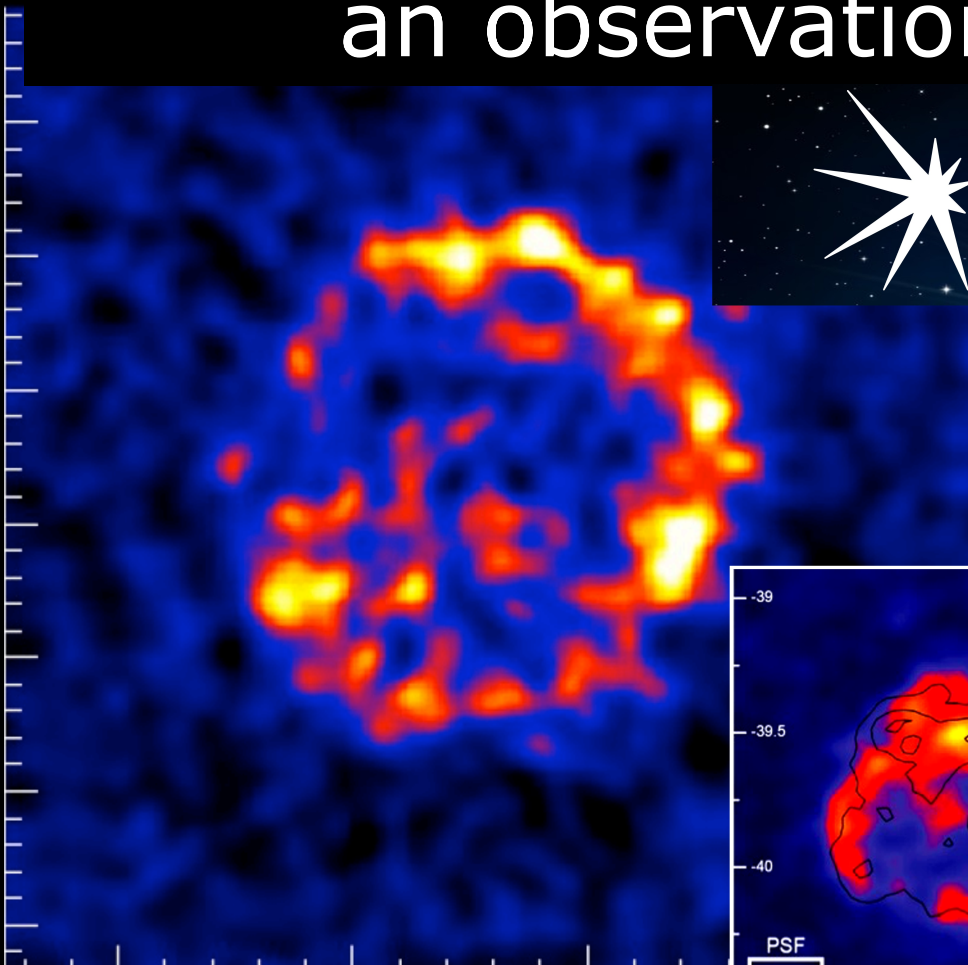
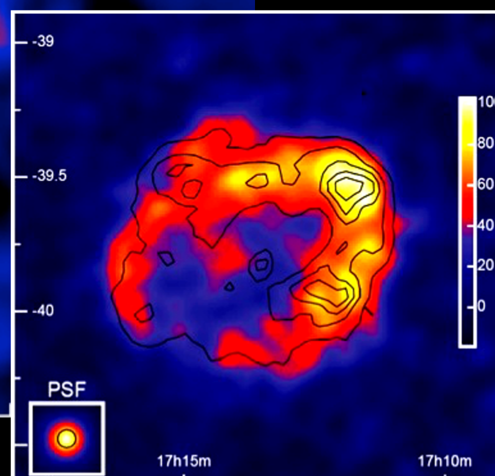
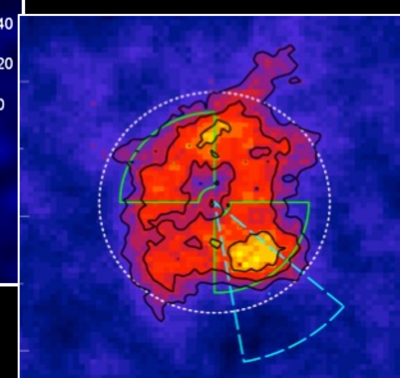
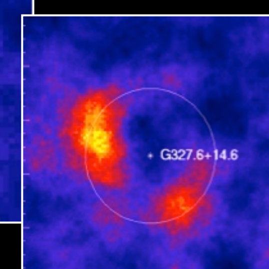
Cosmic Rays and Supernova remnants: an observational challenge



ISCRA-2021







Gerd Pühlhofer

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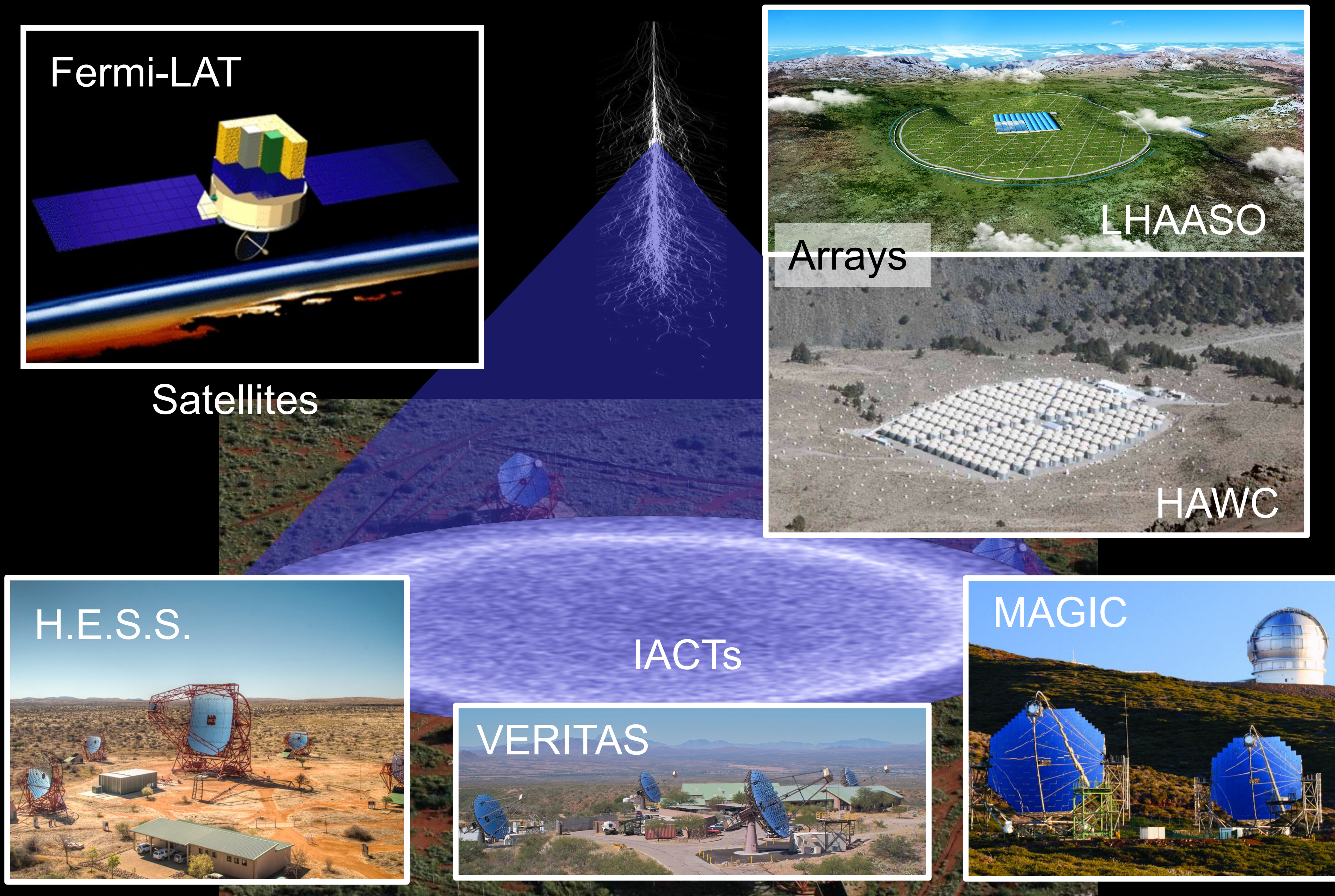
Current generation of HE/VHE/UHE instruments



Energy spectrum of cosmic rays (@ Earth)

Galactic origin?

Best source candidates:

SN explosions
E_{kin} = 10^{51}erg, 1/30 years

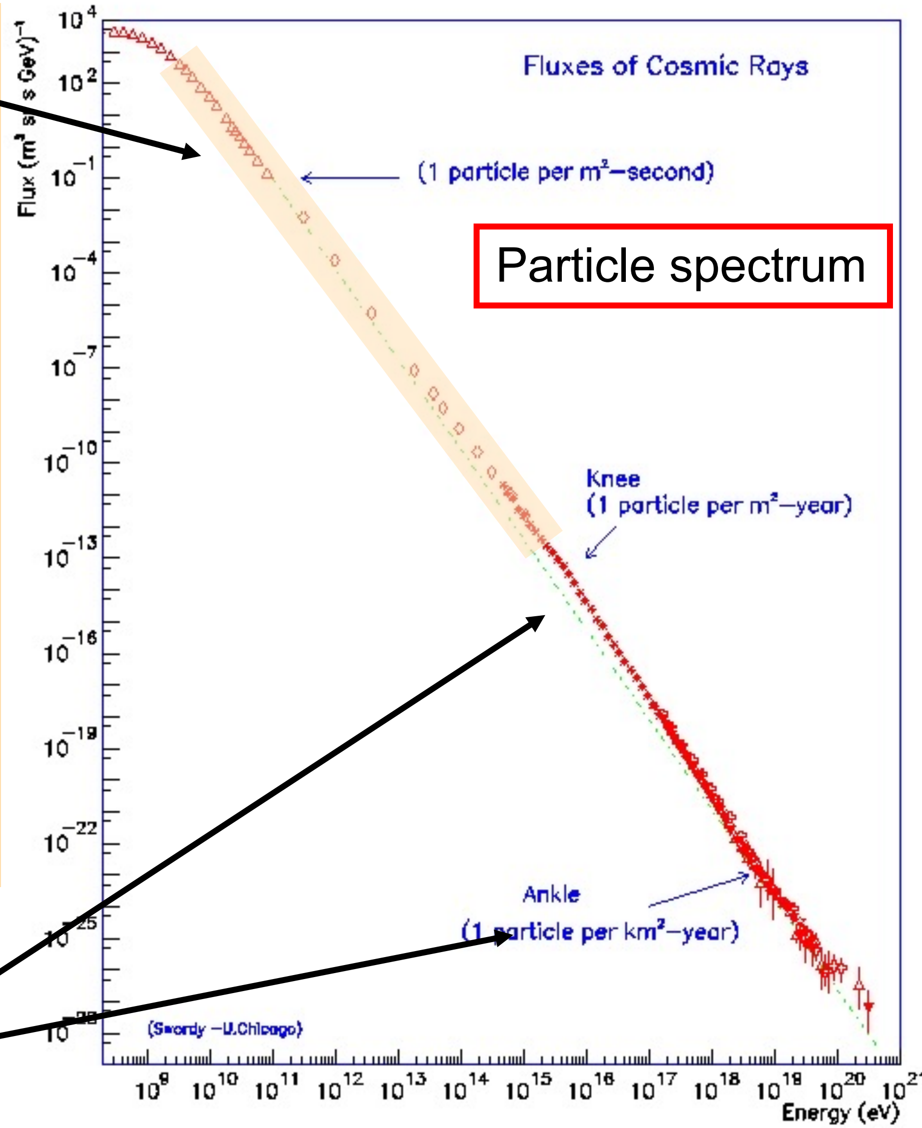
Cf. to
$L_{CR} = \rho_{CR} V/\tau_{esc} = 10^{41}$erg/s

→ ~ 10% efficiency required

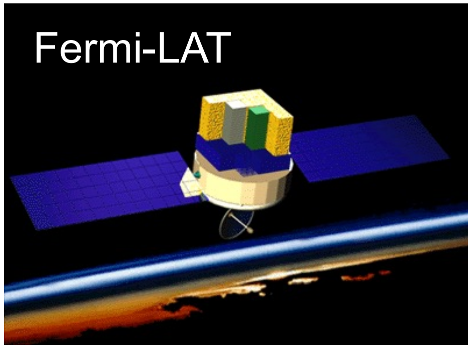
Shock acceleration (1. Fermi) in SNRs, Bohm diffusion + B-field amplification:
→ Efficiency up to 50%
→ E_{max} ~ 10^{15} eV

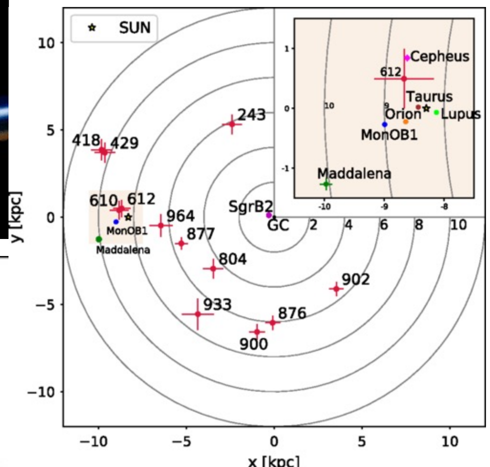
Additional galactic process?

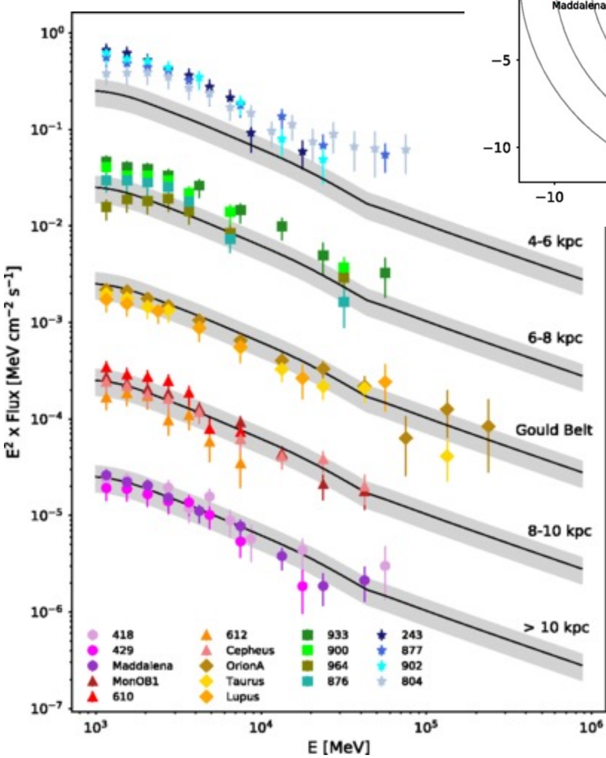
Extragalactic origin



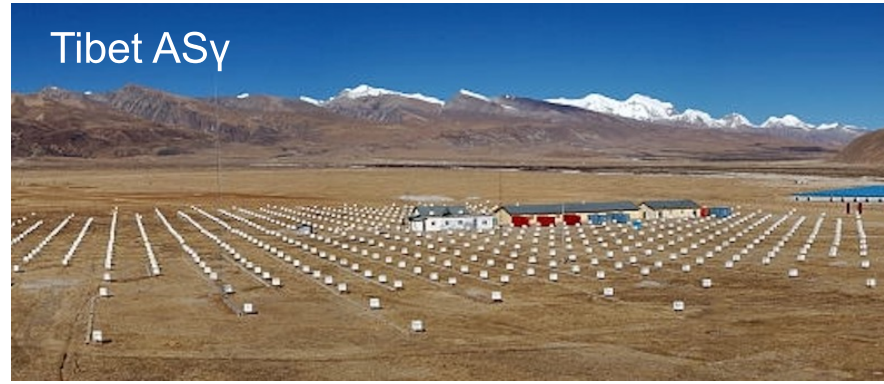
Recent Gamma-ray imaging of the diffuse CR sea

