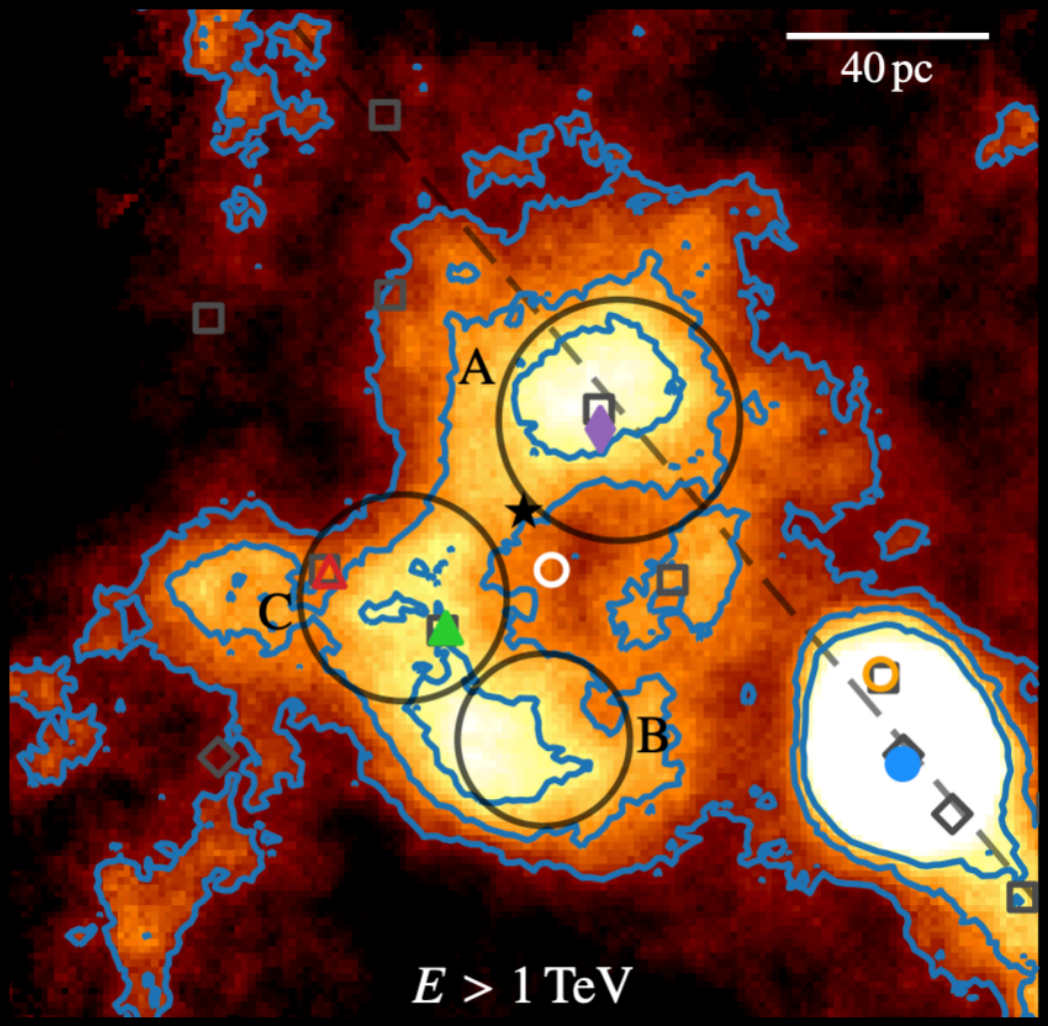
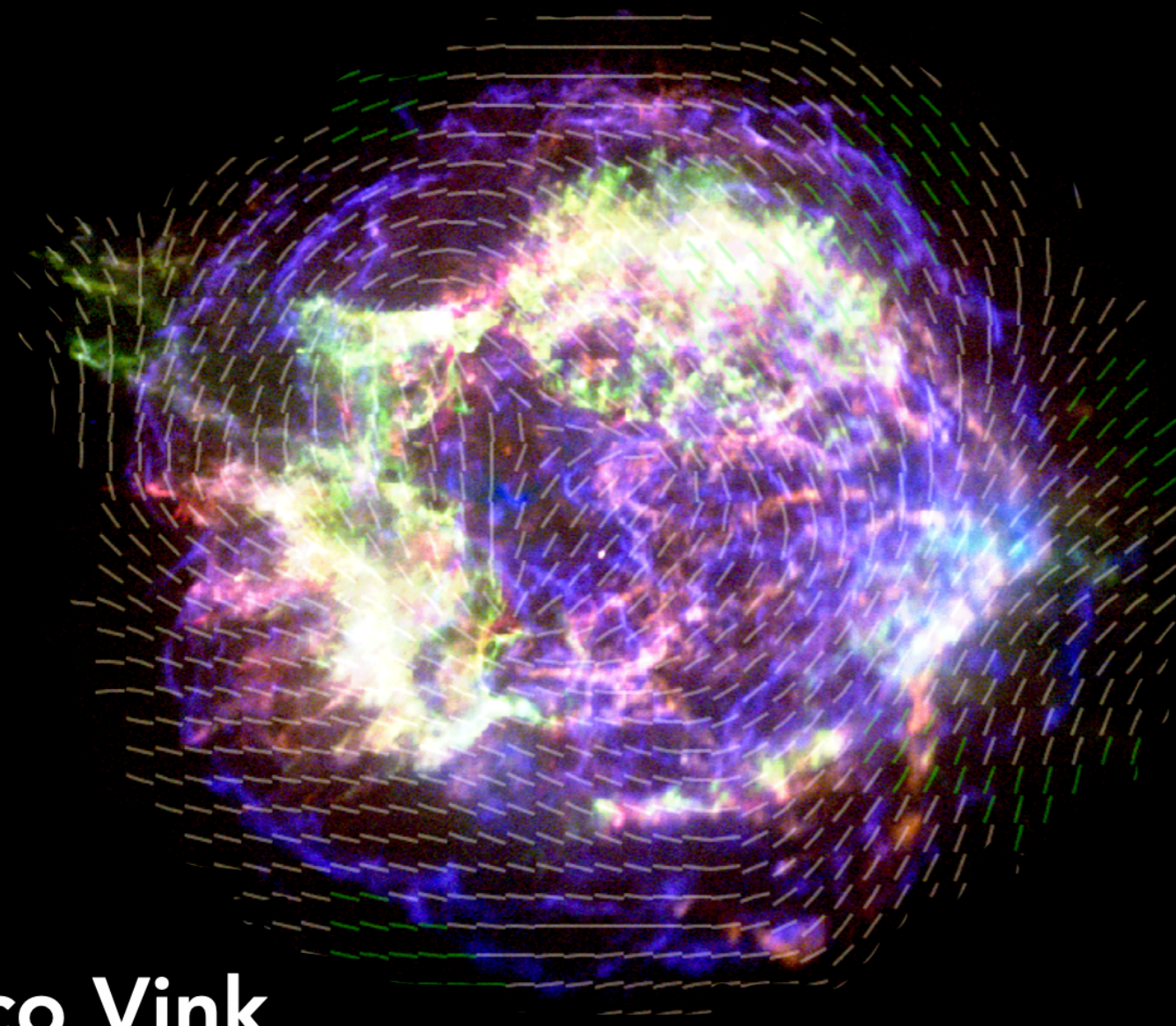
Galactic accelerators





Jacco Vink

University of Amsterdam

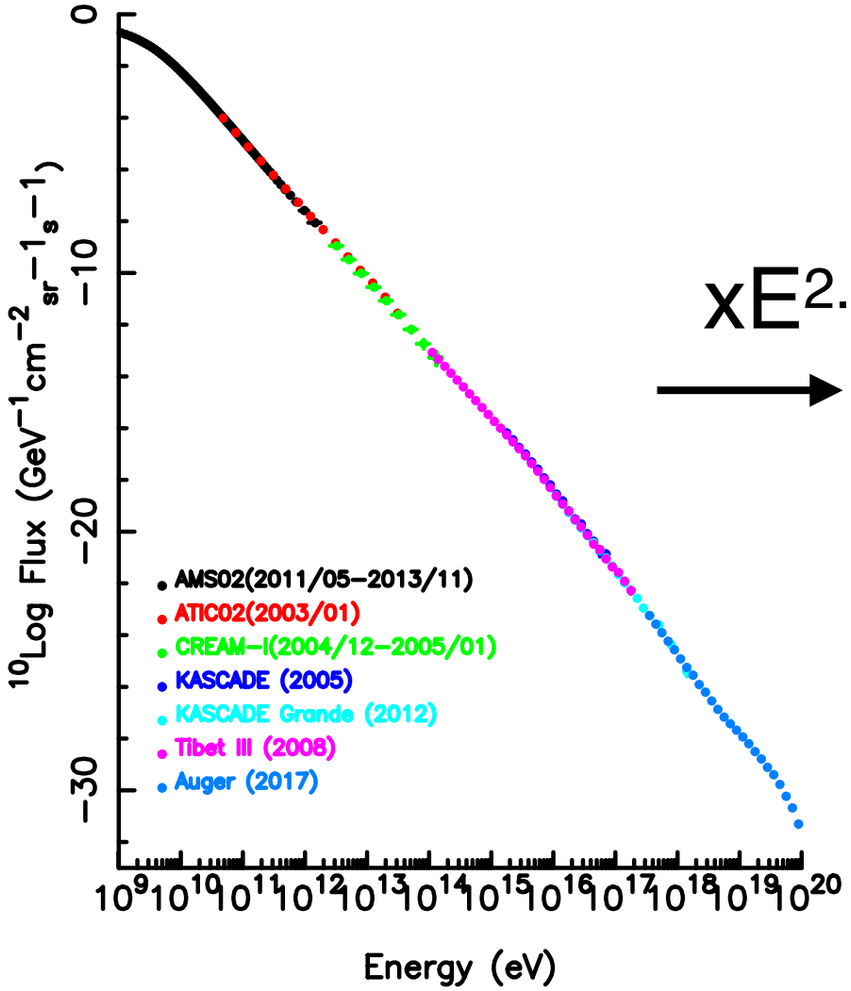
Vulcano Workshop 2022 @ Elba (25-9—1-10)

