SUPERNOVA REMNANTS IN THE VERY-HIGH-ENERGY SKY: PROSPECTS FOR CTA

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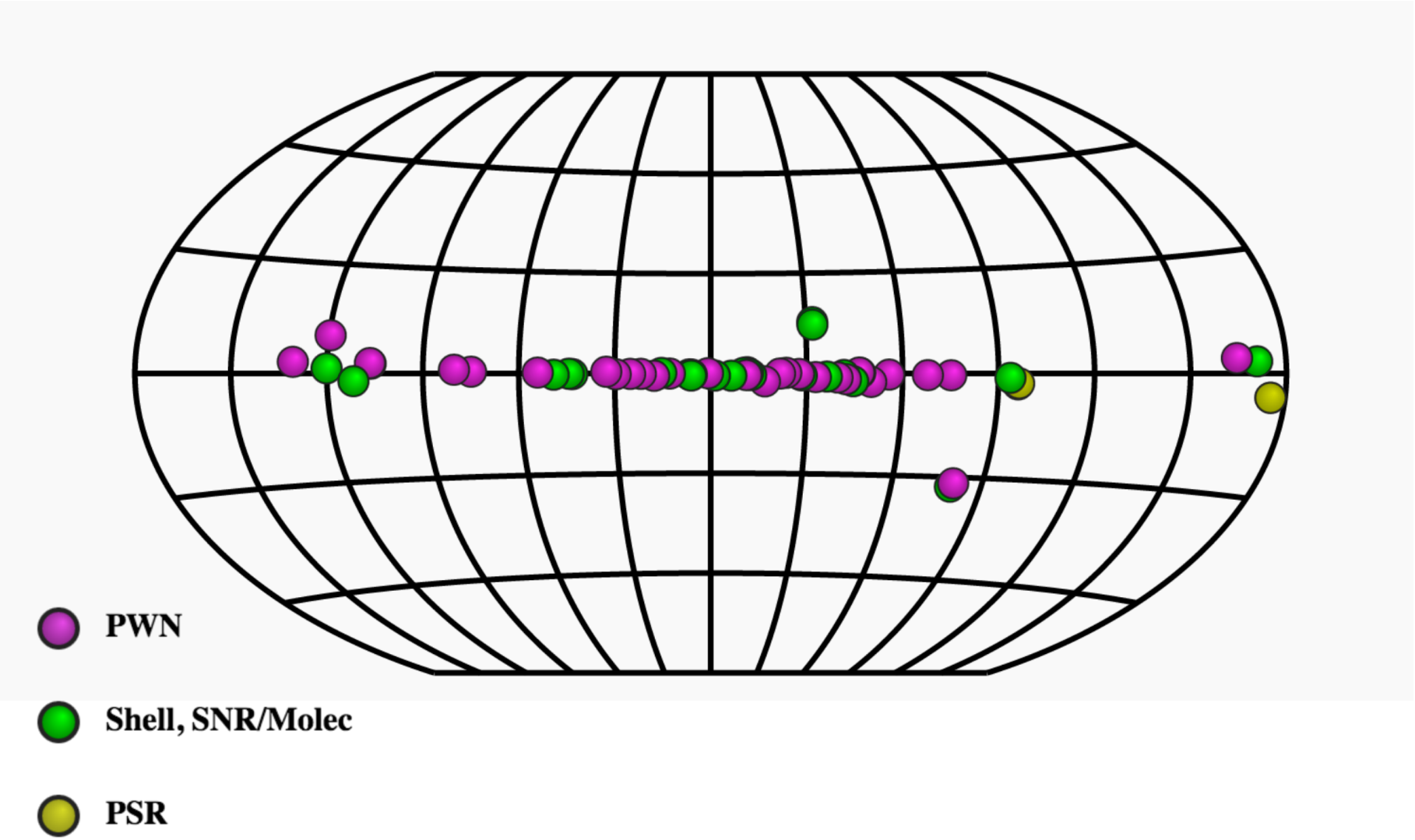
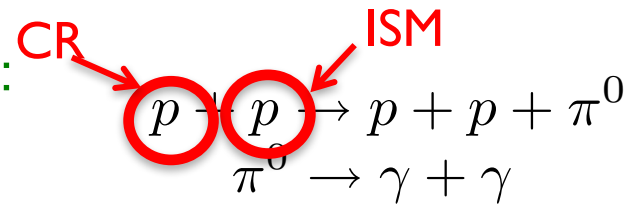
SNRs in the TeV sky