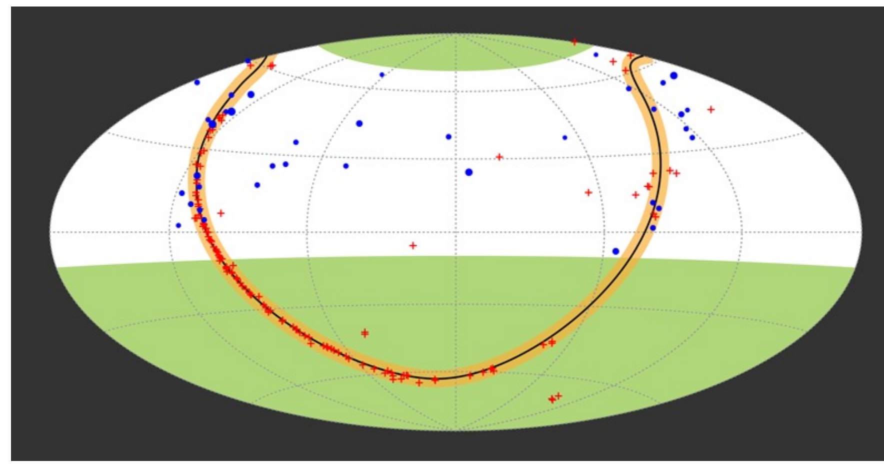






Aharonian+, Phys Rev D 2020; see also Peron+, ApJL 2021

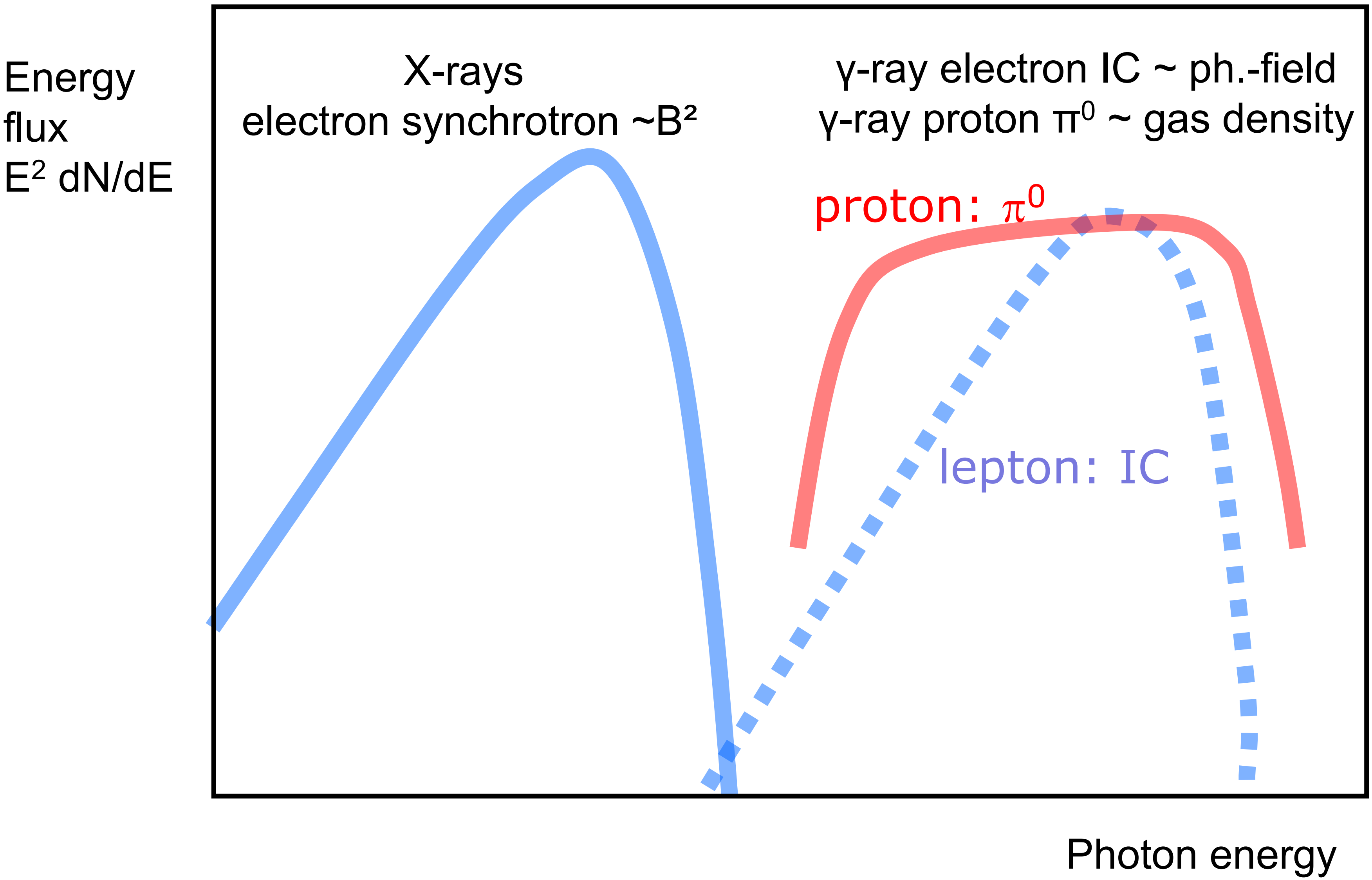




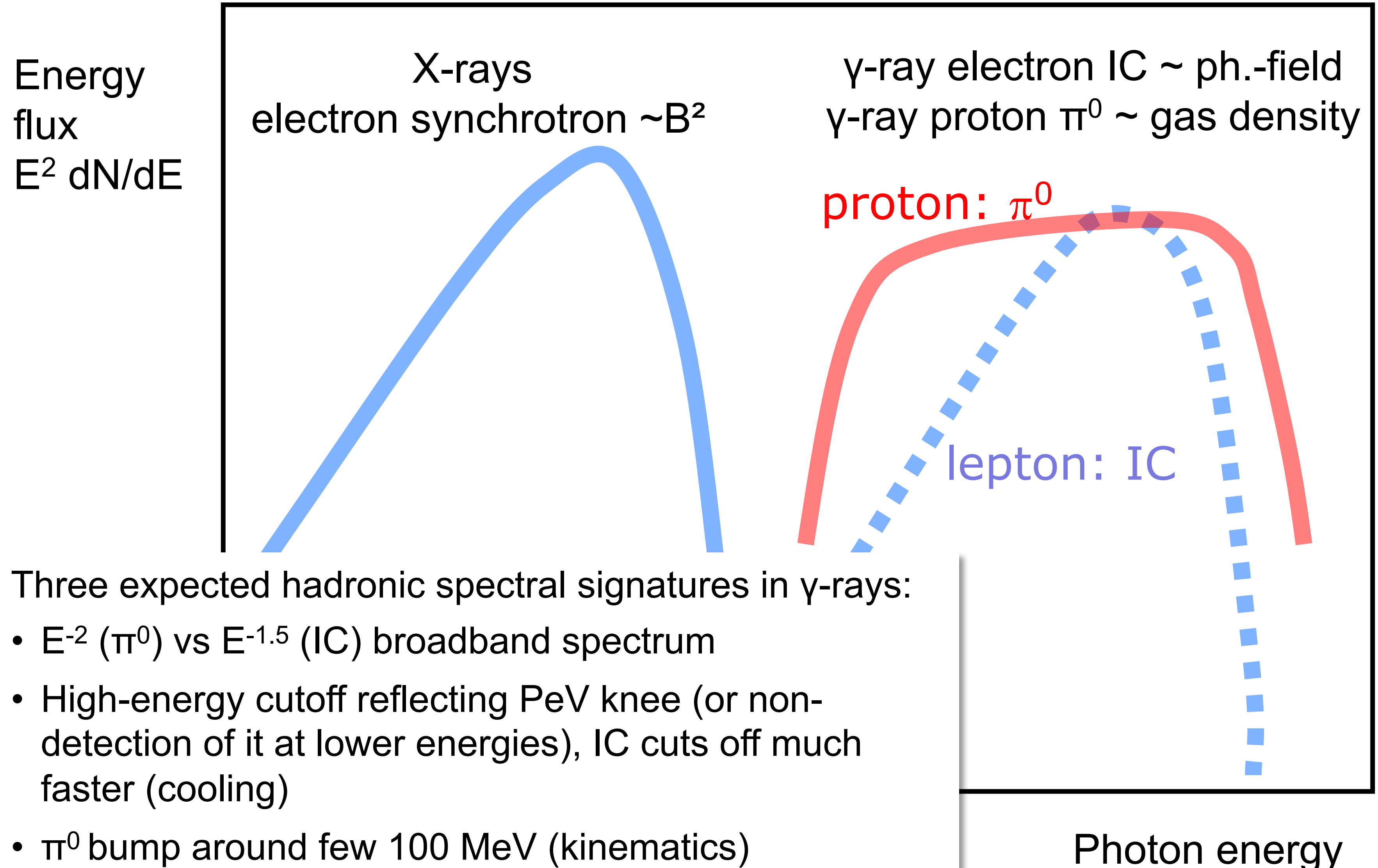
Tibet ASγ coll, Phys Rev Lett 2021, image adapted by APS/A. Stonebraker

- Molecular clouds as probes for sea CRs: ok
- 100 TeV – PeV γ-rays from the Galactic plane: ok

Hadronic vs. leptonic sources



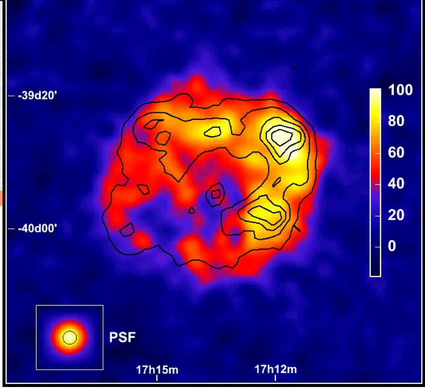
Hadronic vs. leptonic sources



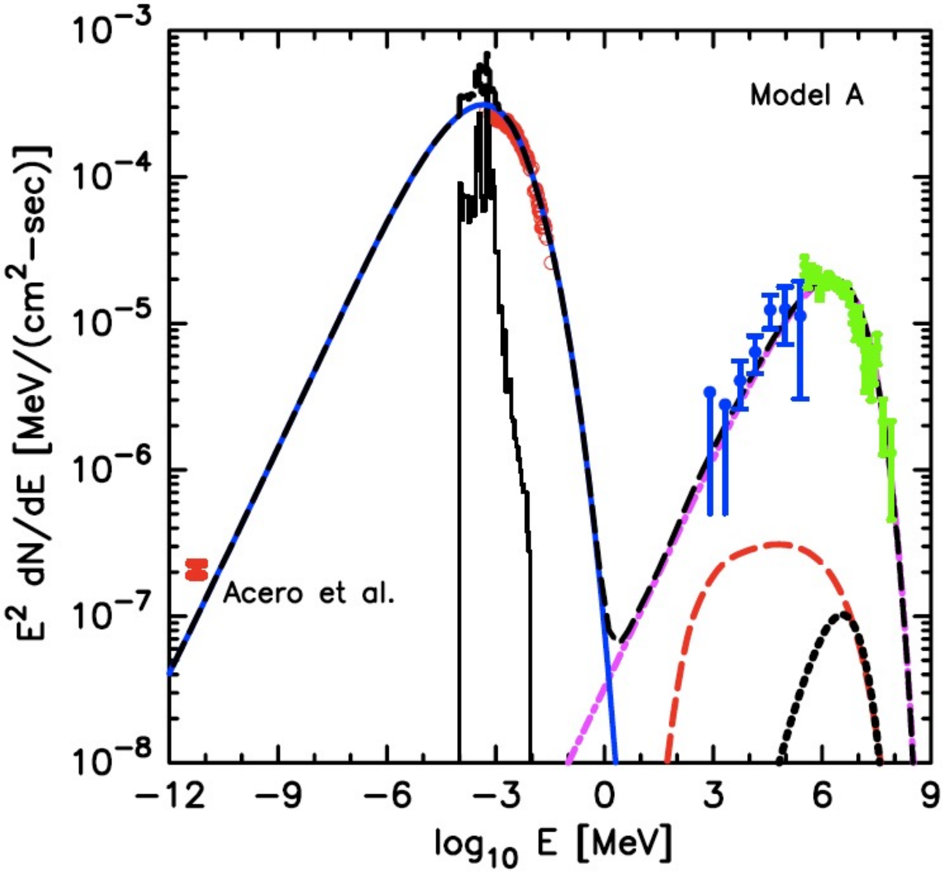
Three expected hadronic spectral signatures in γ-rays:

- E^{-2} (π^0) vs $E^{-1.5}$ (IC) broadband spectrum
- High-energy cutoff reflecting PeV knee (or non-detection of it at lower energies), IC cuts off much faster (cooling)
- π^0 bump around few 100 MeV (kinematics)

RXJ 1713.7-3946: towards a consistent leptonic model?

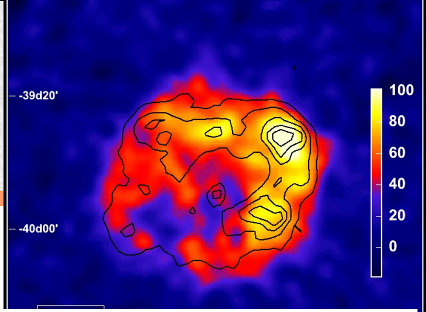


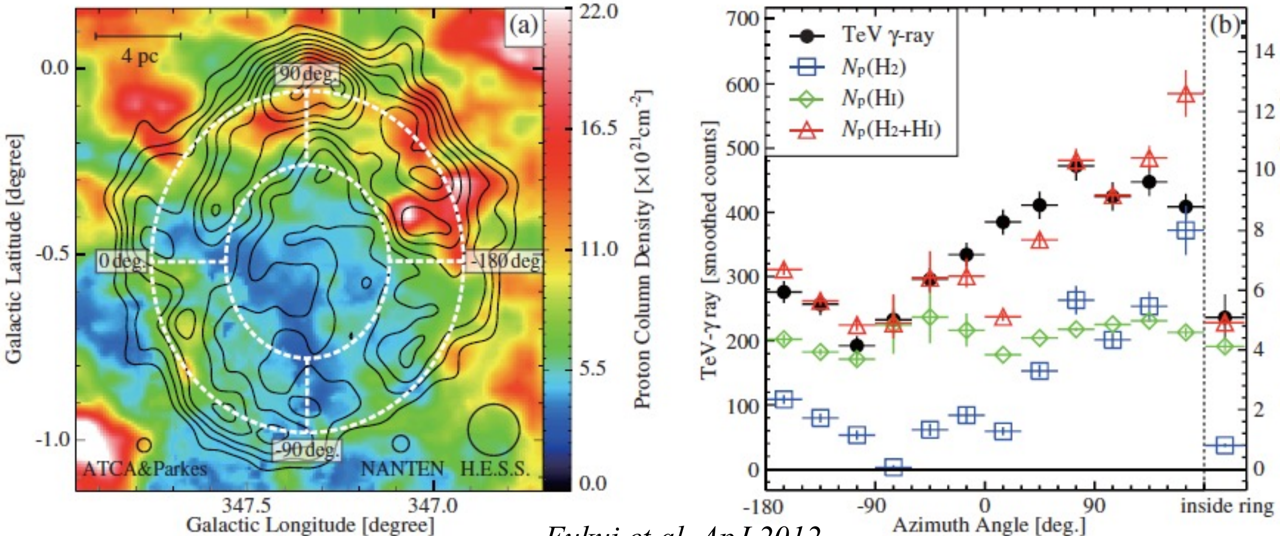
Ellison et al, ApJ 2012



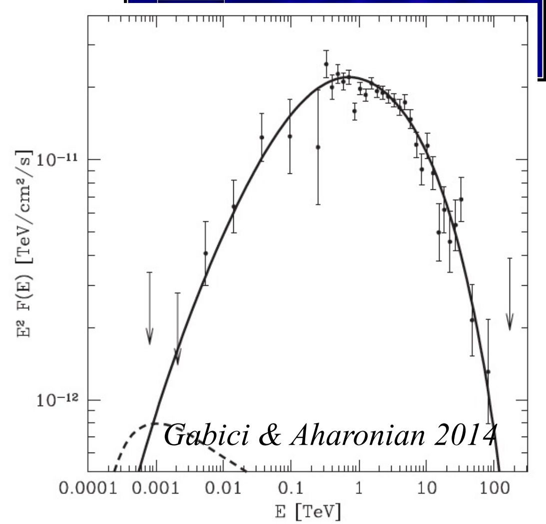
- TeV emission and (nonthermal) X-ray emission well correlated (e.g. *Acero et al. 2009*)
- *Ellison et al, ApJ 2012:* Low B-field in wind bubble blown by progenitor star, with very low (< μG) B-field; even with turbulent B-field amplification B~10 μG
- Model easily fits GeV data from Fermi-LAT
- Model accounts for low thermal X-ray emission

RXJ 1713.7-3946: towards a consistent hadronic model?



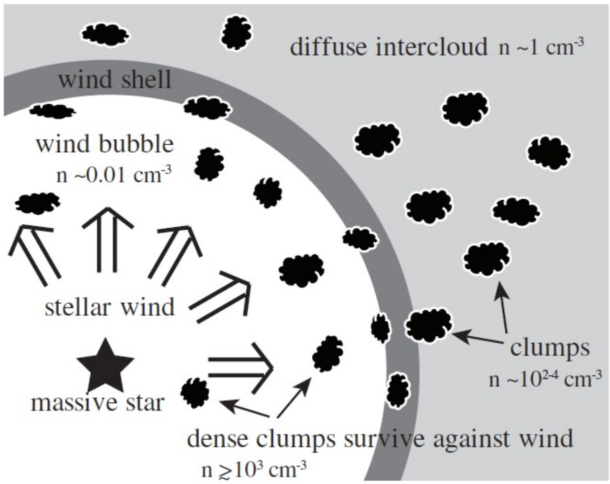


Fukui et al, ApJ 2012



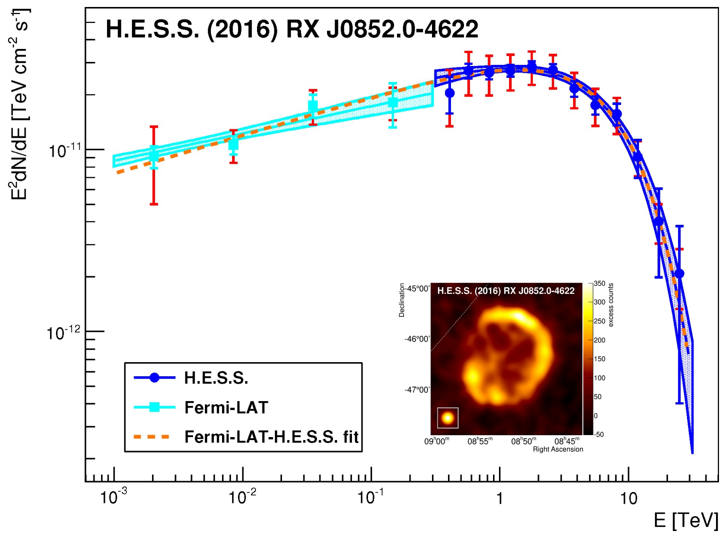
Gabici & Aharonian 2014

- Very good correlation between TeV emission and gas density (CO+HI)
- Energy-dependent propagation of accelerated particles into post-shock gas clumps
- Suppression of thermal X-ray emission because of clumping