SHARP

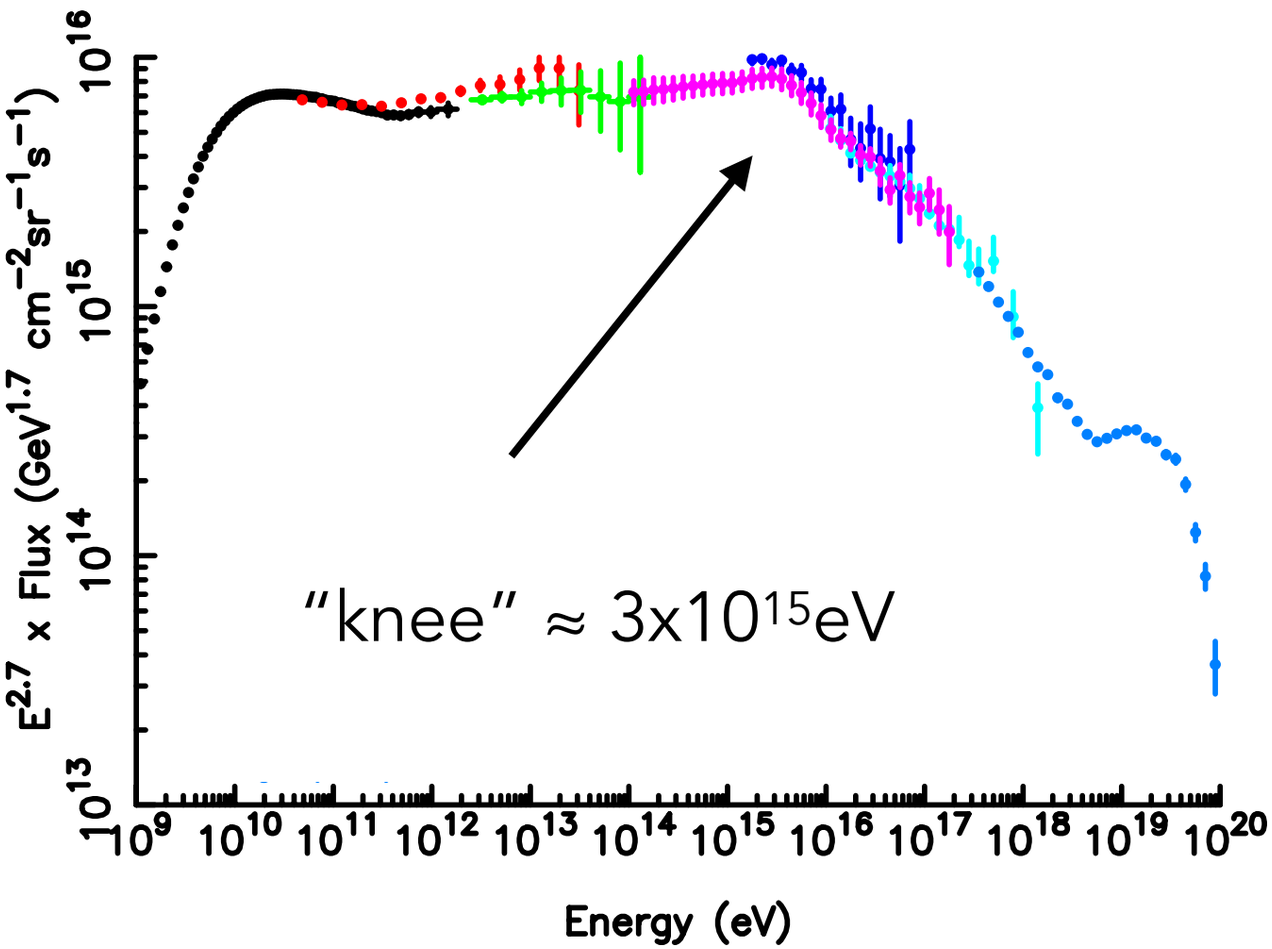
GRAPPA
GRavitation AstroParticle Physics Amsterdam

ANTON PANNEKOEK INSTITUTE

Galactic cosmic rays



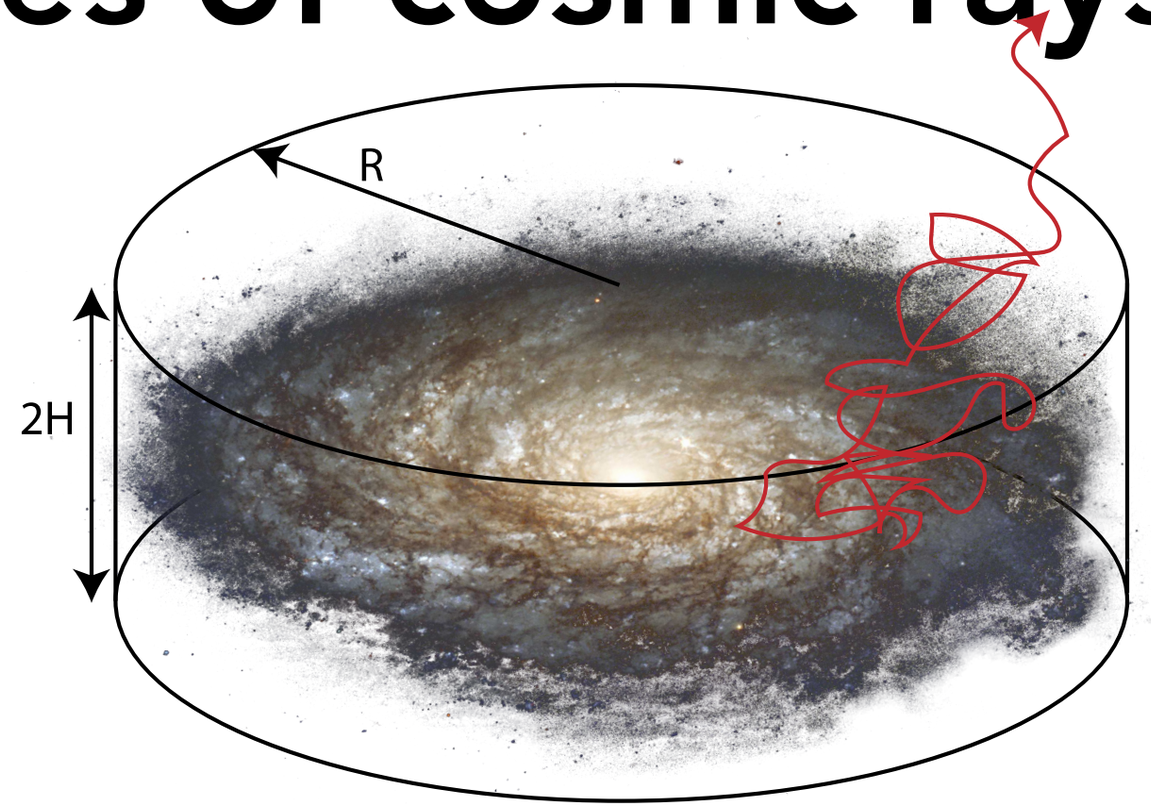
xE$^{2.7}$



- Cosmic rays dominated by cosmic ray nuclei ("hadronic cosmic rays")
- ~1% electron (+/-) cosmic rays ("leptonic cosmic rays)
- > ~10^{18} eV(?): extragalactic
- < 3x10^{15}eV: galactic *proton* cosmic rays

Dominant sources of cosmic rays?

Talk by S. Celli



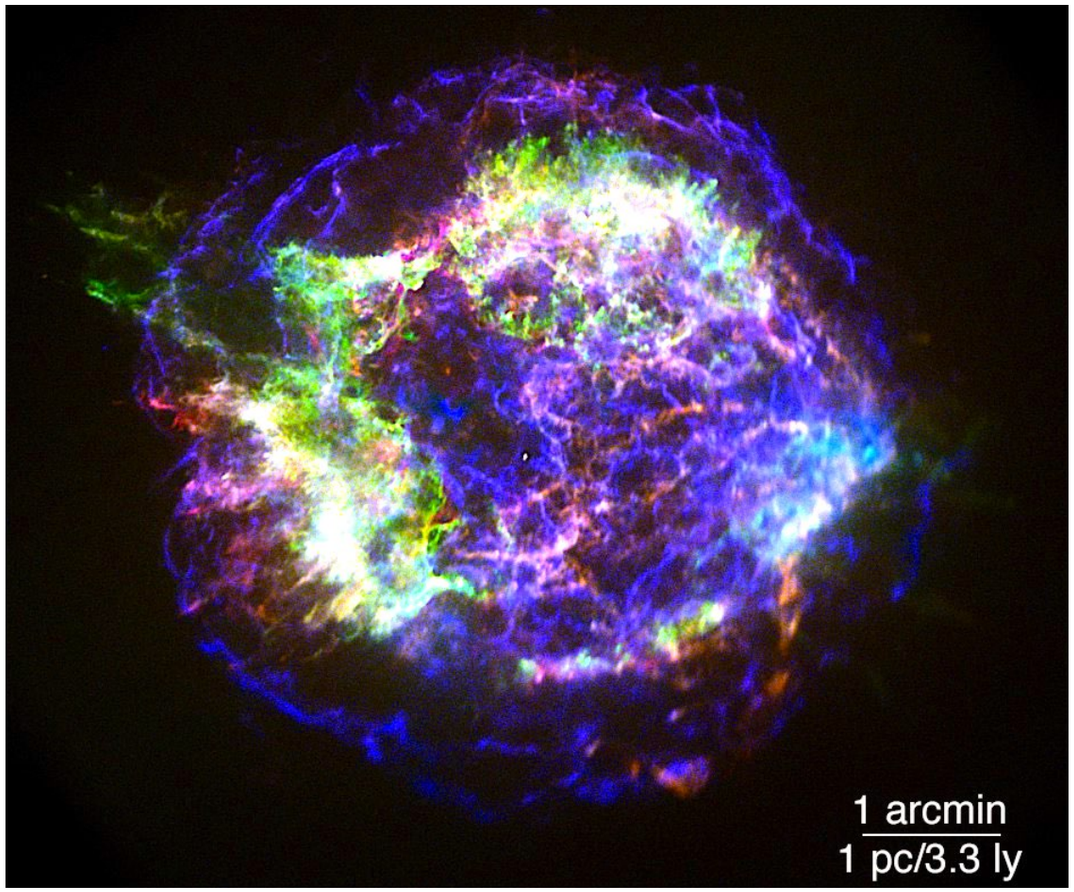
Constraint A:

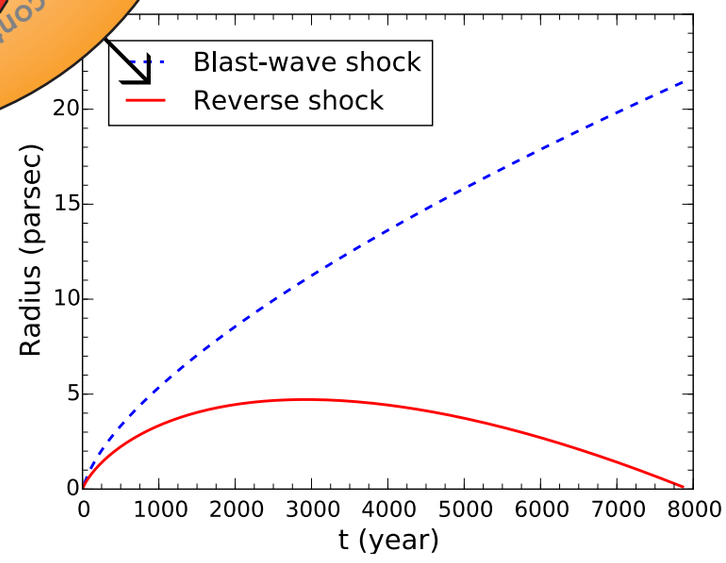
- Need to be able to accelerate protons to 3×10^{15}eV

Constraint B:

- local energy density CRs ≈ 1 eV cm^{-3}
- escape time $\tau \approx 15 \times 10^{6}$ yr
- Galactic volume ≈1250 $kpc^3 \approx 3 \times 10^{67} cm^3$
- To fill Galaxy: need a power of $\dot{E}_{\rm cr} \approx 10^{41}\ {\rm erg\ s^{-1}}$

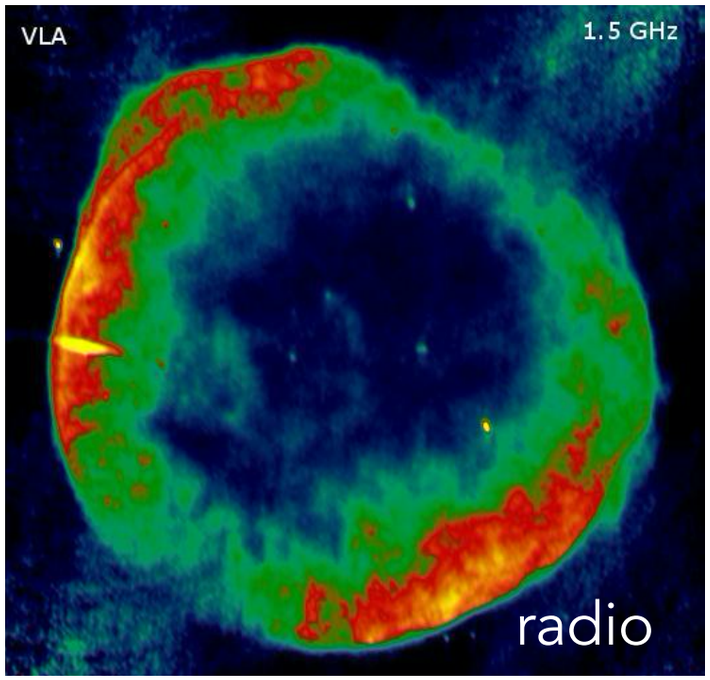
Supernova remnant paradigm

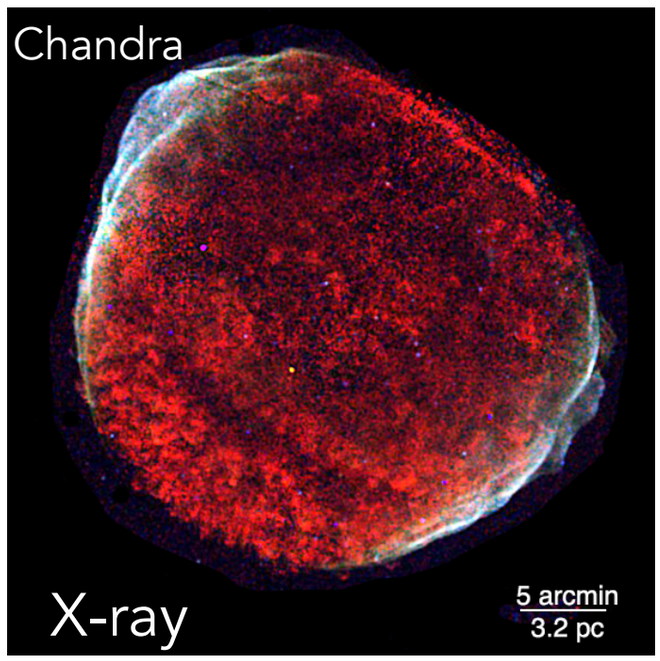


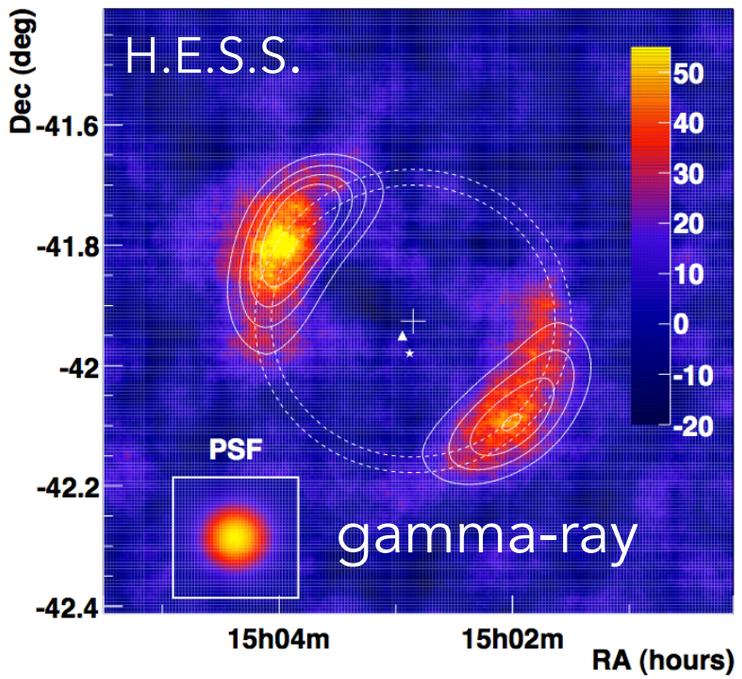


- 2—3 SNe/century
- Explosion energy: 10^{51} erg
- Power: $\dot{E}_{\rm sn} \approx 10^{42}\ {\rm erg\ s^{-1}} \approx 10 \times \dot{E}_{\rm cr}$!

Supernovae vs remnants

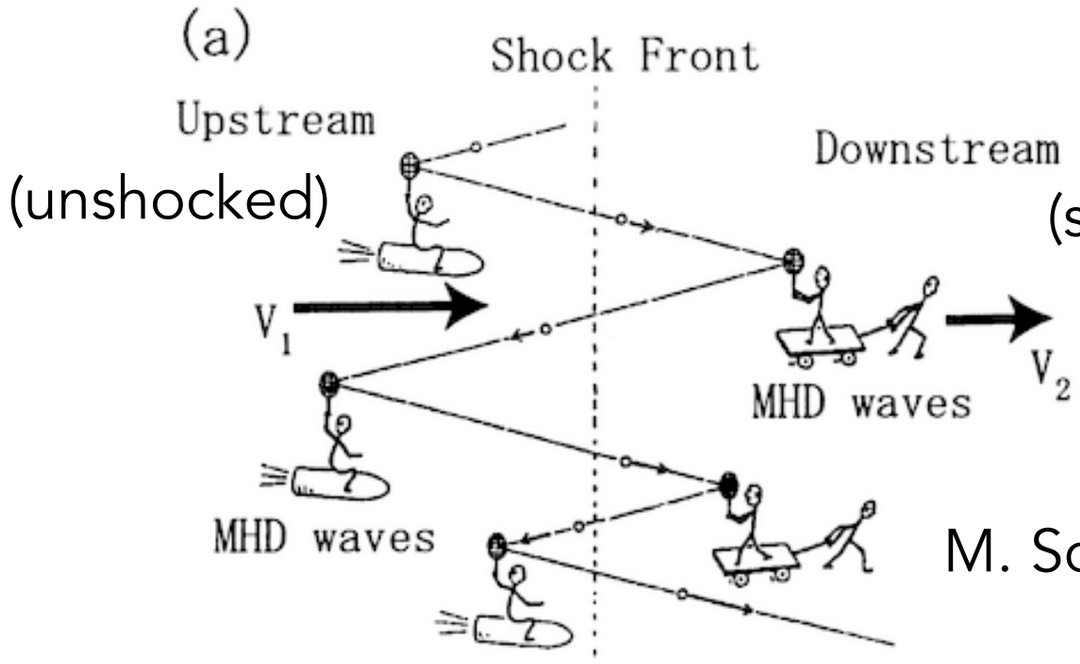






- Supernovae singled out by Baade & Zwicky as srcs of CRs
- Identifying SNRs as sources of synchrotron radiation -> paradigm shift from supernovae to SNRs
- Identifying Fermi shock acceleration in late 1970s as most likely mechanism (diffusive shock acceleration=DSA)
- X-ray synchrotron 1995+: short lived energetic electrons near shocks