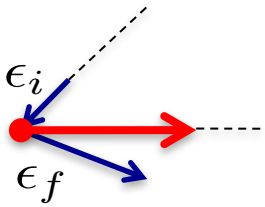
Scott Wakely & Deirdre Horan
tevcat2.uchicago.edu

Gamma rays from SNRs

Hadronic interactions :
Pion decay

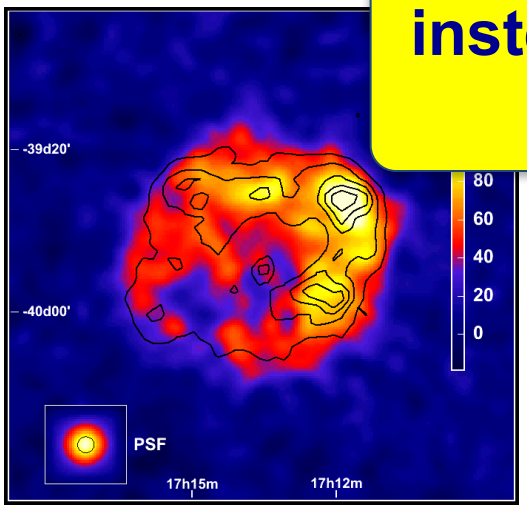


Leptonic interactions :
Inverse Compton scattering



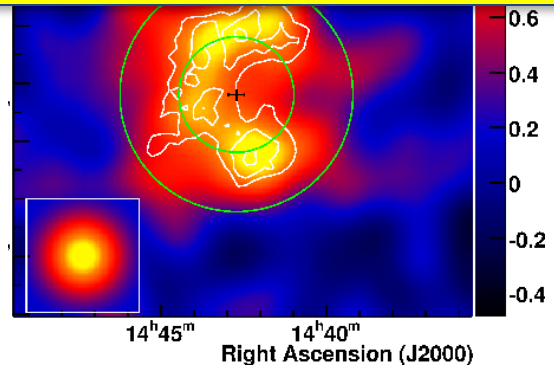
Situation unclear for many SNRs: instead of individual study, study of the entire population

Aharonian et al. (2006)



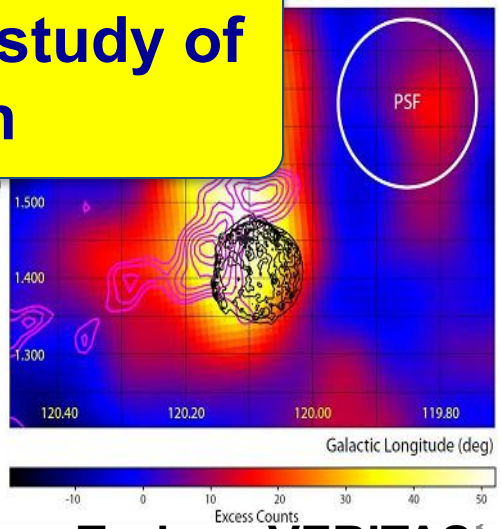
RXJ 1713 - HESS

Aharonian et al. (2009)



