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# Cosmic-ray acceleration by supernova remnants

Cosmic Rays and Neutrinos in the Multi-Messenger Era APC, 9-13 December 2024

## Supernovae & supernova remnants



- 2-3 SNe/century ( $\Delta t \approx 40$  yr), E=10<sup>51</sup> erg •  $\frac{1}{4} \approx \frac{1}{84} \approx 8 \times 10^{41} \text{ erg s}^{-1} \approx 5\% - 10\% E_{cr}$ *dE dt* ≈ *E* Δ*t*  $\approx 8\times 10^{41}$  erg s<sup>-1</sup>  $\approx 5\%-10\,\%$ ·  $E g s^{-1} \approx 5\% - 10\% E_{cr}$  $J_{11} - 10$ and heat deposition by radioactive decay of freshly synthesised, unstable elements.
- . Power sufficient, but can they accelerate to the "knee"? to a rapid decline in the pressure *P. For an ideal property accelerate to the P. P. F. P. P. P. P. P. P. P. P. P.*
- Mechanism: diffusive shock acceleration mostly by forward shock )





## Diffusive shock acceleration

- Particles interact w. plasma thru magnetic fields
- Particles gain energy by crossing shock:
- $\bullet$   $\Delta V_{plasma}$   $\rightarrow$  Lorentz boost of Δ*E E* ≈
- Diffusion: particles can cross shock  $D =$ *c* 1 3 <sup>IIII</sup><sup>2</sup> 3'<sup>8</sup> 3  $c\lambda_{\rm mfp} =$ 1  $\eta r_{\rm g} =$ 1 *η cE eB*
- Acceleration time:  $\tau_{\text{acc}} \approx \frac{v}{V^2}$  $\tau_{\rm acc} \approx$  $8D_{\rm 0}$ *V*2 s  $E_{\text{max}} \propto \eta^{-1} B V_{\text{s}}^2 t \propto \eta^{-1}$ *Bt* 2*m*−1
	- $R \propto t^m$ , E<sub>max</sub> increases for m>0.5 (Sedov m=0.4) *m*
- Higher energy: keep V<sub>s</sub> for long time (t), strong, turbulent B (  $\eta \approx \left\langle (\delta B/B)^2 \right\rangle^{-1} \approx 1$ ) 2 ⟩ −1  $\approx 1$









- Earliest evidence (50s): radio synchrotron emission (GeV electrons) • 1990s (Koyama+95): X-ray synchrotron (10-100 TeV electrons) • 2000s: gamma-ray emission (Fermi, IACTs) • pion-production and decay → cosmic-ray ions ( $h\nu \sim 0.1 E_{\rm p}$ ) Figure 12.8: X-ray emission from SN 1006 as observed by the *Chandra* ACIS detecthe synchrotron emission (LieV elect channel to 0.85-2 keV, a combination of X-ray synchrotron emission and line emission keV, which is dominated by X-ray synchrotron emission. sion from the young supernova remnant Cas A, with hard X-ray detectors on board the  $C$ ay  $\rightarrow$  cosmic-ray ions  $(h\nu \sim 0$  [*H*<sup> $\prime$ </sup> ].  $\sum_{i=1}^n$  debitties in the nature  $\sum_{i=1}^n$  was some  $\sum_{i=1}^n$
- 
- 
- - inverse Compton scattering → electrons alow-enectrons cosmic-ray spectrom cosmic-ray spectrum  $[1111]$
	- bremsstrahlung → electrons (subdominant) trons (Supuominant) and other young supernova remnants of  $\overline{a}$

### Evidence for cosmic-ray acc. by SNRs *12.2. X-RAY SYNCHROTRON RADIATION* 291

4



## X-ray synchrotron radiation

- Requires >10 TeV electrons: *h<sup>ν</sup>* <sup>≈</sup> <sup>19</sup> (
- $\bullet$  Electrons cool fast:  $\tau_{\rm cool} \approx 12.5$ *B*
	- Acceleration needs to be fast
	-
- Combining acceleration & cooling ( $\tau_{\text{acc}} \approx \tau_{\text{cool}}$ ):  $h\nu_{\text{cutoff}} \approx 1.4\eta^{-1}$