Diffusive shock acceleration

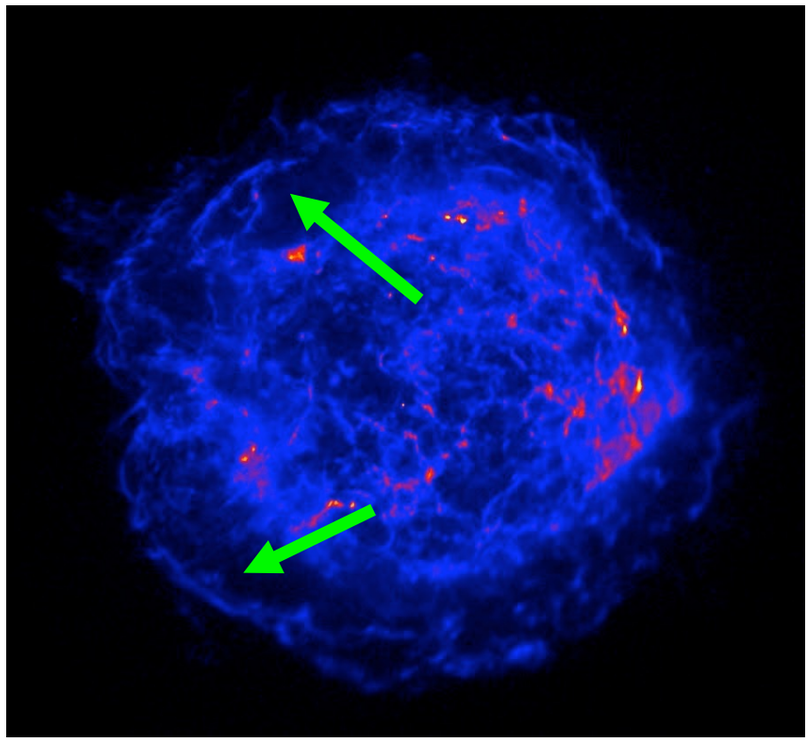


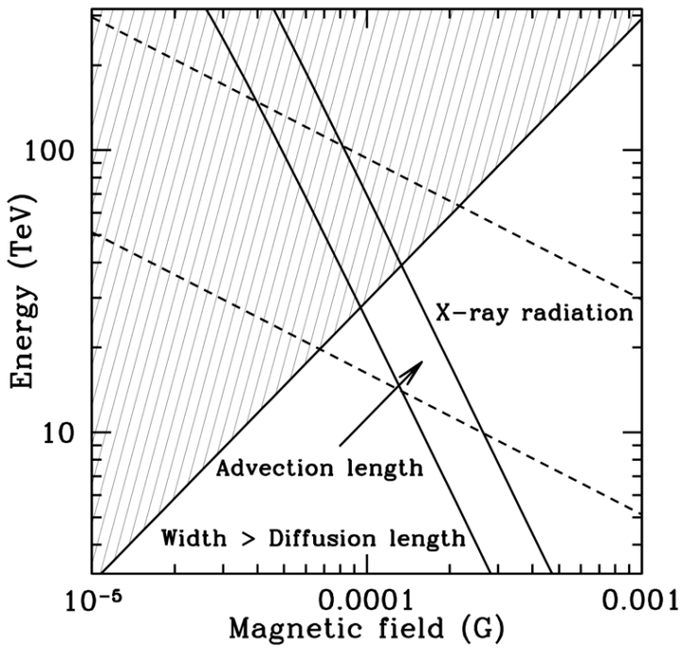
M. Scholer

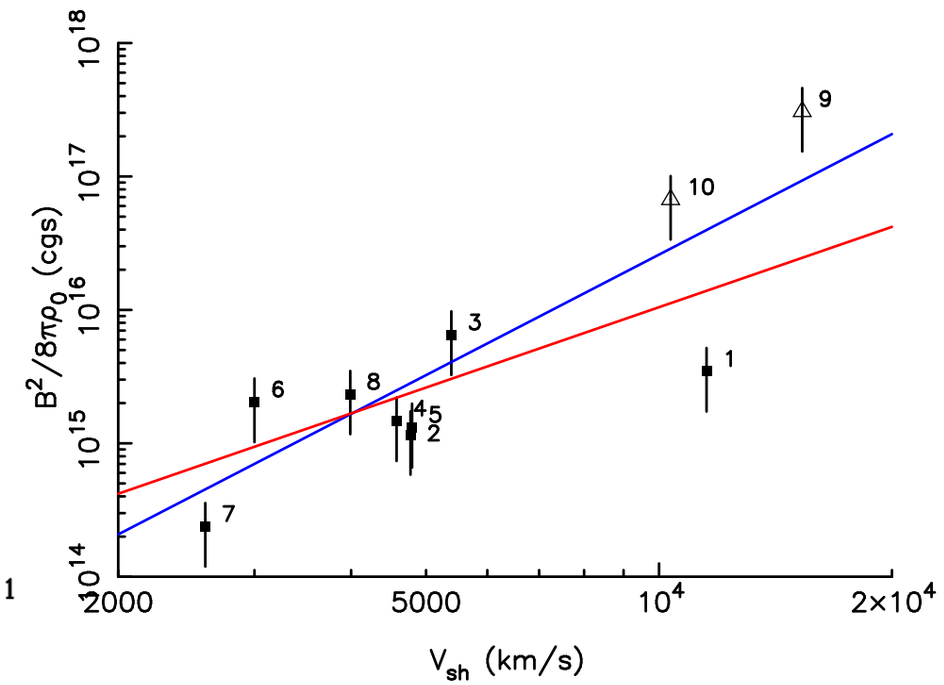
- Particles gain energy by crossing shock:
  - ΔV_{plasma} → Lorentz boost of $\frac{\Delta E}{E} \approx \frac{\Delta V}{c}$
  - Crossing due to diffusion: $D = \frac{1}{3} c \lambda_{\mathrm{mfp}} = \frac{1}{3} \eta \frac{E}{eB}$
  - Acceleration time: $\tau \approx \frac{8 D_0}{V_{\mathrm{s}}^2}$ → $E_{\max} \propto \eta^{-1} B V_{\mathrm{s}}^2 t$
- Higher energy: B high and $\eta \approx 1$

SNRs: *the* sources of cosmic rays?

e.g. Vink & Laming 03





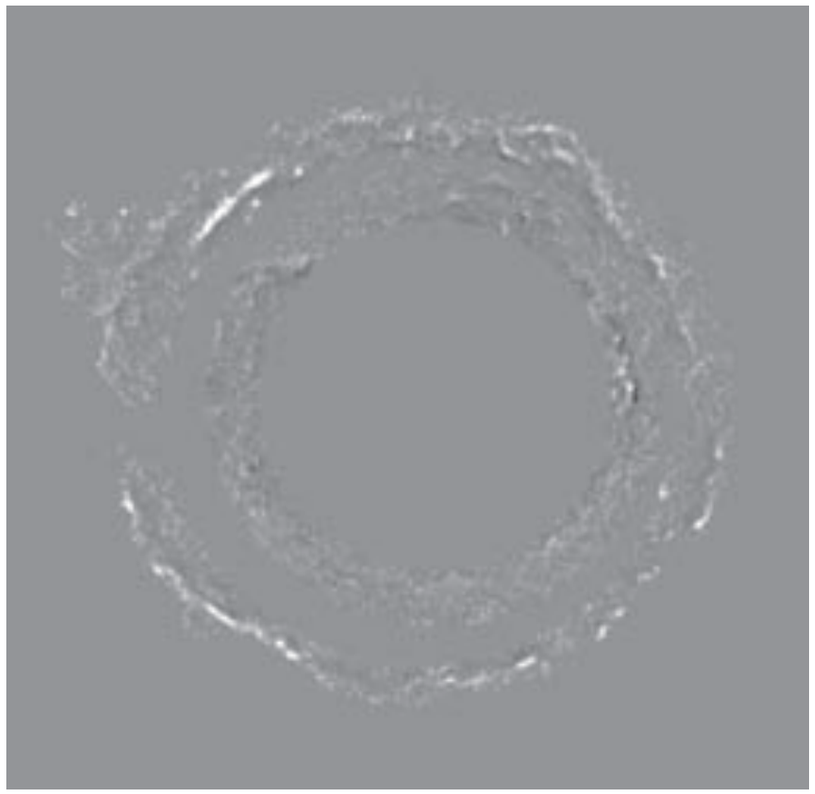


- Narrow X-ray synchrotron filaments: evidence magnetic-field amplification (B~200μG) -> boosts E_{max} !
- X-ray synchrotron requires large B-turbulence/small η

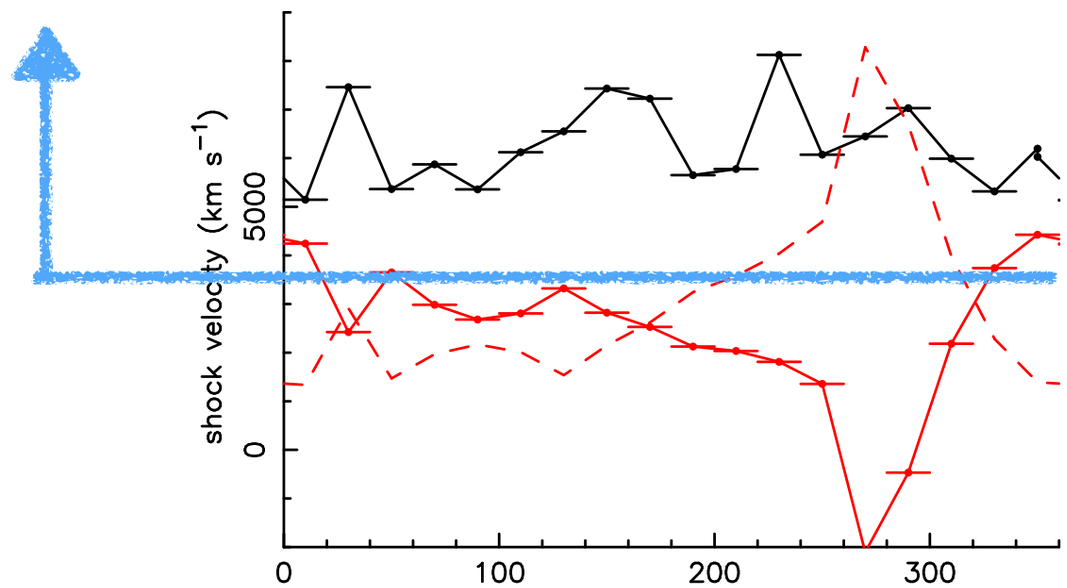
$$h\nu_{\rm cutoff} \approx 3\eta^{-1}\left(\frac{V_{\rm sh}}{5000\ {\rm km/s}}\right)^2\ {\rm keV}$$

- SNRs do better than expected in 1980s!