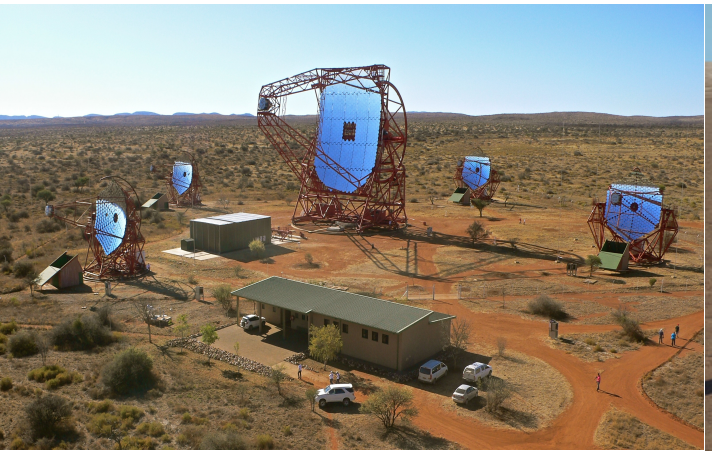
RCW 86 - HESS

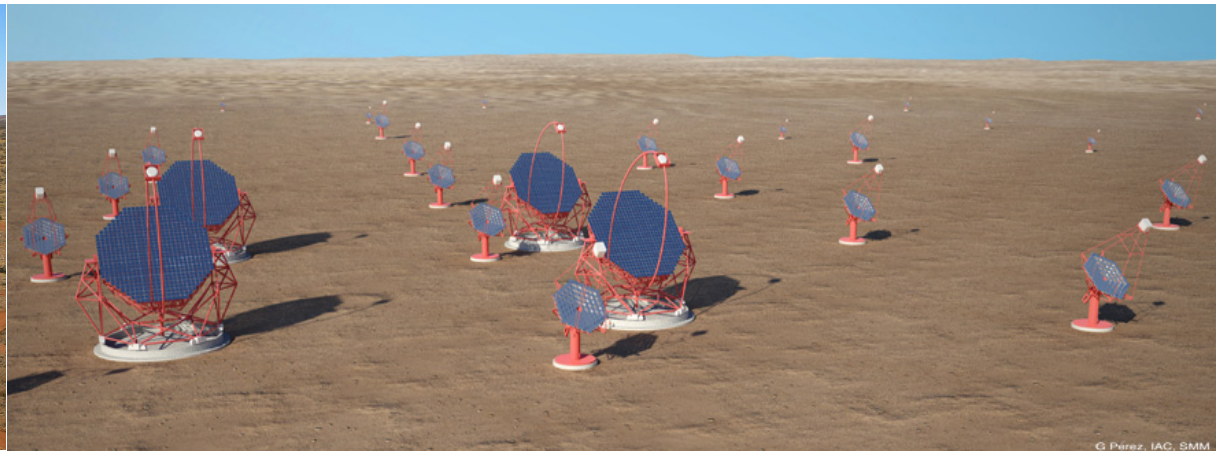
Acciari et al. (2011)



Tycho – VERITAS

Cherenkov Telescope Array (CTA)





H.E.S.S.

CTA

F(>1 TeV)

≈ 15 mCrab
≈ 0.1°
|b|<40° ; |l|<3°

≈ 1 mCrab
≈ 0.05°
|b|<60° ; |l|<2°

≈ 3 mCrab
≈ 0.05°
All-sky survey

A Monte Carlo approach

What we need:

Time and Spatial distribution of SNRs + Gas density distribution in the Galaxy + Model for acceleration of cosmic rays in one SNR

Gamma emission of one SNR

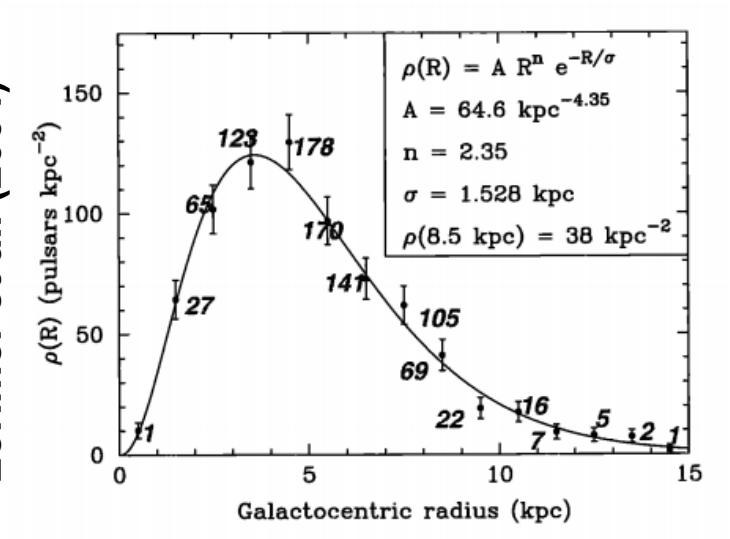
Number of detectable SNRs by a given telescope