Electrons "out of contact with shock" will not emit X-rays  $\rightarrow$ Narrow X-ray filaments  $\overline{\phantom{0}}$ *V*sh 5000 km/s) 2 keV



### SN1572 (Chandra)

## X-ray synchrotron radiation

- Requires >10 TeV electrons: *h<sup>ν</sup>* <sup>≈</sup> <sup>19</sup> (
- $\bullet$  Electrons cool fast:  $\tau_{\rm cool} \approx 12.5$ *B* 100 *μ*G)
	- Acceleration needs to be fast
	-
- Combining acceleration & cooling ( $\tau_{\text{acc}} \approx \tau_{\text{cool}}$ ):  $h\nu_{\text{cutoff}} \approx 1.4\eta^{-1}$
- X-ray synchrotron: requires  $η ≈ 1$  and  $V_{sh} ≥ 3000$  km/s





Electrons "out of contact with shock" will not emit X-rays  $\rightarrow$ Narrow X-ray filaments  $\overline{\phantom{0}}$ *V*sh 5000 km/s) 2 keV



### SN1572 (Chandra)

## Turbulent, amplified magnetic fields

6  $\overline{\textbf{C}}$ 

$$
\frac{B^2}{8\pi} \propto \rho_0 V^{-3}
$$
  
\n
$$
B \sim 50 \text{ Gauss}
$$
  
\n
$$
B \sim 50 \text{ Gauss}
$$



- All young (<2000 yr) SNRs show evidence for X-ray synchrotron
- - $B_2 \sim 20 500 \,\mu\text{G}$
- Prediction Bell (2004) instability  $U_B =$
- Very early on in stellar wind interaction
	- e.g SN1993J, Fransson&Björnson '98

• Width limitations due to synchrotron cooling:  $B_2 \approx 110 \eta^{1/3} \left( \frac{\Delta T}{10^{17} \text{ cm}} \right)$  uG  $\overline{\phantom{0}}$ Δ*r* 1017 cm)  $-2/3$ *μ*G sity (*B*<sup>2</sup>  $2^{2^{n+1}}$  $\Lambda r$  and  $\sim$ t 107

## X-ray synchrotron radiation from reverse shock



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## X-ray synchrotron radiation from reverse shock



X-ray synchr.

1 arcmin  $1$  pc/3.3 ly

# reverse shock

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### X-ray synchrotron radiation from reverse shock The Astrophysical Journal, 802:15 (110), 2015 March 2015 March 2015 March 2015 March 2015 March 2016 March 201

NuStar Grefenstette +15

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Figure 2. Deconvolved NuSTAR images of Cas A: red (15–20 keV), green reverse shock X-ray synchr. reverse shock

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Figure 6 shows a comparison between the radio (6 cm Vink+ 2022Figure 4. Residual in a Residual in the masked of the masked data in the masked data in the masked of the masked data in the ma





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- Reverse shocks moves back in western part • Rev. shock velocities peak there: 7000-8000 km/s  $\bullet$  Rayarea chacke mayae hack in we the remnant when seen in projection on the sky and "central" remnant when seen in projection on the sky. We also adopt a Fig. 4. Same image as Fig. 1 but now with a spider diagram
- Rev. has high B-field despite low ejecta field -> very efficient amplification  $\bullet\,$  kev. has nigh B-field despite low spite low elec
- Rev. shock may be important for accelerating dust or high metal plasmas under the Boundary of the monormant for be linearly extended regions of emission.

