Search for Galactic Cosmic Ray Sources with H.E.S.S.

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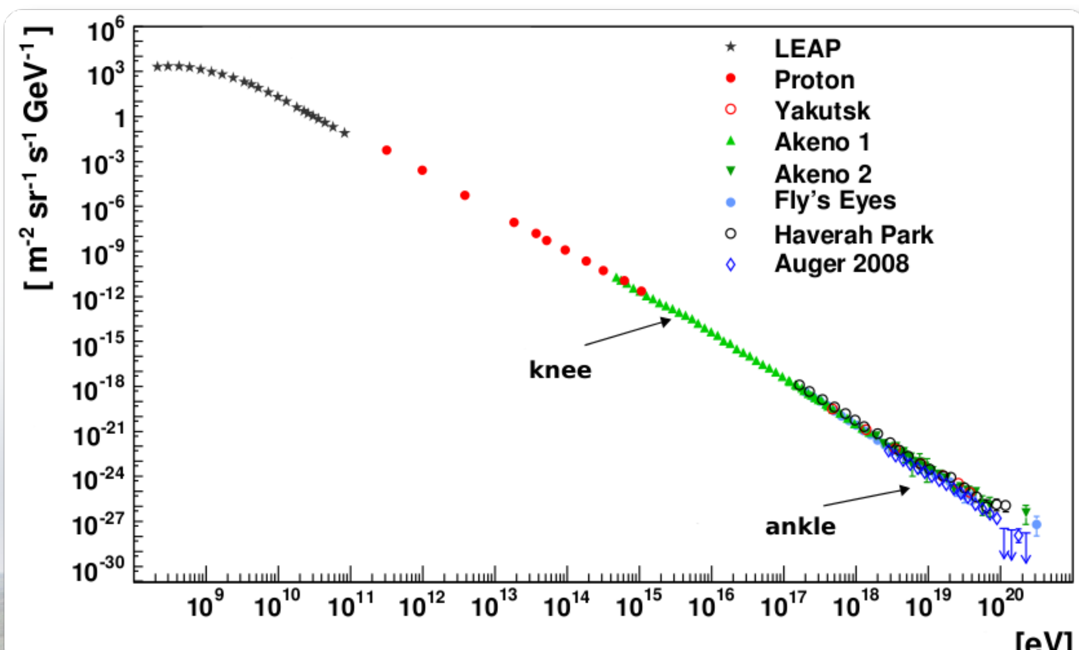
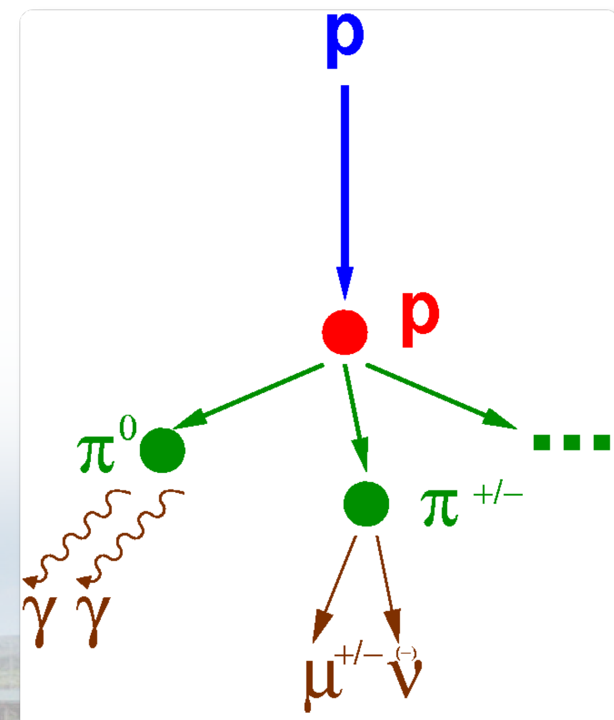
for the H.E.S.S. collaboration

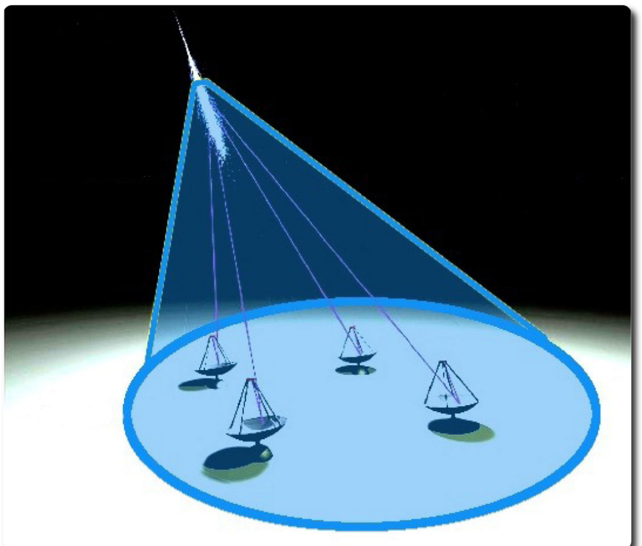
Motivation

- 1912 V.F. Hess discovered the Cosmic Rays (CRs)
- supernova remnants (SNRs) very promising candidates
  - energetics: ~10% of each explosion (10^{51} erg) enough to explain all CRs
  - shock fronts as effective accelerators
- 10 TeV protons produce TeV gammas in hadronic interactions
  - → need target material
- downside: TeV electrons produce TeV gammas (inverse Compton)
  - synchrotron radiation → to be observed in X-rays