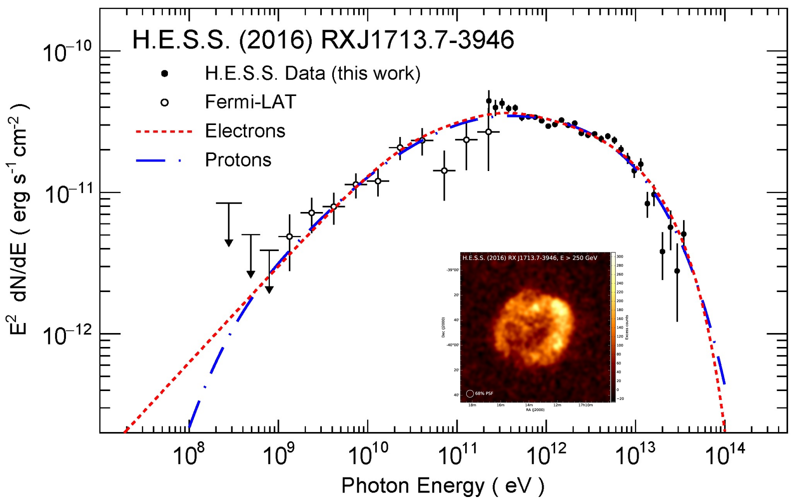


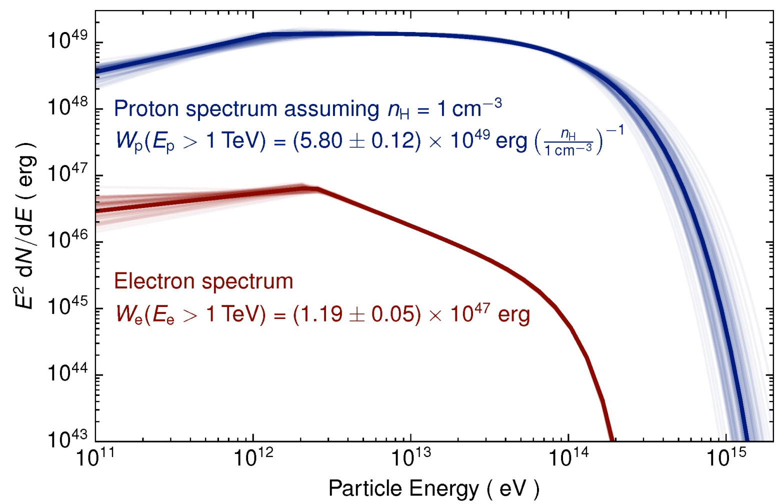
Inoue et al, ApJ 2012

Spectral cut-offs



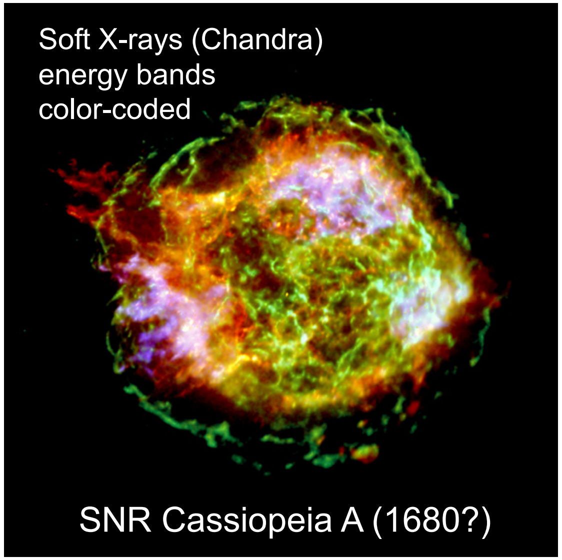
- Young, TeV-selected, resolved SNRs
- Clear detection of cut-offs (spectral indices 1.6 ... 1.8)
  → RX J1713.7–3964: 12.9 ± 1.1 TeV
  → Vela Junior: 6.7 ± 1.2 TeV
  → RCW 86: 3.5 ± 1.2 TeV
- Only up to $E_p \sim 100$ TeV
- These SNRs themselves are currently not PeVatrons



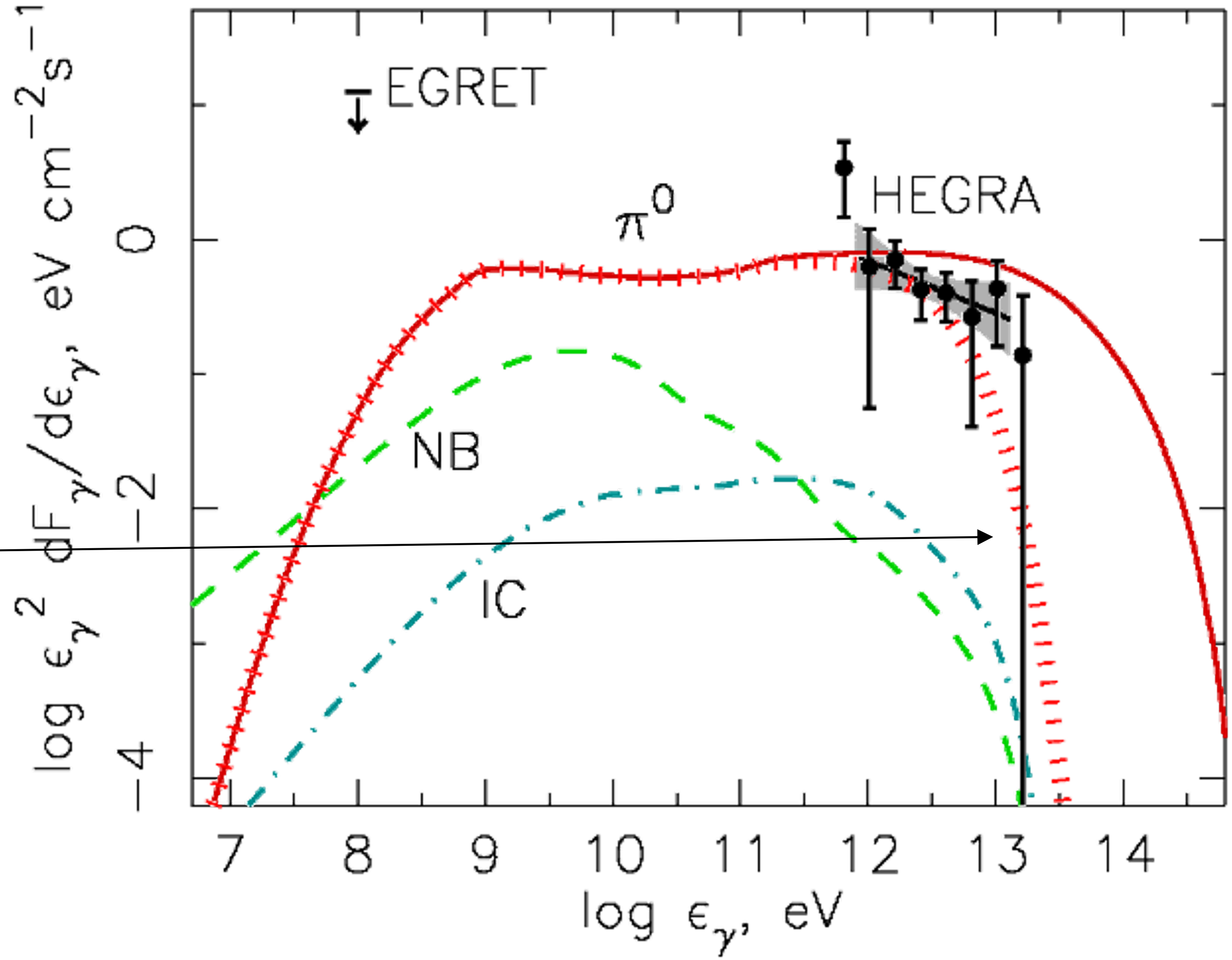


HESS 2018, A&A, 612, 6; HESS 2018, A&A 612, 7; HESS A&A 612 (2018) A4

Cassiopeia A: escape to explain soft spectrum?



TeV data: HEGRA collaboration (2001), A&A, c.a. GP
Model: Berezhko, GP, & Völk (2003), A&A



Soft spectrum: from escape?

(|||| - escape model)

➔ soft TeV spectrum confirmed with MAGIC+, continues also to lower energies (Fermi-LAT)

➔ geometrical model of Cas A superseded

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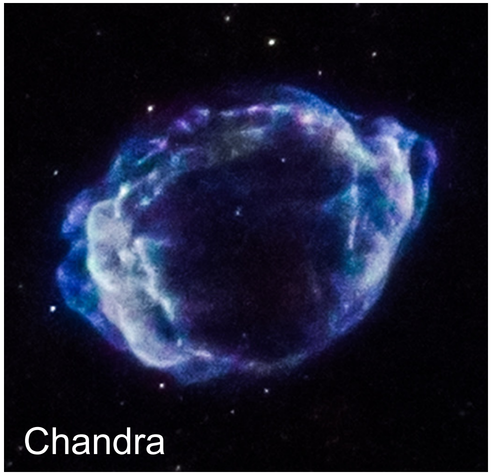
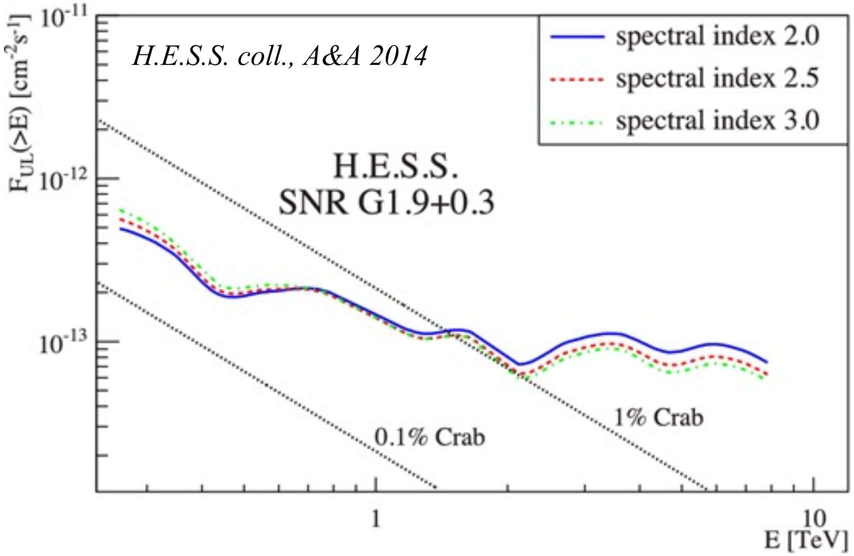
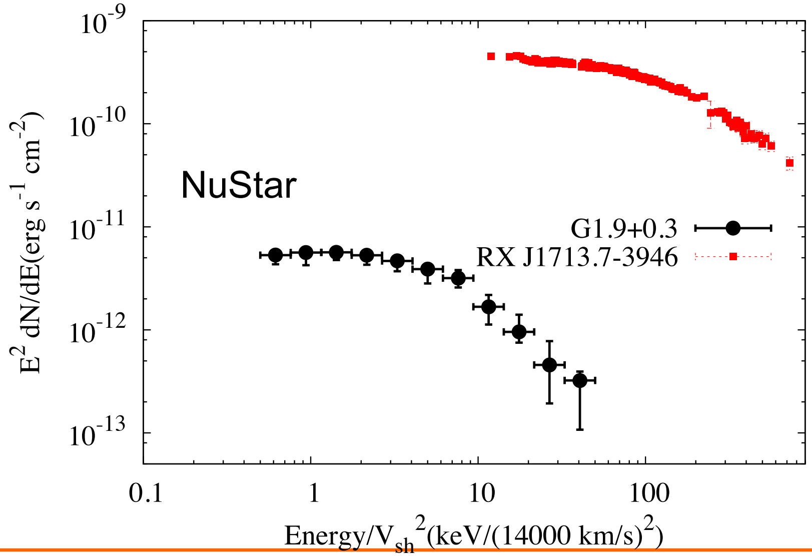
G1.9+0.3: probing escape





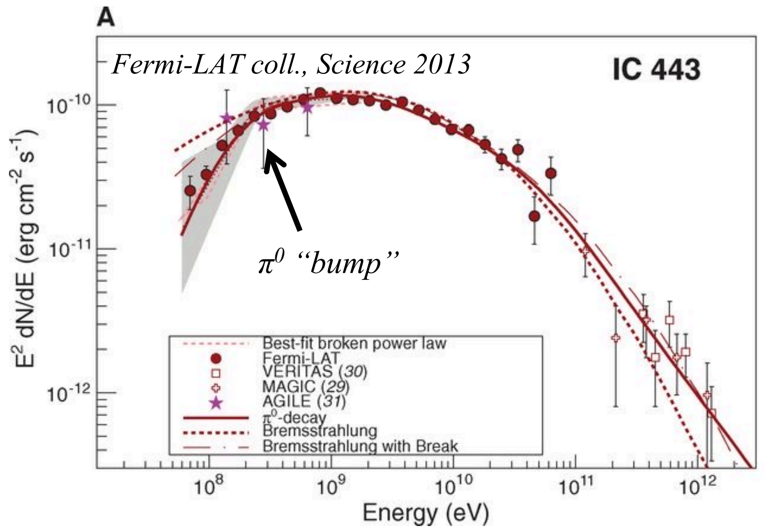


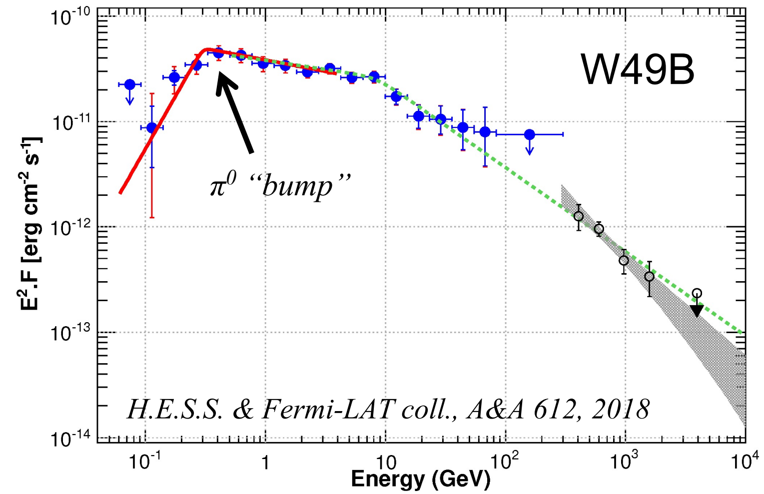
- Youngest known Galactic SNR (~100 years)
- Hard X-ray spectrum: no PeV particles (indirect)
- H.E.S.S. TeV limit: no relevant PeV escape

Aharonian+, A&A 2017
See also ISAPP 2019 lecture of F. Aharonian

Characteristic π^0-feature with Fermi-LAT

- Several SNRs have been advocated in the last years to be hadronic SNRs, based on π^0-bump
- Examples: IC 443, W44, W49B, W51C
- Middle-aged SNRs, possibly interacting with molecular clouds
- GeV-dominated, soft spectra: No access to presence of PeV particles (if present)
- Fresh injection or reacceleration?





- See *Lemoine et al. (Fermi symposium 2021)* for a search for new π^0-bump sources

- π^0-bump also seen in Cas A and Tycho's SNR: young SNRs

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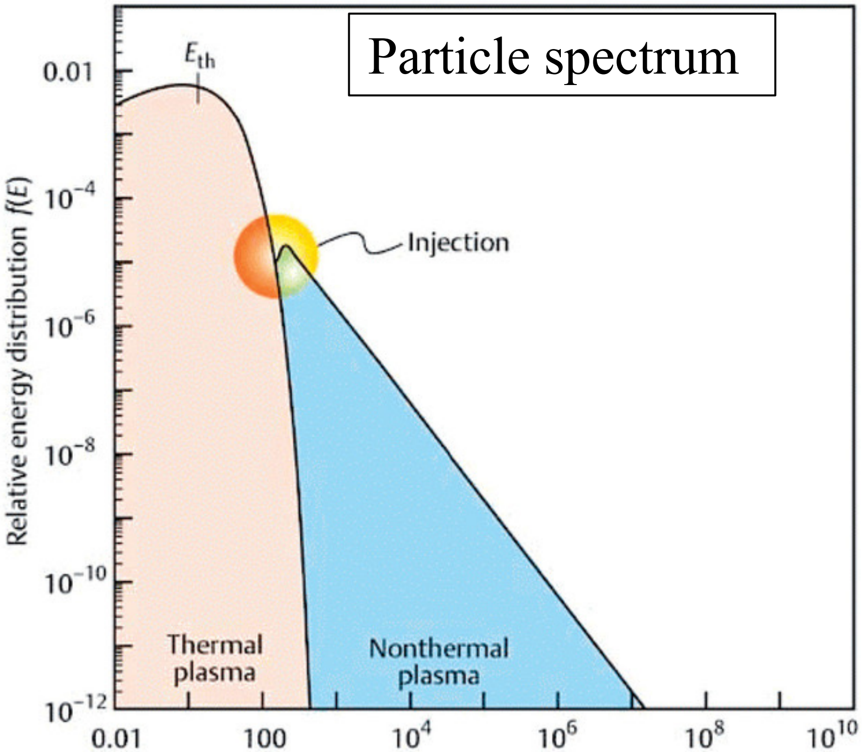
Injection

Injection from thermal plasma

Reacceleration (of escaped or sea CRs)



