Constraining the production of cosmic rays by pulsars

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Hadronic Cosmic Rays

- Required luminosity of CR sources: $L \simeq 10^{41}\ \mathrm{erg/s}$
- Proven to be produced in supernova remnants (SNR W44, IC 433)
- Some issues remain unsolved: not clear if enough, observed spectra are softer than theoretical etc.
- Other sources also possible (superbubbles, pulsars)

Ackermann et al'11

Neronov, Semikoz (1201.1660)

$$L \simeq 10^{41}\ \frac{\mathrm{erg}}{\mathrm{s}} \left[\frac{\mathcal{E}_{CR}^{tot}}{2\times 10^{50}\ \mathrm{erg}}\right] \left[\frac{\mathcal{R}_{SN}}{1/50\ \mathrm{yr}^{-1}}\right]$$

$$E_{rot} = \frac{I_{NS}\Omega^2}{2} \simeq 2\times 10^{50}\ \mathrm{erg} \left[\frac{I_{NS}}{10^{45}\ \mathrm{gcm}^2}\right] \left[\frac{10\ \mathrm{ms}}{P_{ini}}\right]^2$$

Pulsars

May have enough initial rotation energy

Are well-established sources of e+e- CRs;
theory predicts that ions have even bigger energy

Hoshino, Gallant, Arons et al’92-94

Hard to extract the hadronic flux

There should be large (~100 pc)
diffusive gamma-ray halos around young pulsars

Neronov and Semikoz (1201.1660):
blind search for gamma-ray halos => pulsars +, SNR -

Diffusive gamma-ray halos

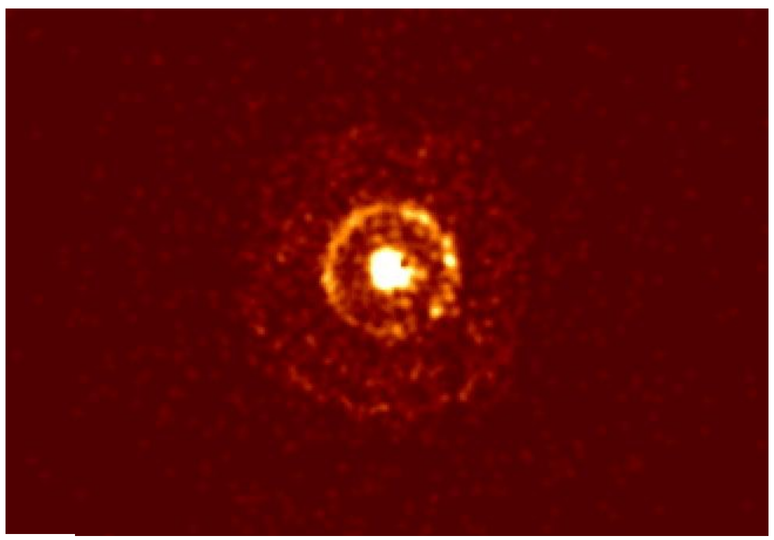
- **Size:**

$$r_{CR} \simeq 2\sqrt{D T_{SD}}$$

$$D = D_{28} \times 10^{28} \left[\frac{E_{CR}}{3\ \mathrm{GeV}}\right]^{\delta} \mathrm{cm}^2/\mathrm{s}\,,$$

$$\delta = 0.4 \pm 0.1\,,$$

$$r_{CR} \simeq 120 \times D_{28}^{1/2} \left[\frac{T_{SD}}{10\ \mathrm{kyr}}\right]^{1/2} \left[\frac{E_{CR}}{1\ \mathrm{TeV}}\right]^{0.2} \mathrm{pc}$$



*this picture may or may not represent the actual halo

$$R_{halo} = \frac{r_{CR}}{r_s}$$

$$\simeq 1.4^\circ D_{28}^{1/2} \left[\frac{5\ \mathrm{kpc}}{r_s}\right] \left[\frac{T_{SD}}{10\ \mathrm{kyr}}\right]^{1/2} \left[\frac{E_\gamma}{200\ \mathrm{GeV}}\right]^{0.2}$$

~ 1 TeV in CRs

- **Luminosity:**

$$L_\gamma^{E_\gamma \gtrsim 1\ \mathrm{GeV}} \sim \kappa \frac{\mathcal{E}_{CR}^{halo}}{t_{int}}$$

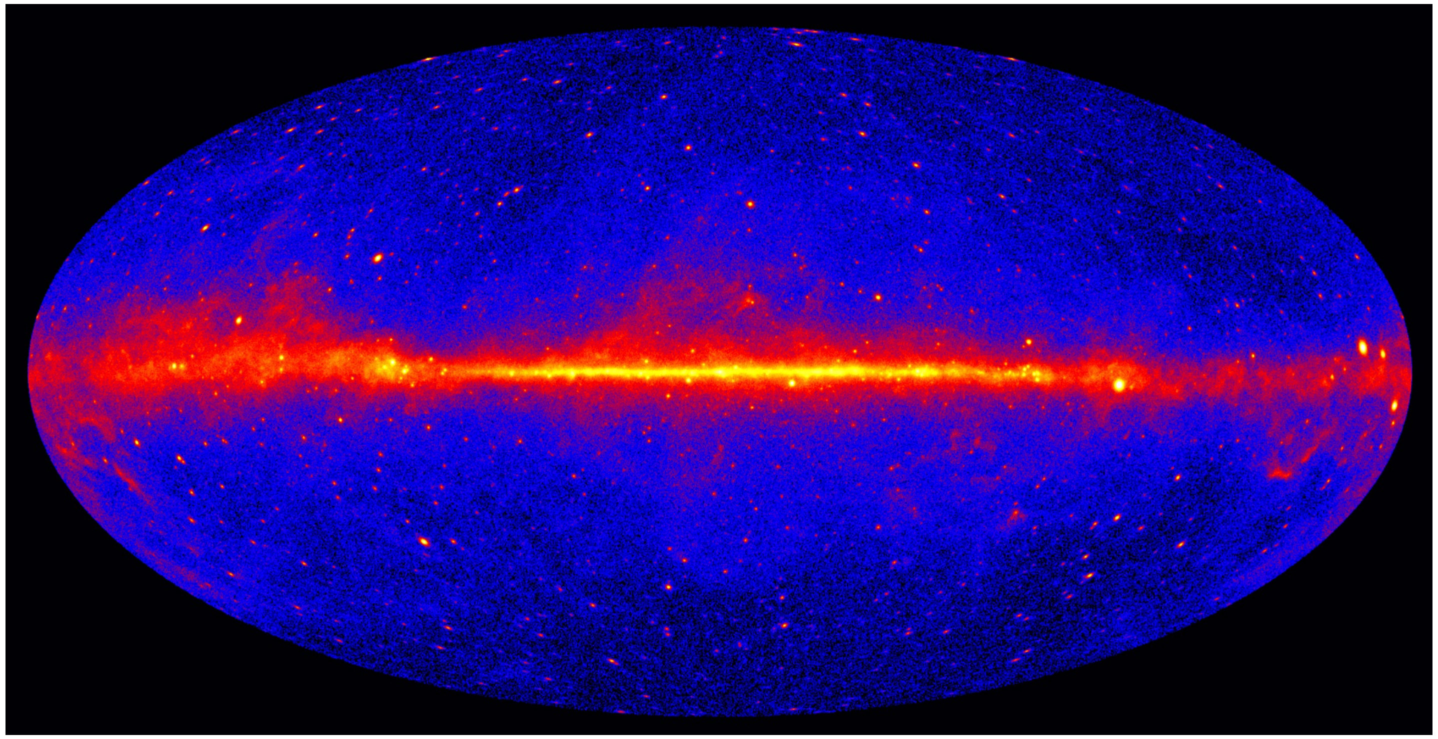
$$\simeq 4 \times 10^{34} \left[\frac{\kappa}{0.2}\right] \left[\frac{\mathcal{E}_{CR}^{halo}}{2 \times 10^{50}\ \mathrm{erg}}\right] \left[\frac{n_{ISM}}{1\ \mathrm{cm}^{-3}}\right] \frac{\mathrm{erg}}{\mathrm{s}}$$