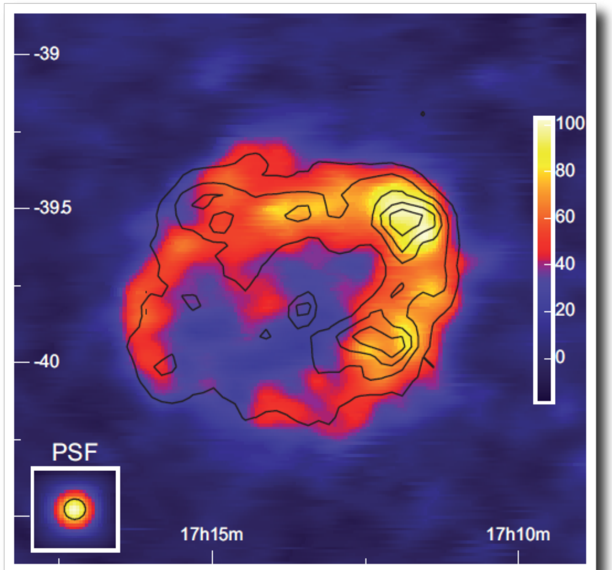


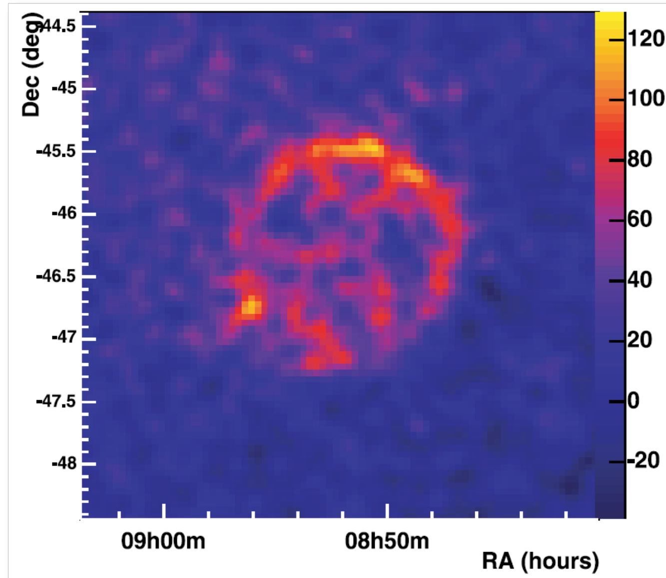
H.E.S.S. in a Nutshell

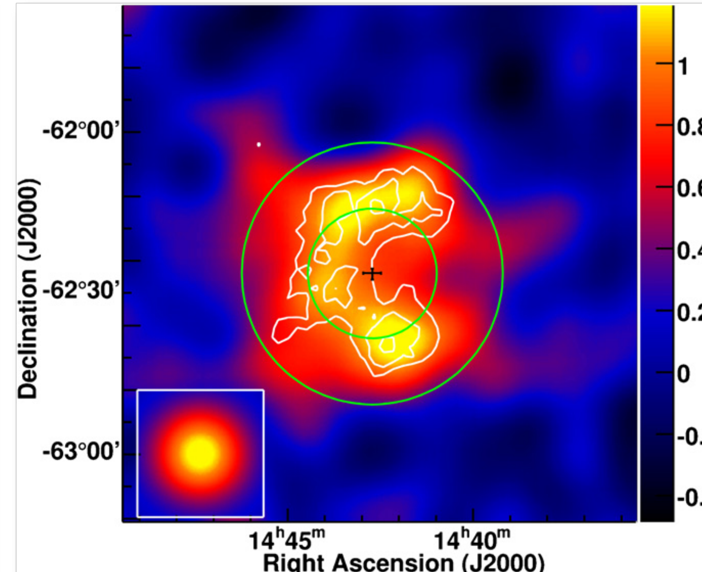


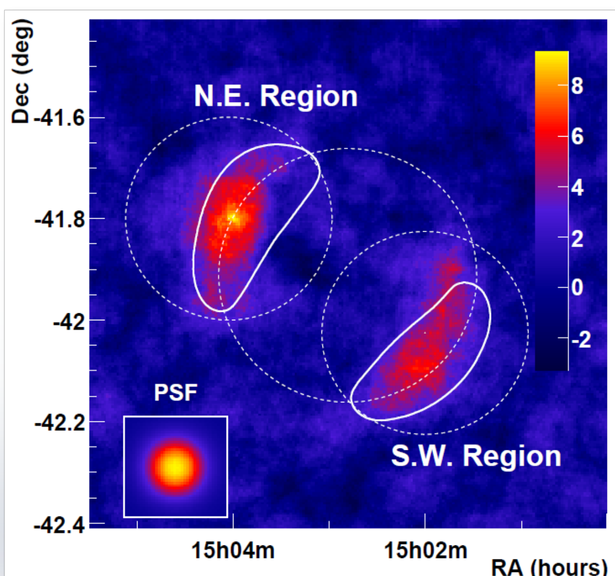
High **E**nergy **S**tereoscopic **S**ystem
- ~100 GeV – tens of TeV
- <0.1°single gamma-ray reconstruction
- 5° field of view
- scanning mode for large extended sources

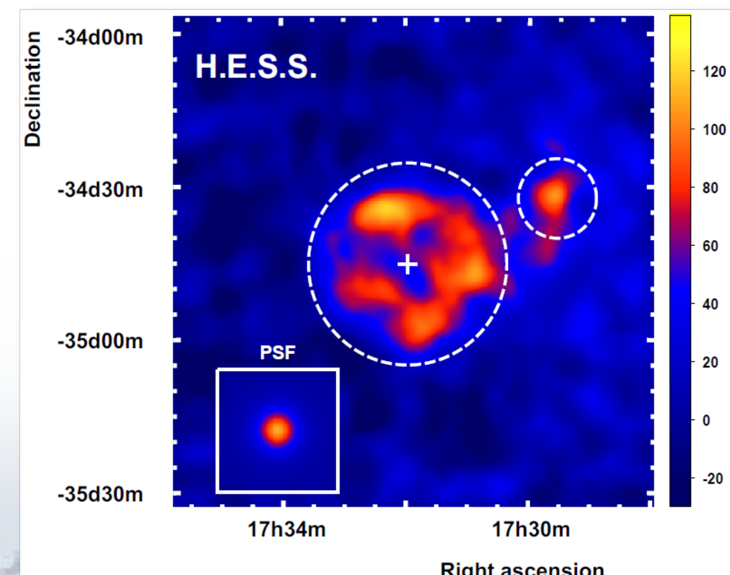
Shell-Type SNRs







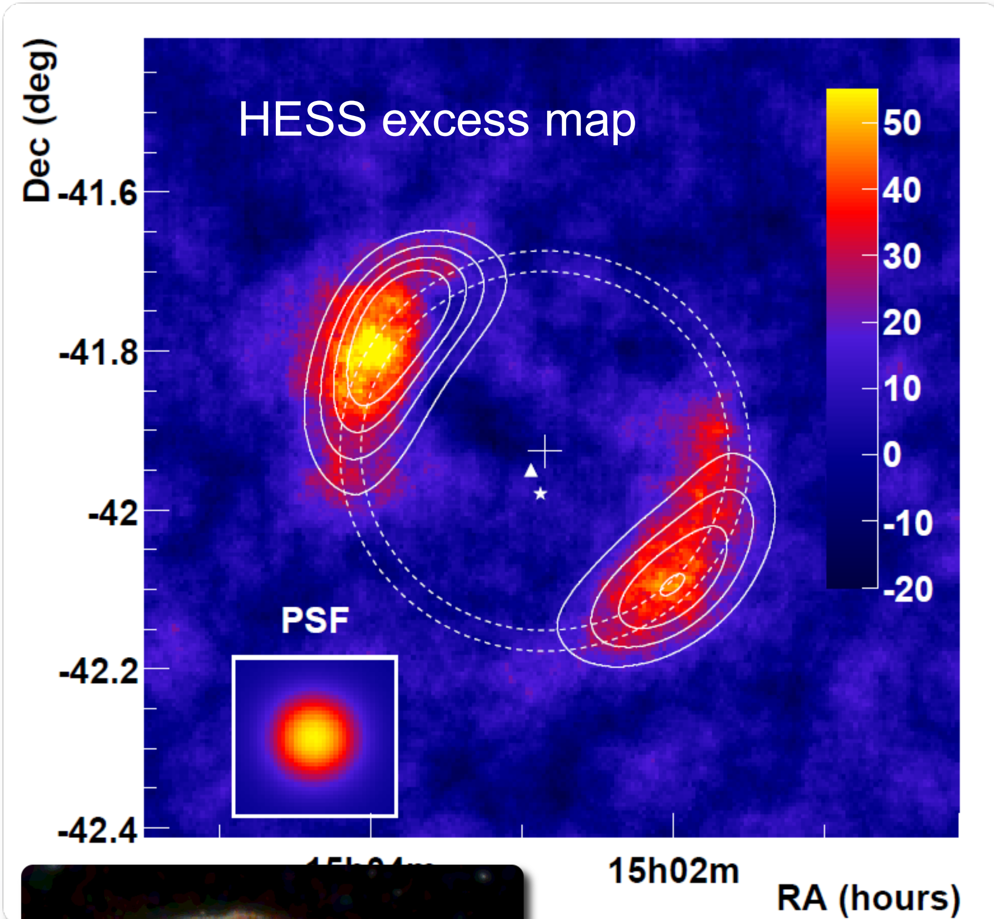


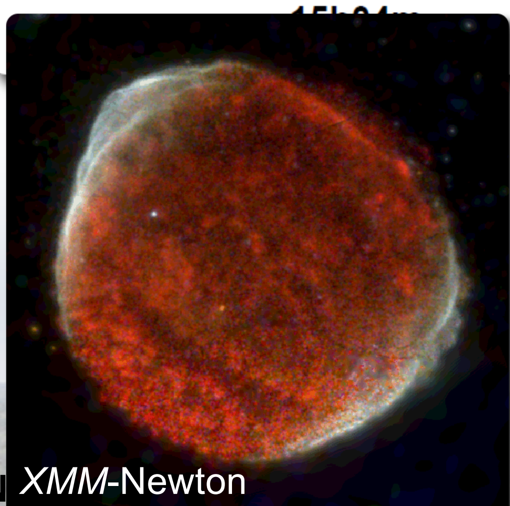


RX J1713.7–3946 (2004)
Vela Junior (2005)
RCW 86 (2006)
SN 1006 (2010)
HESS J1731–347 (2010)

SN 1006

[HESS 2010, *A&A* **516**, A62]