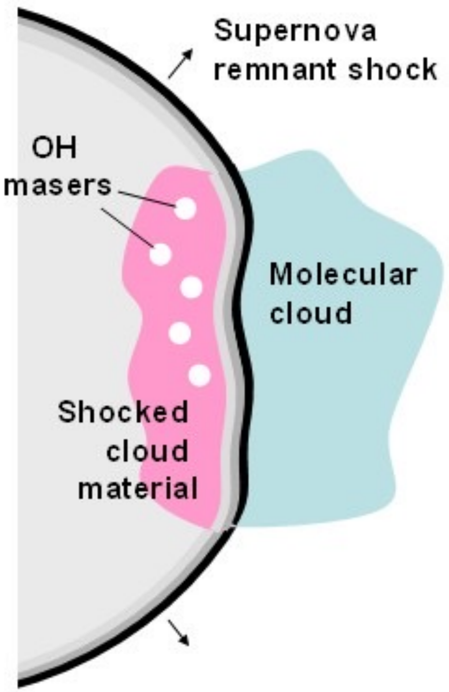
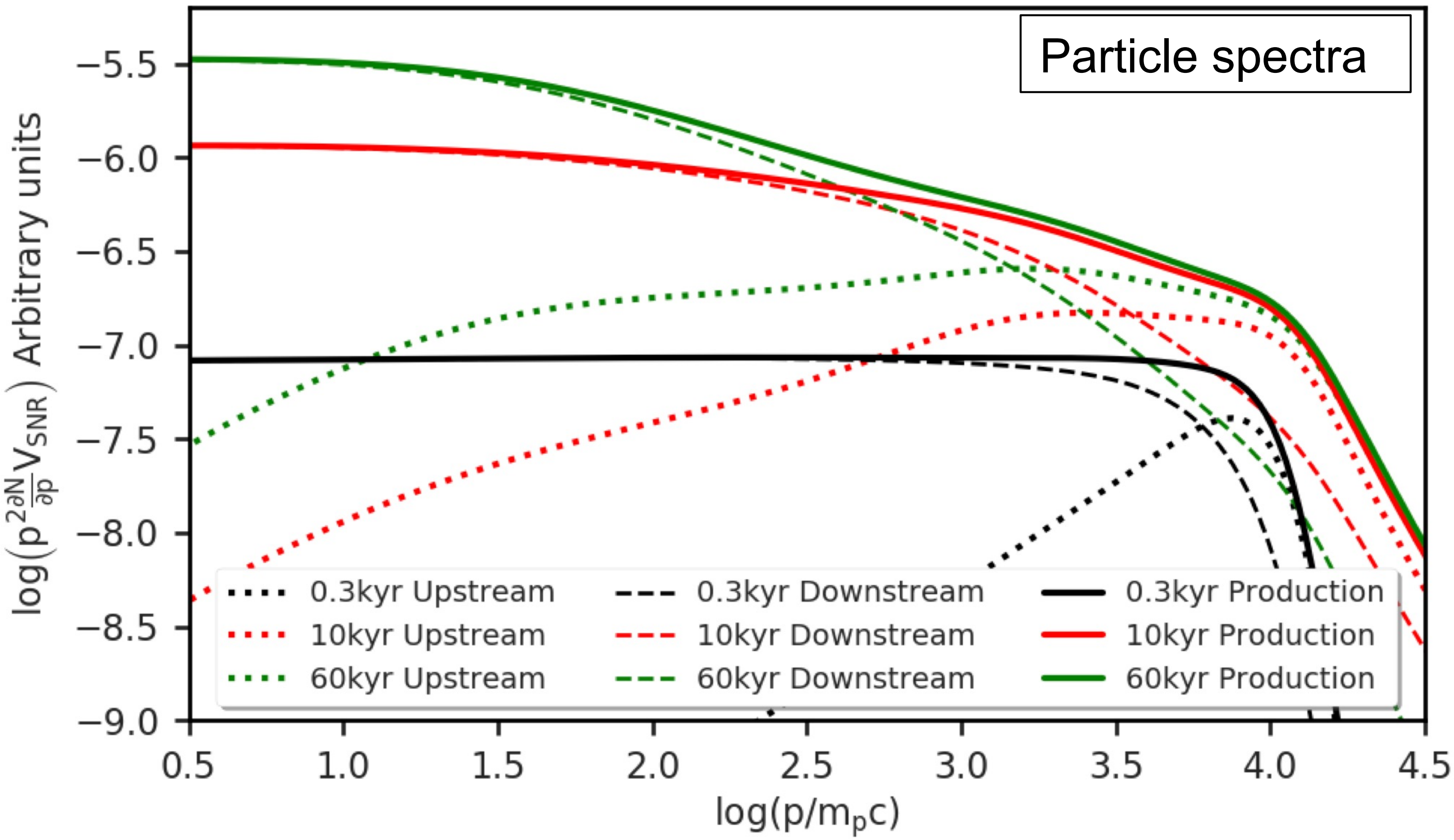


Image Credit: H. Völk, 2006

Image credit: Wardle & Yusef-Zadeh, 2002

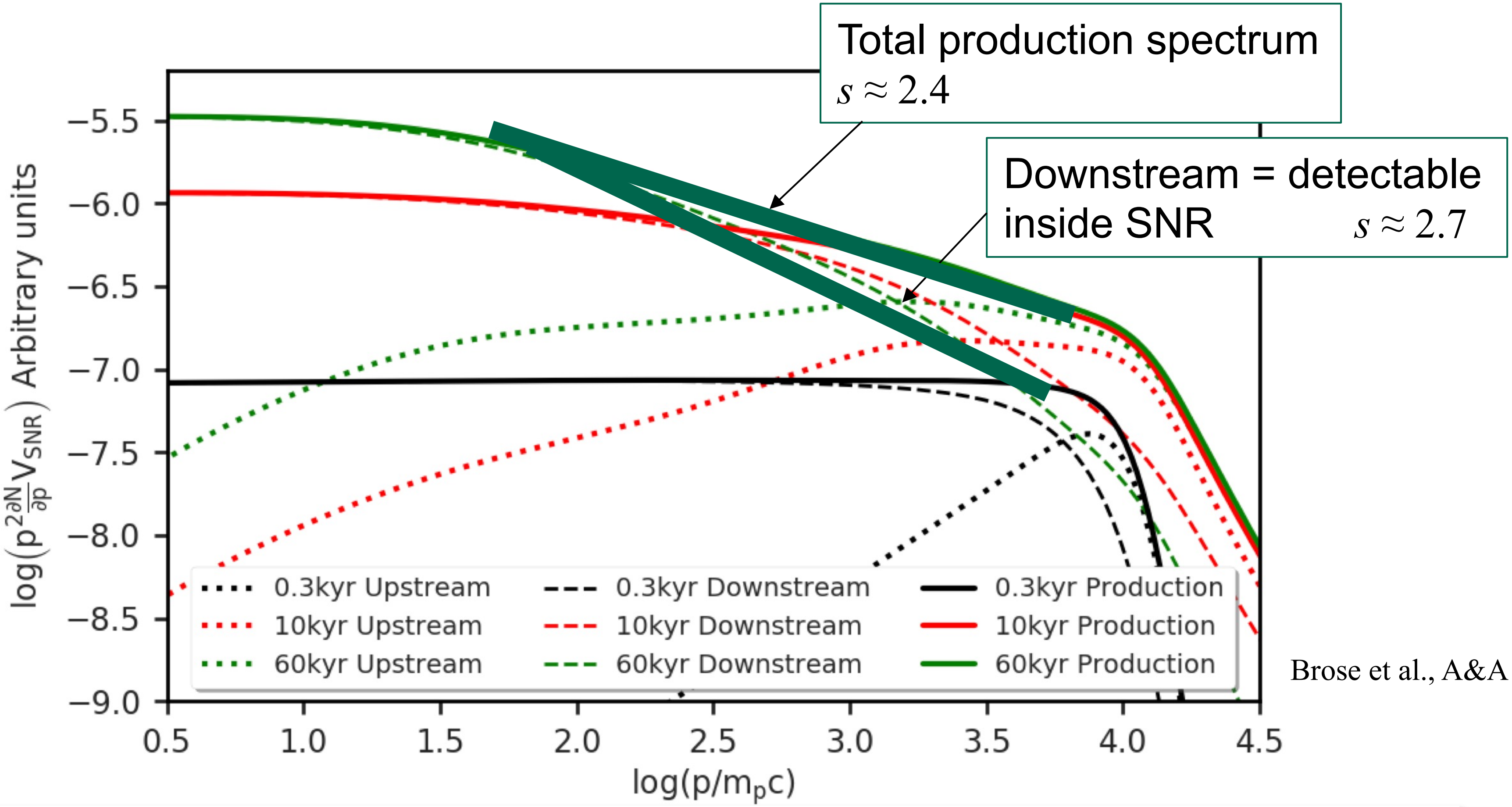
Diffusive shock acceleration + Escape



Brose et al., A&A 2020

- Alfvenic vs. Bohm diffusion
- No free boundary layer for escape

Diffusive shock acceleration + Escape



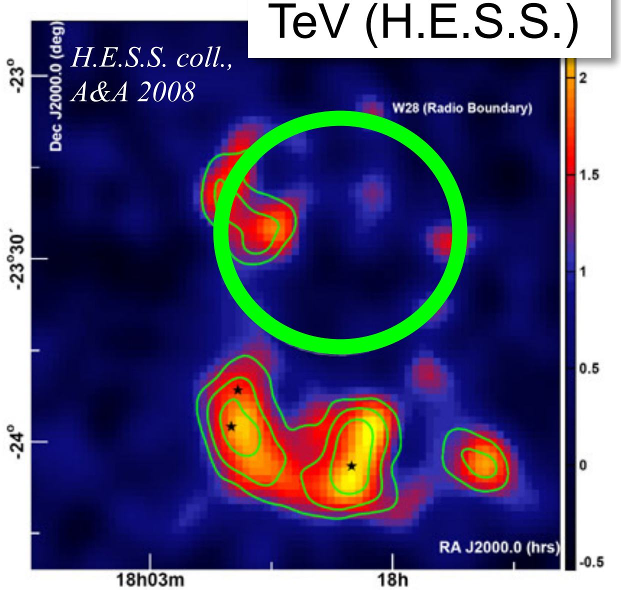
Brose et al., A&A 2020

- An explanation for the typical soft spectra of middle-aged SNR ?
- Constraints on proton maximum energy possible from γ-ray data ?

W 28:
a middle-aged SNR with likely CR escape

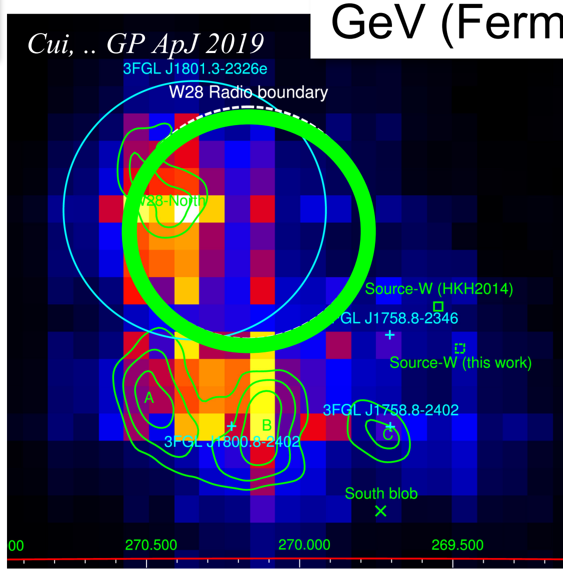
TeV (H.E.S.S.)

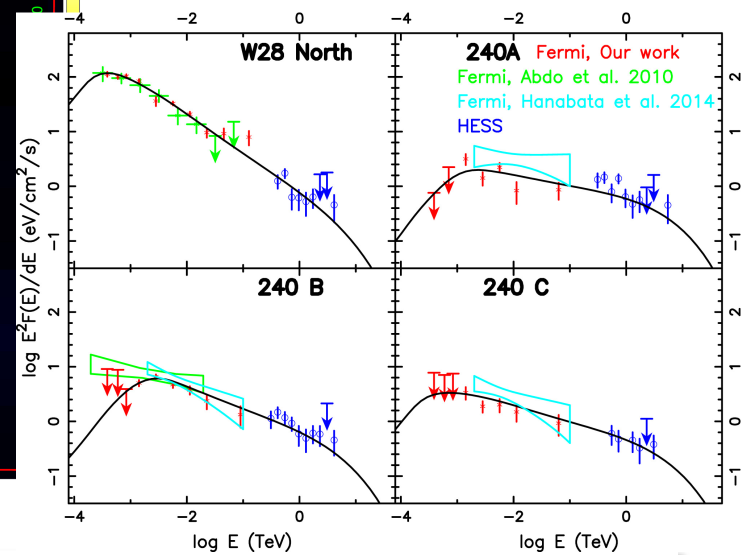
H.E.S.S. coll., A&A 2008



GeV (Fermi-LAT)

Cui, .. GP ApJ 2019

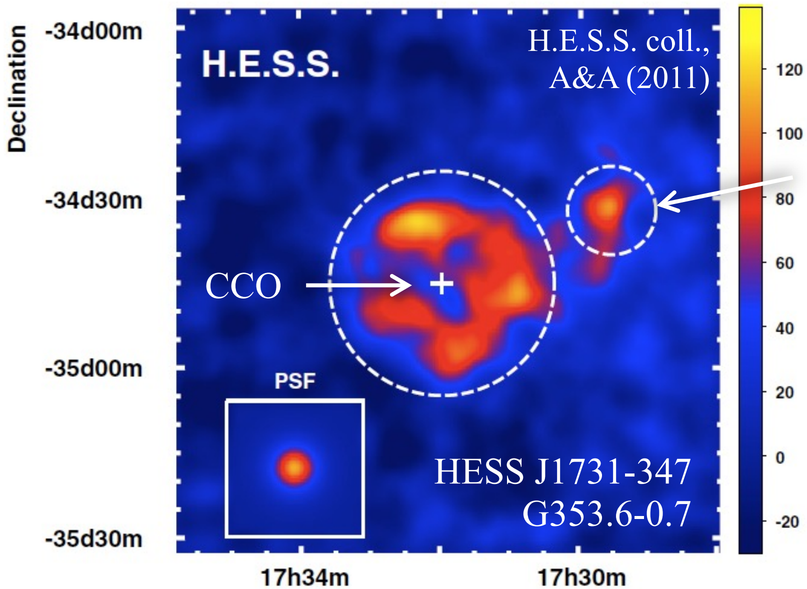


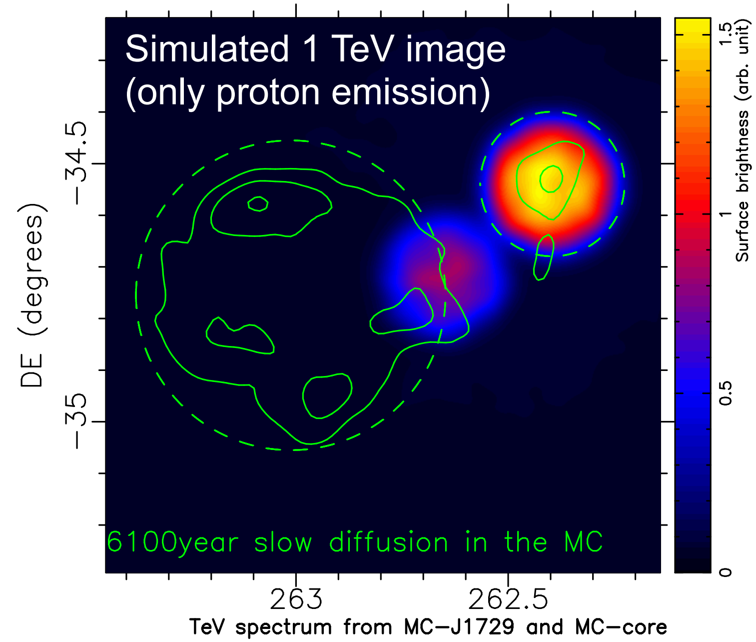


Cui, .. GP ApJ 2019:

- 8 $M_\odot$ progenitor, no wind bubble (could also be Ia), 37 kyr old SNR (snow-plough, shock ~100 km s^{-1})
- Escape of ~TeV particles throughout evolution from entire shell, escape of GeV particles through broken shell; in the „damping“ case, additional escape of GeV particles from entire shell at late times; both models fit the data
- TeV diffusion coefficient in ICM ~ 10% Galactic standard
- Some constraints on diffusion coefficient index δ $(D(E) = 10^{27}(E/10\text{GeV})^{\delta}\ \text{cm}^2/\text{s})$

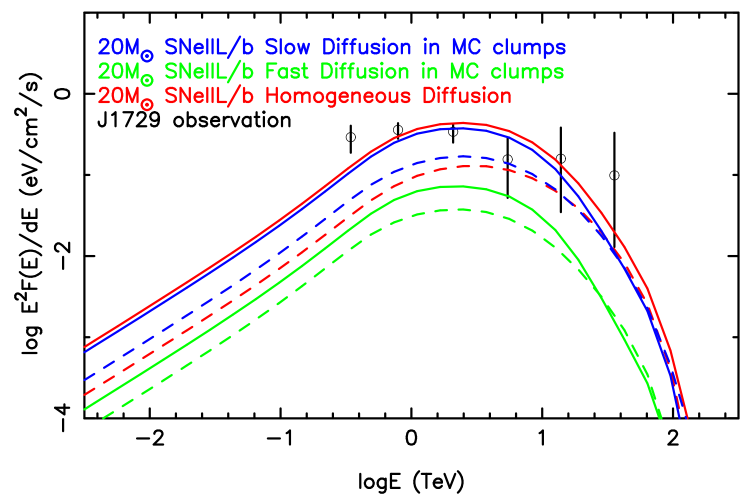
HESS J1731-347: a young SNR with possible CR escape





Cui, GP +, A&A 2016:

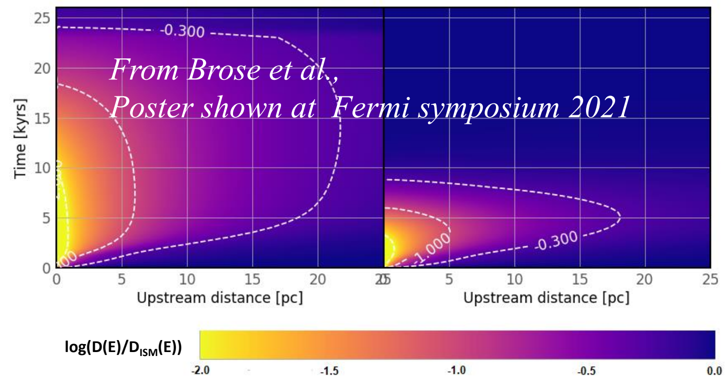
- 20 $M_{\odot}$ progenitor, 6 kyr old SNR still inside wind bubble (shock ~2000 km s^{-1})
- SNR emission likely with large leptonic component(IC)
- Only escape of ~TeV++; for a possible escape of ~GeV particles see *Cui, ..., GP, ApJ 2019*
- Short timescales imply that TeV and MC morphology don‘t need to match perfectly
- Diffusion coefficient in ICM ~ Galactic standard