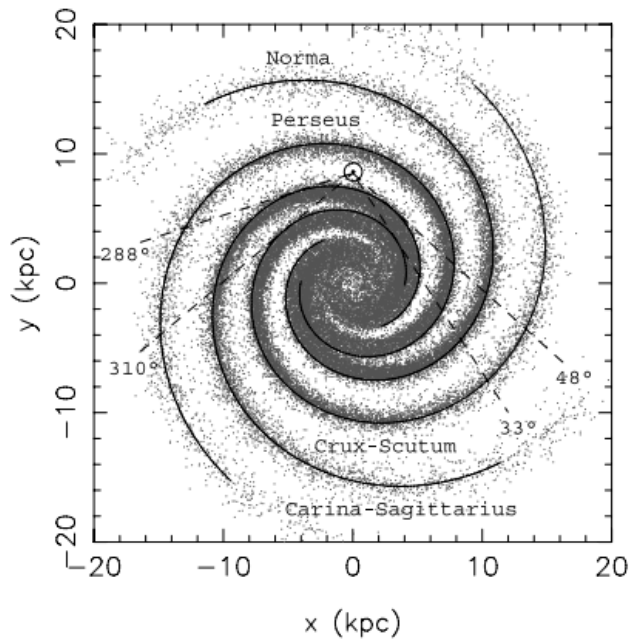
Time and spatial distribution of SNRs

Time distribution: SN rate: 3/century

Spatial distribution:

Lorimer et al. (2004)





Faucher-giguère, Kaspi (2006)

SN progenitor types

Thermonuclear ←

Core-collapse ←

Type	$\mathcal{E}_{51}$	$M_{ej,\odot}$	$\dot{M}_{-5}$	$u_{w,6}$	Rel. rate
Ia	1	1.4	–	–	0.32
IIP	1	8	1	1	0.44
Ib/c	1	2	1	1	0.22
IIb	3	1	10	1	0.02

Ptuskin et al. (2010)

Evolution of SNRs : type Ia

Free expansion

$$R_{\rm sh} = 5.3 \left(\frac{\mathcal{E}_{51}^2}{n_0 M_{{\rm ej},\odot}}\right)^{1/7} t_{\rm kyr}^{4/7} \ {\rm pc}$$

$$u_{\rm sh} = 3.0 \times 10^3 \left(\frac{\mathcal{E}_{51}^2}{n_0 M_{{\rm ej},\odot}}\right)^{1/7} t_{\rm kyr}^{-3/7} \ {\rm km/s}$$

$$t \gg 260 \left(\frac{M_{{\rm ej},\odot}}{1.4}\right)^{1/5} \mathcal{E}_{51}^{-1/2} n_0^{-1/3} {\rm yr}$$

Sedov phase

$$R_{\rm sh} = 4.3 \left(\frac{\mathcal{E}_{51}^2}{n_0}\right)^{1/5} t_{\rm kyr}^{2/5} \left(1 - \frac{0.06 M_{{\rm ej},\odot}^{5/6}}{\mathcal{E}_{51}^{1/2} n_0^{1/3} t_{\rm kyr}}\right)^{2/5} \ {\rm pc}$$

$$u_{\rm sh} = 1.7 \times 10^3 \left(\frac{\mathcal{E}_{51}^2}{n_0}\right)^{1/5} t_{\rm kyr}^{-3/5} \left(1 - \frac{0.06 M_{{\rm ej},\odot}^{5/6}}{\mathcal{E}_{51}^{1/2} n_0^{1/3} t_{\rm kyr}}\right)^{-3/5} \ {\rm km/s}$$

Chevalier (1982) Truelove& Mckee (1999) Ptuskin (2005)

