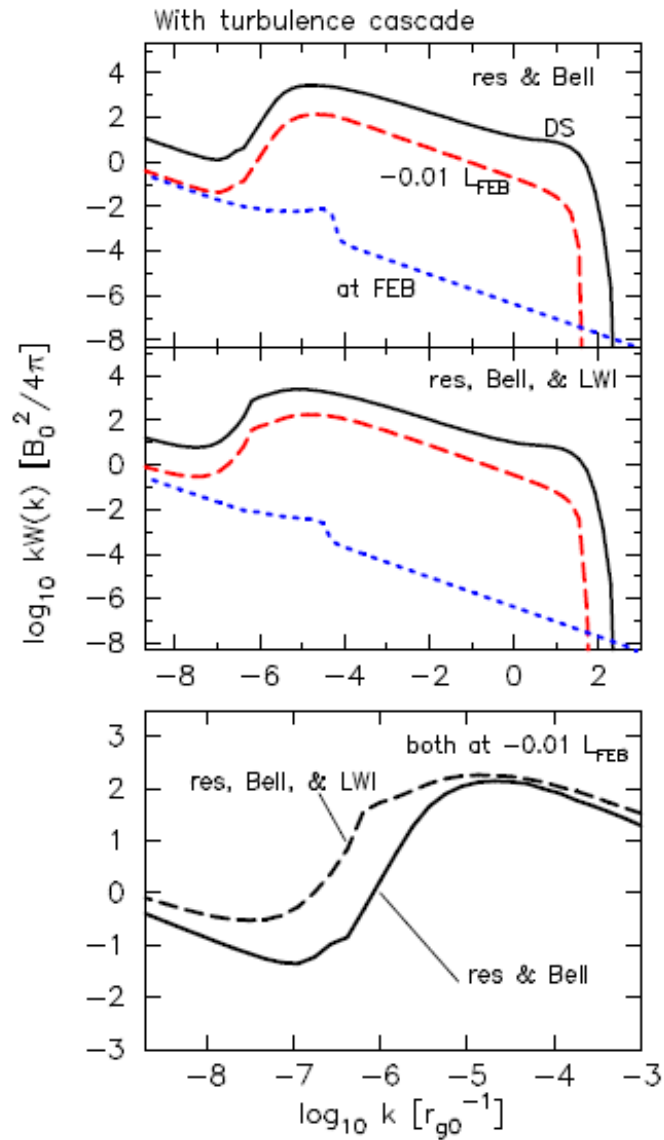
# Bulk velocity and magnetic field profiles