Evidence for limiting V_s for X-ray synchrotron



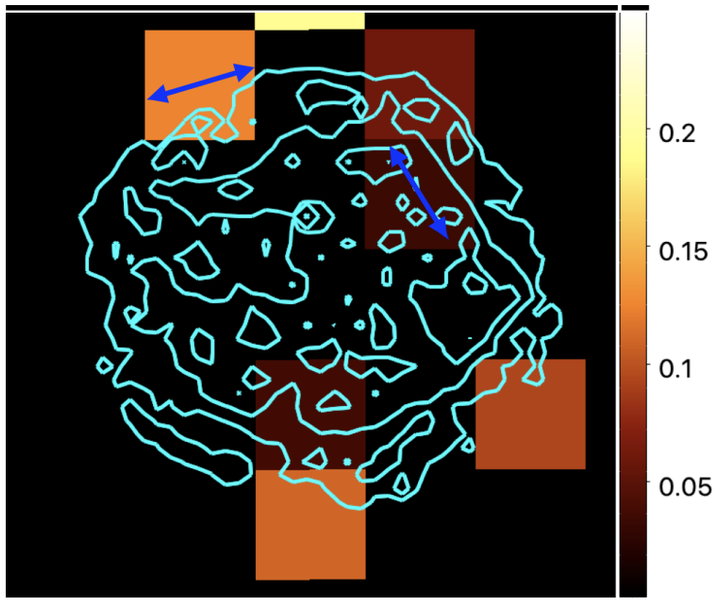
X-ray synchrotron

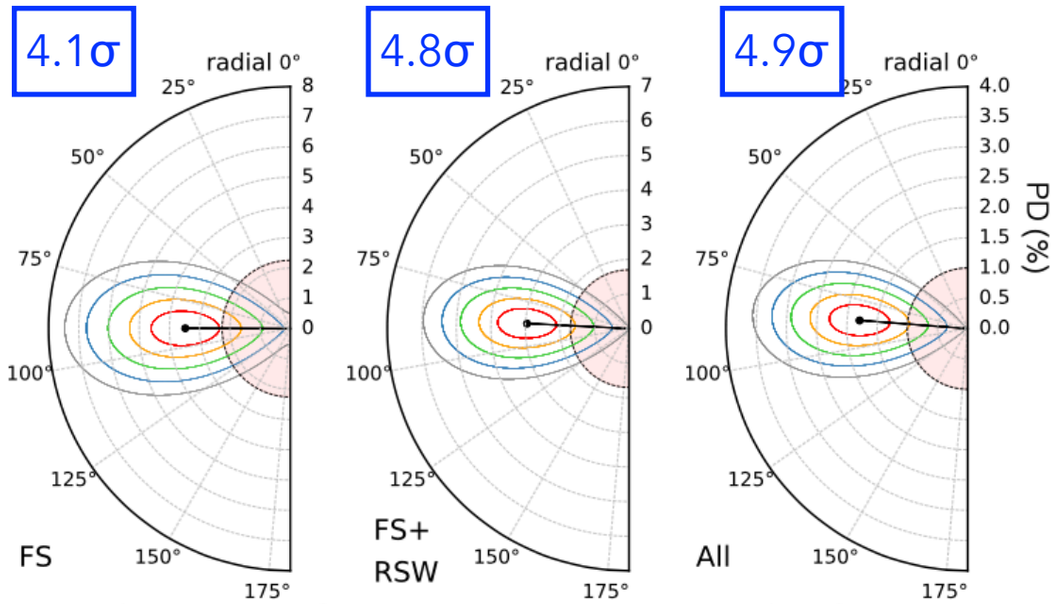


Vink+ 2022

- Proper motion study Cassiopeia A using Chandra
- Observations from 2000-2019 used simultaneously
- Measure Vs *forward* and *reverse* shock
- Reverse shock in West moves back
  - Head on collision with ejecta → V_s>3000km/s
  - Only in West X-ray synchrotron from reverse shock!

Implications of IXPE results Cas A

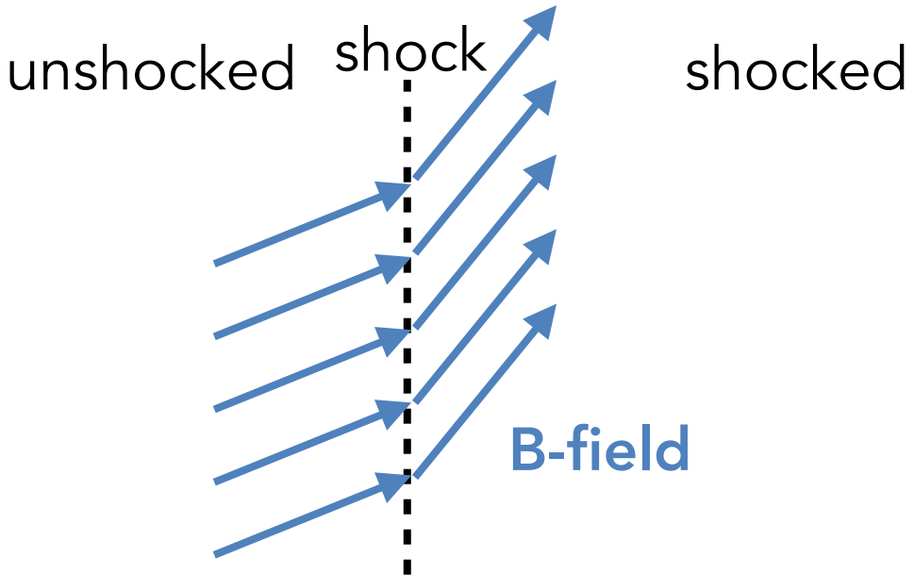


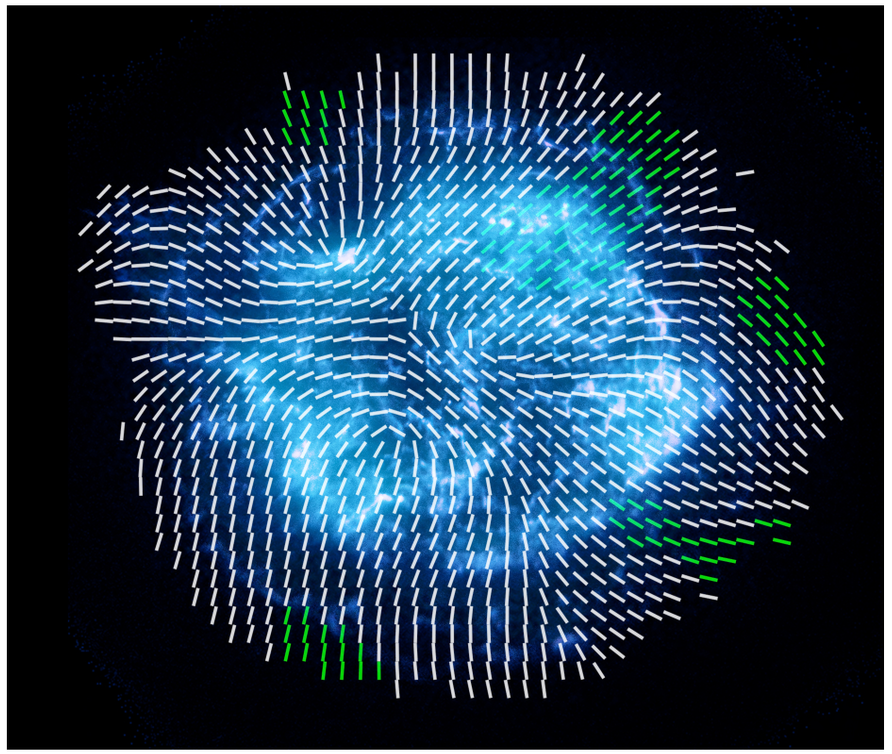


Vink+ 2022b

- X-ray Synchrotron: low pol. fraction <5%
- Implies high B-field turbulent!
- Residual magnetic field is radially aligned

