MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Maximum energy in SNR shocks

HONEST Workshop 29.11 - 01.12
PeV sources and their environments

Brian Reville

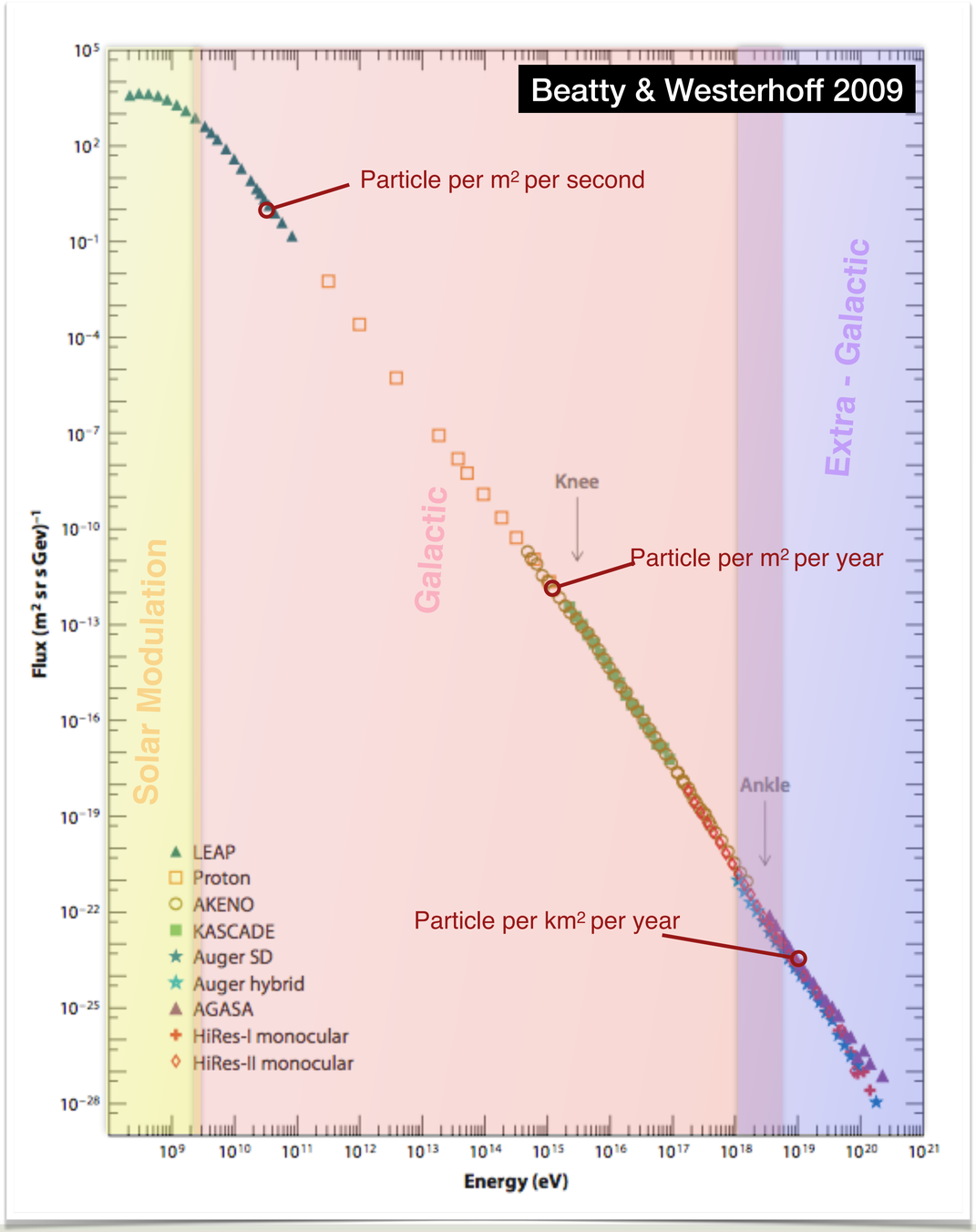
Work done in collaboration with T. Vieu, G. Giacinti, T. Bell, J. Kirk, L. Härer, J. Hinton, L. Mohrmann, F. Aharonian