**NuStar** Grefenstette +15

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 $rn<sub>na</sub>$ e low ejecta field -> very efficient amplification ≡ substantial ly different (Figure 7). The outer filaments in t intant for accelerating dust or nigh metal plasmas up the southwestern jet, whereas the northeastern jet encounin western part  $u + h \sim r \sim 7000$  and  $h \sim l \sim$ all individual models for each sector. The grayscales for both residuals in the grayscales for both residuals in a vack in western part sition angle. For the forward shock (green) the radial extent of the spider diagram is linearly proportional to the expansion rate. For the reverse show of  $\sigma$  and  $\sigma$ expansion relative to the dashed circle–inside the circle i ferent epochs. We illustrate this by showing in Fig. 3 also *|V*rs*,*ef*|* =  $\overline{\phantom{a}}$  *R*rs *<sup>t</sup> dR*rs  $\sim$   $\sim$   $\sim$   $\sim$  *,* (7) with *t* the age of the SNR.

# Synchrotron radiation polarization

Synchrotron

Radiation emitted from any part of trajectory



• B-orientation perpendicular to EM E-vector

 $\, {\bf B} \,$ 

Electron with acceleration  $\underline{\mathbf{a}}$  ( $\perp$  to  $\underline{\mathbf{B}}$ ), velocity  $\underline{\mathbf{v}}$ , pitch angle  $\alpha$  (not shown) 田  $\sim \gamma^{-1} \, \mathrm{rad}$ Polarisation To observer



# Synchrotron radiation polarization

Synchrotron

Radiation emitted from any part of trajectory



• B-orientation perpendicular to EM E-vector

 $\, {\bf B} \,$ 





### intrinsically ~70% polarized



- X-ray synchrotron → requires turbulent magnetic fields!  $\mathsf{A} \vee \mathsf{S}$  radio  $\mathsf{A} \rightarrow \mathsf{A}$  requires turbulent maquetic tield  $\mathsf{A}$ SNR Cas A at 32 GHz; *right* SNR CTB1 at 10.55 GHz (courtesy of W. Reich)
	- Theory: CR resonant perturbations + Bell (2004) instability (upstream) • Isotropic B (?) authors proposed that the observed RM pattern is the imprint of an azimuthal magnetic magnetic magnetic magnetic
- Downstream: expect tangential field
- Radio observations: young SNRs have radial B-fields, old SNRs tangential  $\mathbf{a}$ and Owservatio
	- Magnetic fields radially stretched in young SNRs, but where? minimize the effects mentioned above, the observed degree of polarization in SNRs

## **Magnetic field configuration**



## Measuring B-field orientations in X-rays with IXPE



### Once constructed and environmentally tested, the DUs and the DSU were ready for X-ray calibration (DUs integrated with the DSU are referred to as the Instrument 11. (Instrument 11.) Each DU, including both the flight and spar



- **Imaging X-ray Polarimetry Explorer (IXPE) launched Dec. 9 2021** electronics and the S/C computer.
- Carries 3 gas-pixel detectors comprehensive calibration to characterize the response to both polarized and unpolarized radiation and to measure the  $s_{\rm B}$  and, timing performance. The DUS were also integrated to the DSU and illuminated with  $\sim$
- Uses photo-electron direction to measure B-field EM wave
- Effective energy range: 2-7 keV Calibration of flight units started with DU1 on September 6th, 2019, continued with DU2 and ended with DU3 on  $\epsilon \in V$  $\sim$

to test the operation of the Instrument in the flight configuration. These activities required equipment to generate X-rays  $m \sim n$  moodcure.  $R$  field  $EN$  wough sources specifically designed and built in Italy for this purpose.





### $I\!\!\times$ PE Statistical maps  $(\chi_2^2)$ 2



- ~4-5σ detection of polarization
- correct for thermal contributions
- Cas A: only after some tricks:
	- entire SNR only
	- 5% pol. degree
		- high downstream turbulence





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## X-ray polarization overview

- Radial vs tangential: age (or B-field?) dependence in X-rays • hydrodynamic instabilities close to shock? (Inoue+ '13)
- pol. frac. low (5-10%)/high B turbulence
- -
	- lack of theory regarding downstreem turbulence

Note: turbulence must be high enough to allow X-ray synchrotron (i.e.  $\eta \approx 1$ ) • But: low B: long cooling time -> may affect volume of X-ray emission region