Type II

Thin Shell approximation

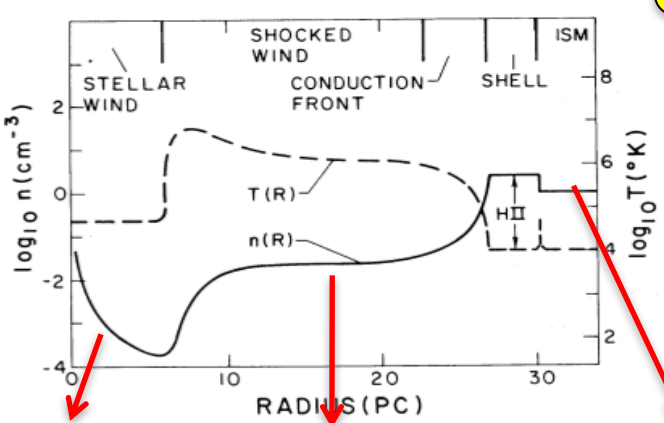
Momentum conservation

$$\frac{\rm d}{{\rm d}t}(M u_{\rm sh}) = 4\pi R_{\rm sh}^2 P_{\rm in}$$

Energy conservation

$$E = \frac{4\pi}{3(\gamma+1)} P_{\rm in} R_{\rm sh}^3 + \frac{1}{2} M u^2$$

Weaver (1977)



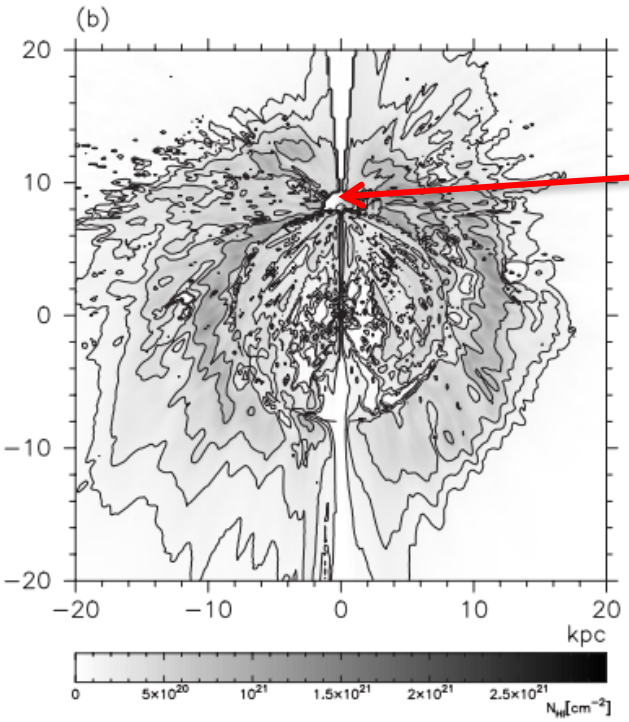
Wind with R^{-2} density profile

Hot and tenuous bubble

ISM

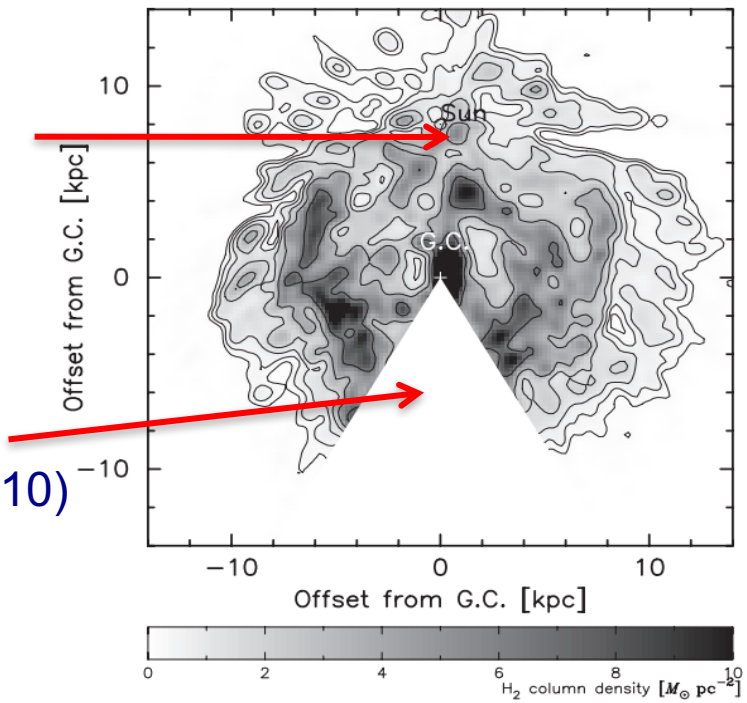
Ostriker & Mckee (1988)