The PeV CR problem…

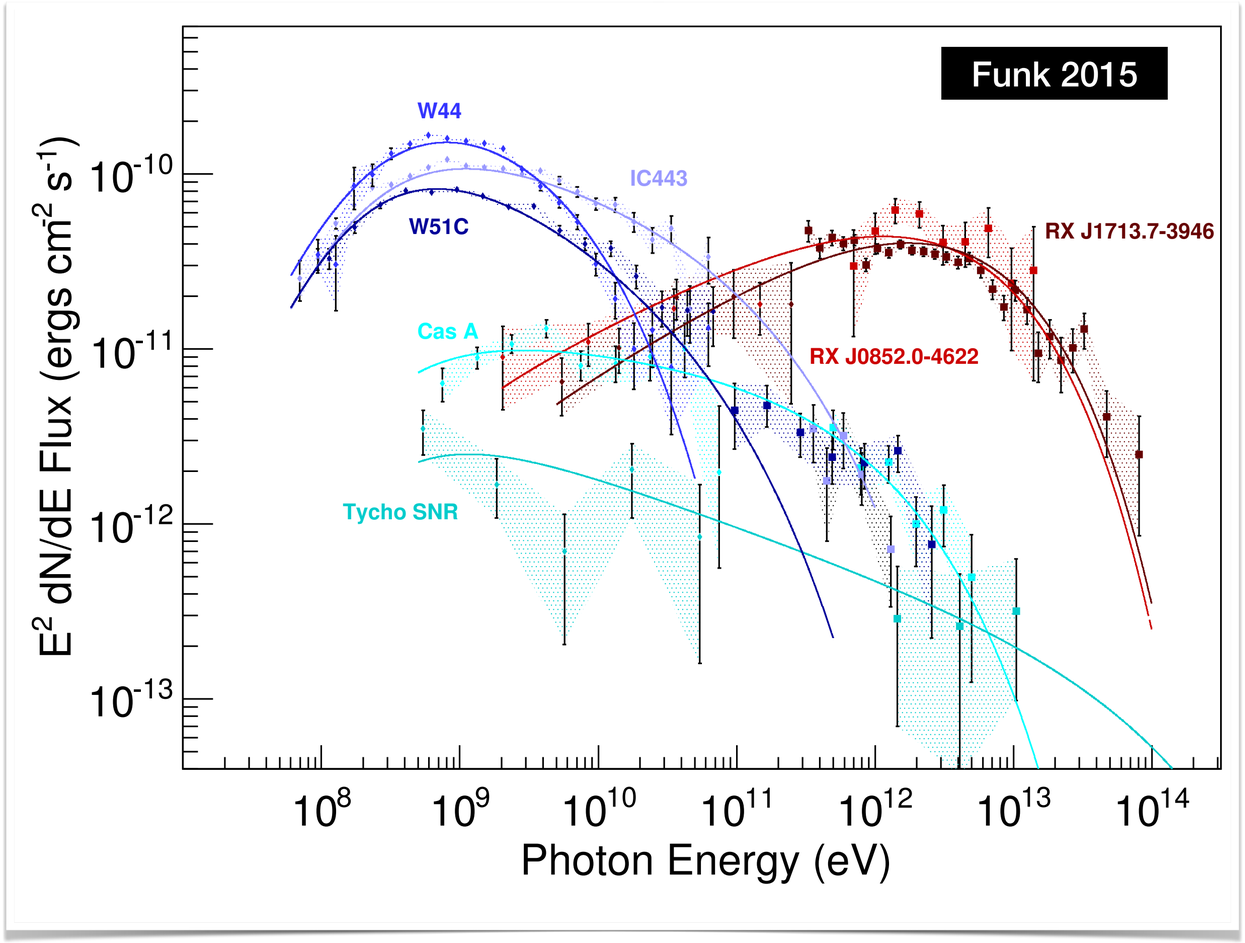
- The knee implies an intrinsic upper limit to the primary class of galactic CR accelerators
- SNRs are the principal suspects
- DSA remains the mechanism of choice, but it appears rather special conditions are needed to accelerate >PeV
- DSA determined by rigidity, i.e.