Pulsar sample

- Young and close $T_{SD} < 30\ \mathrm{kyr}\,, \quad r_s < 5\ \mathrm{kpc}$

- Away from the Galactic plane and center

$$15^\circ < l < 345^\circ\,, \quad |b| > 1^\circ$$



Pulsar sample

	PSRJ	l	b	r_s, kpc	T_{SD}, kyr	$\dot{E}$, erg/s	P, s
1	J0007+7303	119.66	10.46	1.40	13.9	4.5×10^{35}	0.32
2	J0501+4516	161.55	1.95	2.20	15.7	1.2×10^{33}	5.8
3	J1709-4429	343.10	-2.69	2.60	17.5	3.4×10^{36}	0.10
4	J2229+6114	106.65	2.95	3.00	10.5	2.2×10^{36}	0.052
5	J0205+6449	130.72	3.08	3.20	5.37	2.7×10^{37}	0.065
6	J1357-6429	309.92	-2.51	4.09	7.31	3.1×10^{36}	0.17
7	J0534+2200	184.56	-5.78	2.00	1.26	4.5×10^{38}	0.033
8	J1513-5908	320.32	-1.16	4.40	1.56	1.7×10^{37}	0.15

Credits: ATNF

Method

- 7 year Fermi-LAT data and Ferm-LAT software

For each pulsar:

- Take all known 3FGL sources within 10° but allow their parameters to vary during *gtlike* (likelihood optimization routine)
- Add to the source model uniformly bright round halo with a desired radius $0.1^\circ - 5^\circ$ with a power-law spectrum
- Split the data into 3 energy bins (the size is different!)

  1 - 10 GeV, 10 - 100 GeV, and 100 - 500 GeV

- *gtlike* it and check out the fit
- Study the distribution of Test Statistics

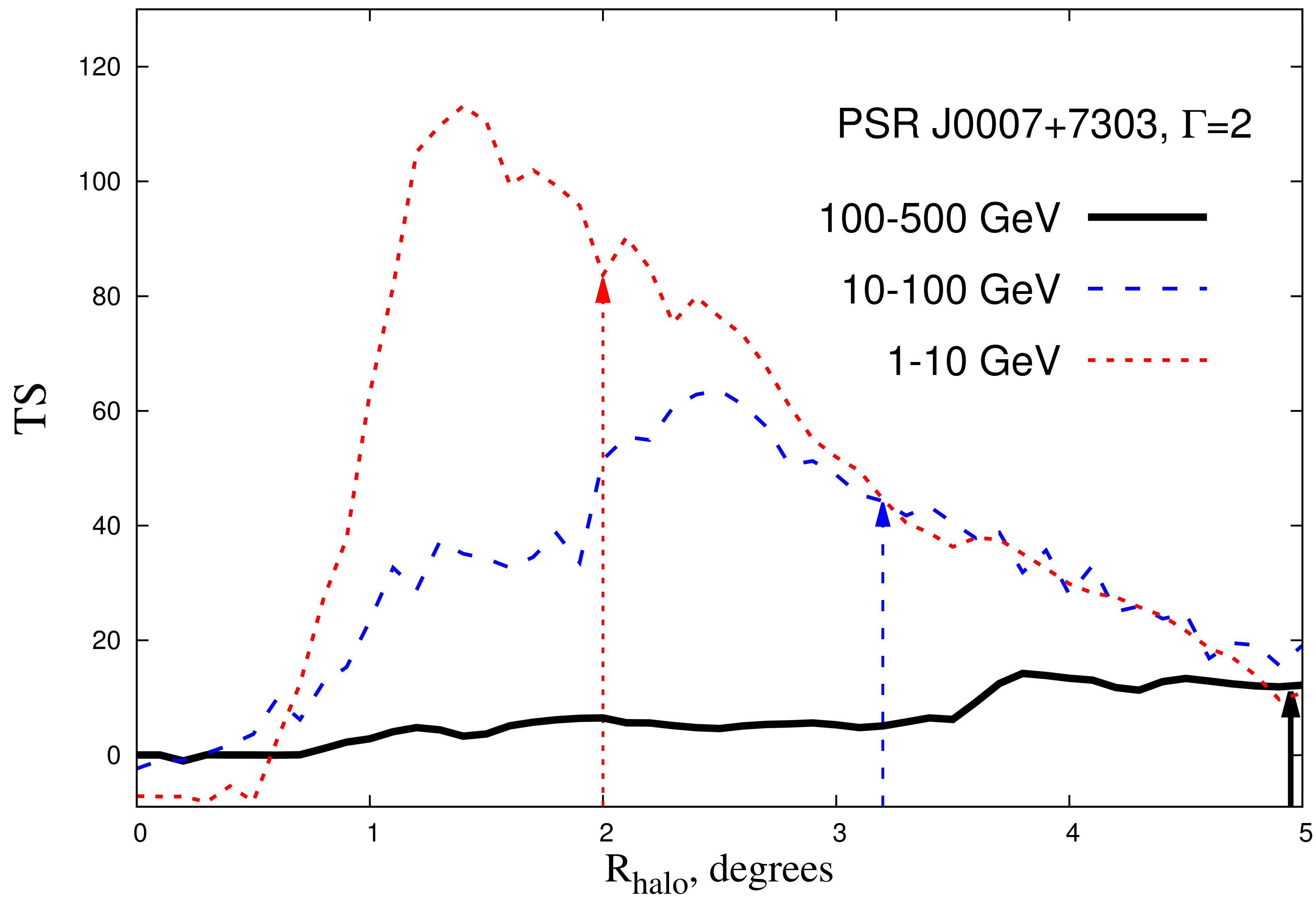
$$TS = -2 \ln \frac{L_{max,0}}{L_{max,1}}$$

no halo ($L_{max,0}$)

w/ halo ($L_{max,1}$)