Gas distribution



We are here

We extrapolate using fits from Shibata et al. (2010)



HI

Nakanishi&Sofue (2003)

H_2

Nakanishi&Sofue (2006)

Particle acceleration

1. Efficiency :

$$P^0_{\rm CR} = \xi_{\rm CR}\ \rho_{\rm up} u_{\rm sh}^2$$

acceleration efficiency at the shock

$$\xi_{\rm CR} = \eta_{\rm CR} \approx 0.1$$

INSTANTANEOUS TIME INTEGRATED

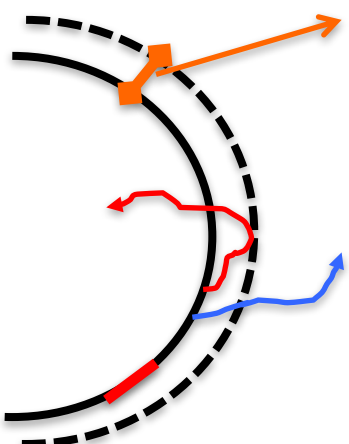
Supported by theoretical work Caprioli (2010), Ptuskin & Zirakashvili (2008)

2. Slope of accelerated particles: free parameter

$$N_{\rm CR} \propto p^{-\alpha}$$

$$\alpha = 4.1...4.4$$

3. Maximum energy of accelerated protons



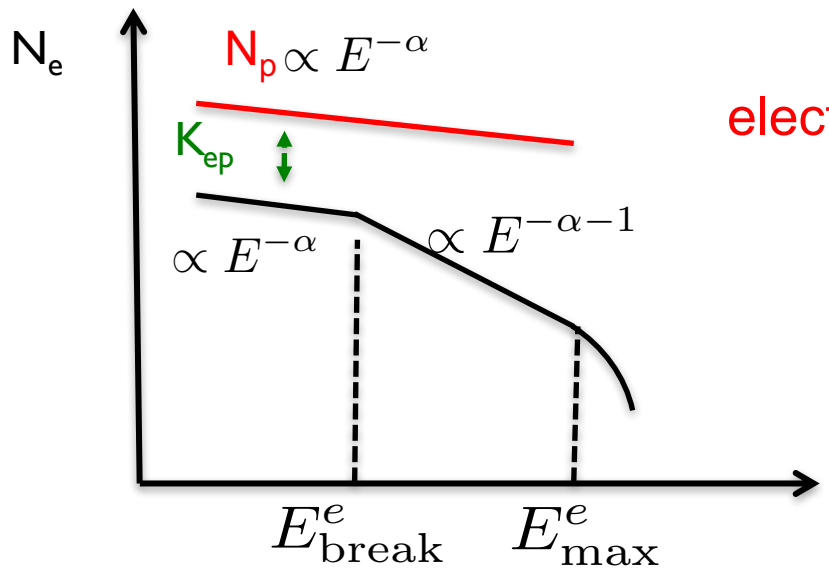
diffusion length

Loss-limited X-ray filaments : fraction of kinetic energy into magnetic field

$$\frac{D(E_{\rm max})}{u_{\rm sh}} \approx 0.05...0.1\ R_{\rm sh}$$

$$B_{\rm down} = \sigma B_0 \sqrt{(u_{\rm sh}/v_{\rm d})^2 + 1}$$

Particle acceleration: electrons



Longair (1990)