## Gamma rays



- In 2 decades big jump in knowledge:
	- GeV gamma rays: Fermi-LAT, Agile
	- TeV gamma rays: H.E.S.S., Veritas, MAGIC
	- TeV-PeV gamma rays: HAWC, LHAASO
- Wide-field Gamma-ray Observatory (SWGO), upgrades LHAASO



• In the future: Cherenkov Telescope Array Observatory (CTAO), Southern





## SNRs in gamma rays

• Not always clear whether leptonic or hadronic (or combination) e Low R-field (<30 G): likely leptonic data points. The input particle spectral index is *q* = 2*.*4. On the left a model domia Gaussian function of width 0.08. The width 0.08. The Galactic plane; the inset shows the PSF of the analysis at the analysis at the position of the PSF of the Analysis at the analysis at the PSF of the analysis at the an same scale for comparison. *Right*: same as in the left panel, but additionally the boundary of the ON region is shown as a white circle and the significance contours at 3, 5, 7, 9, and 11 are shown in black with increasing line width for increasing significance. In addition, X-ray contours from the ROSAT All Sky Survey for energies larger than 1.3 keV are shown in red. The X-ray data were smoothed in the same way as the -ray  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  at 25, 50, 75, 30, 75, 30, 30, 75, and 100 counts. The position of posit



*12.3. GAMMA-RAYS OBSERVATIONS* 309







Fig. 1. *Left*: exposure-corrected excess map for RX J0852.04622. The data were binned in bins of 0.01 on each coordinate and smoothed with

### $\Gamma$  , spectral energy distribution of  $\Gamma$  , see also  $\Gamma$ c or hadronic (or compination)

## Some "mature" SNRs (≳104 yr)

- Clear pion bumps
	- →Hadronic gamma rays
- Proton cutoffs 20—200 GeV
- Highest energy CRs must have escaped by t~10,000 yr
- Direct evidence for escape:
	- W28: nearby TeV source associated with MC
	- RX J1713: evidence for TeV gamma-rays outside X-ray **boundary**





### Ackermann+ '13 (Fermi-LAT)

Supernova W44 & IC 443 Neutral Pion Decay Spectral Fit







### Escape of cosmic rays from RX J1713? H.E.S.S. Collaboration: Observations of RX J1713.73946



- Escape: CRs diffuse ahead with  $\Delta r \gtrsim 0.1r$  (no longer in acc. process) Fig. 1. H.E.S.S. gamma-ray excess count images of RX J1713.73946, corrected for the reconstruction acceptance. On the *left*, the image is made  $\blacksquare$  Fronno: CRc diffuso obond u the angular resolution. Both images are smoothed with a two-dimensional Gaussian of width 0.03, i.e. smaller than the 68% containment radius
- RX J1713: measured 13% -> evidence for escape  $\overline{N}$  and  $\overline{N}$  and  $\overline{N}$  are indicated by the mages. The indicated by the indicated by the images.  $\bullet$  RX  $\bullet$  in integration is  $\sim$  -
	- Diffusion inferrence: *B η* Diffusion inferrence:  $\frac{1}{n} \approx 1.1$ *E*
		- suggest low B, or sudden dying down of turbulence (η»1) Year Mean o↵set1 Mean zenith angle Livetime 2009 10.74 51 3000

$$
\frac{E}{10 \text{ TeV}} \bigg) \left( \frac{\Delta t}{500 \text{ yr}} \right) \left( \frac{\Delta r}{pc} \right)^{-2} \left[ 1 + \frac{u_{\text{shock}} \Delta t}{\Delta r} \right]^{-1} \mu \text{G}
$$
ng down of turbulence (η»1)



- γ-rays: unresolved **• V-rays: unresolved**
- Inferred proton cutoff: E<sub>c</sub>≈3 TeV (MAGIC '17;Veritas '20) fitting the MAGIC spectrum with equation (1). The black solid line is the bla **•** Interred proton cuto