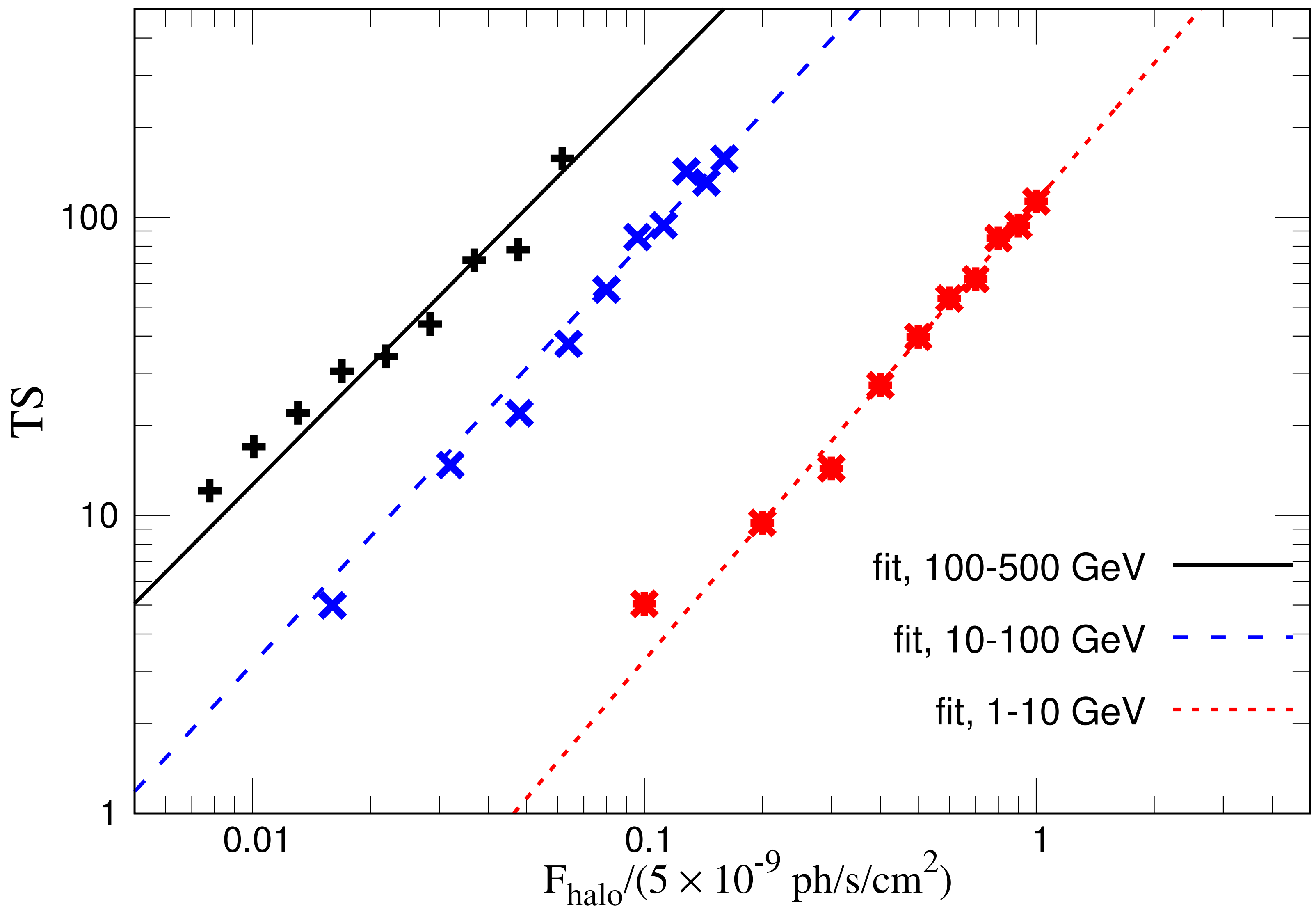
n.b. Rule of thumb: $\# \text{ of } \sigma \approx \sqrt{TS}$

Simulations



Input a halo ➔ Simulate with *gtobssim* ➔ Analyze like real data

Simulations: TS (flux) scaling



best fits:

$$TS_{1-10} \simeq 100 \left[\frac{F^{1-10\ \mathrm{GeV}}}{4.6\times10^{-9}\ \mathrm{ph/cm^2s}}\right]^{b_1},$$

$$b_1 = 1.54 \pm 0.06\,,$$

$$TS_{10-100} \simeq 100 \left[\frac{F^{10-100\ \mathrm{GeV}}}{5.7\times10^{-10}\ \mathrm{ph/cm^2s}}\right]^{b_2},$$

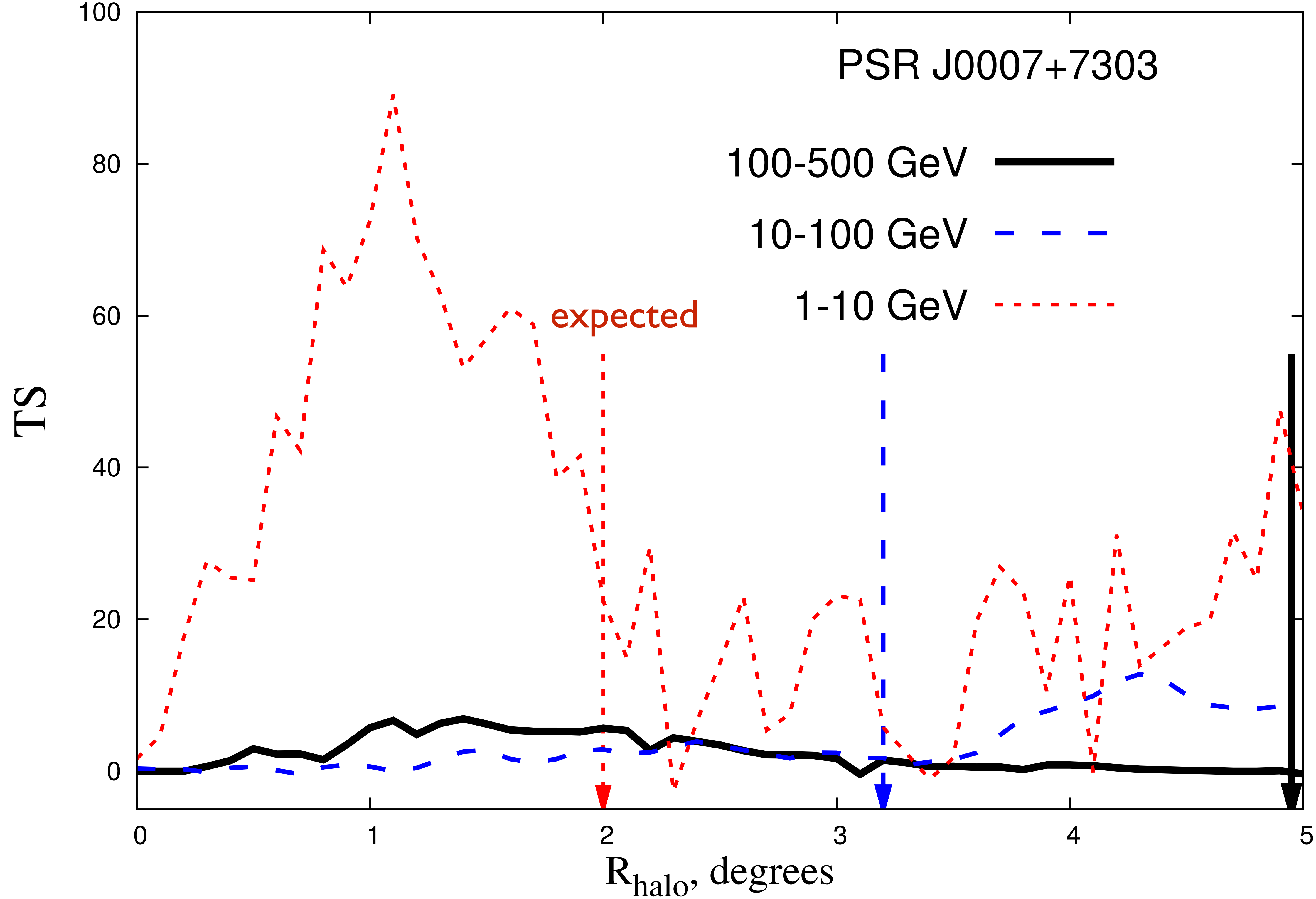
$$b_2 = 1.42 \pm 0.14\,,$$

$$TS_{100-500} \simeq 100 \left[\frac{F^{100-500\ \mathrm{GeV}}}{2.4\times10^{-10}\ \mathrm{ph/cm^2s}}\right]^{b_3},$$

$$b_3 = 1.33 \pm 0.10\,.$$

a halo with a given flux
yields detection @ which TS ?