electron-to-proton ration

$$K_{\rm ep} = 10^{-5} ... 10^{-2}$$

acc rate= synch loss rate

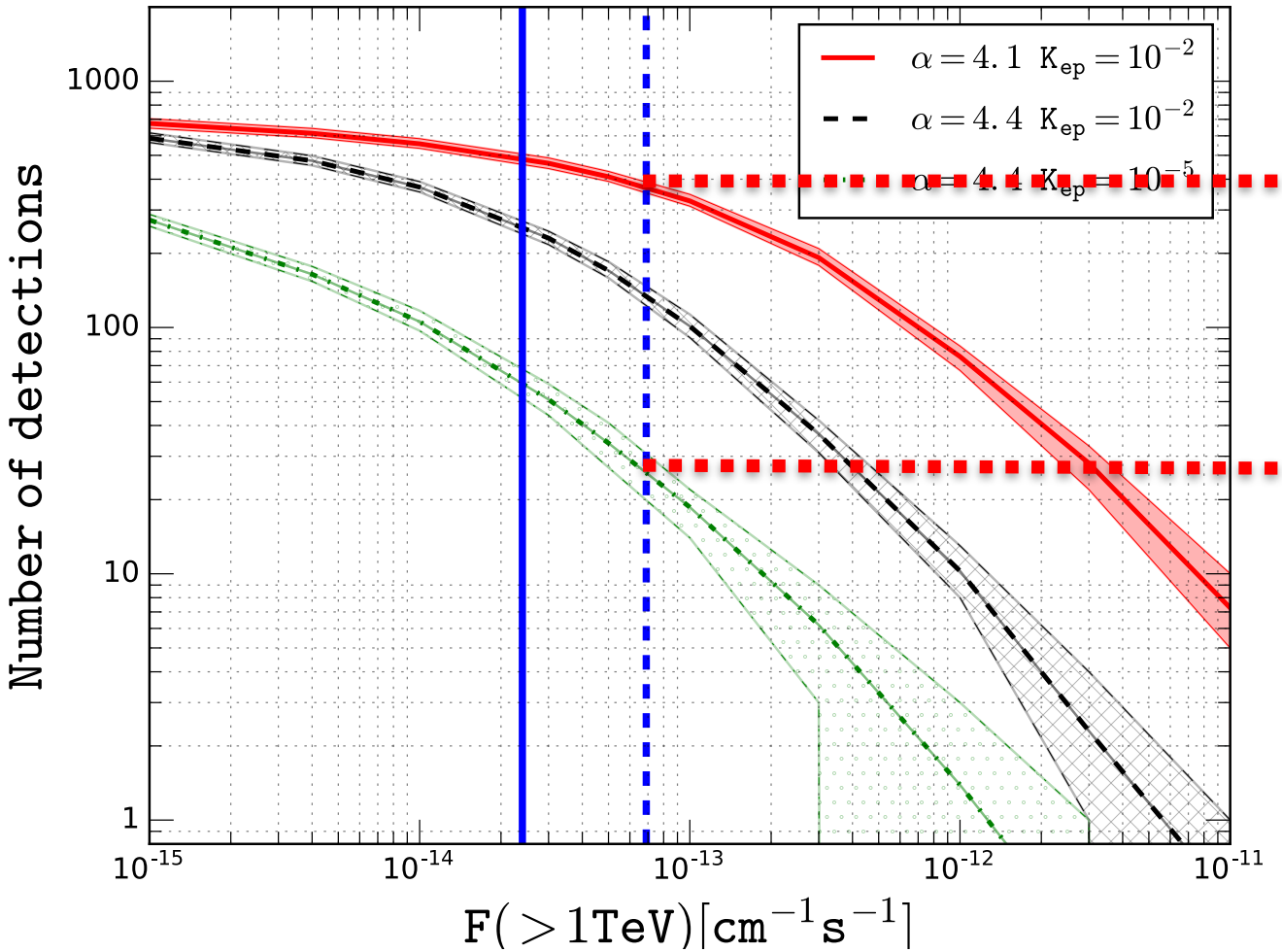
$$E^e_{\rm max} \approx 7.3 \left(\frac{u_{\rm sh}}{1000{\rm km/s}}\right) \left(\frac{B_{\rm down}}{100\mu{\rm G}}\right)^{-1/2} \ {\rm TeV}$$