 $s$  is a periodic to be below the below  $\mathcal{L}(s)$ 



# The puzzle of gamma rays from Cas A



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- $\overline{\phantom{a}}$

17  $\overline{17}$  $\frac{1}{2}$  contribution comes down to  $33$ 

### The puzzle of gamma rays from Cas A 1098 HELDER & VINCENT WAS ARREsted at the second series of the second series of the series of th



X-ray spectral index map (Helder&JV '08)

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• most hadronic  $\gamma$  rays from reverse shock region (dense!) with  $V_s \sim 1500$ -8000 km/s • in addition: most hadrons are not protons: Cas A oxygen dominated!; CSM: He/N! mated source spectrum. This does not produce a simple shift of the shock region (densel) with V. Even in the unlikely scenario in which, through the 158 h of obre not protons: Cas A oxvgen dominate  $15$  per cent relative to the MC, by applying the  $\sim$  $B$ the procedure description in Vincent Control in Vietname and the results are shown in Vietname and the results image next to the Chandra image smoothed to roughly the same  $ROMkm/c$  $\boldsymbol{\theta}$ CSM: He/N! thermal flux above 4 keVof 2:7 ; 10 erg s 2:7 ; 10



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- $\overline{\phantom{a}}$
- CTAO/future: reveal a forward shock component to higher energies d*E* = *N*<sup>0</sup> ! *E E*<sup>0</sup> 0/future *E*c  $\mathsf{d}$

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## A peculiar SNR N132D (LMC)

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- Powerful SNR (E~5x10<sup>51</sup> erg) evolving in windblown cavity  $\begin{array}{ccc} \begin{array}{ccc} \begin{array}{ccc} \end{array} & \begin{array}{ccc} \end{array} & \end{array} & \begin{array}{ccc} \end{array} & \begin{array}{ccc} \end{array} & \end{array} & \begin{array}{ccc} \end{array} & \begin{array}{ccc} \end{array} & \begin{array}{ccc} \end{array} & \end{array}$  $O$ wertul SNR (F~5x10<sup>51</sup> erg below 1 Tev for an die 15
- Oxygen-rich: "older version" of Cas A, t~2500 yr Ixyden-rich: Older version  $\overline{\phantom{a}}$
- Interacting with molecular cloud in SW itaracting with molecular c neerdeemig with molecular e  $\overline{a}$   $\overline{a}$ rather large offset, for which the acceptance is reduced compared
- H.E.S.S. (2021): no need for cutoff ( $E_c = 19^{+60}_{-10}$  TeV, not significant)  $\mathbf{F} \cap \mathbf{F}$  for the observations presented here, only about 5% of  $\mathbf{F}$ the data were data were the full contact th mance depends on the zenith angle, configuration cuts, and the
- Proton cutoff ~120 TeV idtuil cutuil
- Older than Cas A, but cutoff (if any) at much higher energy! *2.2. Data set: LMC survey 2.3. H.E.S.S. data analysis*

pointings were mostly directed toward N157B in the Tarantula  $\Omega$  of  $\Omega$  ac  $\Delta$  +  $\sim$  2500  $\mu$ r UI COUT, L'EUUU JI 13. The observations are thus taken at

 $_{-10}^{+60}$  TeV  $\sim$   $\sim$  00  $\sim$   $\sim$  00  $\sim$ cutaff  $IF$   $-$  10<sup>+00</sup> TaV no CULUII  $L_c = 17^{10}$  TeV, TO  $\overline{\phantom{a}}$  $\text{H}:\mathbb{R} \to \mathbb{R}$ **FICANT**)



Table 1. Spectral fit parameters for the H.E.S.S. and *Fermi*-LAT plus H.E.S.S. data sets.

*Fermi*-LAT + H.E.S.S ECPL 6.4/5 2.08 ± 0.06 12.3 ± 2.9 *E*<sup>c</sup> = 19<sup>+</sup><sup>60</sup>

Notes. PL stands for "power law", ECPL for "power law with an exponential cutoff", and "BPL" for "broken power law" (see text for details).