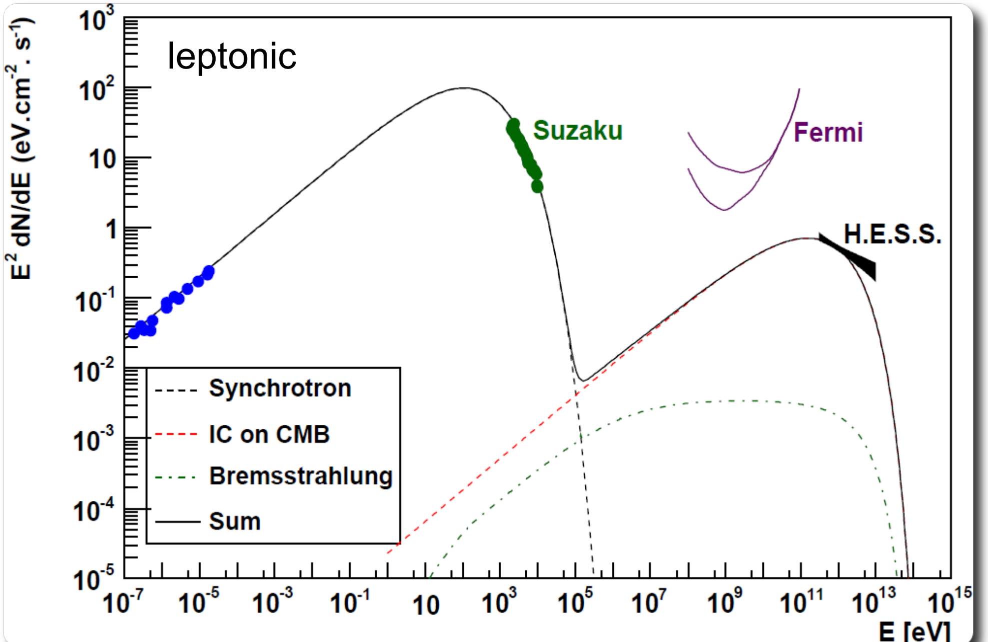


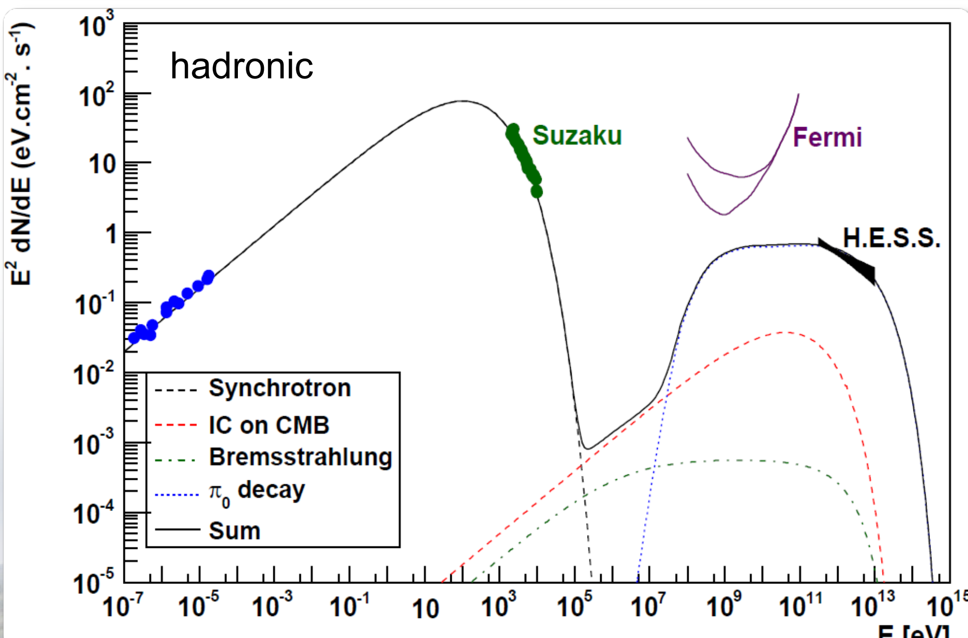


- ➲ SN type Ia
  - off-plane, 14º
- ➲ deep observations:
  - 130h exposure
- ➲ two spots
  - NE: 495 γ, 7.3σ
  - SW: 315 γ, 4.9σ
- ➲ clear correlation with non-thermal X-ray emission
- ➲ power law spectrum

Region	photon index Γ	$\Phi(>1\mathrm{TeV})$ $(10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1})$
NE	$2.35 \pm 0.14_{stat} \pm 0.2_{syst}$	$0.233 \pm 0.043_{stat} \pm 0.047_{syst}$
SW	$2.29 \pm 0.18_{stat} \pm 0.2_{syst}$	$0.155 \pm 0.037_{stat} \pm 0.031_{syst}$

SN 1006

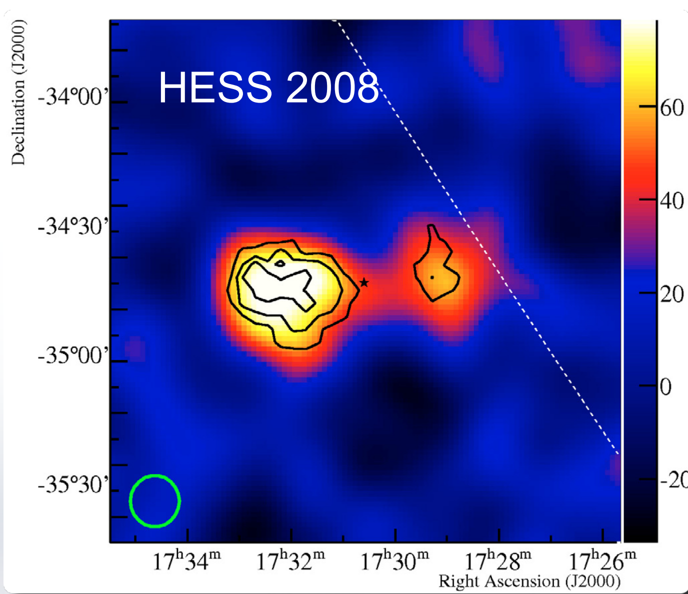


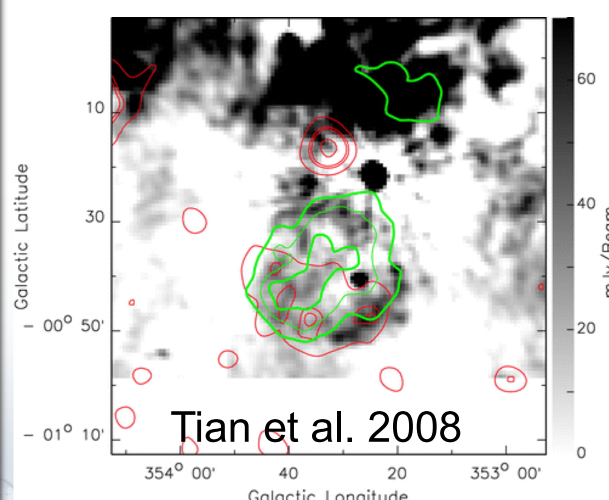


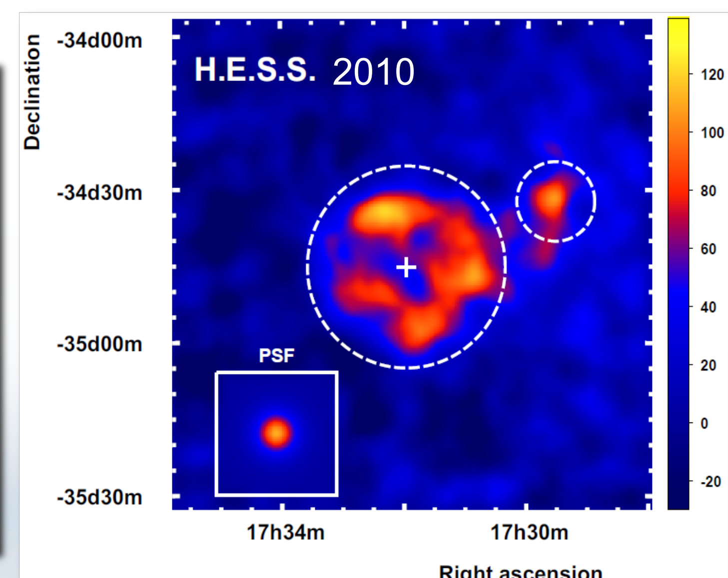
- purely leptonic scenario
  - magnetic field 30μG
- dominant hadronic scenario
  - 120μG
  - 0.085 cm^{-3}
  - total energy in protons $2x10^{50}$ erg
- other parameters
  - electron/proton ratio
  - norm, index, cut-off of *e* and *p*