Issues with escape / diffusion

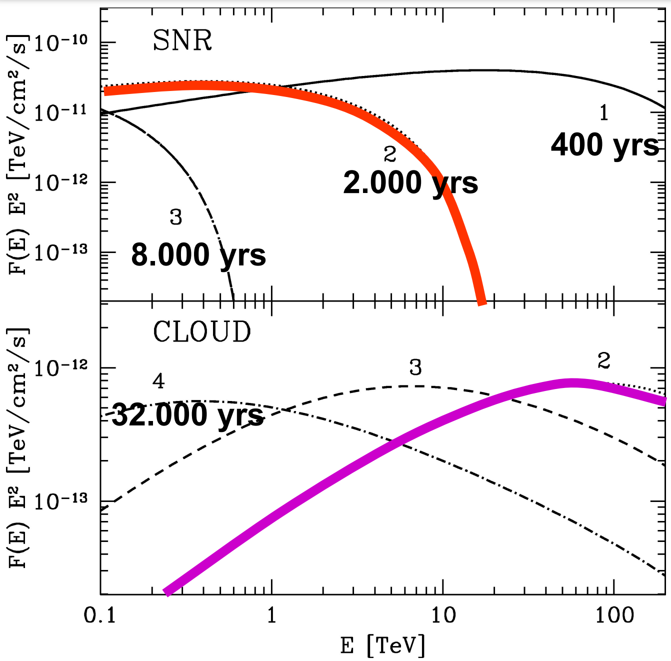
- Most analyses find lower than Galactic diffusion coefficient for W28 (factor 10) → ok
- But no guarantee for (isotropic) diffusion on pc scales

- No evidence for a spectral hardening signature* (maybe HESS J1641-463 next to G338.3-0.0 = HESS J1640-465 ?)
- Data are statistically limited



From Brose et al., Poster shown at Fermi symposium 2021

* Can be used to verify proton diffusion and to discriminate against leptons



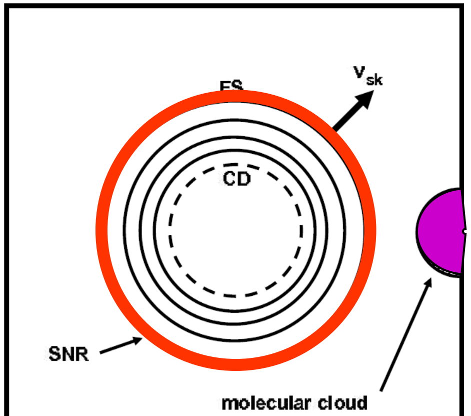
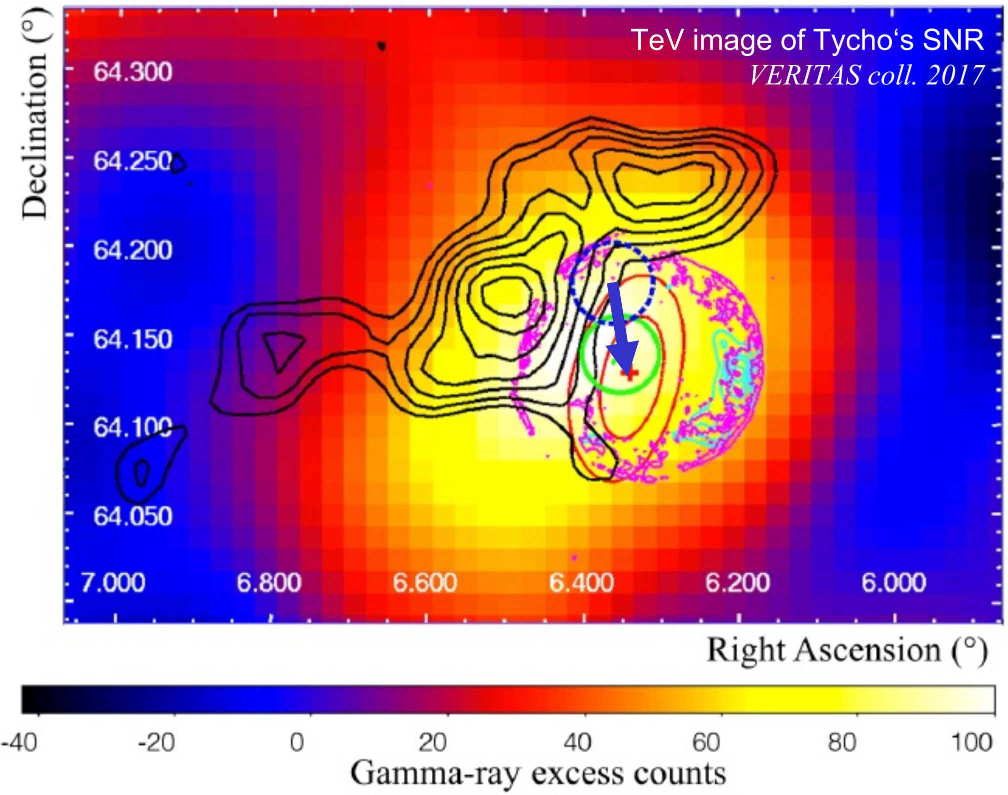


Image credit: Lee et al., ApJ 686, 2008

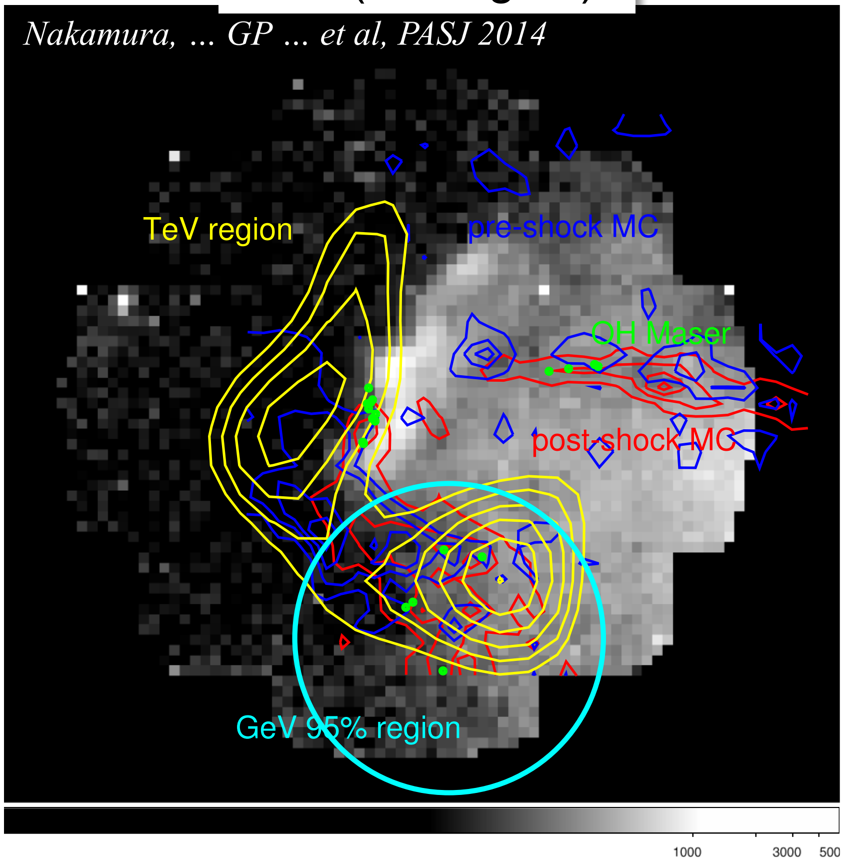
Gabici & Aharonian, ApJ 665, 2007; see also Yamazaki et al. 2006, Lee et al. 2008, …

Escape + Diffusion: Data + limitations

Tycho's SNR



W28 (NE region)



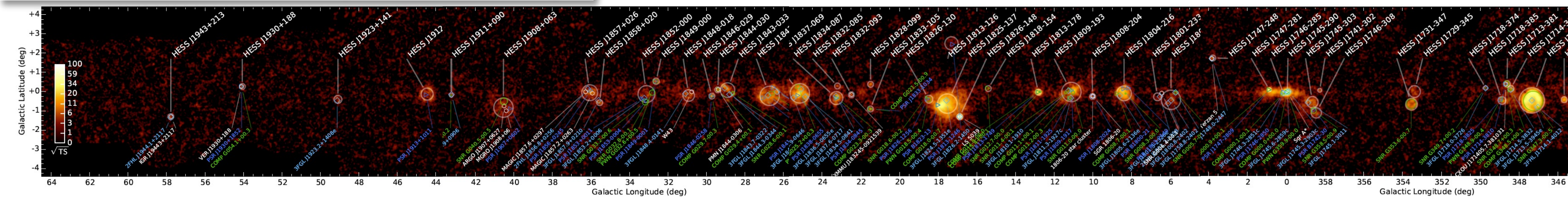
Association of γ-ray emission with gas very uncertain

Association of γ-ray emission with post-shock (=shocked) or pre-shock (=unshocked) gas?

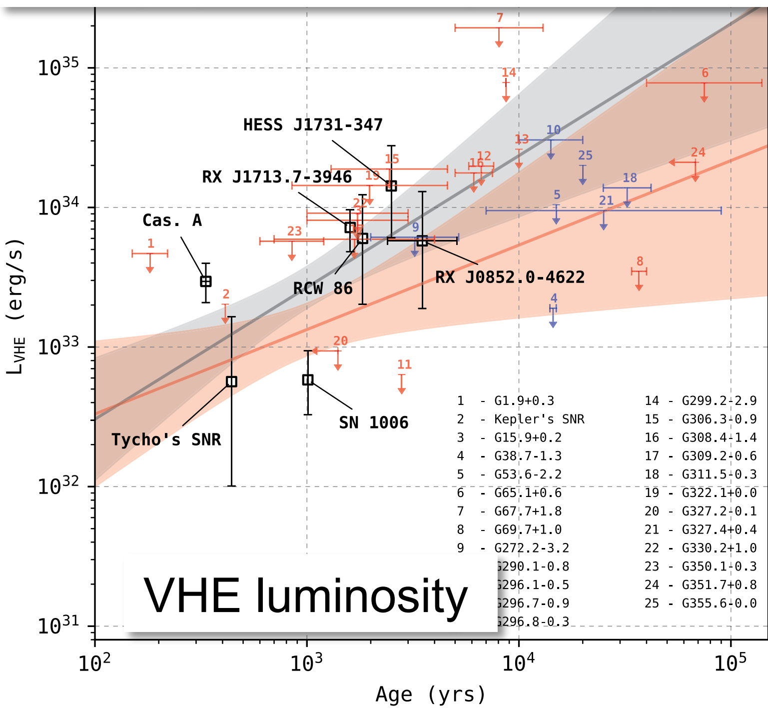
Surveys and population studies

H.E.S.S. Galactic plane survey

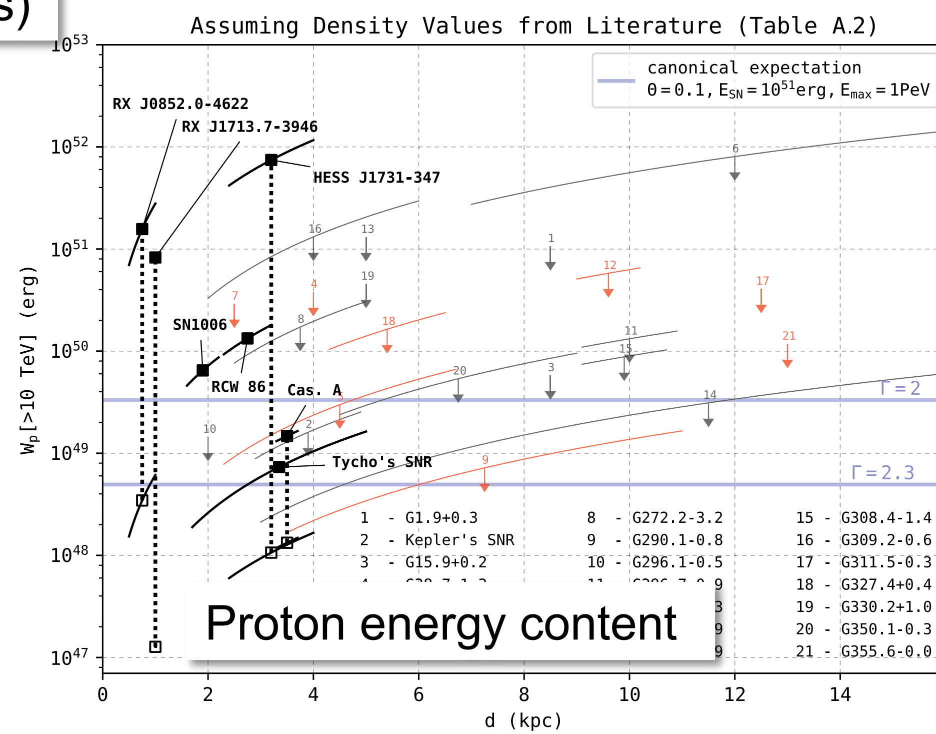
H.E.S.S. coll, A&A 2018



SNR population study (incl. upper limits)