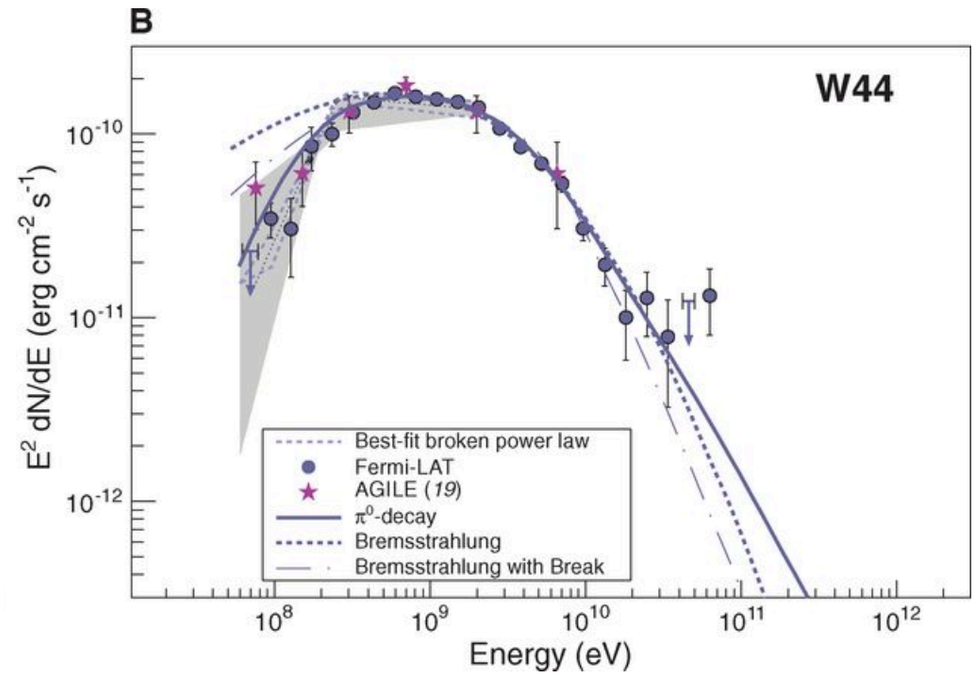
Implications of IXPE results Cas A

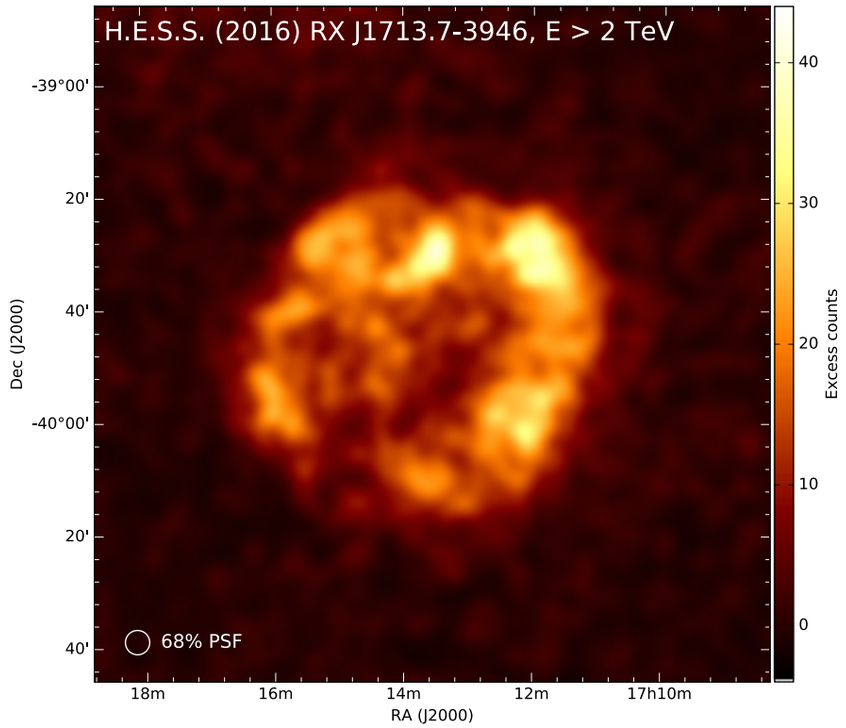




- Theory (Bell B-field amplification, CR resonant turbulence):
  - Isotropy in front of shock (upstream)
  - Behind shock: expect tangential field
- X-ray synchrotron: within 10^{17}cm of shock
- IXPE: need process to change from tangential to radial <10^{17}cm
- Turbulence longest mode < 10^{18}cm -> related to longest Bell mode

SNRs: *the* sources of cosmic rays?

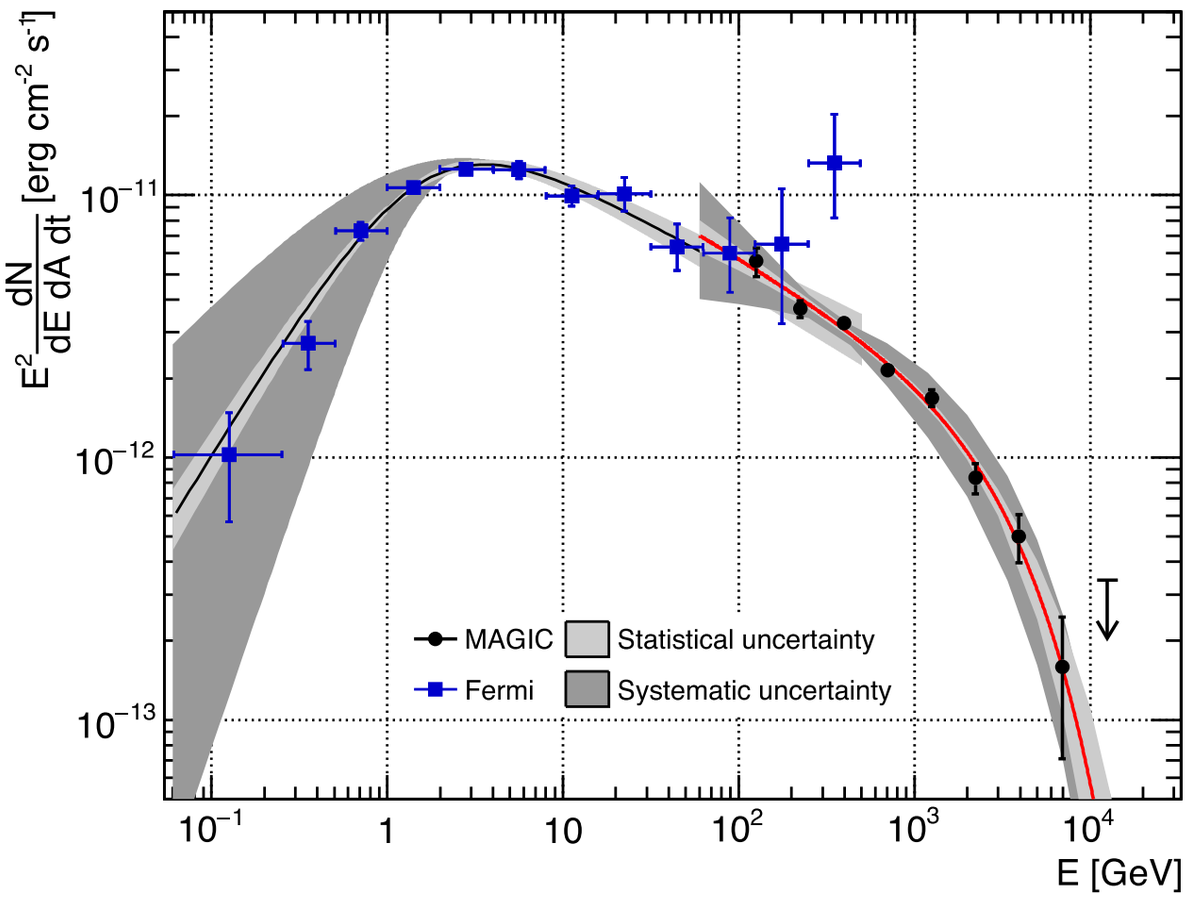


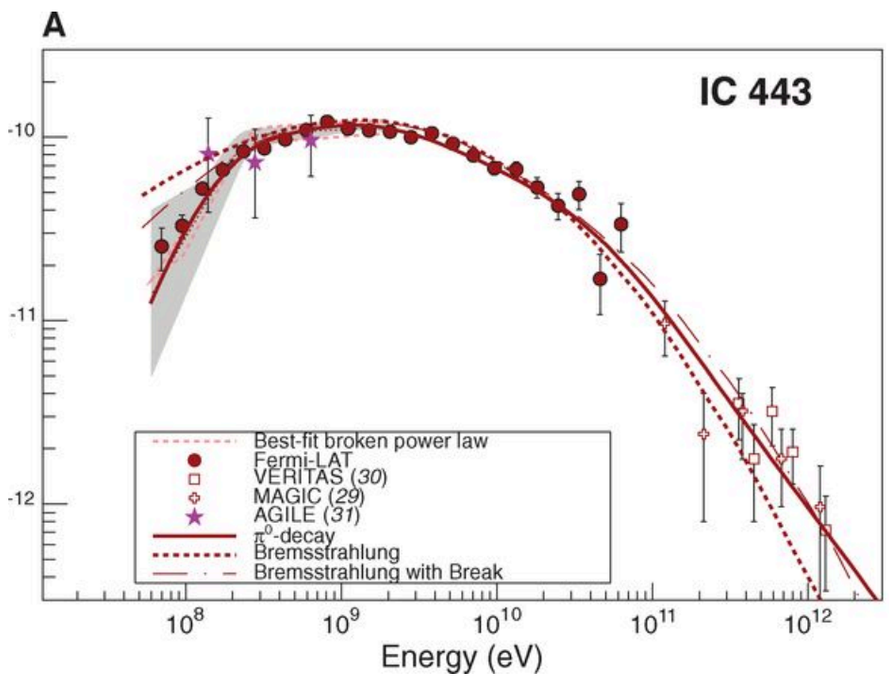


- Many SNRs are found to be gamma-ray sources
- In several SNRs evidence for pion bumps
  - -> hadronic cosmic rays
- Young SNRs have spectra up to 10—100 TeV

But...