HESS J1731–347

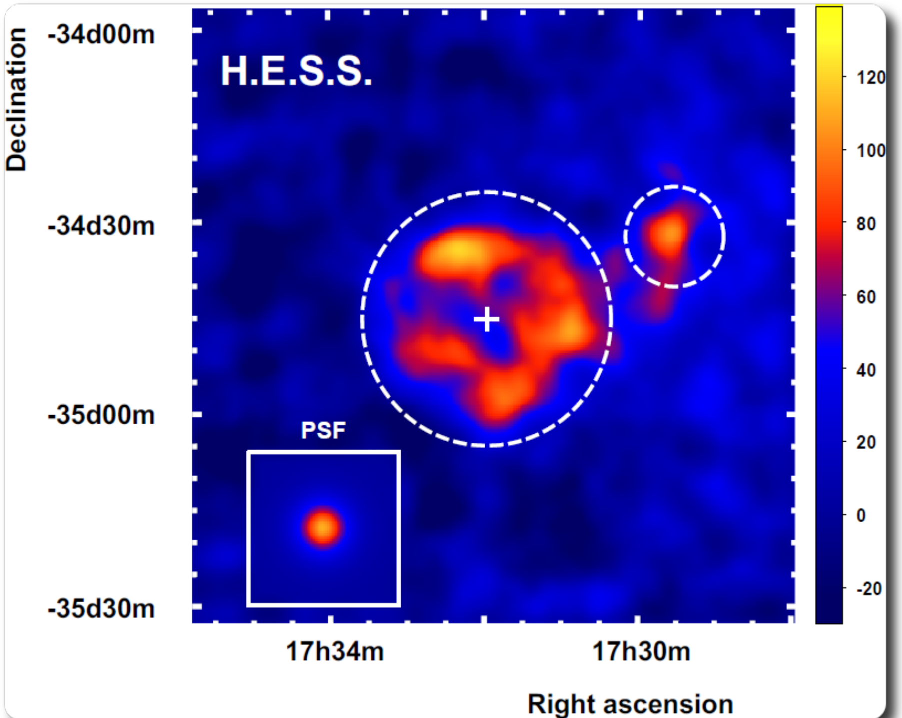
- ➲source with no identified counter-part [HESS 2008 *A&A* **477**, 353]
- ➲detection of radio-shell [Tian et al. 2008 *ApJ* **679**, L85]
  - G 353.6–0.7
- ➲re-observations → detection of TeV shell
- ➲**first SNR discovered based on TeV observations**

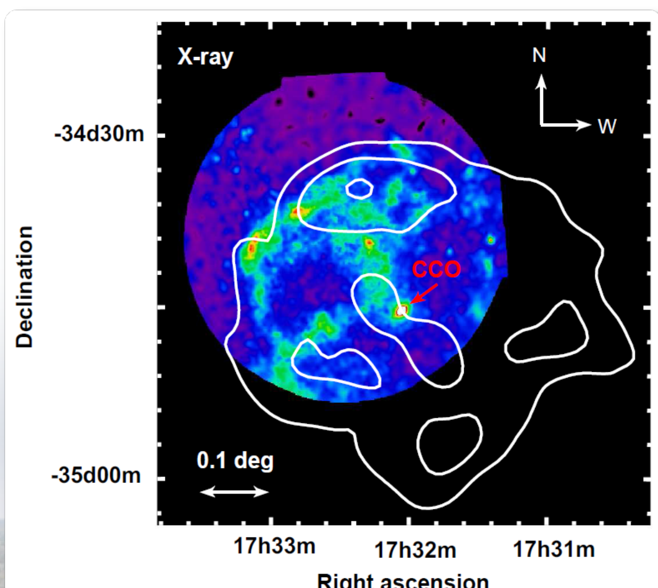






HESS J1731–347



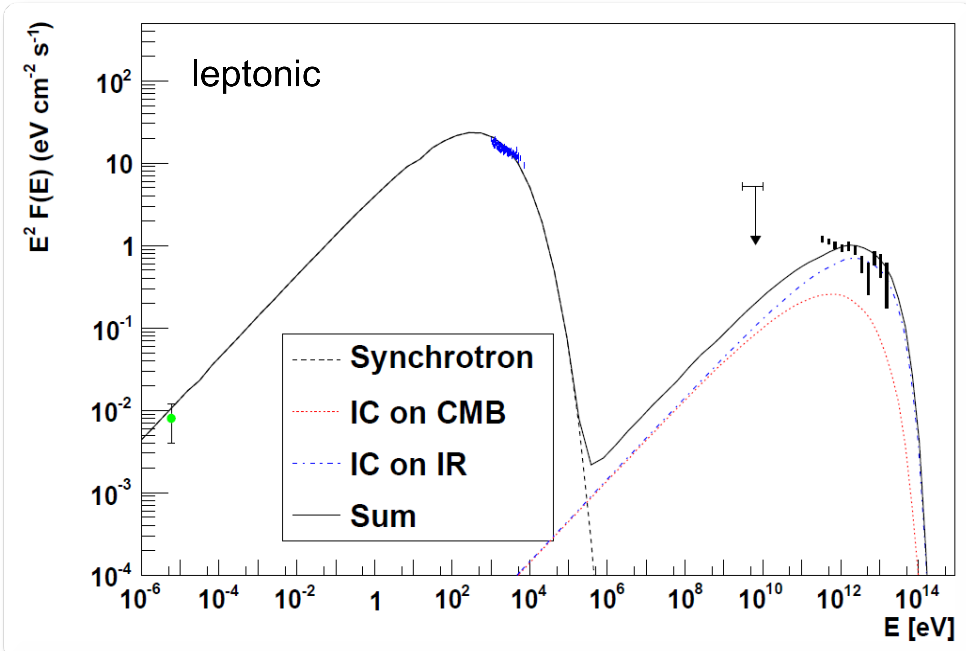


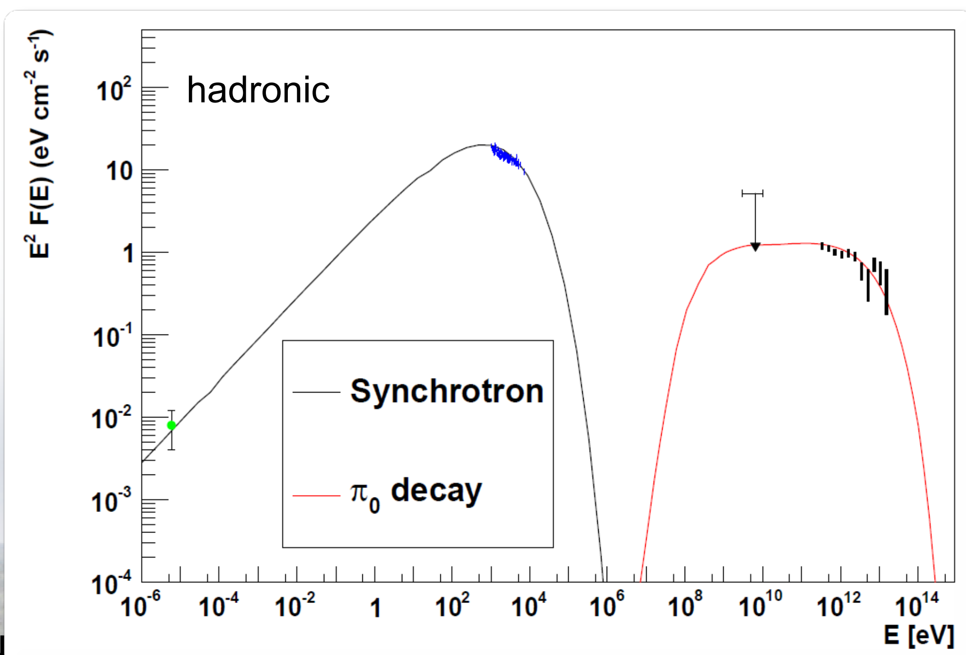
- 59h exposure time
- clear detection of shell
  - radius 0.27° ± 0.02°
- second source nearby
  - HESS J1729–345
- partially X-ray observations
  - correlated with X-ray shell
  - central compact object

Region	Photon index Γ	Decorrelation energy E_0 TeV	Normalization N_0 10^{-12} cm^{-2}s^{-1} TeV^{-1}	1-10 TeV integrated flux 10^{-12} erg cm^{-2}s^{-1}
HESS J1731−347	$2.32 \pm 0.06_{stat}$	0.783	$4.67 \pm 0.19_{stat}$	$6.91 \pm 0.75_{stat}$
sub-region of HESS J1731−347[a]	$2.34 \pm 0.09_{stat}$	0.780	$1.41 \pm 0.11_{stat}$	$2.02 \pm 0.36_{stat}$
HESS J1729−345	$2.24 \pm 0.15_{stat}$	0.861	$0.44 \pm 0.07_{stat}$	$0.88 \pm 0.29_{stat}$