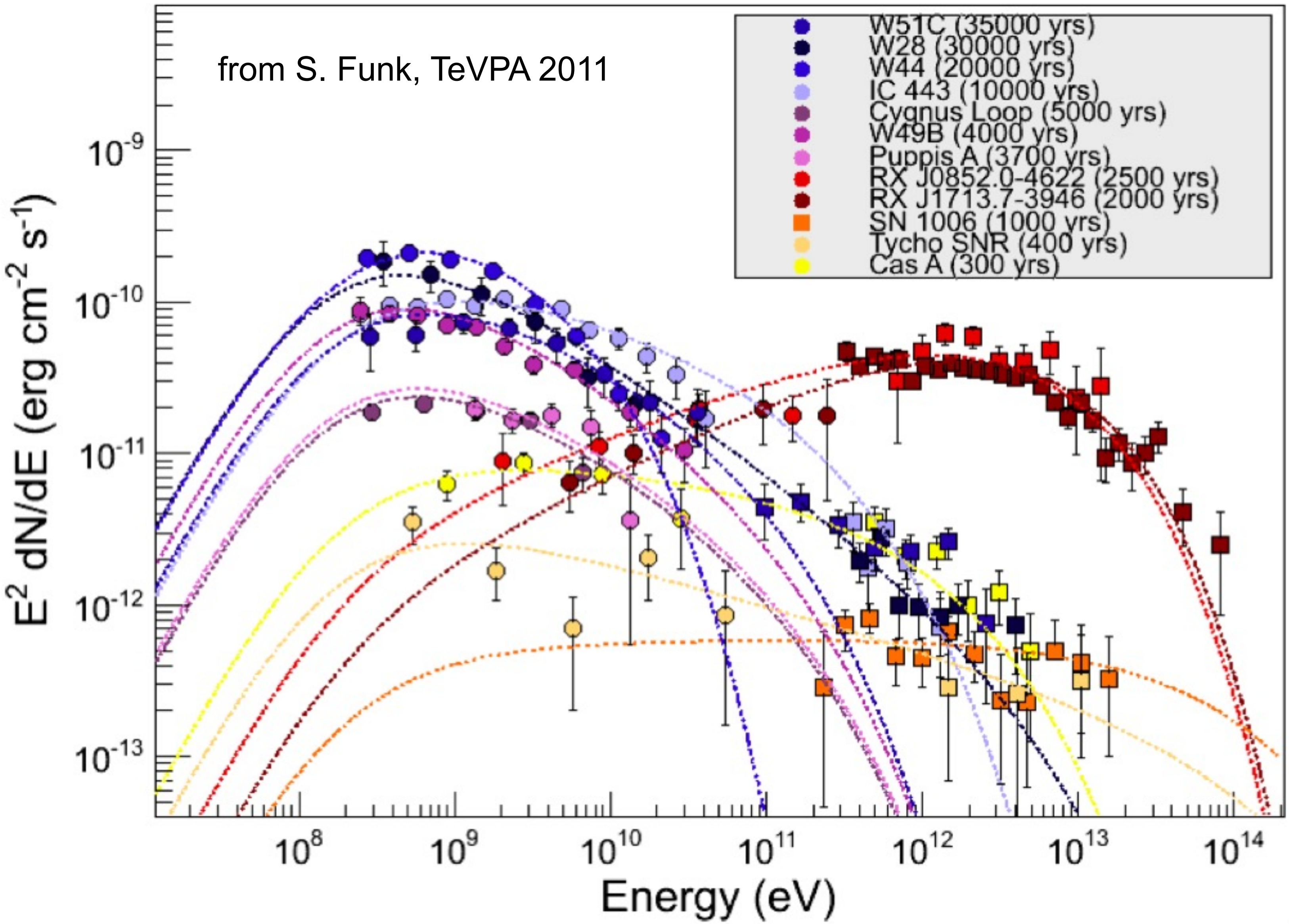
VHE luminosity



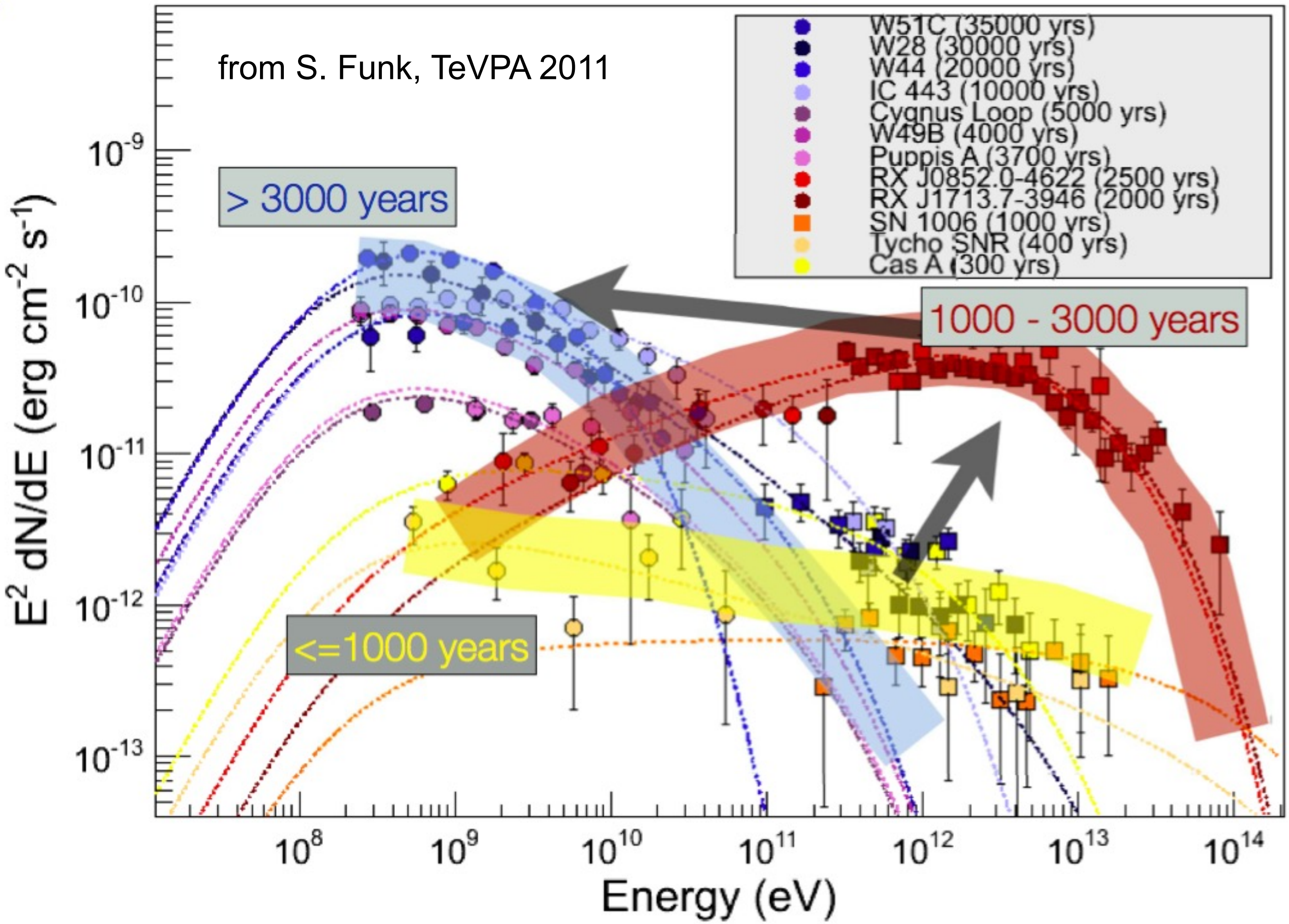
Proton energy content

H.E.S.S. coll, A&A 2018

GeV-TeV spectra of supernova remnants

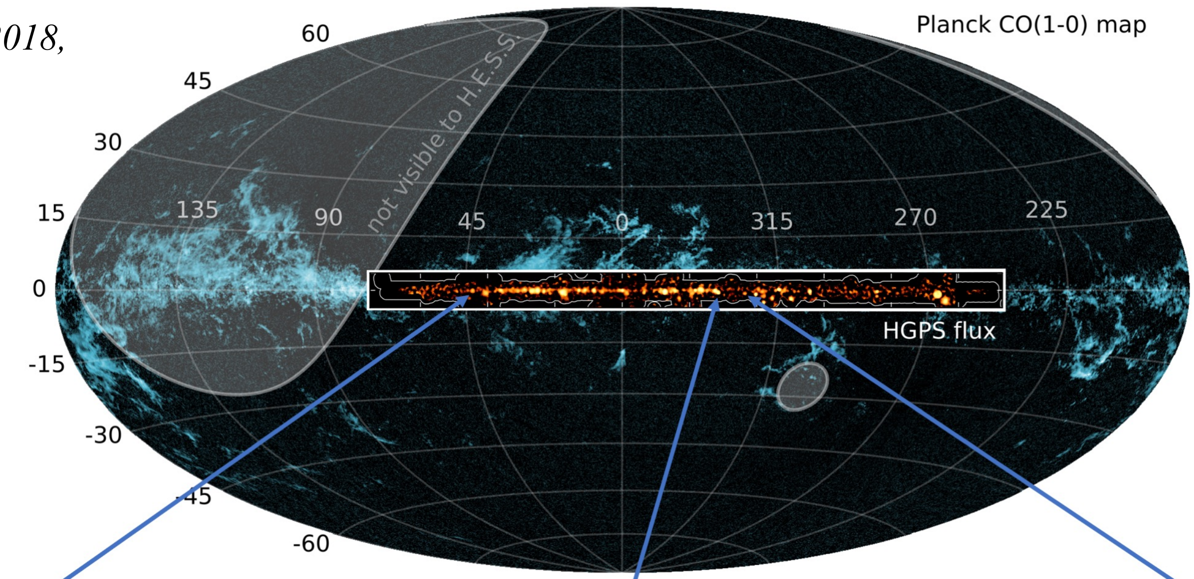


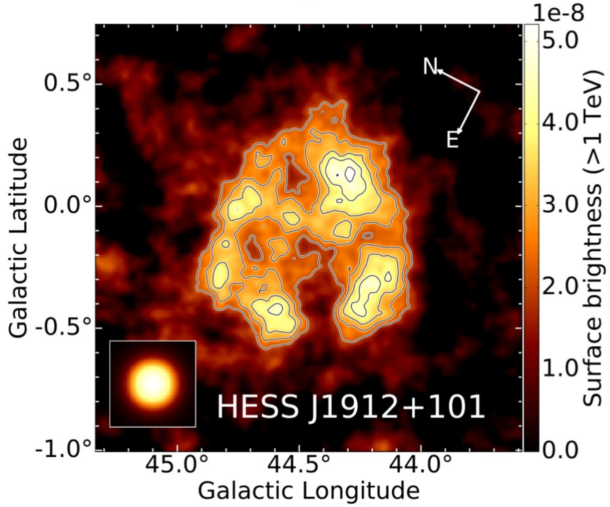
GeV-TeV spectra of supernova remnants

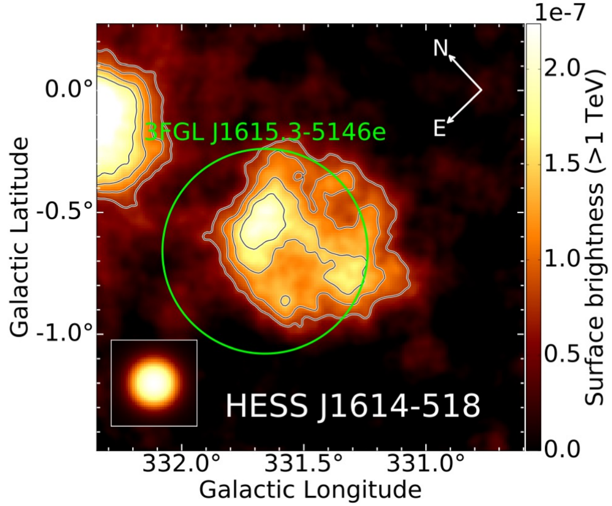


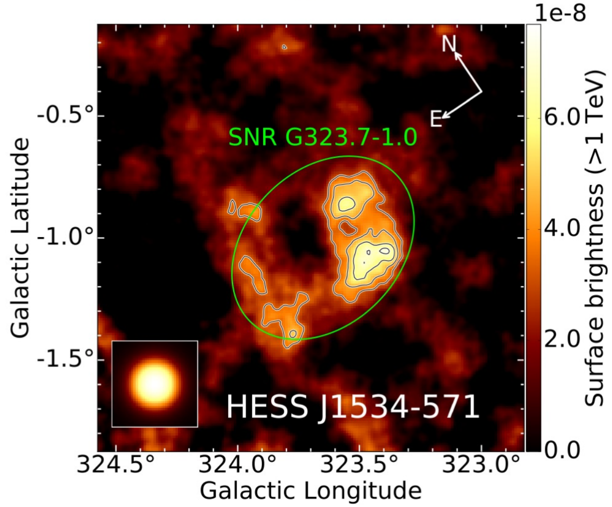
New SNR (candidates) identified in the H.E.S.S. Galactic plane survey

H.E.S.S. coll., A&A 2018, GP+ 2015, …



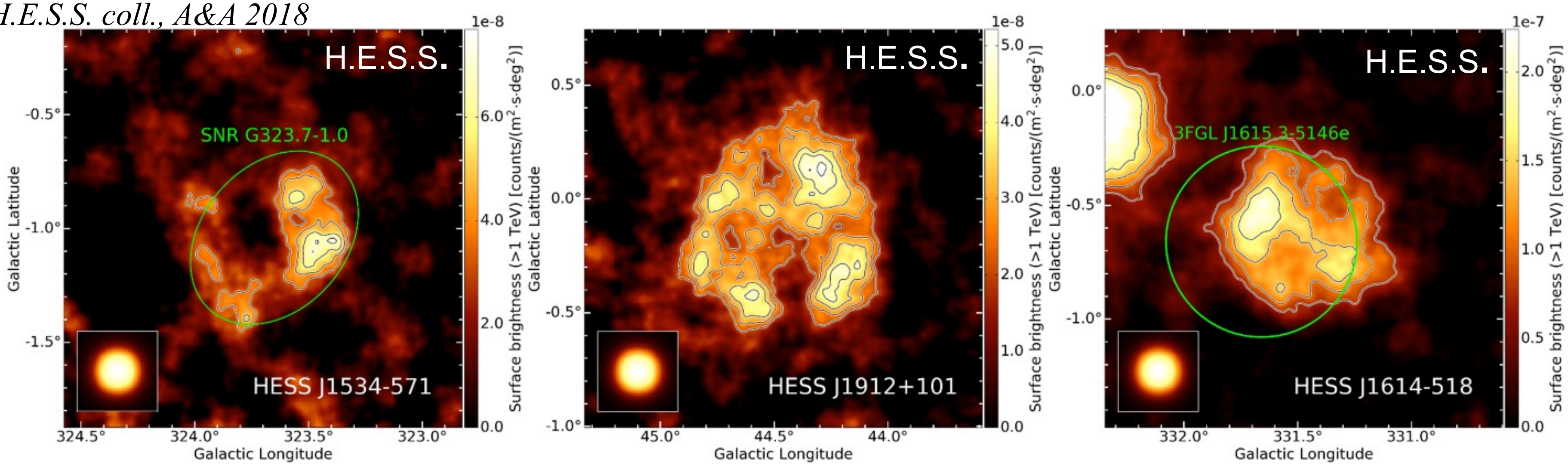






New SNR (candidates) identified in the H.E.S.S. Galactic plane survey

H.E.S.S. coll., A&A 2018

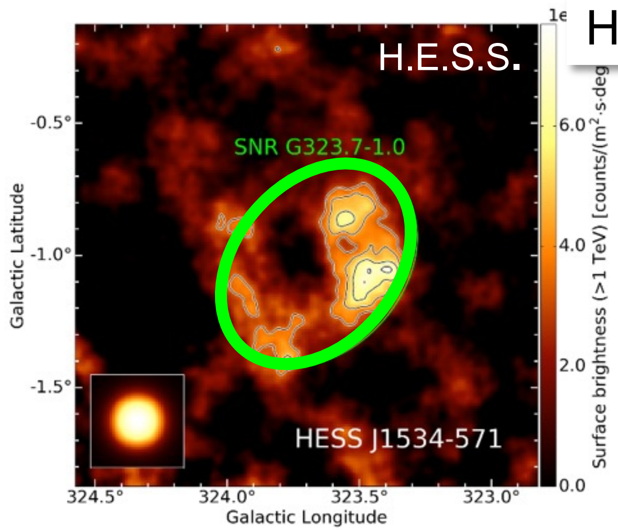


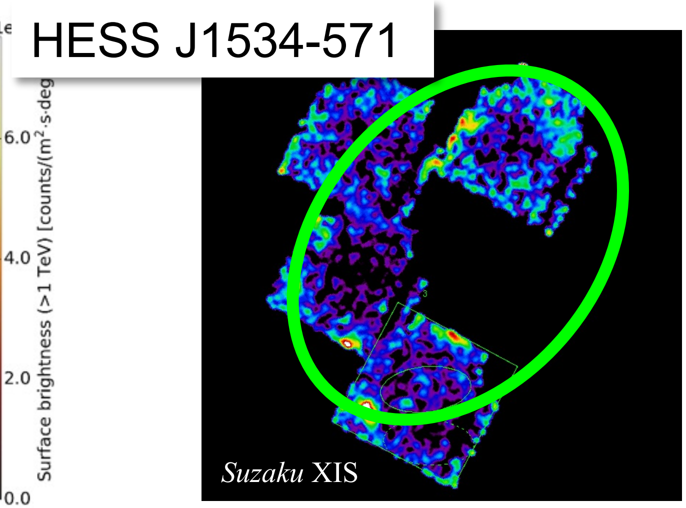
HESS J1534-571: SNR nature confirmed w/ radio counterpart

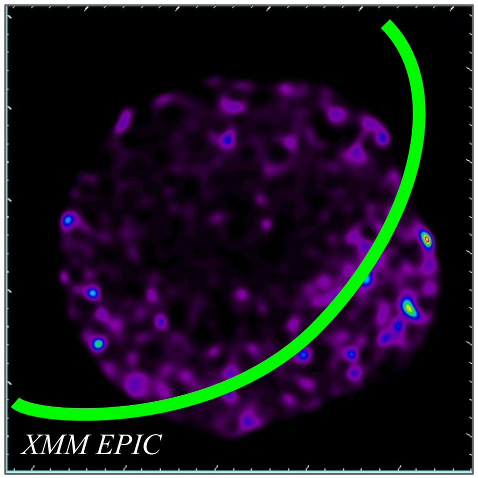
HESS J1912+101, HESS J1614-518: no counterparts that permit identification yet

- Large angular diameters (0.4° .. 0.5°)
- Distances unknown, but in any likely association scenario (spiral arms / molecular gas, other possible counterparts): 3.5 .. 10 kpc
- Soft TeV spectra (Γ≈2.5)
- A possible scenario: young to middle-aged (~1000 .. >10000 years) SNRs, evolving in wind-blown cavities (cf. RX J1713.7-3946, Vela Jr., HESS J1731-347, ...)

Hadrons or relic electrons (cf. PWN halo)?





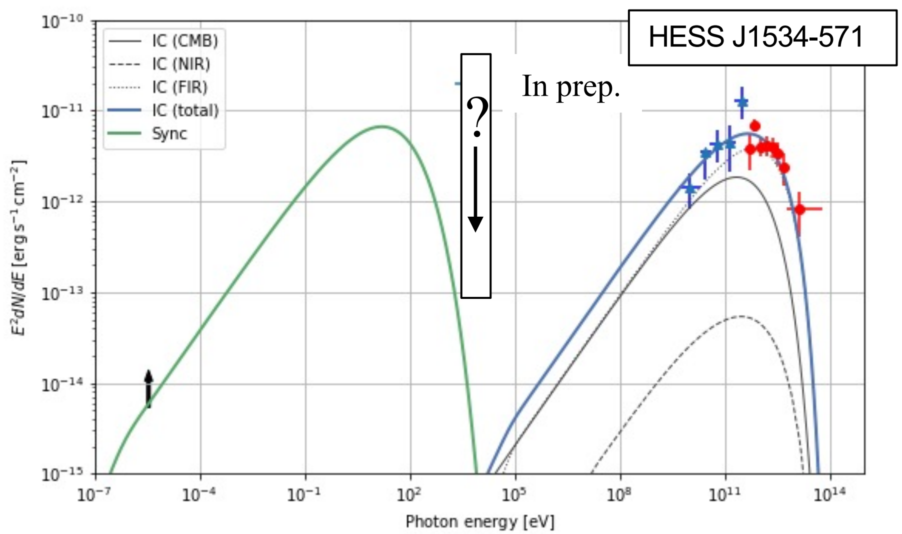


- No X-ray synchrotron emission detected from the new TeV shells

→ Hadronic sources?