### 30 Dor C in LMC: an SNR in a superbubble specific and generic properties. Given a population of ultrarelativistic electrons and positive the PWN luminosity is determined by the strength of the magnetic field and the g-ray luminosity by the









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• H.E.S.S. (2015,2024): detection of a source next to SN1987A: 30DorC • Powered by LH 90 stellar cluster  $\blacksquare$ , integrated above an energy show the maps show the maps show the maps show the  $\blacksquare$  $\blacksquare$  index  $\blacksquare$ . Index and  $\blacksquare$  . Index applied. (a) Entire emission. (b)  $\blacktriangle$  (b) −1 in panel. Oroi (2010/2021). H.E.S. observation at allegeductes aetection of a st signal cluster LATdata and spectral modeling, see S1.2 and S1.3.



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	- Powered by LH 90 stellar cluster H.E.S. observation at allegeductes signal cluster
		- X-rays: big (r≈47pc) round shell emitting X-ray synchrotron (W part)  $X$ -ravs: Dig (r $\approx$ 4/D)  $\ddotsc$ lence, whereas the leptonic scenario requires the
		- requires V> 3000 km/s: much higher than superbubbles (~50 km/s)  $\blacksquare$ **P26 in tedulies v-ray luminosity** m/c: much high/ particle acceleration by a very large, fast-expanding
		- requires SNR with t≈6000 yr expanding in low density n<sub>H</sub>≈5x10-4cm-<sup>3</sup> energy of 0.5 TeV, the integrated luminosities are *L<sup>g</sup>* » 30 Dor C **•** requires SNR with t ably, the luminosity of Westerlund 1 above values exceeding the luminosity of Westerlund 1 above 2 above 2 abov shell. This may provide the right conditions for  $\sim$  6000  $\mu$  vrotons to energies the contract of energy expressed  $\approx$  0000 yr expan
		- long acceleration time → could potentially be a PeVatron!  $\overline{\phantom{a}}$ for Galactic CRs. These observations, therefore,  $ma \rightarrow$  could not thus superbubbles provide tions for particle acceleration to very high energies,

urce riext to arv  $0.71.20\Omega_{\odot}$ 70 / A. JUDOIU

### 30 Dor C in LMC: an SNR in a superbubble specific and generic properties. Given a population of ultrarelativistic electrons and positive the PWN luminosity is determined by the strength of the magnetic field and the g-ray luminosity by the

 $\sim V$  ray cunchro ly A-lay sylichio itself, a PWN, or the numerous supernovae that  $\alpha$ explored in the control internal intervals in Because a large fraction of supernovae are thought to go off in superbubbles, this first unambiguous ing in Jaw danci have broad implications for the circumstances in which a large fraction of CRS are accelerated. 71 I L  $\sim$   $\sim$   $\Lambda$  $\Lambda$ JII (VV NAIL) tion for the Crab nebula is very different from  $\Omega$  150 km/s of N 157B harder (G<sup>e</sup> = 2.0 versus 2.35), exhibiting a lower cut-off energy (Ec = 100 TeV versus 3.5 PeV),  $b \sim h \sqrt{11-4}$ cm-3  $\overline{a}$  independent  $\overline{b}$ particles or magnetic fields. The remainder of the  $\mathsf{tron} \hspace{.01in} \blacksquare$ electrons with energies ≤400 GeV that radiate at



- H.E.S.S. (2015,2024): detection of a source next to SN1987A: 30DorC  $\blacksquare$ , integrated above an energy show the maps show the maps show the maps show the  $\blacksquare$  $\blacksquare$  index  $\blacksquare$ . Index and  $\blacksquare$  . Index applied. (a) Entire emission. (b)  $\blacktriangle$  (b) −1 in panel. Oroi (2010/2021). aetection of a st
	- Powered by LH 90 stellar cluster H.E.S. observation at allegeductes signal cursion
		- X-rays: big (r≈47pc) round  $\frac{1}{2}$   $\frac{1}{4.0}$   $\frac{1}{1}$  $X$ -ravs: Dig (r $\approx$ 4/D)
		- $\blacksquare$ **P26 in tedulies v-ray luminosity** energy of 0.5 TeV, the integrated luminosities are *L<sup>g</sup>* » 30 Dor C
		- **•** requires SNR with t ably, the luminosity of Westerlund 1 above values exceeding the luminosity of Westerlund 1 above 2 above 2 abov
		- long acceleration time + 5 3.0  $\overline{\phantom{a}}$