[HESS 2011, submitted to *A&A*, arXiv:1105.3206]

HESS J1731-347

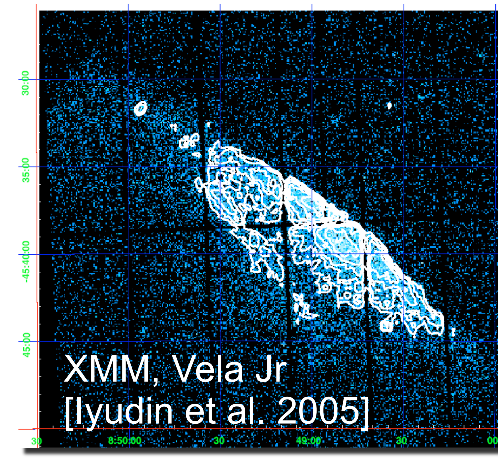




- purely leptonic scenario
  - IC on CMB and infra-red
  - 25μG
- dominant hadronic scenario
  - 50μG
  - energy in protons (⅓ of shell) $2 \times 10^{50}\ (n/\mathrm{cm}^{-3})^{-1}(d/3.2\mathrm{kpc})^2$
  - $1\mathrm{cm}^{-3}$ to high → shock front velocity 410 km/s
  - $0.01\ \mathrm{cm}^{-3}$ more realistic

SNR Summary

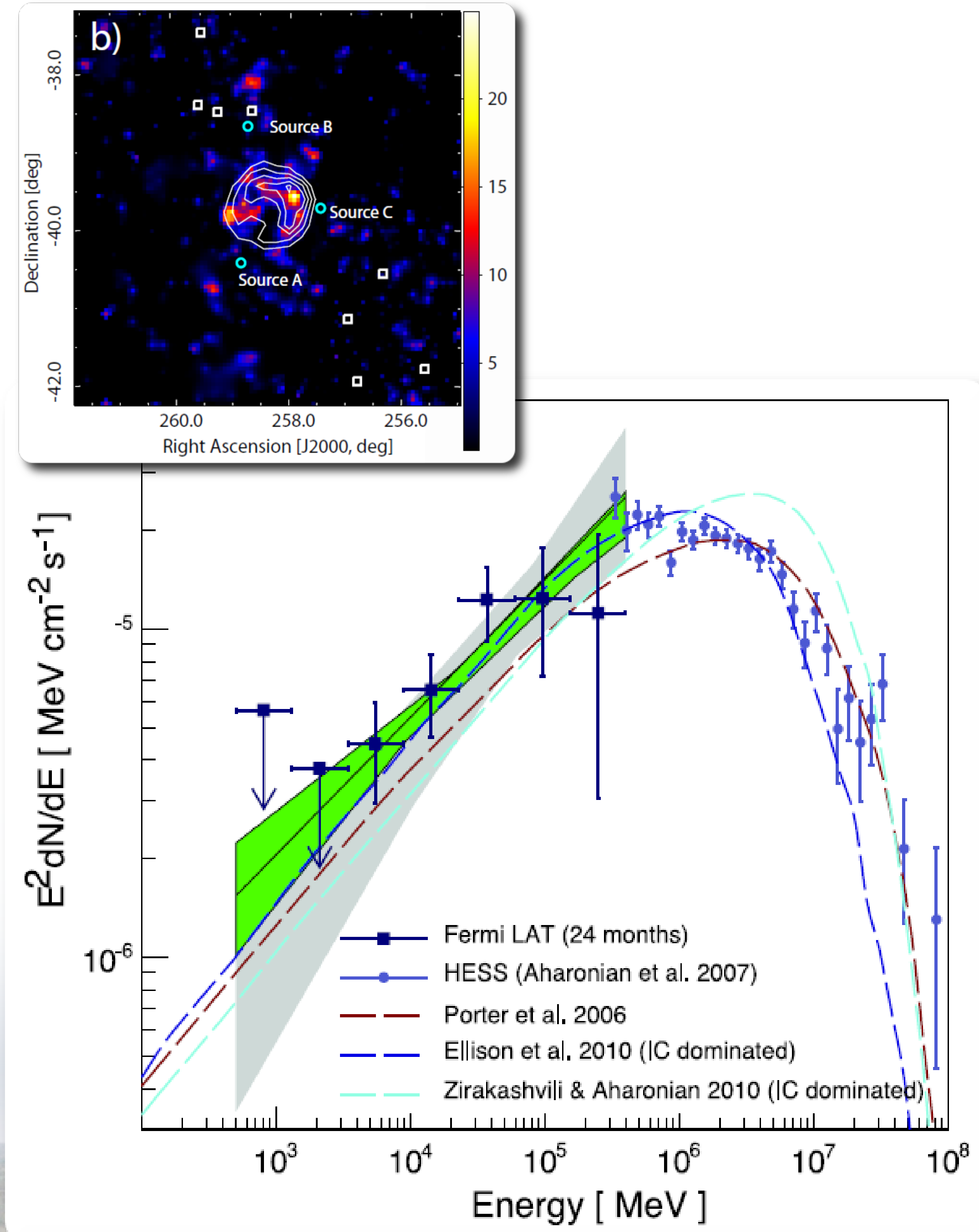
- all SNRs extended, clear shell visible
- correlation with X-ray morphology
  → favours leptonic scenario, low *B*
- thin X-ray filaments indicate strong *B*
- hadronic scenario explained by
  ~10% of SN explosion power


XMM, Vela Jr
[Iyudin et al. 2005]

name	**Ø**	**energy flux $F_\gamma(1-10\ \mathrm{TeV})$**	**X-ray flux F_X**	**magnetic field (leptonic sc.)**	**magnetic field (shock front filaments)**	**total energy in protons (hadronic scenario)**
RX J1713.7–3946	1.2°	7.5 10^{-11} erg $cm^{-2}s^{-1}$	(1–10 keV) 5.5 10^{-10} erg $cm^{-2}s^{-1}$ [Acero et al. 2009, *A&A* **505**, 157]	≈ 10 μG	≥ 65 μG [Berezhko&Völk 2006, *A&A* **451**, 981]	0.1...0.3 $(d/1\mathrm{kpc})^2(n/1\mathrm{cm}^{-3})^{-1}\ E_{SNR}$
RX J0852–4622 (Vela Junior)	2°	5.3 10^{-11} erg $cm^{-2}s^{-1}$	(0.5–10 keV) 9.9 10^{-11} erg $cm^{-2}s^{-1}$ [Slane et al. 2001, *ApJ* **548**, 814]	≈ 6 μG	270 μG [Katsuda et al. 2008, *ApJ* **678**, L35]	0.08 $(d/750\mathrm{pc})^2(n/1\mathrm{cm}^{-3})^{-1}\ E_{SNR}$
RCW 86	0.9°	8.5 10^{-12} erg $cm^{-2}s^{-1}$	(0.7–10 keV) 2.1 10^{-10} erg $cm^{-2}s^{-1}$	15..30 μG	24 μG [Vink et al. 2006, *ApJ* **648**, L33] ≈100 μG [Völk et al. 2005, *A&A* **433**, 229]	0.2...0.4 $(d/2.5\mathrm{kpc})^2(n/0.7\mathrm{cm}^{-3})^{-1}\ E_{SNR}$
SN 1006	0.48°	8.3 10^{-13} erg $cm^{-2}s^{-1}$	(0.5–10 keV) 1.1 10^{-10} erg $cm^{-2}s^{-1}$	≈ 30 μG	≥ 120 μG [Völk et al. 2005, *A&A* **433**, 229]	0.2 $(d/2.2\mathrm{kpc})^2(n/0.085\mathrm{cm}^{-3})^{-1}\ E_{SNR}$
HESS J1731–347	0.54°	6.9 10^{-12} erg $cm^{-2}s^{-1}$	3.7 10^{-11} erg $cm^{-2}s^{-1}$ (⅓ of shell)	25 μG	–	0.2 $(d/3.2\mathrm{kpc})^2(n/1\mathrm{cm}^{-3})^{-1}\ E_{SNR}$

- hadronic scenario predicts 2.4 10^{-11} $cm^{-2}s^{-1}$ (10 neutrinos per year)