$$E_{\max}(^{26}\mathrm{Fe}) \approx 26 E_{\max}(^{1}\mathrm{H})$$

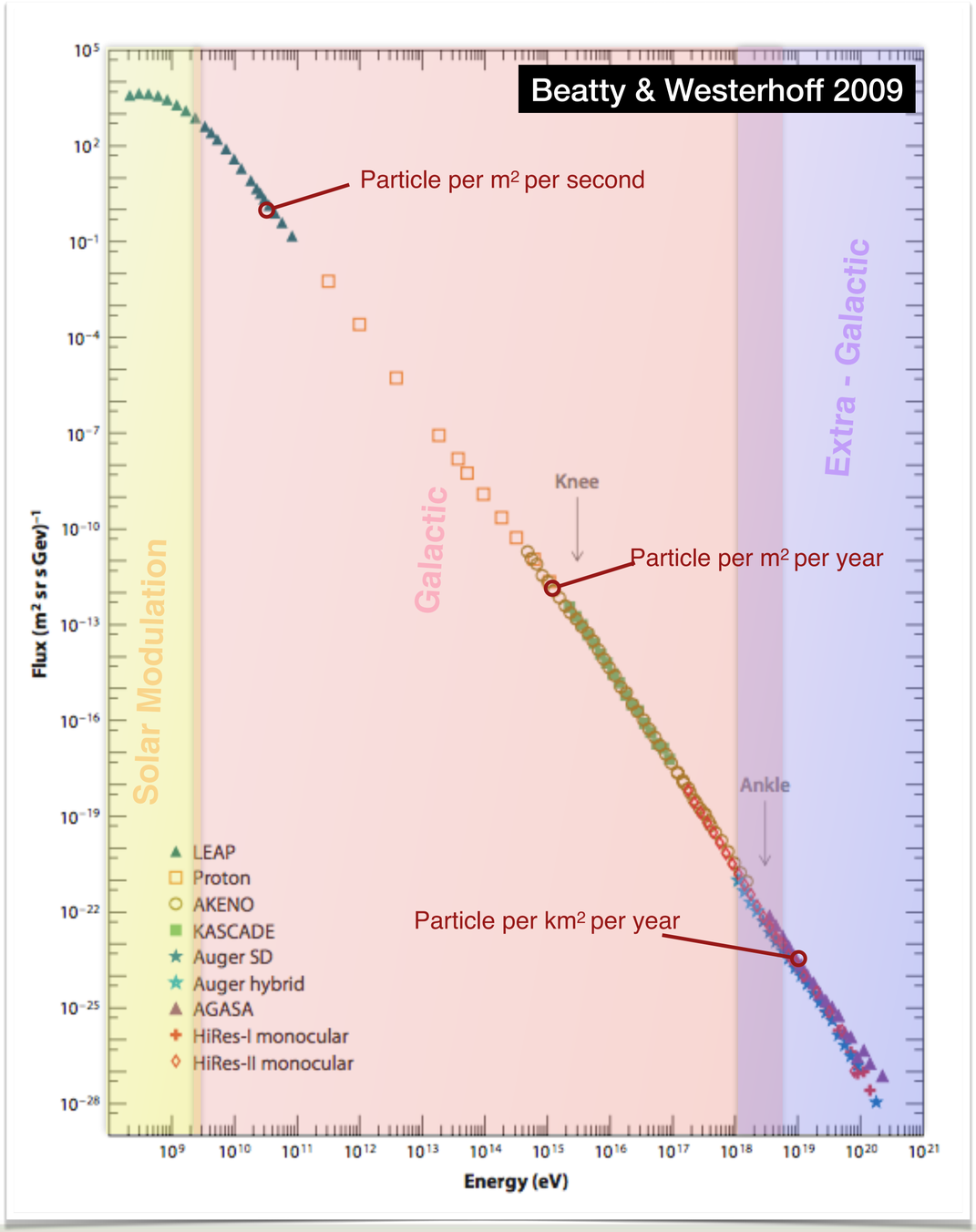
- Energy distributed over all nucleons (Kafexhiu et al. ’14, Breuhaus et al. ’22)