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

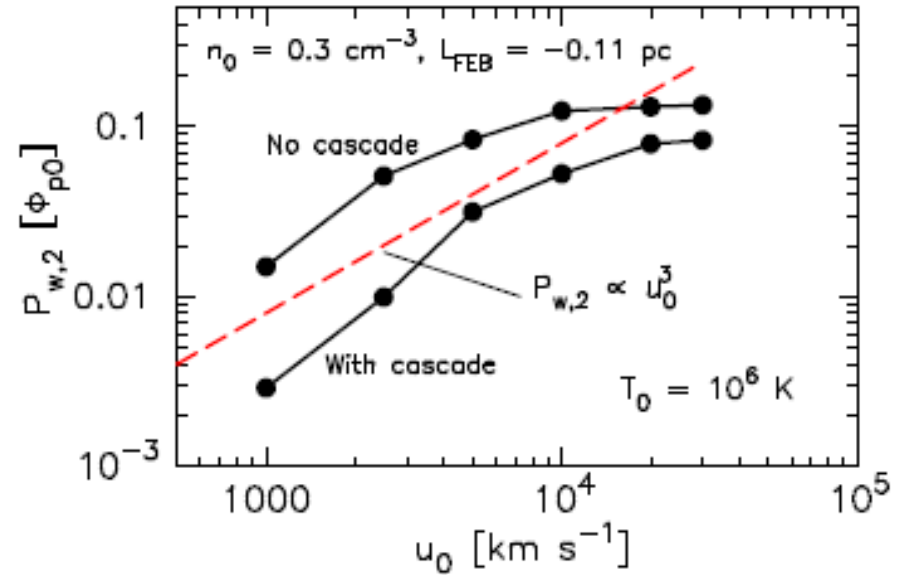
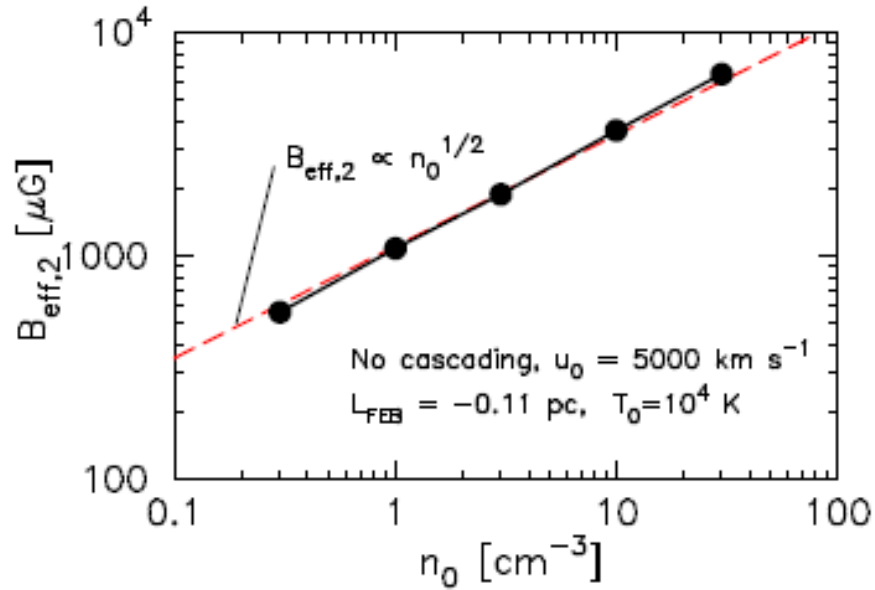
$$n_0 = 0.3 \text{ cm}^{-3}; u_0 = 5000 \frac{\text{KM}}{\text{c}}; B_0 = 3 \text{ mK}\Gamma\text{c}$$