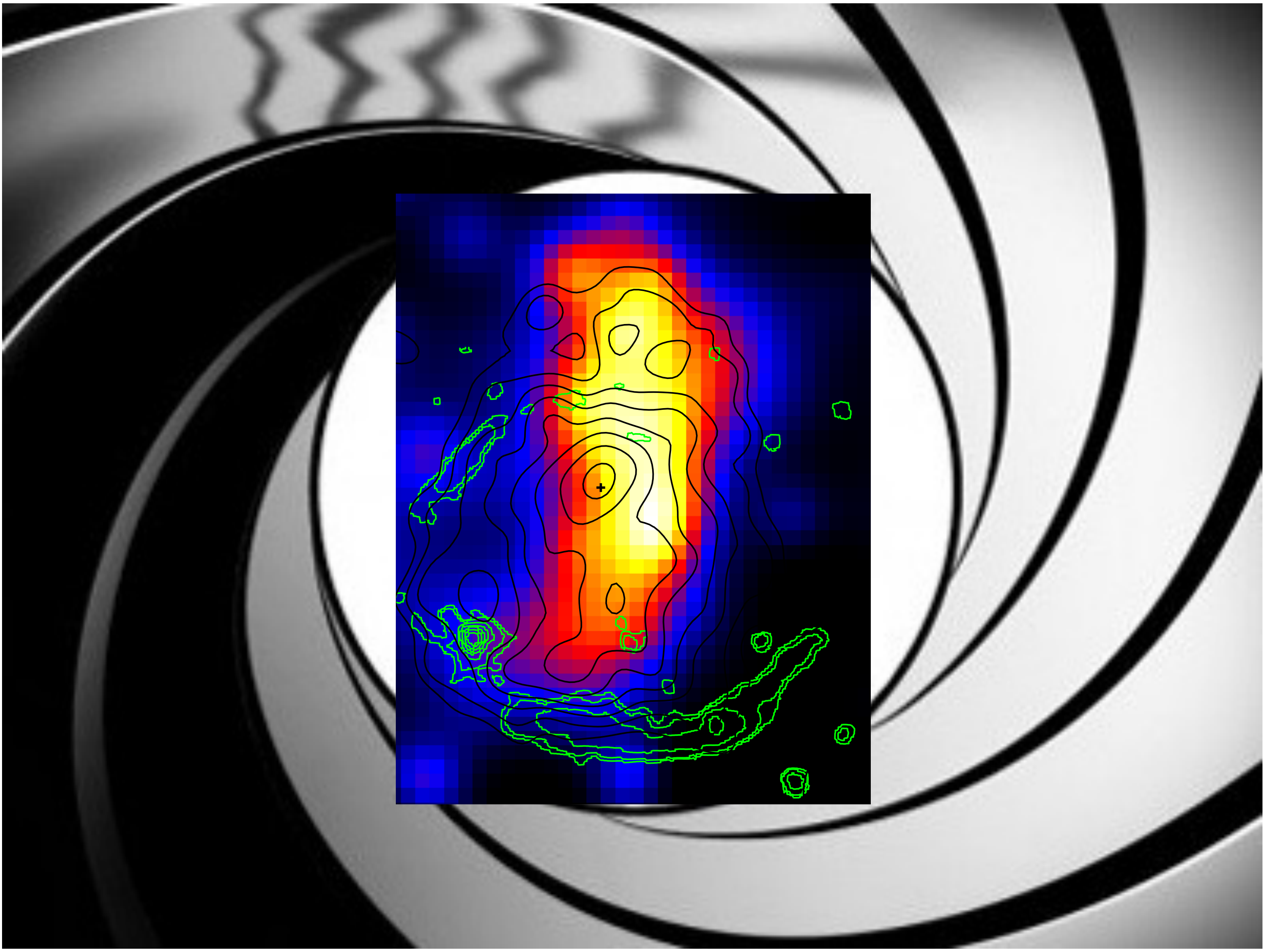
Results



PSR J0007+7303
100-500 GeV
10-100 GeV
1-10 GeV
expected
TS
100
80
60
40
20
0
0
1
2
3
4
5
R_{halo}, degrees

PSR J0007+7307

$\sim 10\sigma$ detection of 1-degree halo



There are already PWN and SNR around this pulsar

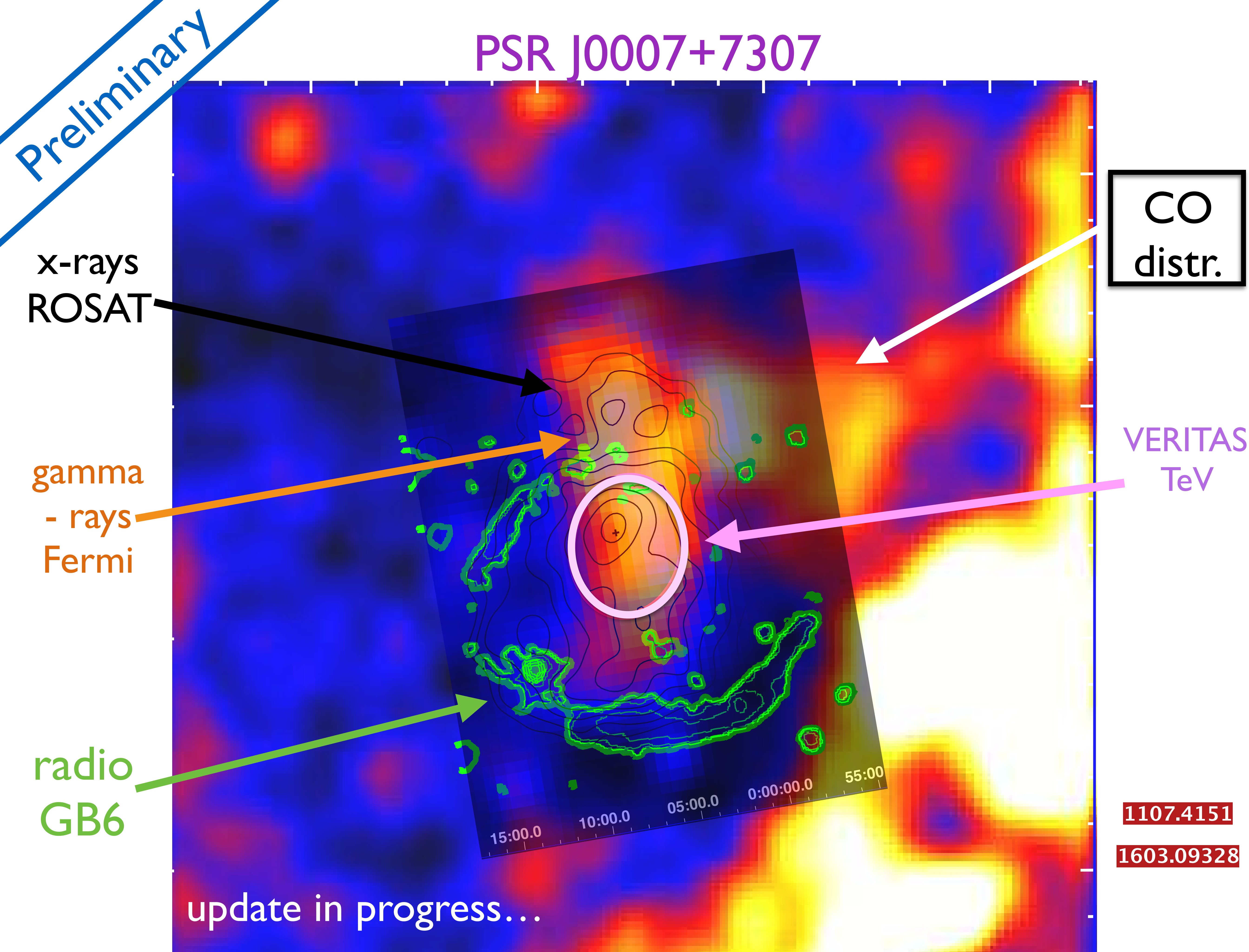
but might also be a halo! one has to disentangle between other sources there