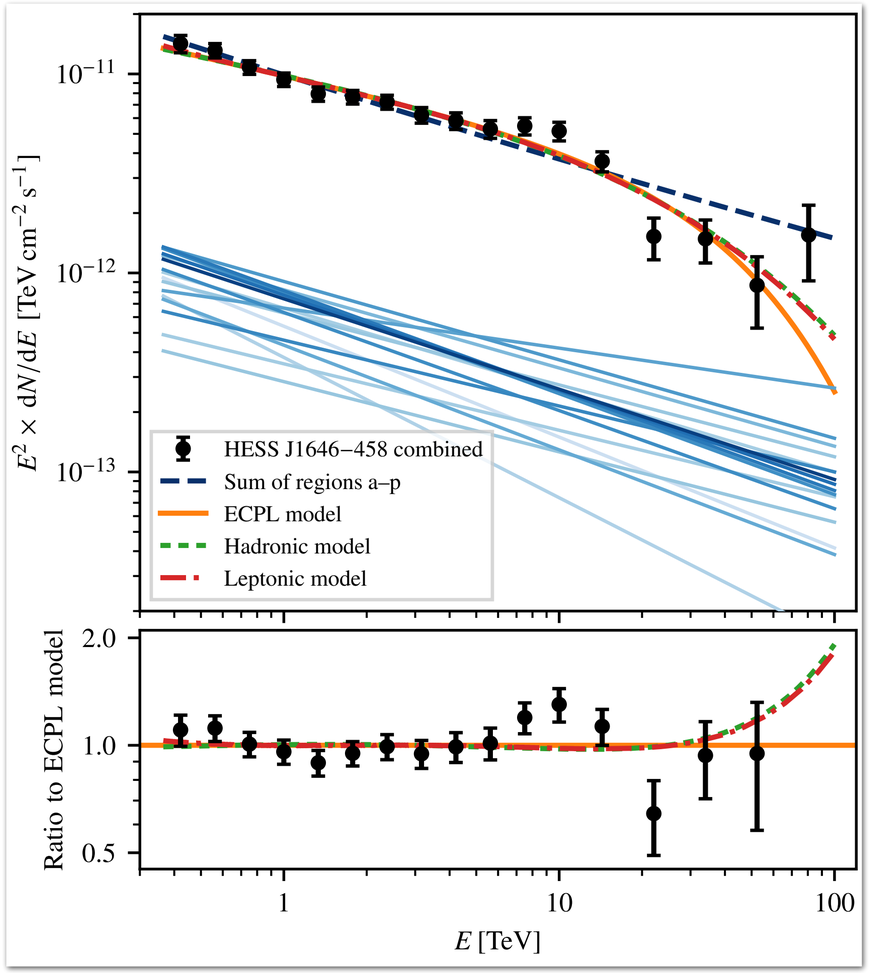
The PeV CR problem…

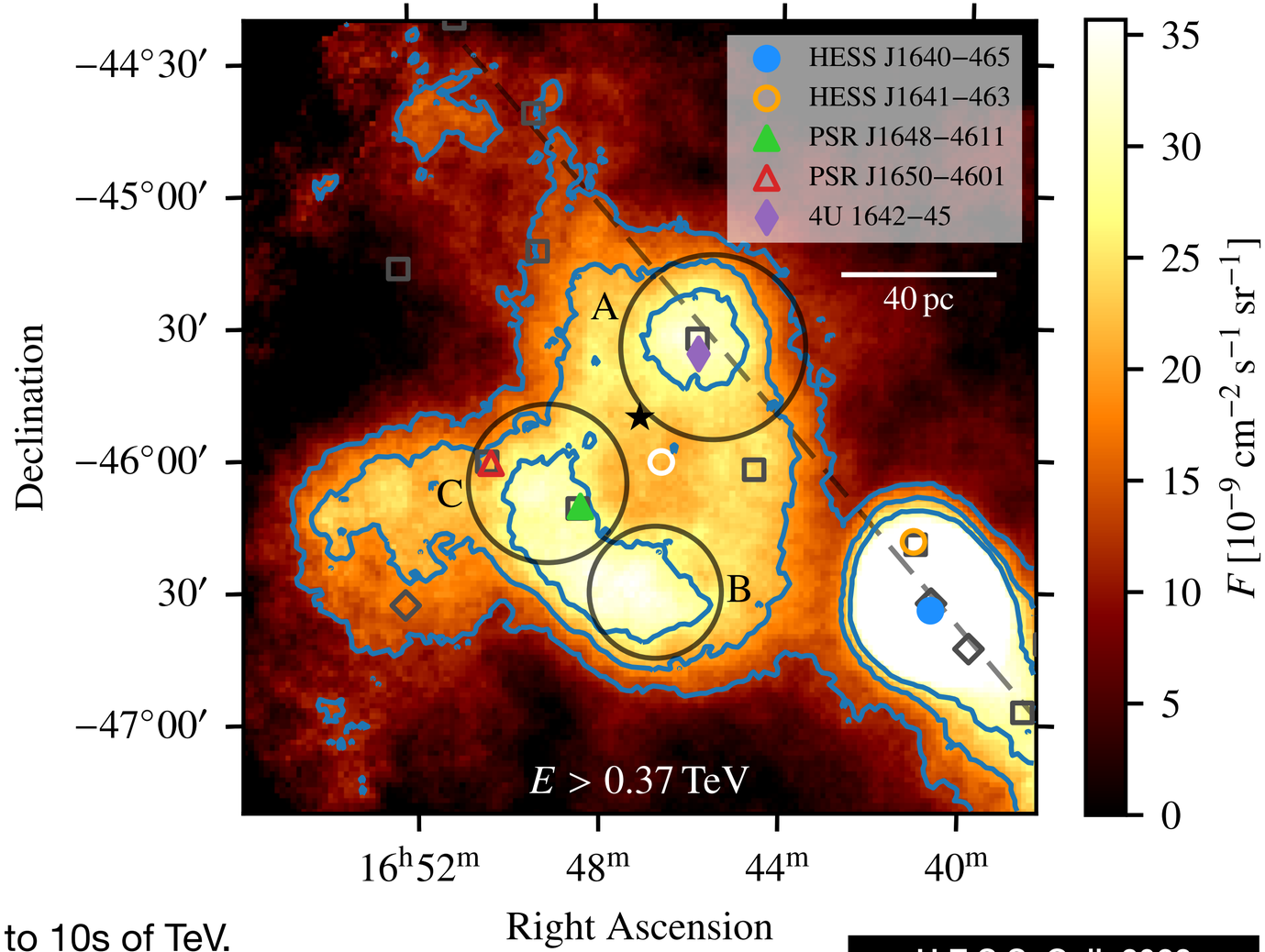


Gamma-ray SNR observations are a powerful constraint



Hard >10 TeV Galactic sources I - Wd1

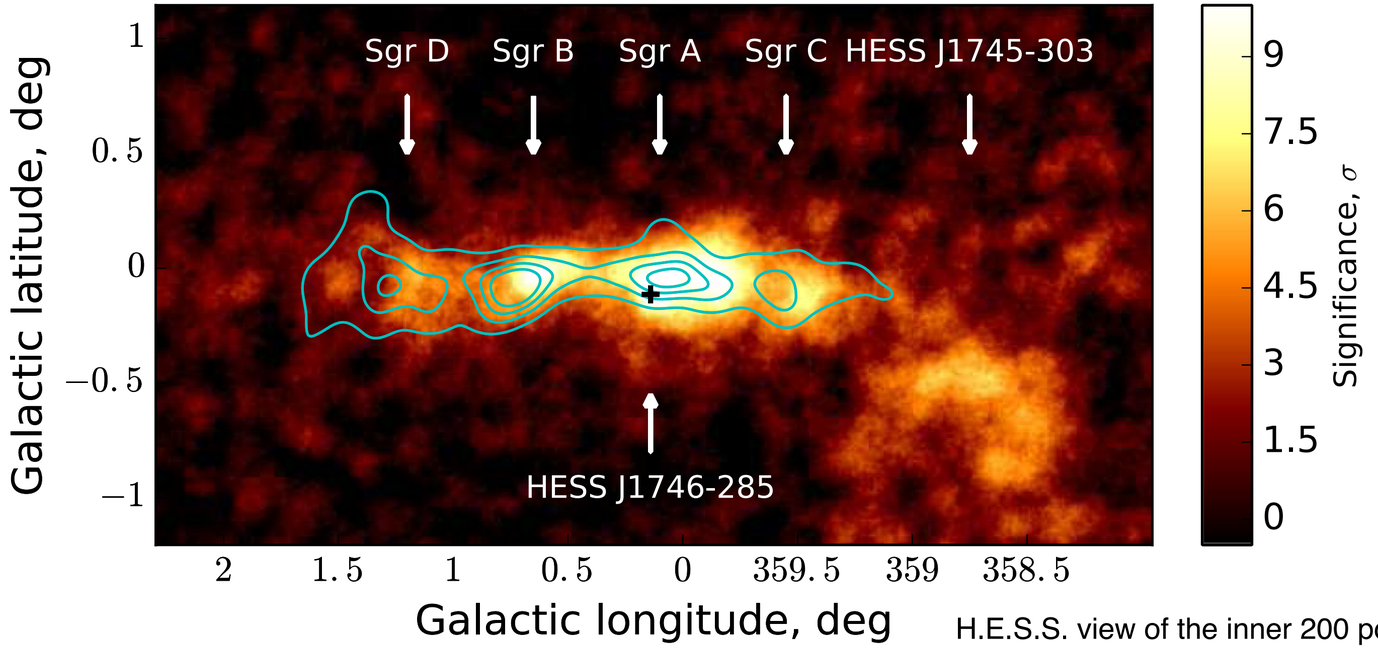




Gamma-ray spectrum extends (with power-law index 2.4) to 10s of TeV.