# Magnetic turbulence spectra



$$n_0 = 0.3 \text{ cm}^{-3}; u_0 = 5000 \frac{\text{KM}}{c}; B_0 = 3 \text{ mK}\Gamma\text{c}$$

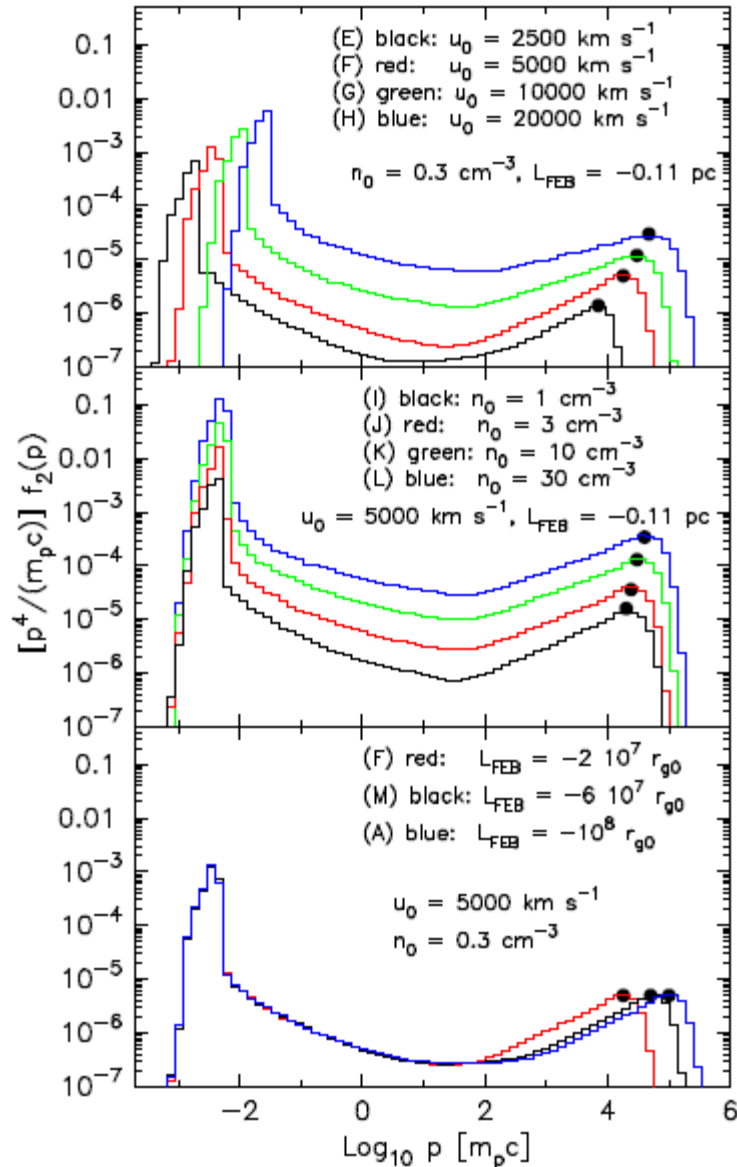
# Fluctuating magnetic field and magnetic pressure scalings