$$L_\gamma^{E_\gamma \geq 1\ \mathrm{GeV}} \simeq 3.0 \times 10^{33} \mathrm{erg/s}\,.$$

$$\mathcal{E}_{CR}^{halo} \sim (2-4) \times 10^{50}\ \mathrm{erg}.$$

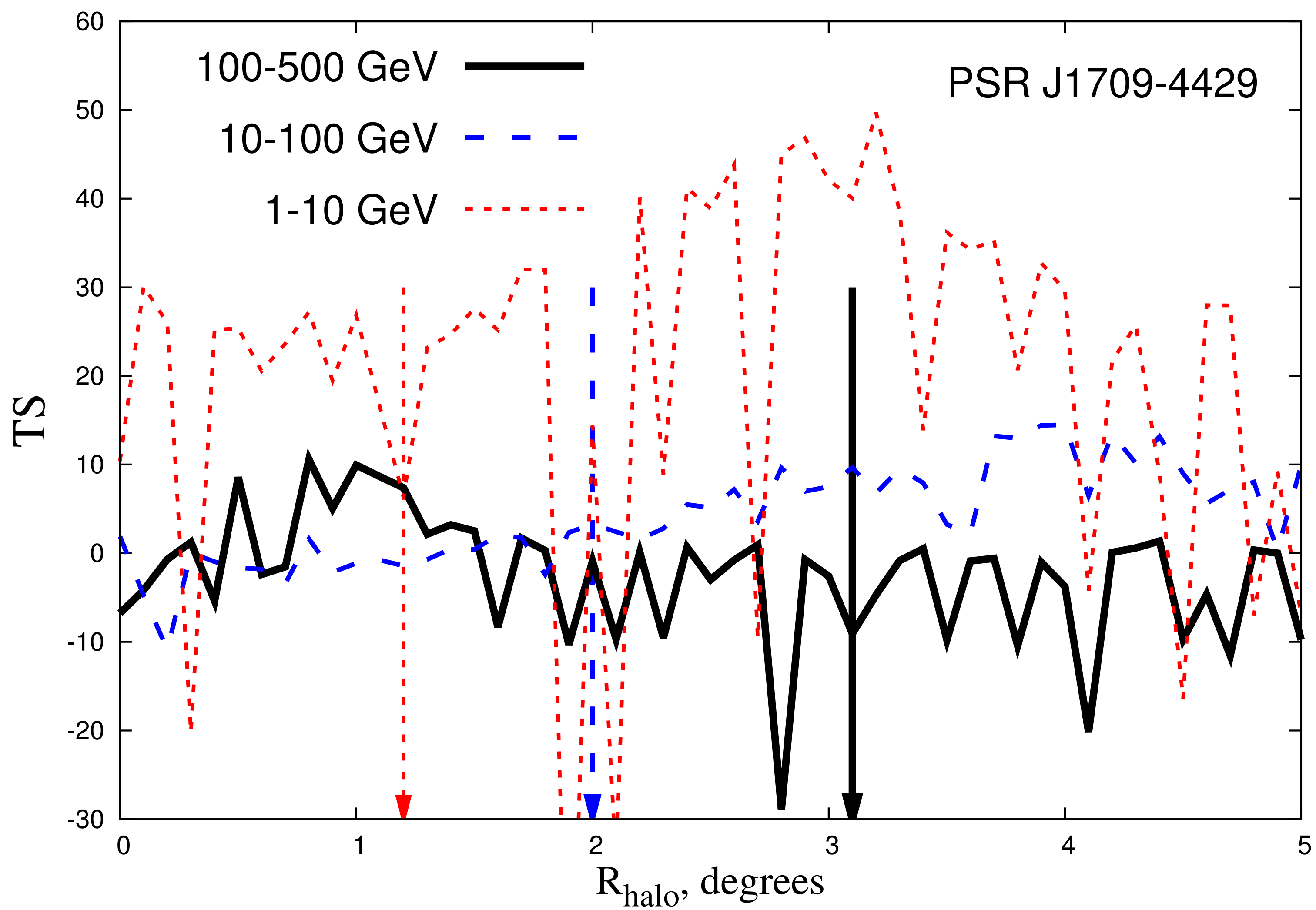
$$F^{1-10\ \mathrm{GeV}} = (3.53 \pm 0.23) \times 10^{-9}\ \mathrm{photons/cm^2 s}\,,$$
$$\Gamma = 2.798 \pm 0.081\,.$$

PSR J0007+7307



Constraints

No halo seen for other pulsars



Nonobservation of halos:

$$TS_{1-10} < 50$$

$$\Rightarrow$$

$$F^{1-10\ \mathrm{GeV}} < 3.0 \times 10^{-9}\ \mathrm{ph/cm^2 s}$$

$$L_\gamma^{halo} \lesssim (1-2) \times 10^{34}\ \mathrm{erg/s}$$

Discussion

$$\frac{\mathcal{E}_{CR}^{halo}}{2\times 10^{50}\ \mathrm{erg}} \simeq \left[\frac{L_\gamma^{halo}}{2\times 10^{34}\ \mathrm{erg/s}}\right]\left[\frac{1\ \mathrm{cm}^{-3}}{n_{ISM}}\right]$$

Nonobservation of halos (fixed ISM density):

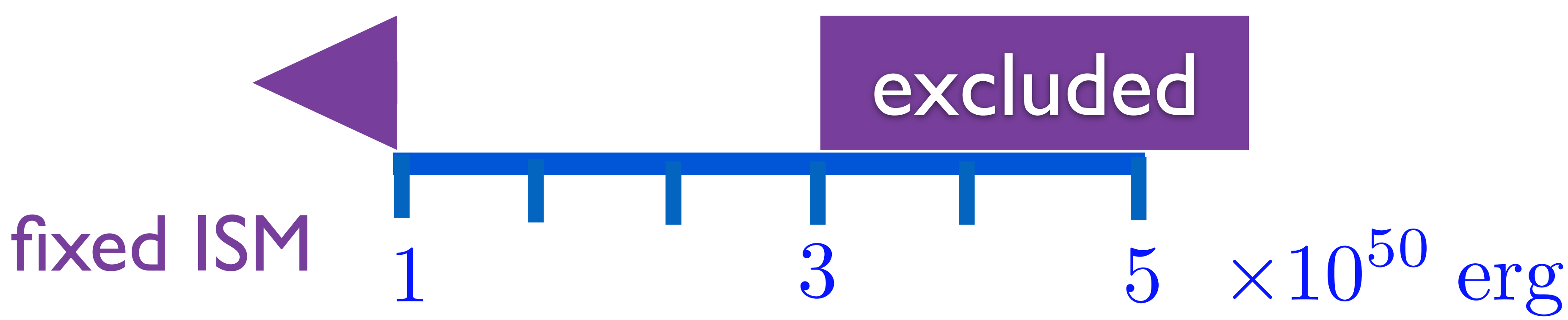
$$L_\gamma^{halo} \lesssim (1-2)\times 10^{34}\ \mathrm{erg/s}$$

$$\mathcal{E}_{CR}^{halo} \lesssim (0.5-1)\times 10^{50}\ \mathrm{erg}$$

Degeneracy with ISM density:

$$n_{ISM} \simeq 0.3 \div 1\ \mathrm{cm}^{-3}$$

$$\mathcal{E}_{CR}^{halo} \lesssim (0.5-3)\times 10^{50}\ \mathrm{erg}$$



we need to explain all CRs with pulsars
(scatter = uncertainty in birthrates: 1 per 30-120 yr)

Conclusions:

- Pulsars might be sources of hadronic CRs:
  diffusive gamma-ray halos to test this scenario

- One candidate is found, thorough study required

- Apart from that,
  no definitive diffusive gamma-ray halos were found

- Bounds on luminosity → bounds on CR flux

- Pulsars are pinned down as main CR factories
  (not completely ruled out though!
  beware of degeneracies and uncertainties)

Thank you for your attention !