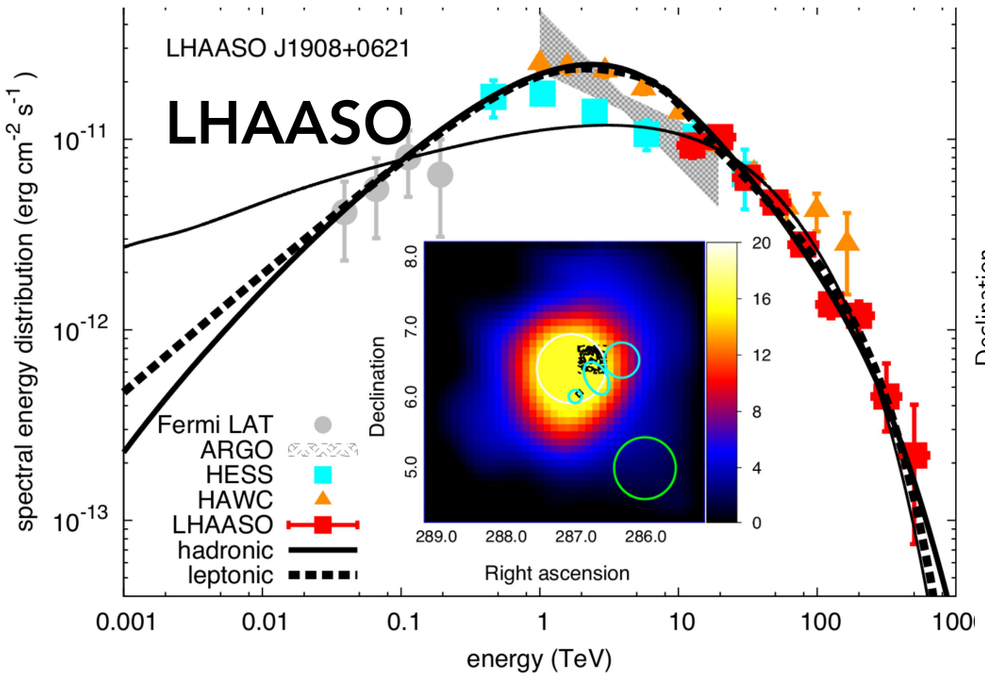
SED Cassiopeia A (MAGIC)

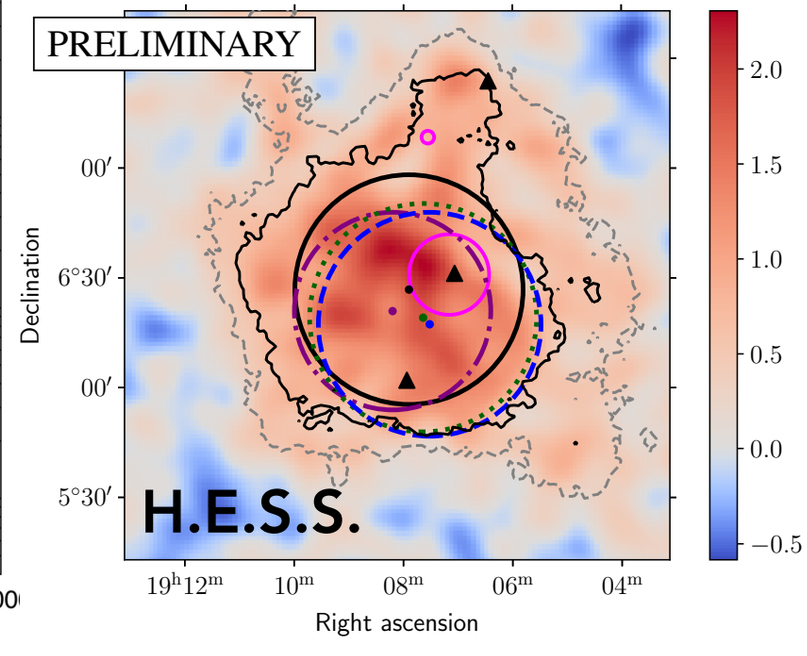




- Young SNR spectra have turnovers < 10 TeV
  - *Young SNRs do not appear to be PeVatrons!*
  - *Also theoretically SNRs are unlikely to be PeVatrons*
- Old SNRs even have turnovers below 100 GeV!

PeVatrons found: what are they?



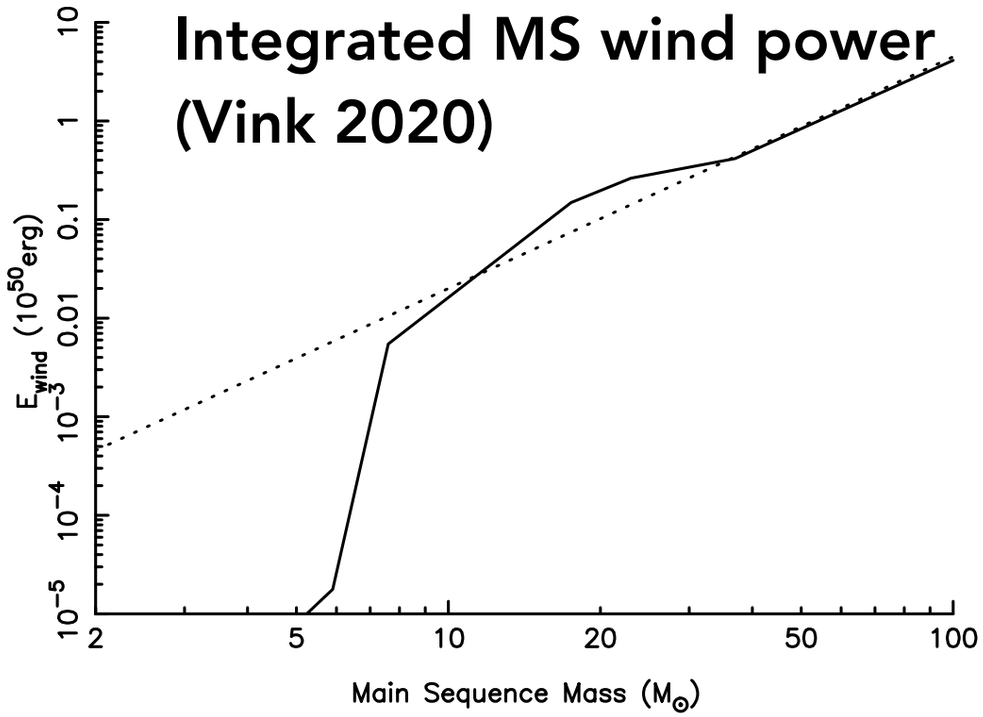


- LHAASO has found Galactic PeVatrons
- But are these sources?
  - Some pulsars (Crab): leptonic?
- PeVatrons identified in gamma-ray tend to “messy”
  - Several candidate sources/starforming regions with lots going on!
  - *But perhaps messiness is not a problem but the answer!*

Alternatives to SNRs as dominant sources of cosmic rays

- Pulsars?
  - yes some are PeVatrons, but leptonic(?)
  - do not provide enough energy
  - Pulsar energy $E_0 = \frac{1}{2} I \Omega^2 \approx 10^{49} \left(\frac{P_0}{50\ \mathrm{ms}} \right)^{-2}\ \mathrm{erg}$
  - Birth rate < SN rate
  - Galactic power: $\dot{E}_{\mathrm{psr,gal}} \lesssim 10^{40} \overline{\left(\frac{P_0}{50\ \mathrm{ms}} \right)^{-2}}\ \mathrm{erg/s}$
  - Insufficient to explain CR energy density

Stellar winds



- MS winds integrated over IMF: $\ll 10^{51} = E_{sn}$
- What about Wolf-Rayet stars?
  - $V_w \approx 2000$ km/s, $\Delta M = 10 M_{sun} \rightarrow E_{wr} \approx 4 \times 10^{50}$erg $\lesssim E_{sn}$
  - Only small fraction of massive stars have WR phase
- NB: WR stars important in *early* phase of starforming regions!
- Could explain some PeVatrons
- Cannot explain Galactic cosmic ray energy density!

Overview of alternatives

Vink 2020

Table 11.1: Powerful Galactic source classes and the total associated mechanical power.

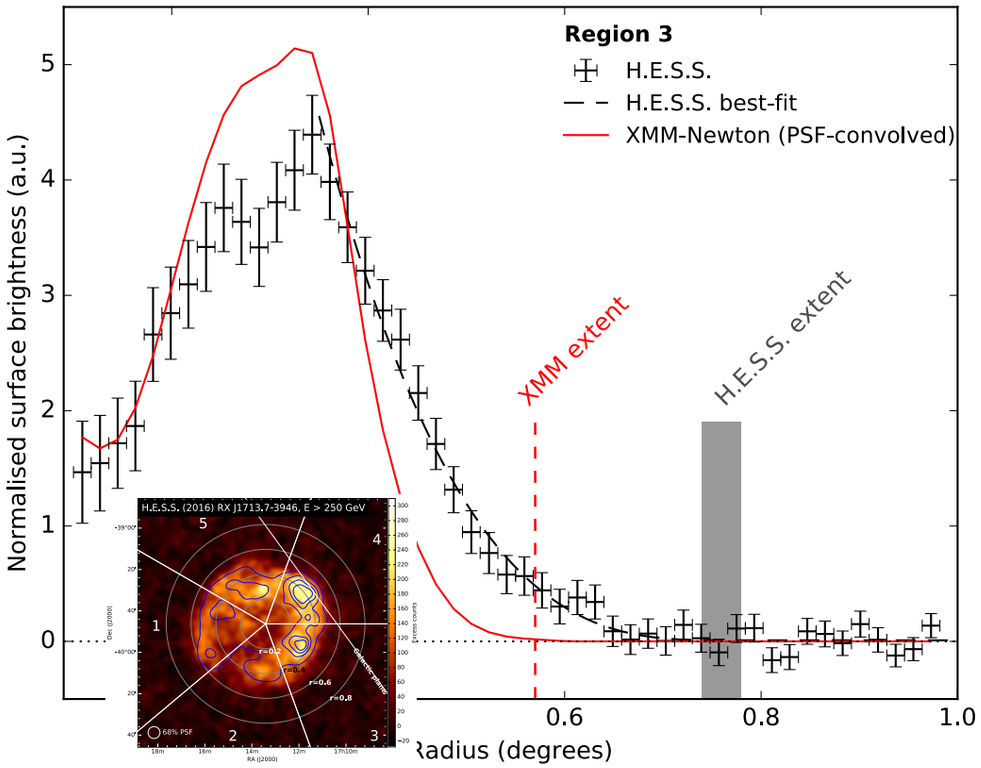
Source type	Energy per source or event (erg)	Frequency (yr^{-1})	Total Galactic Power (erg s^{-1})	Remarks
supernova remnants	10^{51}	$\approx 1/30$	$\approx 10^{42}$	
pulsars	$10^{49}(P/50\,\mathrm{ms})^{-2}$	$< 1/30$	$\lesssim 2\times10^{40}$	Eq. (6.3). e^+/e^- source.
stellar winds	$\approx 2\times10^{49}$	$< 1/30$	$\lesssim 5\times10^{40}$	Sect. 5.8.
superbubbles	10^{51}	$< 1/30$	$\lesssim 10^{42}$	[887]
Novae	$\approx 10^{46}$	≈ 50	$\approx 2\times10^{40}$	[1043]
X-ray binaries/micro-quasars	$< 10^{49}$	$50-200$ sources	$\lesssim 2\times10^{40}$	[347]
Central Black Hole		10^{-4}	$10^{36}-10^{44}$?	[45, 430, 524, 106]