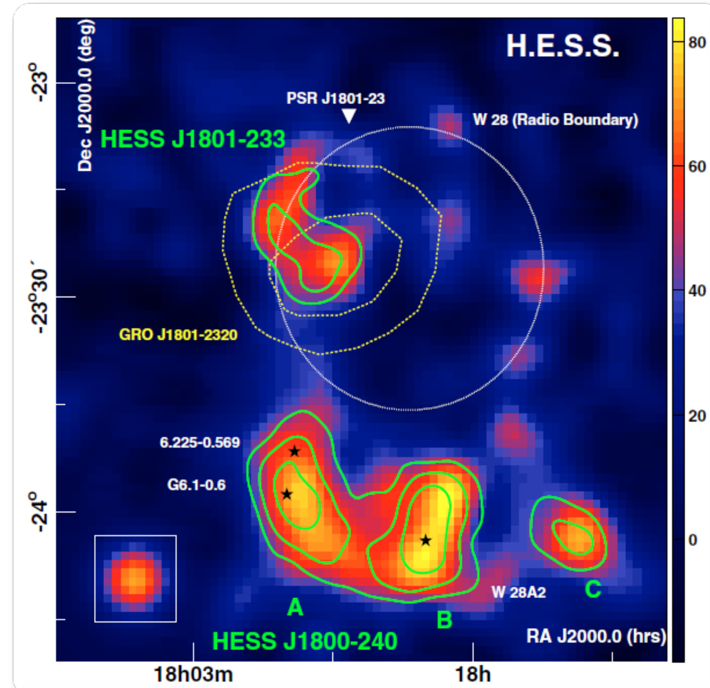
But RXJ 1713 with Fermi

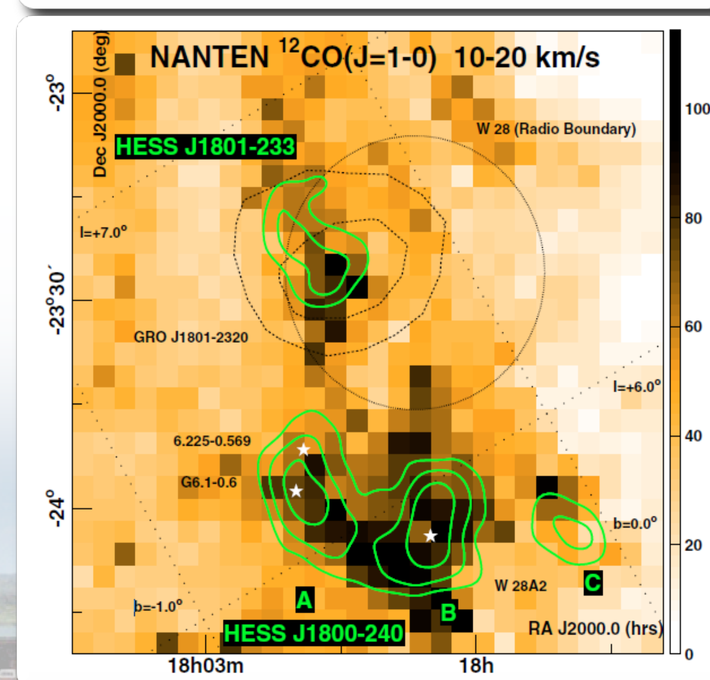


- Fermi result [Abdo et al. 2011, arXiv:1103.5727v1] favours leptonic scenario
  - does not exclude hadronic contribution
  - weak magnetic field 10μG? (filaments only local enhancements?)
- acceleration models used in interpretation may be too simple [e.g. Schlickeiser 2011]

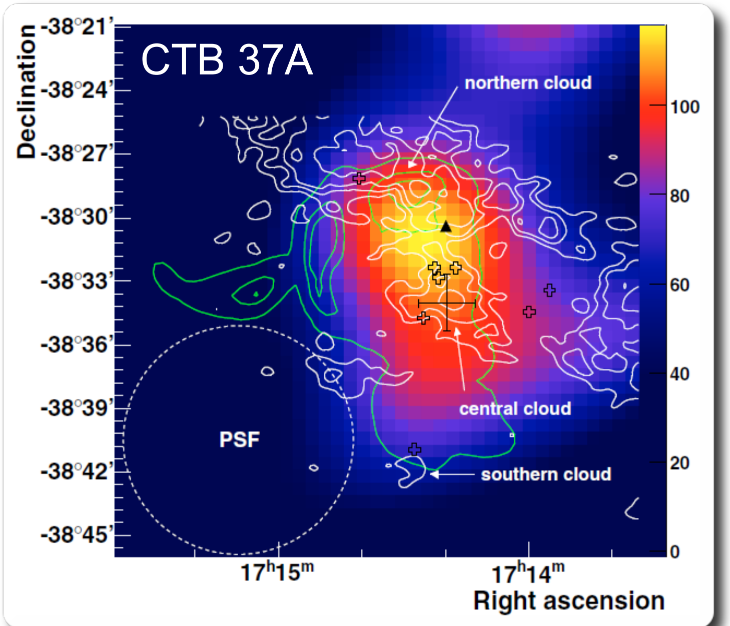
Molecular Cloud Interactions

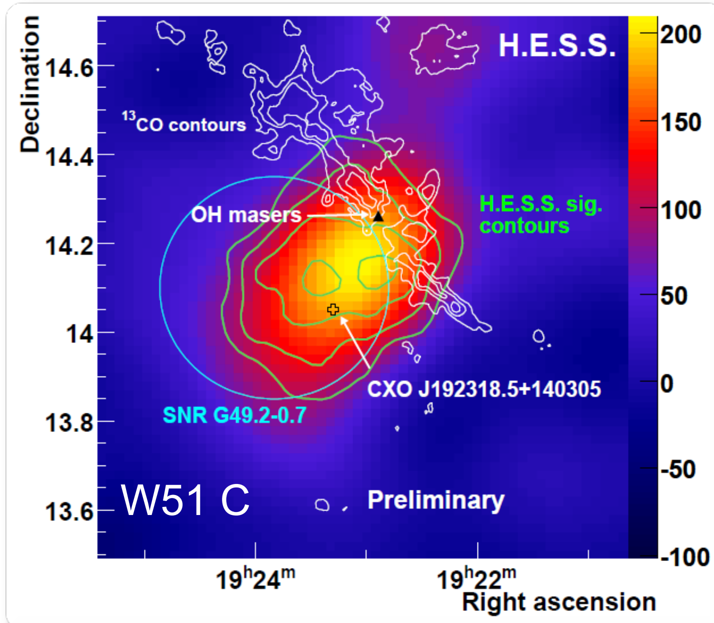
- ➲high target density results in stronger gamma-ray emission
  - look for Molecular Clouds (MCs) traced by CO line emission
- ➲SNR/cloud interaction traced by OH masers (excited by shock front)
- ➲CR over-density k_{CR} (compared to local value)
- ➲W 28 [HESS 2008 *A&A* **481**, 401]
  - k_{CR}: up to 70