Backup slides

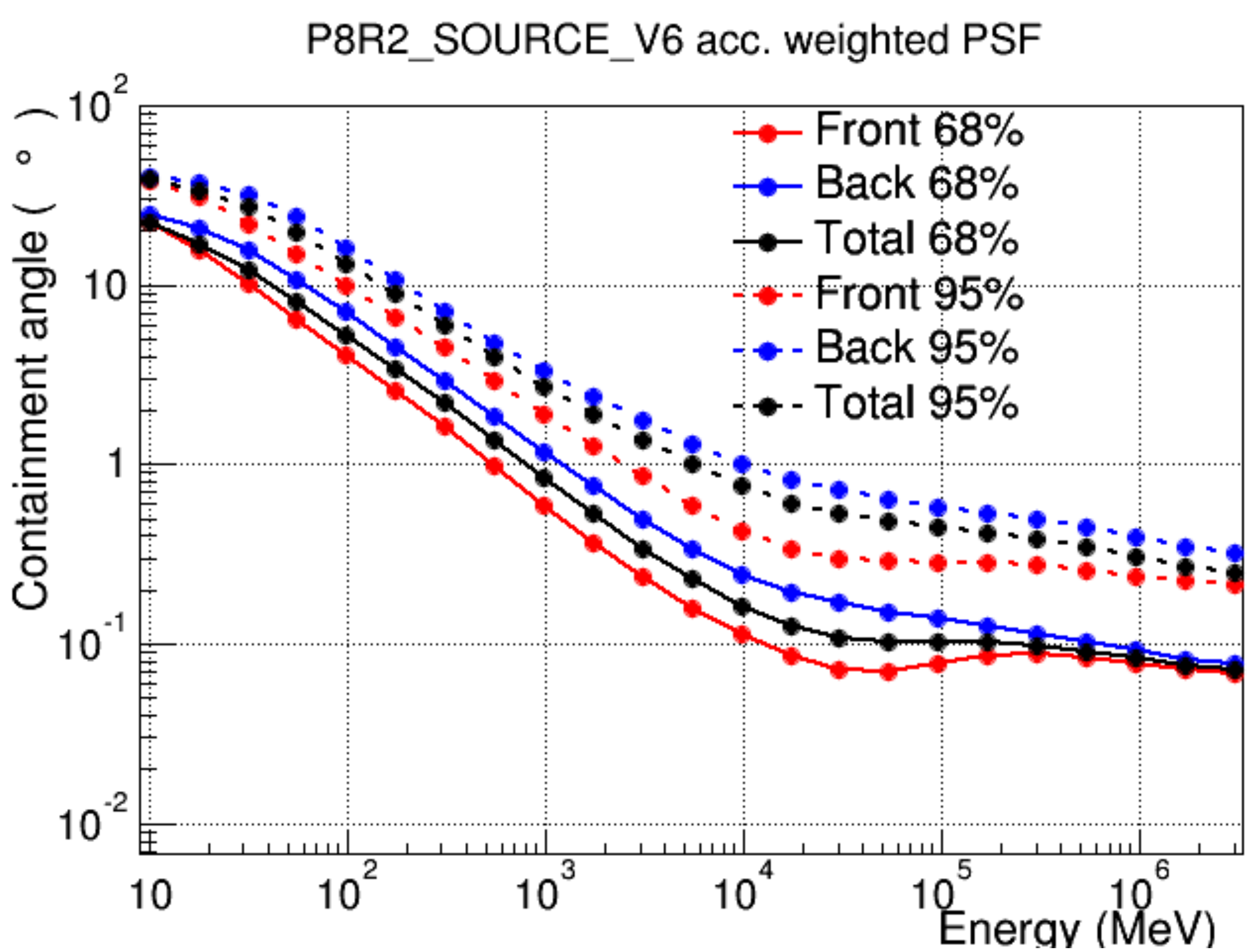
Why only above 1 GeV?

1) @ 1 GeV the two coincide

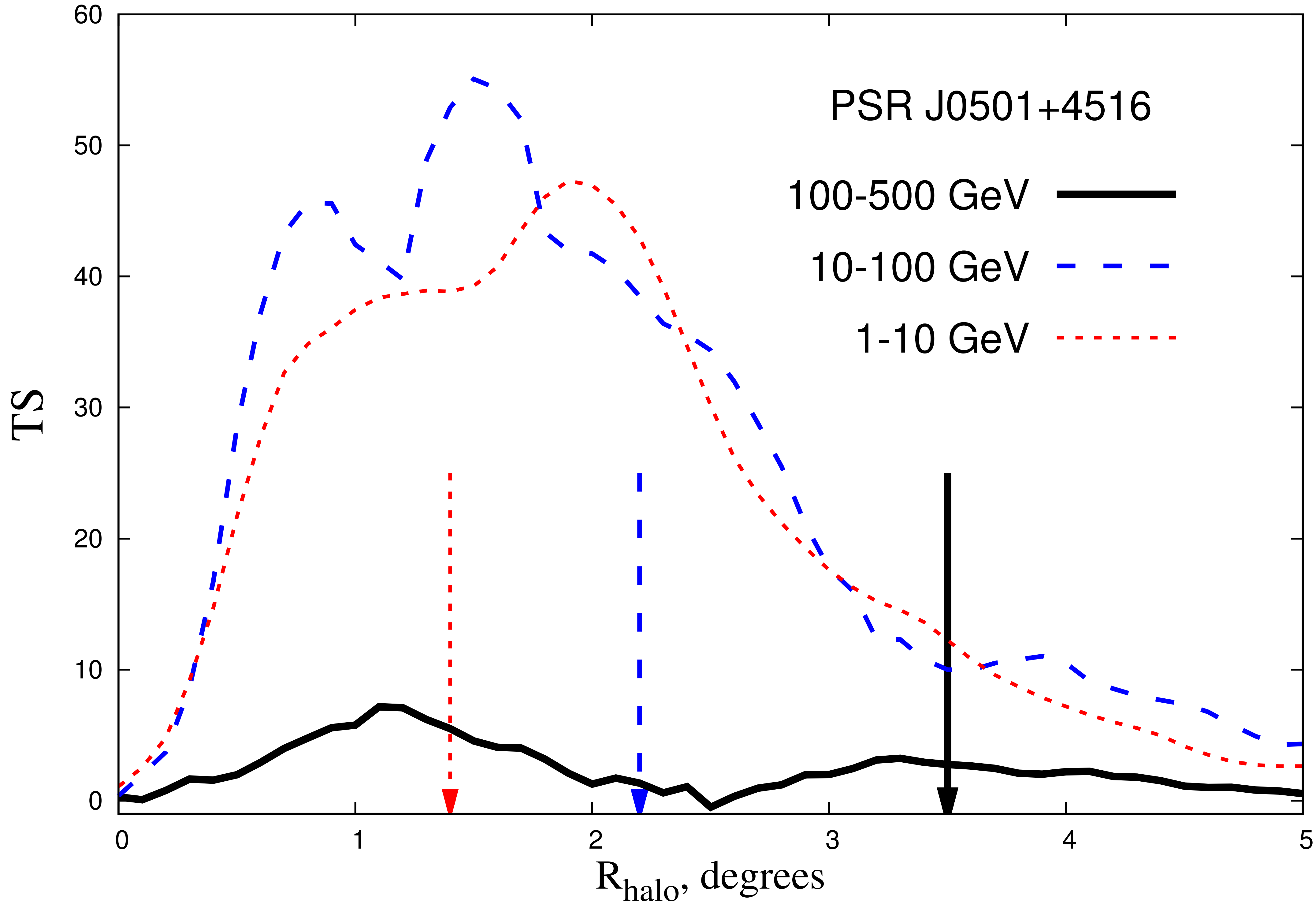
$$R_{SNR} = \frac{r_{SNR}}{r_s} \simeq 0.1^\circ \left[\frac{5\mathrm{kpc}}{r_s}\right] \left[\frac{t}{10\ \mathrm{kyr}}\right]^{0.4} \times \left[\frac{\mathcal{E}_{SN}}{10^{51}\mathrm{erg}}\right]^{0.2} \left[\frac{1\ \mathrm{cm}^{-3}}{n_{ISM}}\right]^{0.2}$$