$t_{synch}=t_{age}$

$$E^e_{\rm break}$$

Vannoni et al. 2009

Number of detections by CTA



≈ 400 SNRs

≈30 SNRs
Above the most optimistic scenario with H.E.S.S

Cristofari et al. 2017

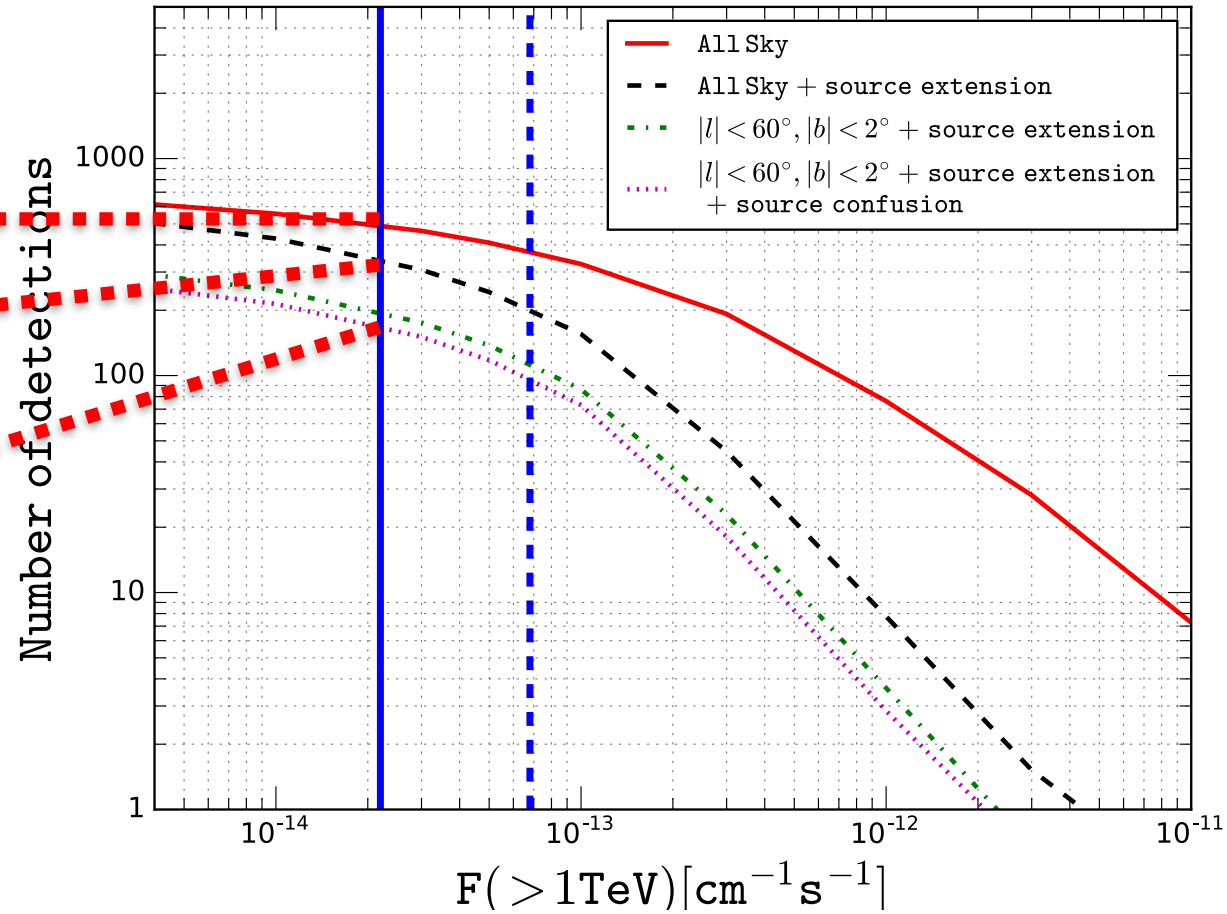
Number of detections by CTA

α=4.1
$K_{ep}=10^{-2}$

≈ 500 SNRs

≈ 350 SNRs

≈ 180 SNRs



Cristofari et al. (2017)

Conclusions and future perspectives

- A new test for the SNR hypothesis
- Constraining parameters governing particle acceleration
- Estimation on the SNR population accessible by CTA:
  - Improvement compared to H.E.S.S
  - Caracterization of the population
    - Detection ≈ 22 - 120 SNRs
    - Size ≈ 0.2°
    - Distance ≈ 7-10 kpc
    - Ages ≈ 4-6 kyr
- Results of our approach confronted with other instruments (HAWC, HiSCORE)
- Detections of neutrinos from SNRs, search of PeVatrons