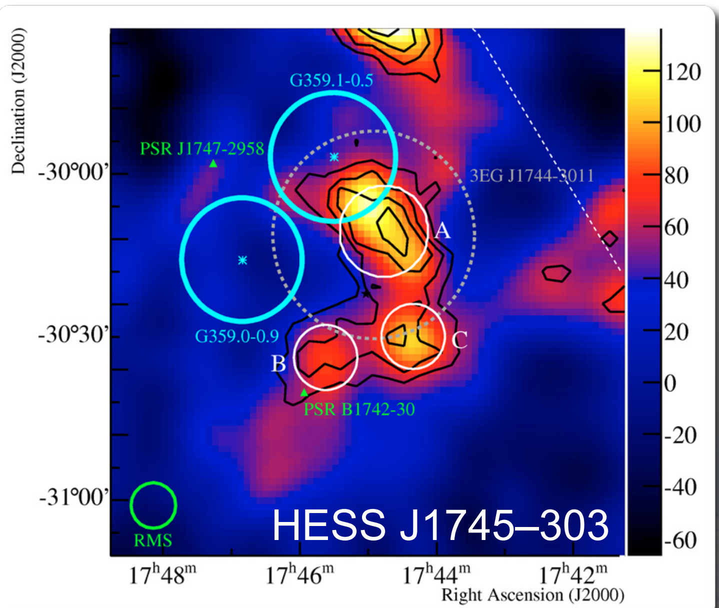


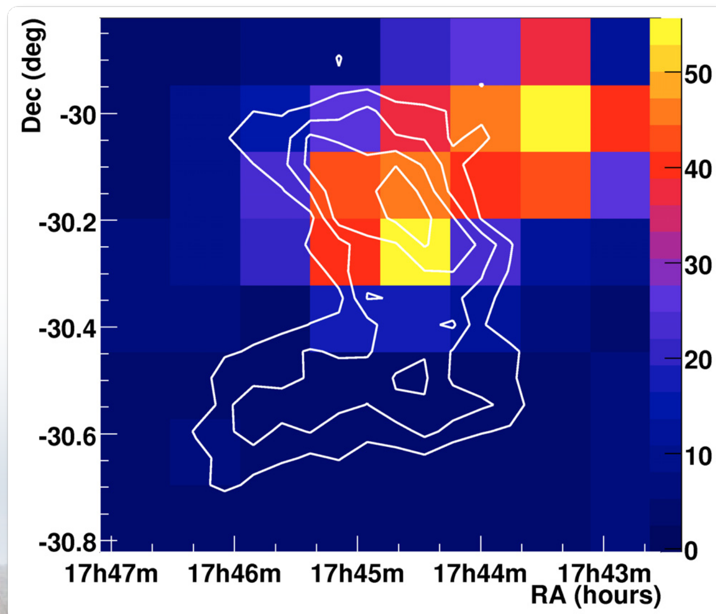


Molecular Cloud Interactions







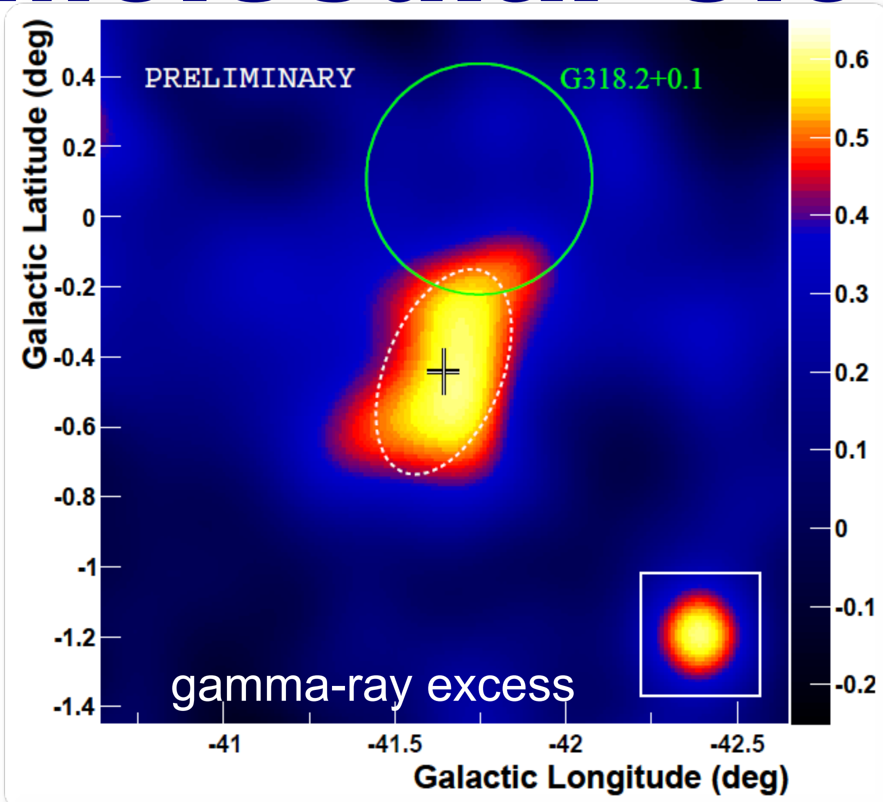


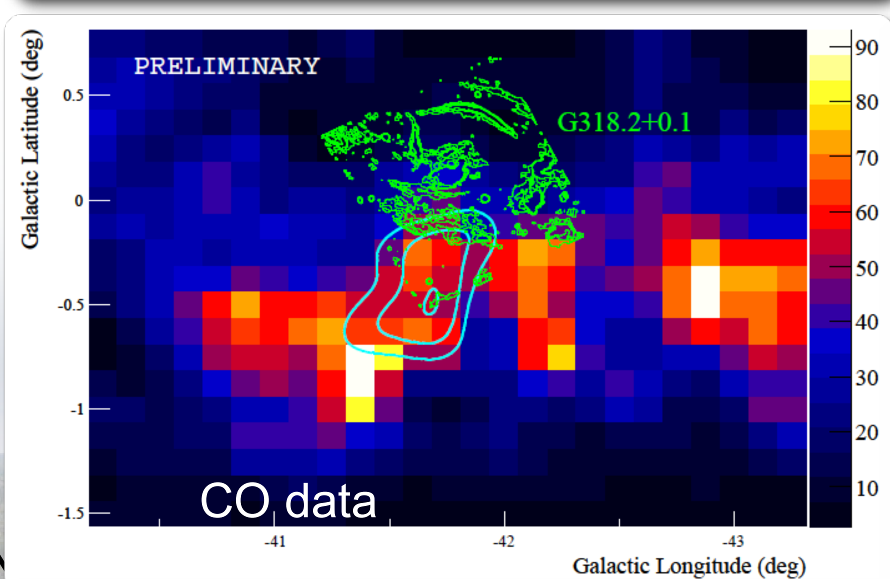
CTB 37A
[HESS 2008 *A&A* **490** 685]

W51C
[Fiasson et al. ICRC 2009]

HESS J1745–303
[HESS 2008 *A&A* **483**, 509]

Molecular Cloud Interactions





- ➲new sources revealed in ongoing Galactic Plane scan
- ➲G 318.2+0.1
- ➲TeV emission coincident with Giant Molecular Cloud
- ➲connection allows conclusion on the distance to the SNR: 3.5kpc
- ➲[HESS 2011, Texas Symp. arXiv:1104.5119v1]

MC Interactions, Summary

- gamma-ray sources connected to Molecular Clouds
- consistent with Fermi sources
  - flat spectrum expected from hadronic interactions
- best indication for CR acceleration in SNRs

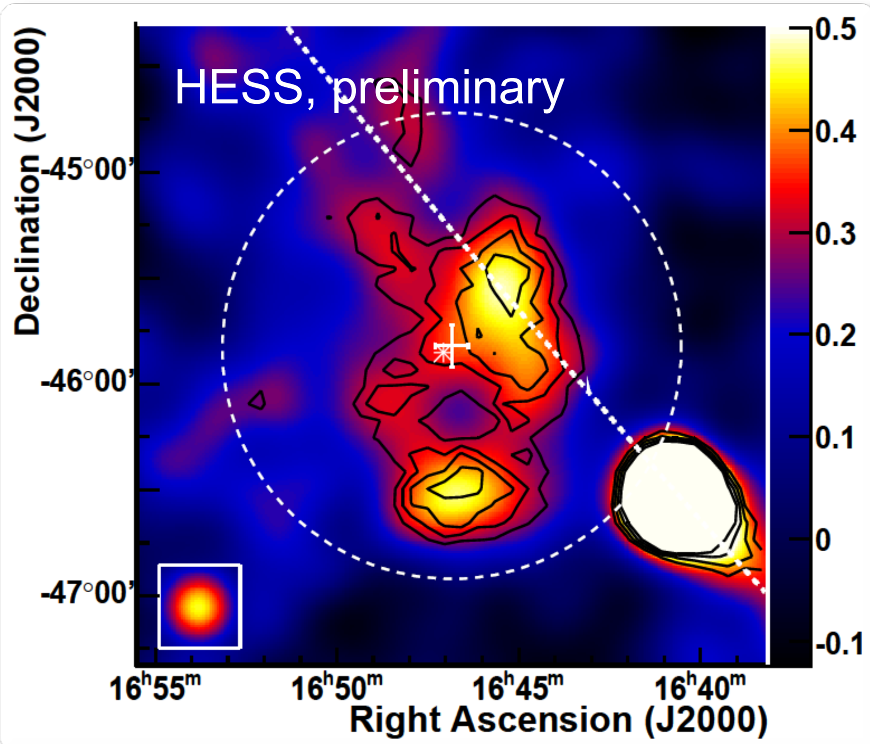
name	HESS name	spectral index	flux (1 – 10 TeV) [10^{-12} $cm^{-2}s^{-1}$]	k_{CR}
	J1745-303	2.71 ± 0.11	1.60	101
$W28_1$	J1800-240	2.49 ± 0.14	1.20	18 – 70
CTB 37A	J1714-385	2.3 ± 0.13	0.64	449
W51C	J1923+141	-	0.62	43
$W28_2$	J1801-233	2.66 ± 0.27	0.44	13 – 51