$$R_{halo} = \frac{r_{CR}}{r_s} \simeq 1.4^\circ D_{28}^{1/2} \left[\frac{5\ \mathrm{kpc}}{r_s}\right] \left[\frac{T_{SD}}{10\ \mathrm{kyr}}\right]^{1/2} \left[\frac{E_\gamma}{200\ \mathrm{GeV}}\right]^{0.2}$$

2) LAT PSF is big: localization capability reduced



Supernova example



SNR G160.4 + 02.8

Pulsar sample

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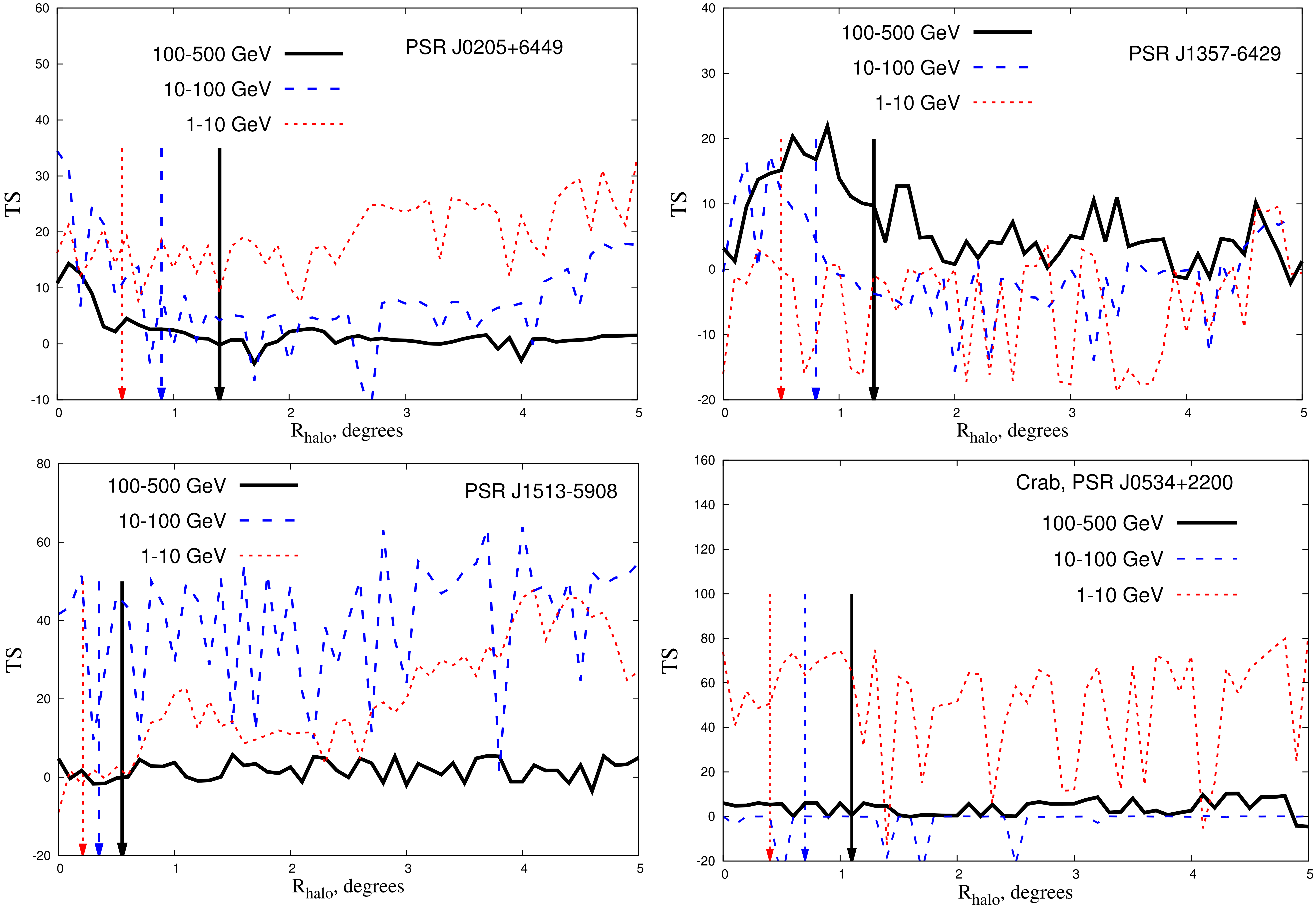
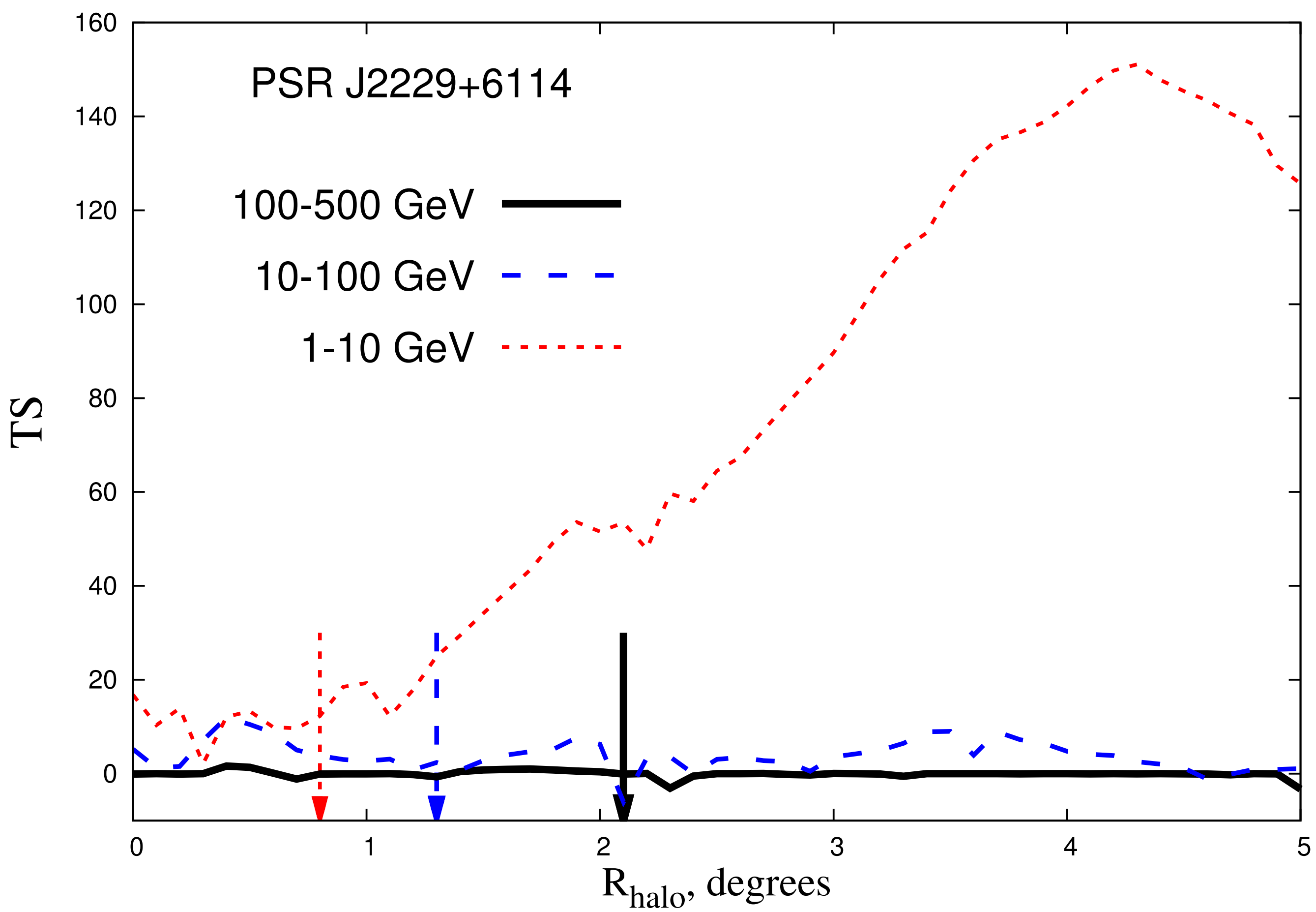
	PSRJ	R_{halo}(1 GeV)	R_{halo}(10 GeV)	R_{halo}(100 GeV)
1	J0007+7303	$2.0°$	$3.2°$	$5.0°$
2	J0501+4516	$1.4°$	$2.2°$	$3.5°$
3	J1709-4429	$1.2°$	$2.0°$	$3.1°$
4	J2229+6114	$0.8°$	$1.3°$	$2.1°$
5	J0205+6449	$0.6°$	$0.9°$	$1.4°$
6	J1357-6429	$0.5°$	$0.8°$	$1.3°$
7	J0534+2200	$0.4°$	$0.7°$	$1.1°$
8	J1513-5908	$0.2°$	$0.4°$	$0.6°$