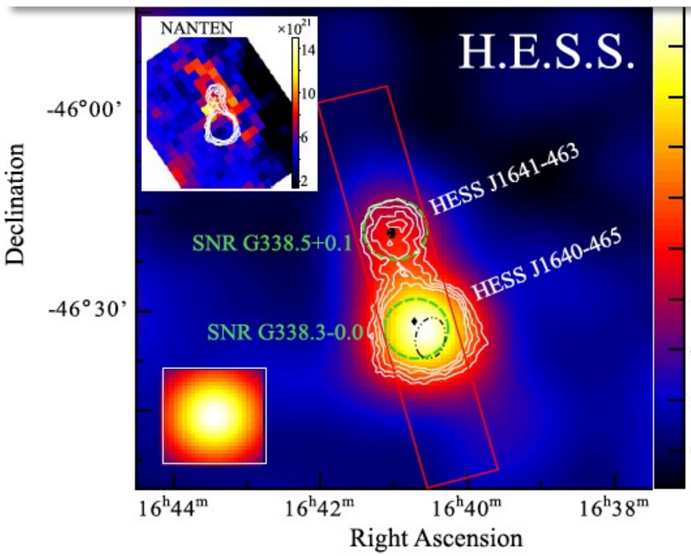
- Best limit of non-thermal X-rays with Suzaku-XIS and XMM-Newton on HESS J1534-571

→ Hardly possible to constrain relic electron scenario this way



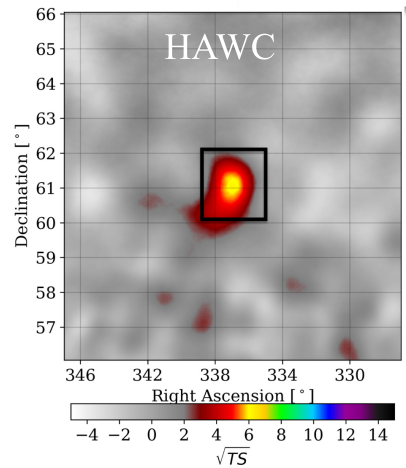
Pevatrons near SNRs

HESS J1641-463 @ G338.3-0.0

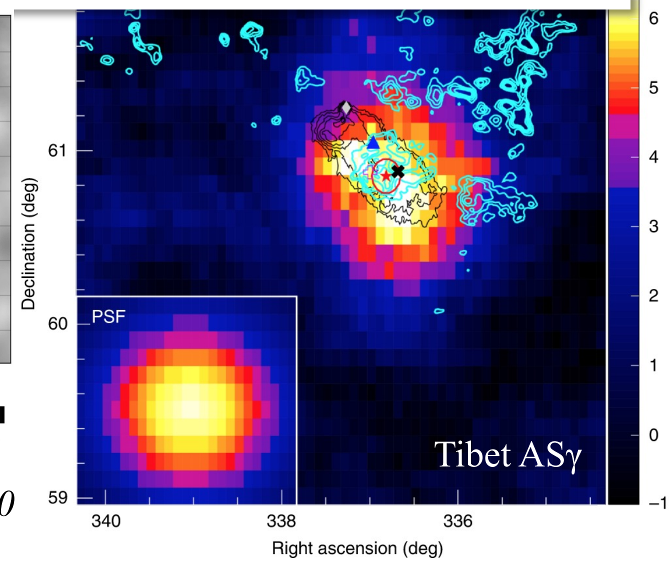


H.E.S.S. colL., A&A 2014

HAWC J2227+610 @ G106.3+2.7



HAWC colL., APJL 2020



Tibet ASγ coll, Nat. Astr. 2021

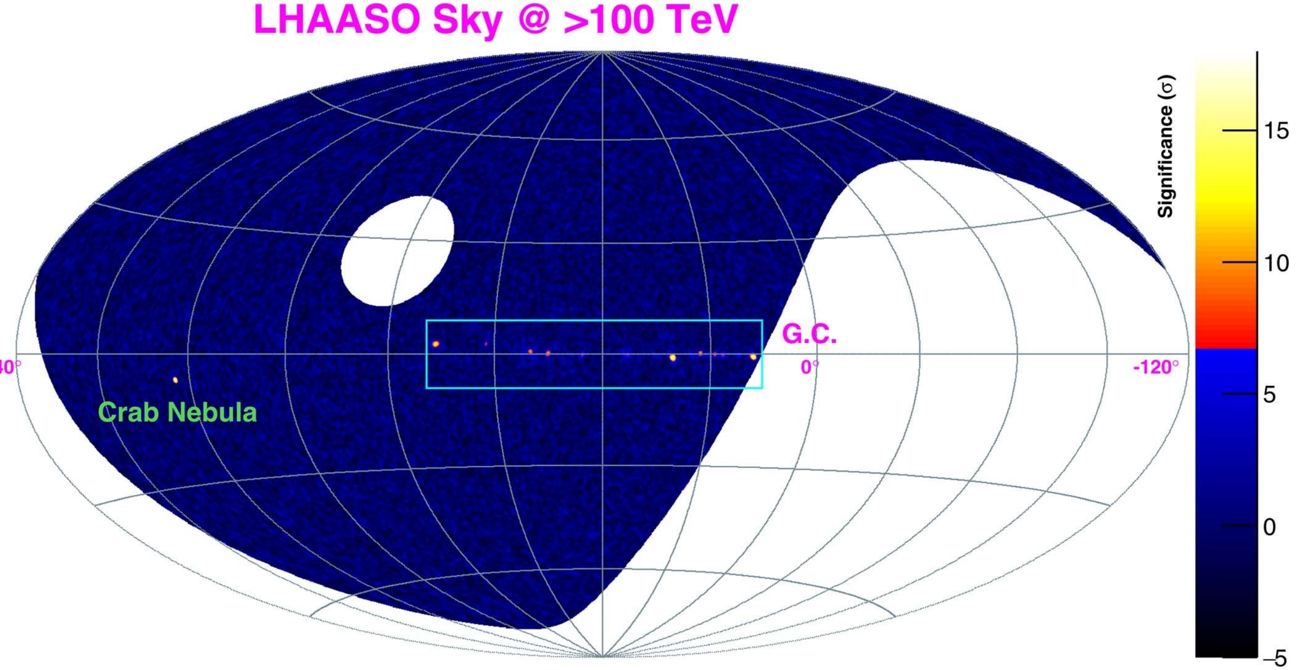
→ Angular resolution ok, but γ-energies up to 20 TeV only

(Pevatron candidate!)

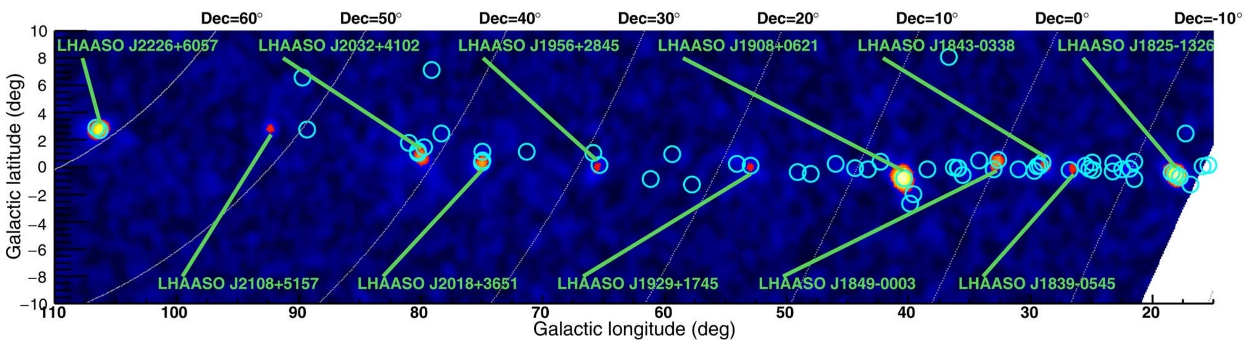
→ γ-energies up to 100 TeV, but angular resolution not sufficient

Pevatrons near SNRs: first UHE map with LHAASO

LHAASO coll, Nature 2021

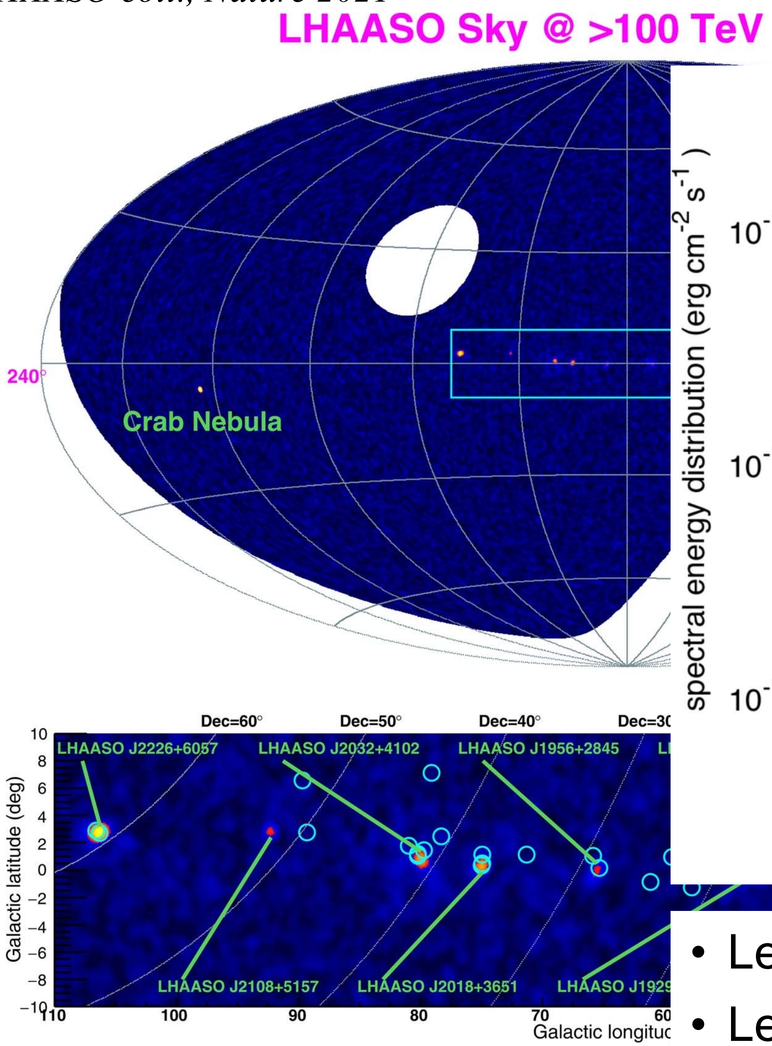


- Crab is a pevatron
- Other PWN (halos) potential pevatrons
- SNRs?



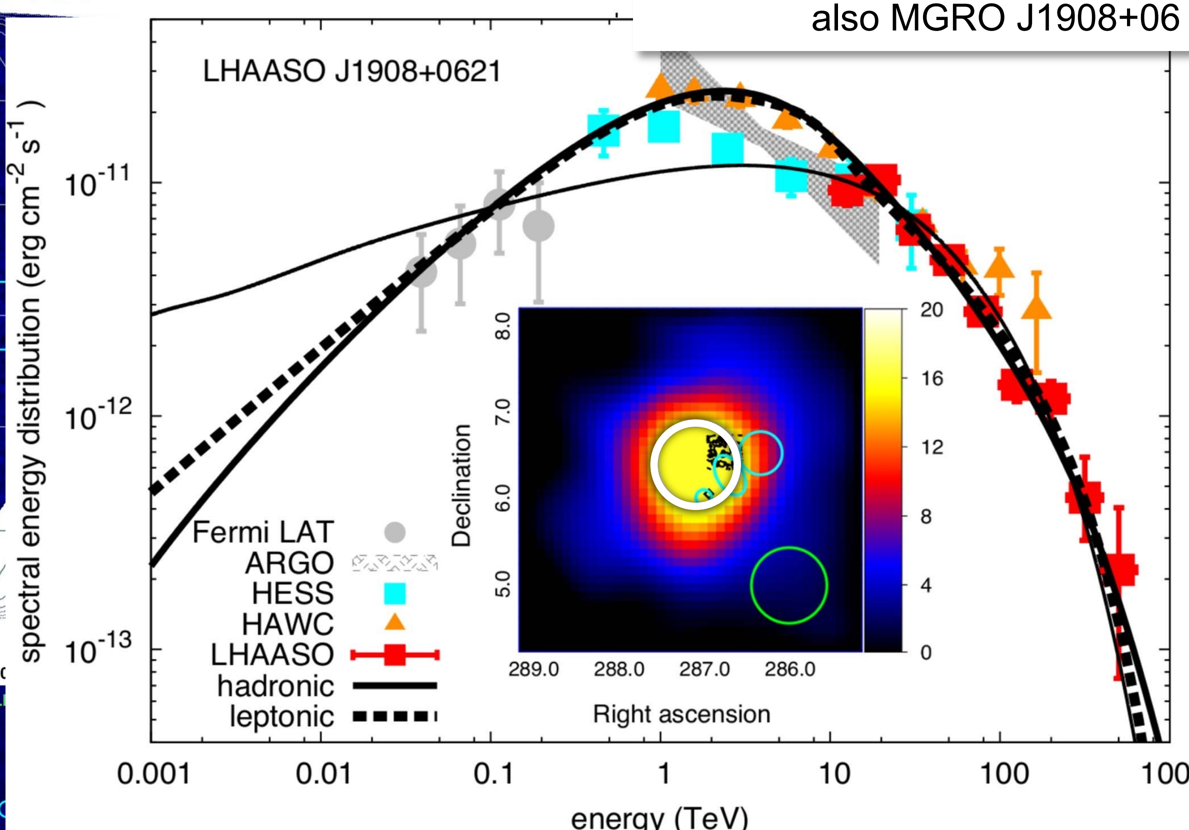
Pevatrons near SNRs: first UHE map with LHAASO

LHAASO coll., Nature 2021



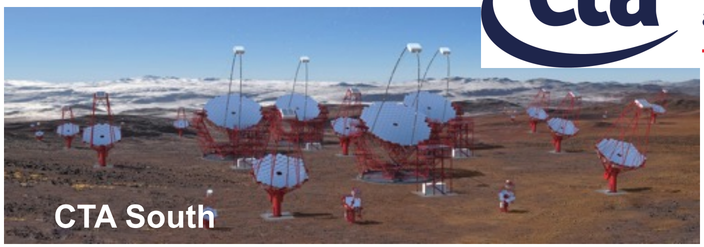
HESS J1908+063 @ G40.5-0.5

also MGRO J1908+06

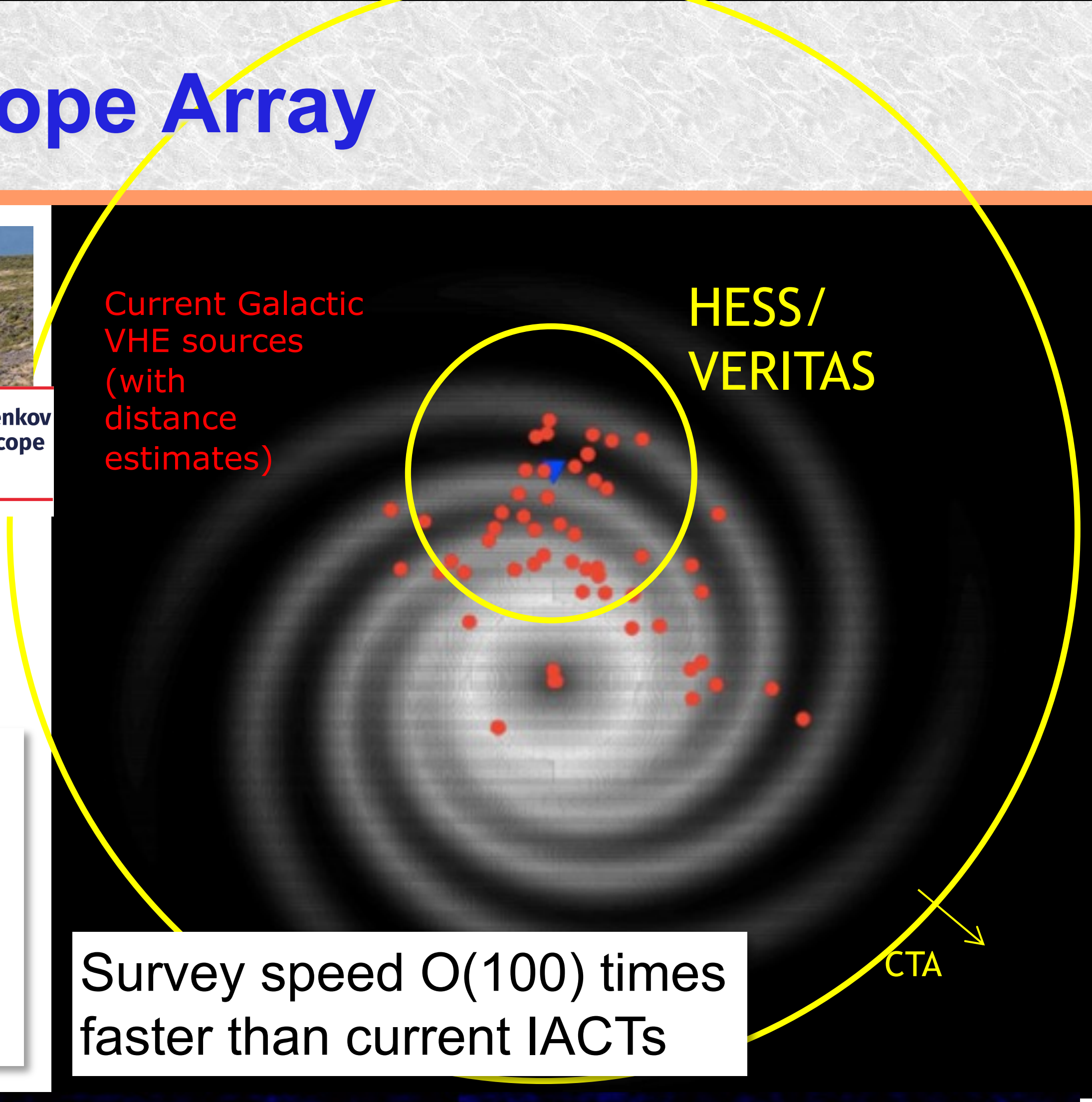


- Leptonic model from pulsar injection
- Leptonic emission from relic electrons from SNR?