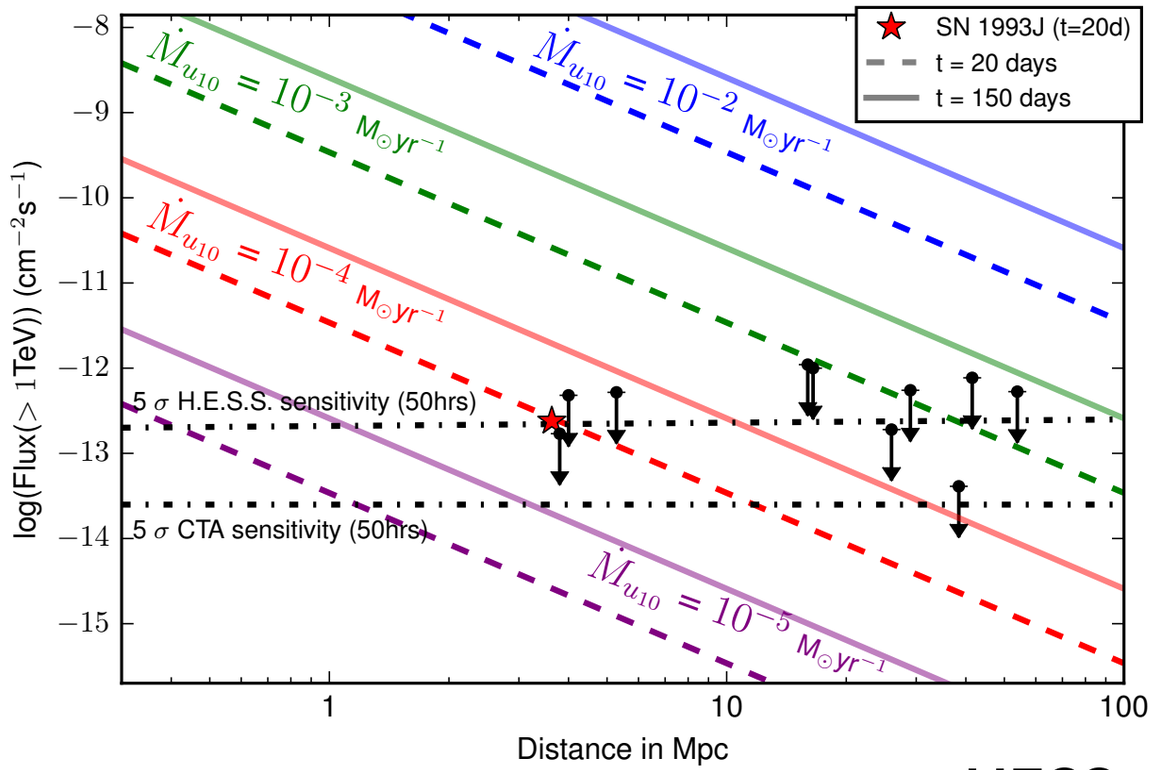
Use supernova power, but when?

- Take away: SNRs may provide bulk of cosmic rays but are not PeVatrons
- Supernova power is sufficient
- CR solutions:
  - Use SN power earliest phase (e.g. Marcowith+ 18)
  - Or use SN collectively (Bykov&Fleishman 92, Parizot ’04)

SN/early SNR phase

HESS+ 2018

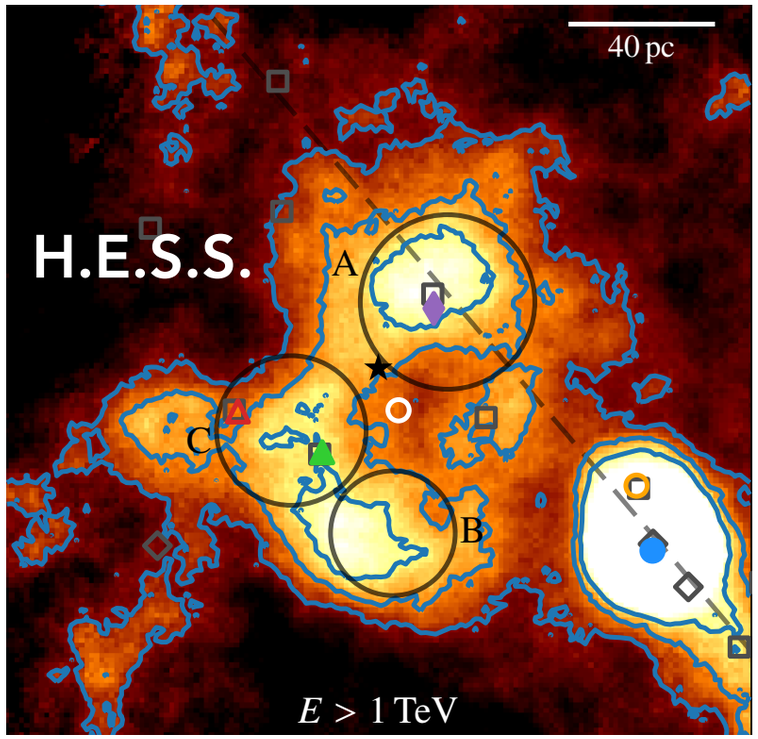




HESS+ 2019

- Escape of CRs important for SNRs
- Perhaps PeV CRs from earliest phase have long escaped?
- Only a subclass of dense wind SN valid:
  - high density early on (seed particles, drives up B)
  - very high speeds ~20,000 km/s
- H.E.S.S. UL in gamma-ray exist
- Need luck and sensitivity -> CTA

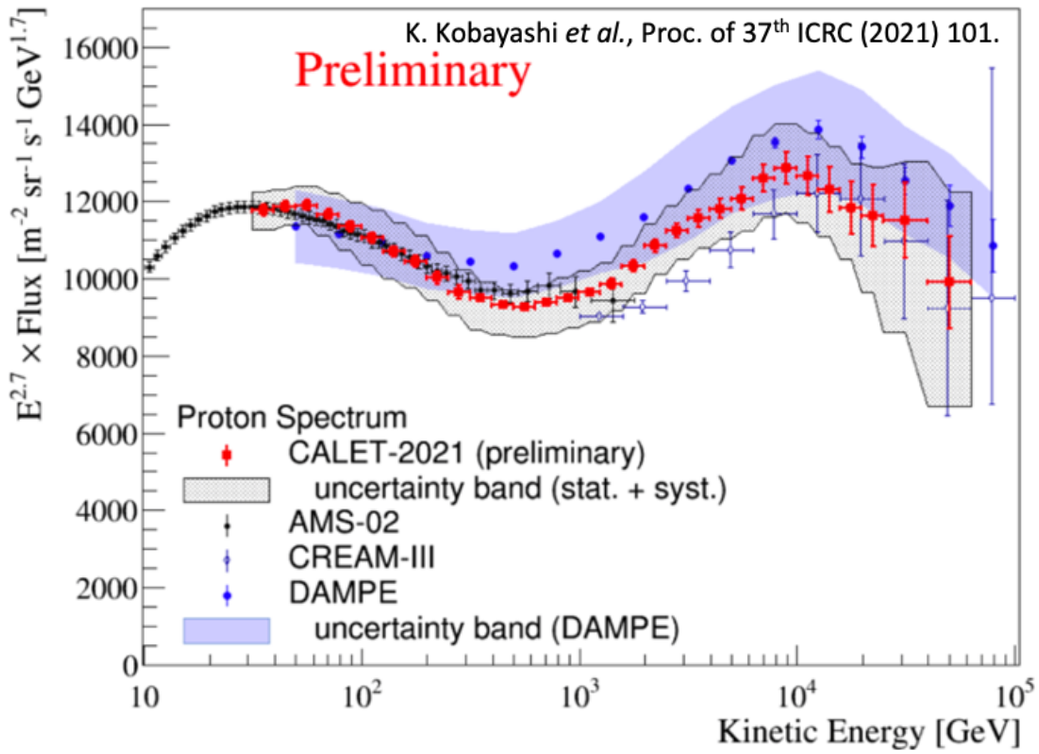
Starforming regions/ superbubbles



Westerlund 1
H.E.S.S.+ 2022 (arXiv:2207.10921)

- Energy source: SN power + stellar winds + pulsars!
- Idea: total is more than sum of its parts!
- Mechanism: power drives turbulence/internal shocks
  - Energy increase: Fermi shock + Fermi turbulent acceleration
  - Acceleration continues for million of year
  - Escape slow: turbulence results in small D
- Idea fits well with recent LHAASO observations and H.E.S.S. observations of e.g. Westerlund 1, HESS J1908
- *Indeed messiness may be the solution not the problem!*

Do SN/SNRs need to be PeVatrons?



See
Talks by R. Parvoli
F. Alemanno

- Search for PeVatrons driven by idea: CR "knee" is maximum proton energy
- New fits to CR data: spectrum is complex: proton spectrum declines above ~10^{13} eV
- Fits well with an overall SNR origin of Galactic CRs up to 10^{13}eV
- There are CRs above 10^{13} eV, but they could be from additional source class (srcs of CR energy≠src of PeV CRs)

Take away points

- Supernovae likely dominant power for Galactic cosmic rays
- SNRs are excellent accelerators but are not PeVatrons
  - That may be okay: proton CR spectrum steepen >1013eV
- Zoom on PeVatrons candidates: they are messy
- Messiness fits with “total>**Σ**” of superbubble model