### 30 Dor C in LMC: an SNR in a superbubble two extreme PWNe and to disentent objectspecific and generic properties. Given a population of ultrarelativistic electrons and positive the PWN and positive luminosity is determined by the strength of the magnetic field and the g-ray luminosity by the g-ray luminosity by the g-ray luminosity by the g-ray luminosity intensity of radiation fields, which serve as tar-

hadronic scenario requires locations with high densities and a high degree of magnetic turbulence, whereas the leptonic scenario requires the stellar cluster to be extremely rarified. Moreover, the g-ray and x-ray observations suggest active particle acceleration by a very large, fast-expanding shell. This may provide the right conditions for accelerating some protons to energies exceeding 3 × 1015 eV, which is the maximum energy detected for Galactic CRs. These observations, therefore, lend support to the view expressed in (29, 34, 35) that superbubbles may provide the right conditions for particle acceleration to very high energies, because they are thought to contain very turbulent

urce riext to arv  $0.71.20\Omega_{\odot}$ 70 / A. JUDOIU  $\mathcal{L} = \mathcal{L} = \mathcal$ ction of a source next to SNT987,

 $\blacksquare$ 



object to 30 Dor C is the stellar cluster Westerlund

index of the pulsar and only relies on the



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	- leptonic and a hadronic model (see Appendix C for details). For the hadronic case, we find spectral indices of the

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## Can SNRs be PeVatrons

- In general not PeVatrons:
	- Not observationally (at best  $E_{max}$ ~100 TeV)
	- SNRs V<5000 km/s, B~10 μG, 1000 yr:

 $E_{\rm max} \approx 3 \times 10^{14} \eta^{-1}$  $\overline{\phantom{0}}$ *B*0 10 *μ*G) (

- But some hope: special cases (1% of SNe, see Giacinti talk)
	- long t → 30DorC in superbubble?
	- - example: SN 1993J (B~50 Gauss, V~20000 km/s)
- Observationally: target young extragalactic SNe in dense CSM

### *V*s 5000 km/s) 2  $\overline{\phantom{0}}$ *t* <sup>500</sup> yr) eV

• high  $B \to Cas A$  (now >100 µG) at t=1-30 yr (B amplified,  $V_{s-}$ 10000 km/s)



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	- - example: SN 1993J (B~50 Gauss, V~20000 km/s) U KM/SI hare considered to the 50 h H.E.S.S.S. sensitivity, '2  $\sim$ (Aharonian et al. 2006), bearing in mind the exposure times.
- Observationally: target young extragalactic SNe in dense CSM Parameters are chosen as described in Sect. 3.1, with *q*↵ corre $s_{\rm in}$  dependent  $\mathcal{C}\mathcal{C}N$ time delay since the SN explosion are considered: *t* = 150 days





## Take away points

- SNRs are not generally PeVatrons
	- But some may be (when very young and/or in special environments)
- X-ray synchrotron to study DSA properties:
	- X-ray synchrotron constrains diffusion: close to Bohm for E~10-100 TeV • Clear evidence for B-field amplification (and  $B^2 \propto \sim \rho V^3$ )
	-
	- IXPE: young SNRs radial & turbulent magnetic fields
- Gamma-rays
	- Evidence for particles up to 100 TeV in young SNRs
	- Mature SNRs: >1 TeV particles have escaped
	- Direct evidence for escaping cosmic rays
- Future:
	- Very young SNRs (SNe in dense CSM)
	- Look for SNR haloes of escaping CRs
	- Details in gamma-ray spectrum due to composition Fig. 1. H.E.S.S. gamma-ray excess count images of RX J1713.73946, corrected for the reconstruction acceptance. On the *left*, the image is made

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