Results



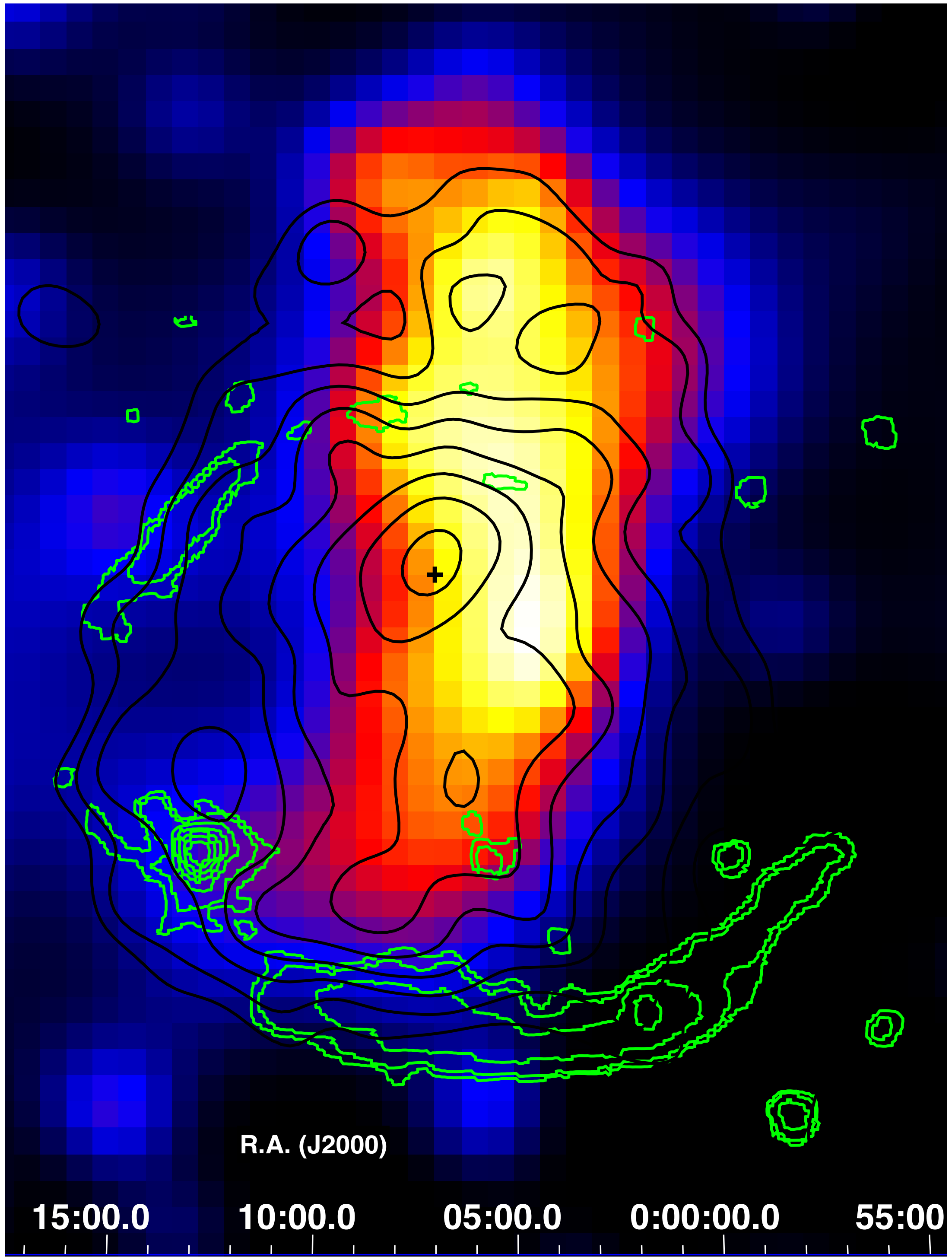
PSR J0205+6449
100-500 GeV
10-100 GeV
1-10 GeV
TS
R_halo, degrees
PSR J1357-6429
100-500 GeV
10-100 GeV
1-10 GeV
TS
R_halo, degrees
PSR J1513-5908
100-500 GeV
10-100 GeV
1-10 GeV
TS
R_halo, degrees
Crab, PSR J0534+2200
100-500 GeV
10-100 GeV
1-10 GeV
TS
R_halo, degrees

Results



PSR J2229+6114
100-500 GeV
10-100 GeV
1-10 GeV
TS
R$_{halo}$, degrees
160
140
120
100
80
60
40
20
0
0
1
2
3
4
5

PSR J0007+7307



x-rays ROSAT gamma-rays Fermi

radio GB6

1107.4151

1603.09328

VERITAS, TeV

CO distr.