- neutrino flux from these sources: 3.3 10^{-12} $cm^{-1}s^{-1}$

Looking further: Star Clusters

- associations of massive stars
  - Wolf-Rayet stars, very massive stars with strong stellar winds
  - short live time of stars → many supernova explosions
- particle acceleration in shock fronts
  - in binary systems
  - combined stellar winds, combined SN explosions
    → formation of super bubbles

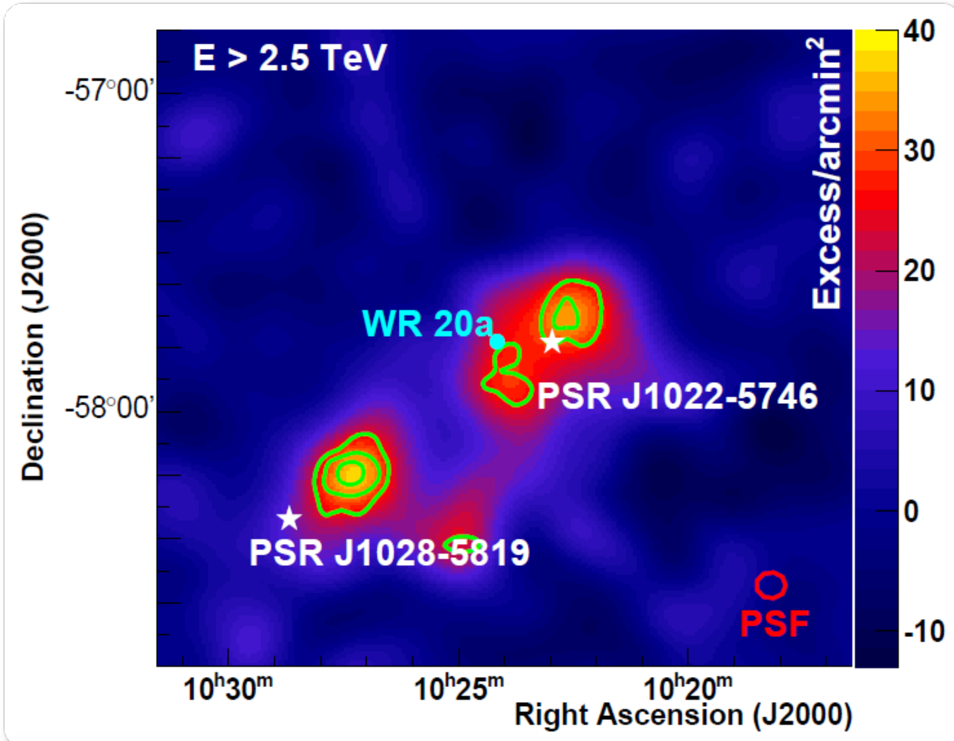
Westerlund 1



[Ohm et al., Texas Symposium 2010]

- large extended source
  - 2° diameter
- F(1 – 10 TeV) = 7x10^{-12} cm^{-2}s^{-1}
- L(0.1 – 100 TeV, 4kpc) = 2x10^{35} erg s^{-1}
- stellar winds and SNe (80–150):
  - 10^{39} erg s^{-1}
- possible confusions:
  - low-mass X-ray binary
  - pulsar
  - magnetar

Westerlund 2

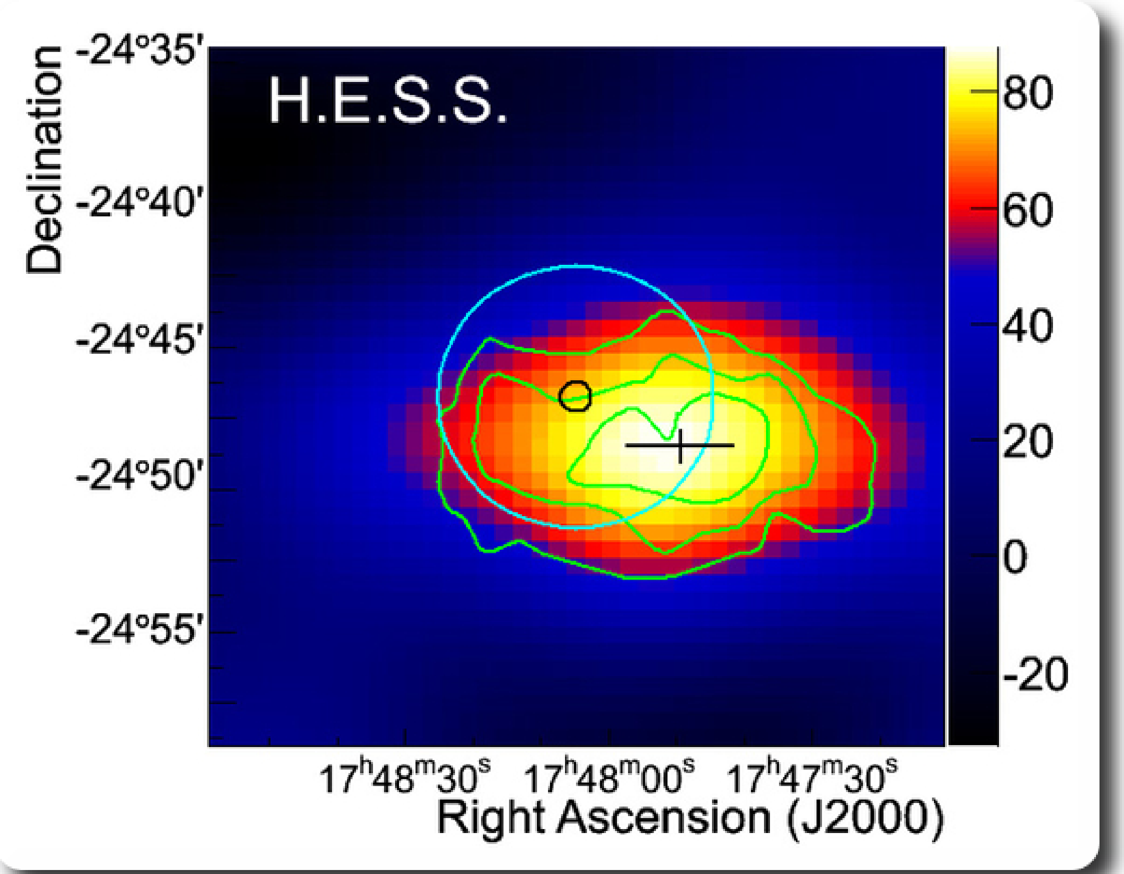


- ➲ $F(1 – 10\ \text{TeV}) = 2\text{x}10^{-12}\ \text{cm}^{-2}\text{s}^{-1}$
- ➲ WR binary 20a
- ➲ Giant Molecular Cloud
- ➲ $3.6\text{x}10^{51}$ erg from stellar winds
  - 0.05% needed to explain gamma-ray emission
- ➲ confusion with Fermi-pulsar PSR J1022–5746

[HESS 2010, *A&A* **525**, A46]

Terzan 5 – a globular cluster

- globular cluster
  - old stellar system
  - high density in core
- TeV emission expected from
  - large population of ms pulsars
  - hadronic scenarios possible
- first GC in TeV gamma-rays
  - displaced from centre
  - extended beyond tidal radius
  - not correlated with X-rays
- interpretation very difficult
  - could be a PWN in the front



[HESS 2011, submitted to *A&A*]

Conclusion

- isolated, large shell-type SNRs best laboratories
  - detailed investigation of shell possible
  - no clear conclusion, dominant leptonic scenario not excluded
  - acceleration models used in interpretation too simple?
  - combination of HESS and Fermi necessary
- SNR/Molecular Cloud interactions
  - best indication for CR acceleration in SNRs
- open star clusters / globular clusters
  - interesting targets
  - proof of CR acceleration not easy
- 2012: 100 years of CR discovery
  - We made some progress
  - no direct evidence yet
- hadronic interactions produce neutrinos
  → looking forward for results from neutrino observatories