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

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

# CR spectra scalings

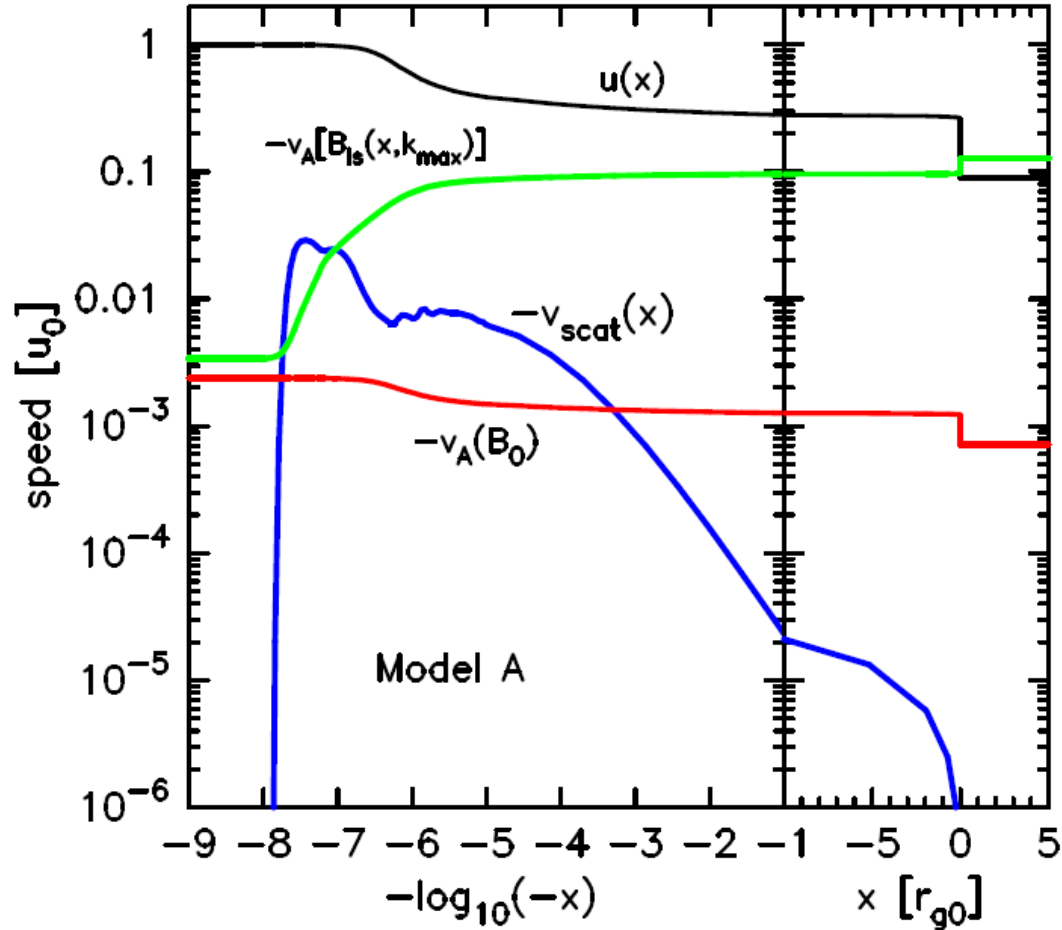


Maximal momentum of accelerated CRs

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

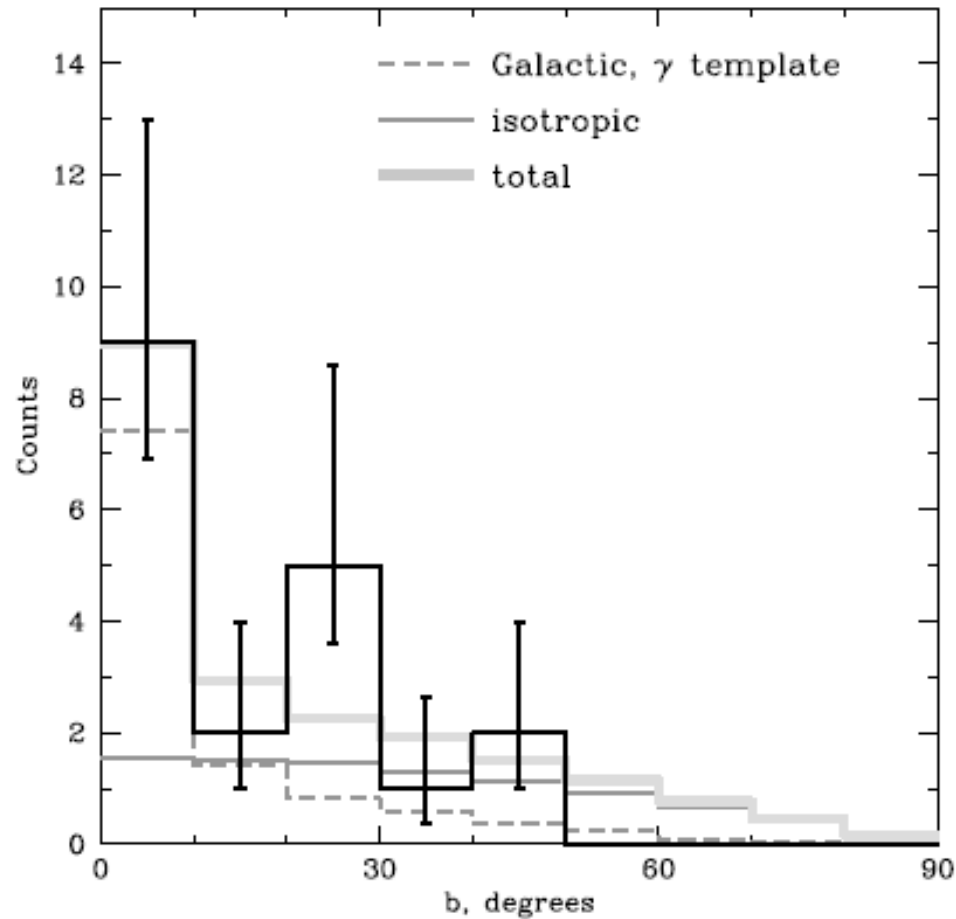
$\delta : 0.25$

# Scattering center velocity vs Alfvén speed



$$n_0 = 0.3 \text{ cm}^{-3}; u_0 = 5000 \frac{\text{KM}}{c}; B_0 = 3 \text{ MK}\Gamma\text{c}$$

# IceCube neutrinos galactic latitude profile > 100 TeV



Evidence for the Galactic contribution to the IceCube astrophysical neutrino flux