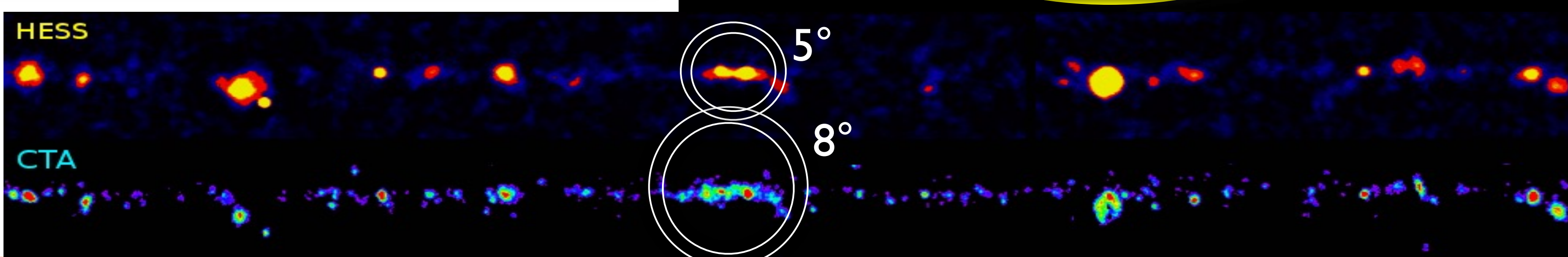
Cherenkov Telescope Array



Surveys of:
- Galactic center
- Galactic plane
- LMC
- Fraction of extragalactic sky

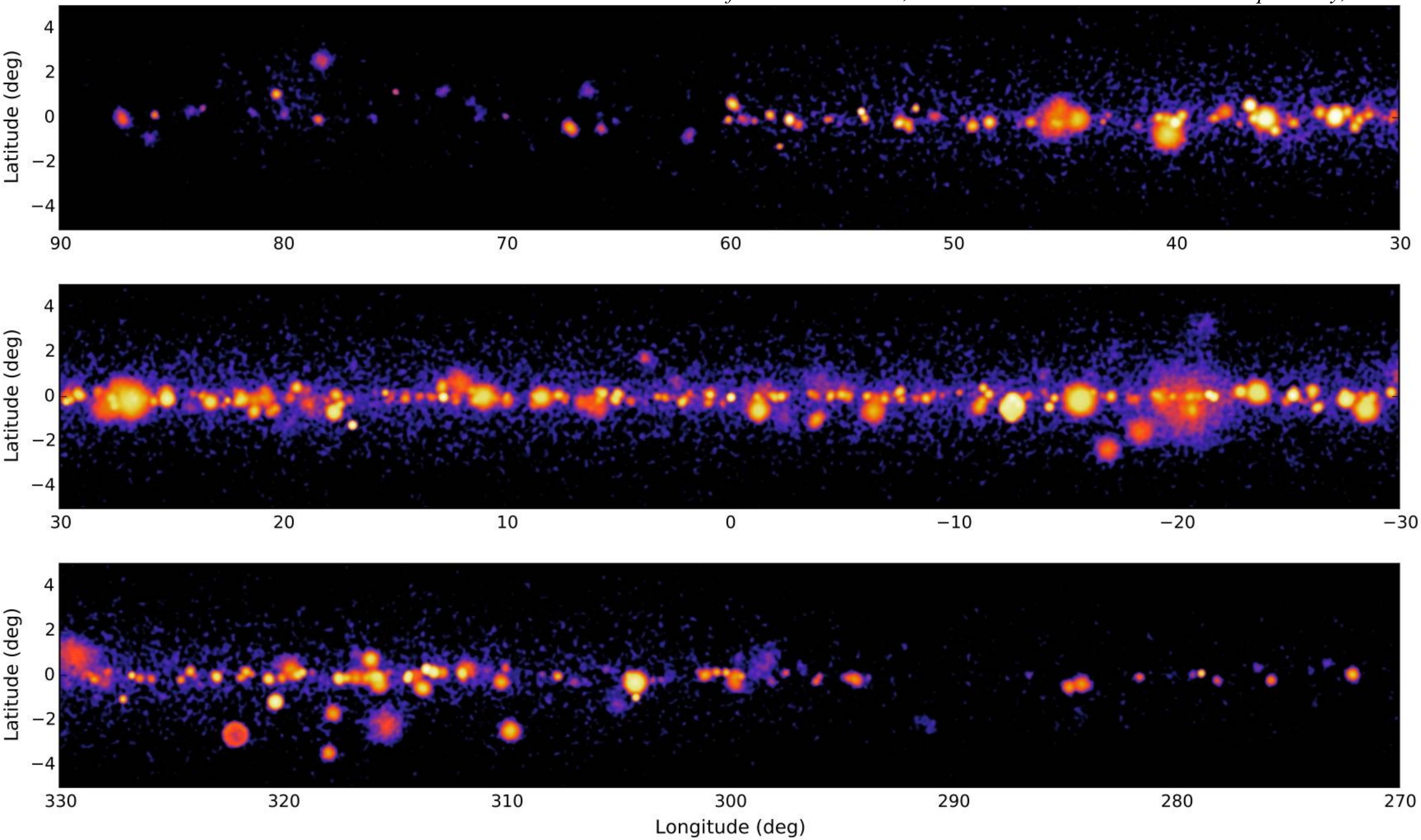


Survey speed O(100) times faster than current IACTs



CTA: simulated survey of the galactic plane

cf. CTA consortium, Science with the Cherenkov Telescope Array, 2019



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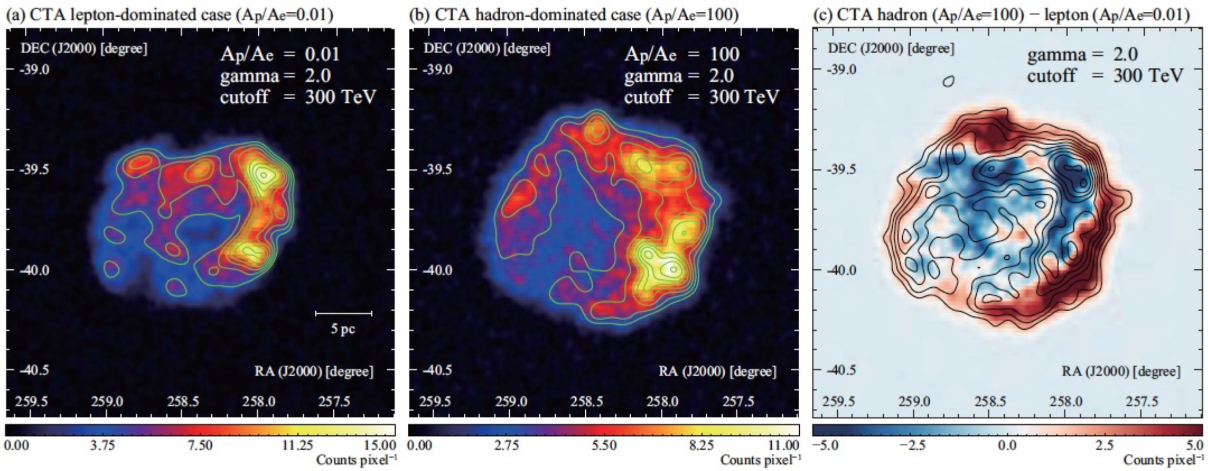
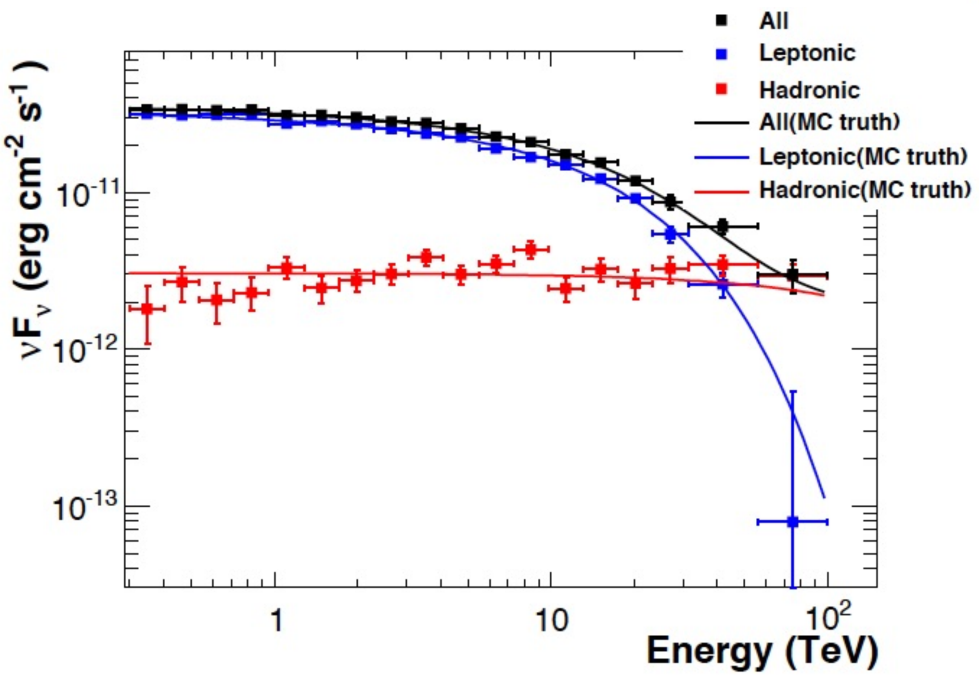
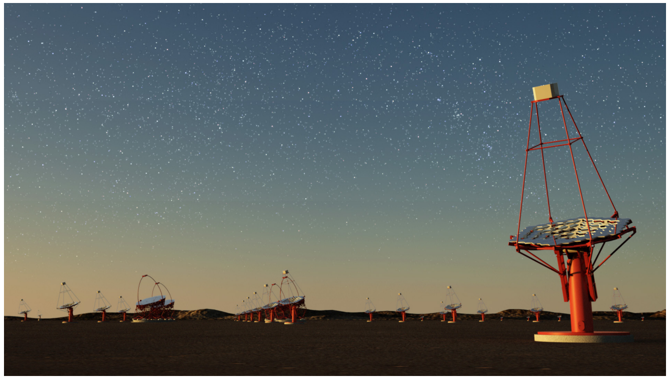
RX J1713.7-3946 with CTA

- Simulation of leptonic and hadronic (pevatron) components
- CTA (Cherenkov telescope array) key target

Acero et al. (for CTA) 2017







Conclusions

- Identification of relativistic particle species (leptonic vs. hadronic) in γ-ray emitting SNRs continues to be an issue; depend on small-scale physics (sub-SNR)
- New H.E.S.S. TeV SNR shells can be interpreted as proton or lepton sources, where SNR shells interact with wind-blown cavities (connecting young TeV shells with evolved LAT-selected SNRs)
- Search for PeVatrons / PeVatron SNRs to identify accelerators up to knee energies: success?
- Being a pevatron is not enough to qualify as proton accelerator
- π^0-bump in LAT spectra of several SNRs likely identifies them as proton sources, but not as PeVatrons; many are evolved/interacting with molecular clouds
- Soft SNR GeV-TeV spectra can be explained with evolution and escape, PeV particles are observationally unconstrained
- Mapping CR escape from SNRs might be used as a tool to
  - identify them as proton accelerators (search for spectral + morphological signature)
  - identify them as PeVatrons (SNR PeVatron lifetime is short)
  - study the ISM through CR propagation

Backups

Galactic Center with H.E.S.S.: a pevatron

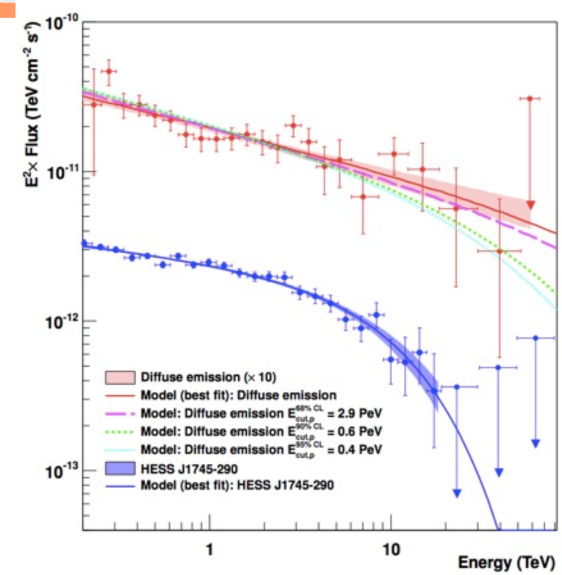
LETTER

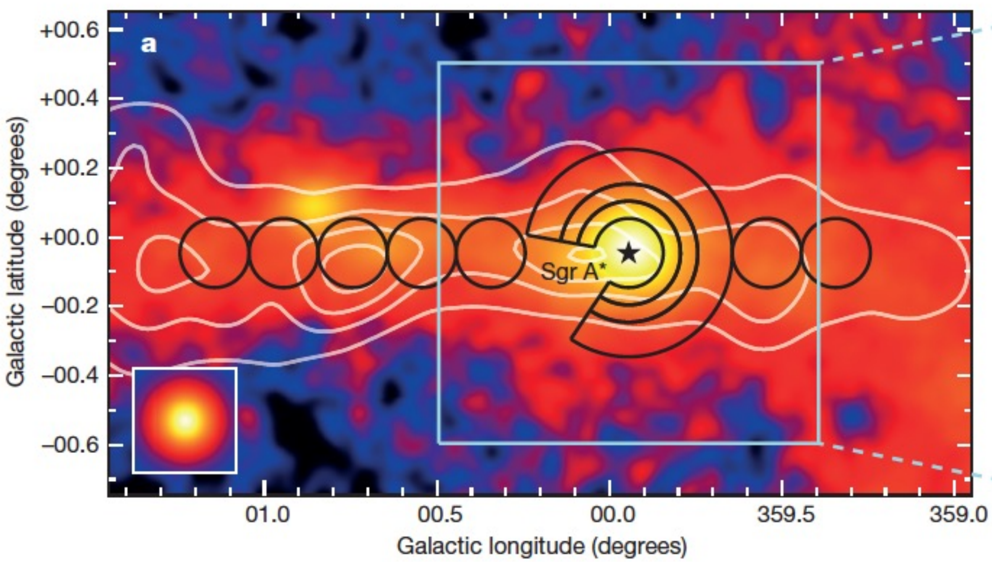
doi:10.1038/nature17147

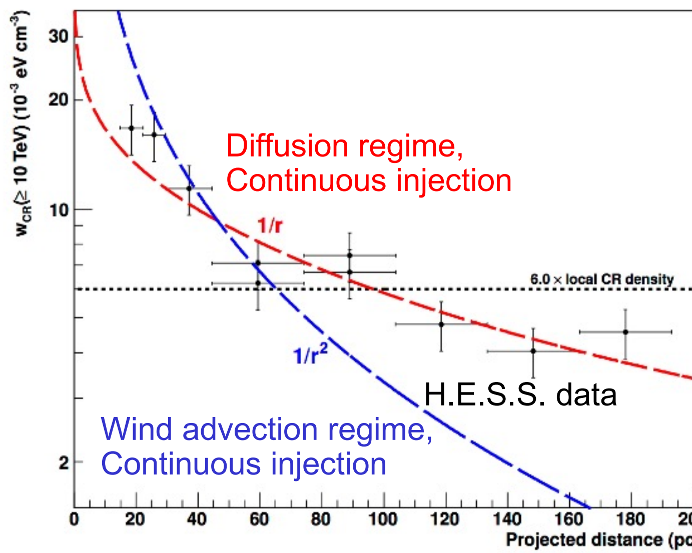
Acceleration of petaelectronvolt protons in the Galactic Centre

HESS Collaboration*

- Point like, central source on top of extended (ridge) emission
- Origin of diffuse emission: Interaction of CR (from central BH) with interstellar medium
- Central point source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well above 10 TeV
- Emission profile consistent with propagation of protons accelerated around central black hole and diffusing away
- Parent proton population up to 1 PeV (2.9 PeV @ 68% CL)
- Central accelerator located within 10 pc and injecting CRs continuously for > 1 kyrs







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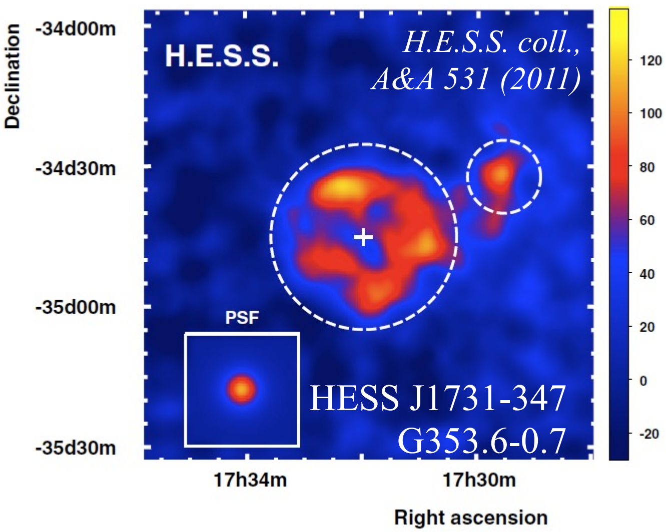
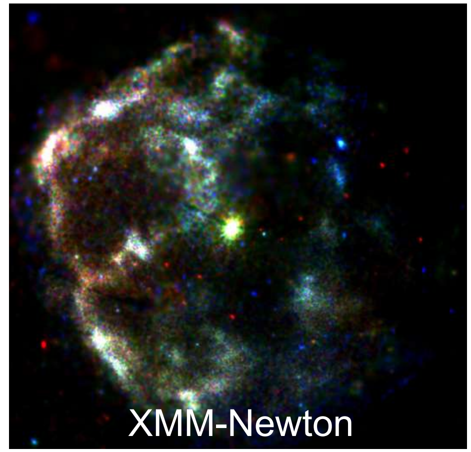
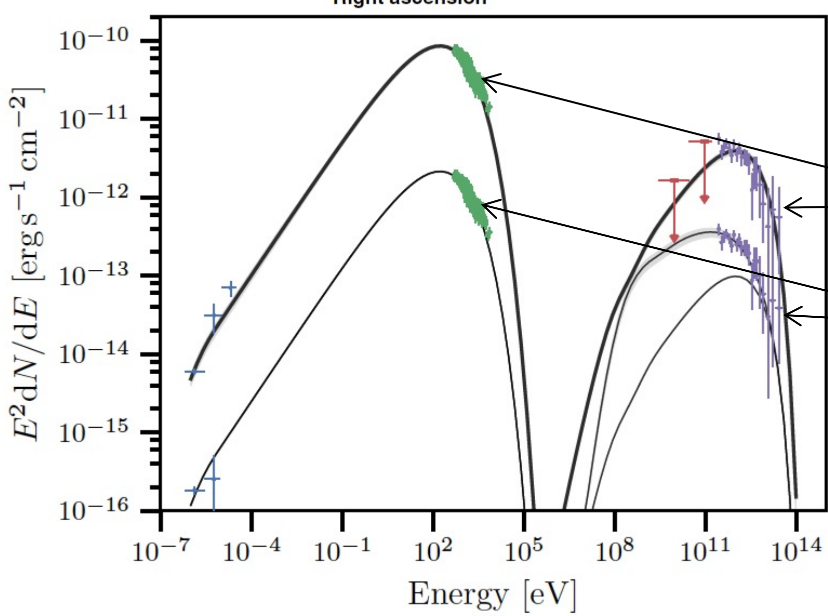
HESS J1731-347: Similar TeV SNR but some extras





- Total γ-ray spectrum possibly a blend of hadronic and leptonic emission
- Large-scale asymmetry because of gas environment
- Spatial separation of hadronic and leptonic emission possible?
- Available γ-ray statistics not yet sufficient for a test



Full SNR

North-West:

TeV excess modeled by additional hadronic component

Not a complete model, just for illustration

Doroshenko, GP+, A&A 2017