Particles acceleration to at least several 100TeV occurring

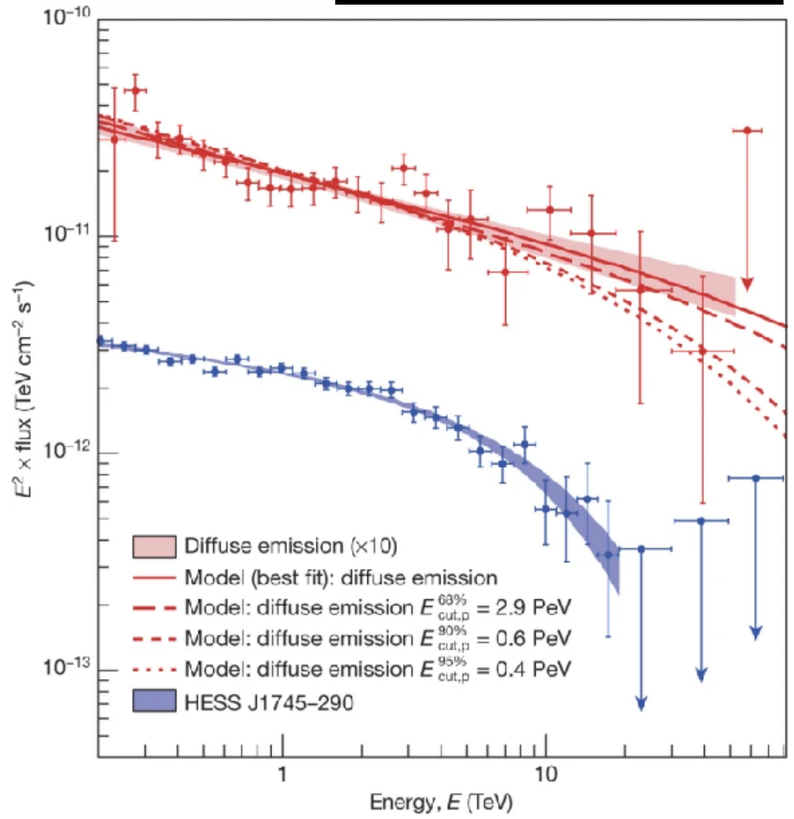
H.E.S.S. Coll. 2022

Hard >10 TeV Galactic sources II - GC



H.E.S.S. view of the inner 200 pc - A&A 2018

H.E.S.S. Coll. 2006



Diffuse emission from Galactic Centre is consistent with a power law (harder than local CR spectrum)

No clear high-energy turnover

GC hosts millions of stars, Red Giants, WRs, OB etc. a unique environment for SNR explosions

New possibilities with UHE gamma-rays

Article | Published: 17 May 2021

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

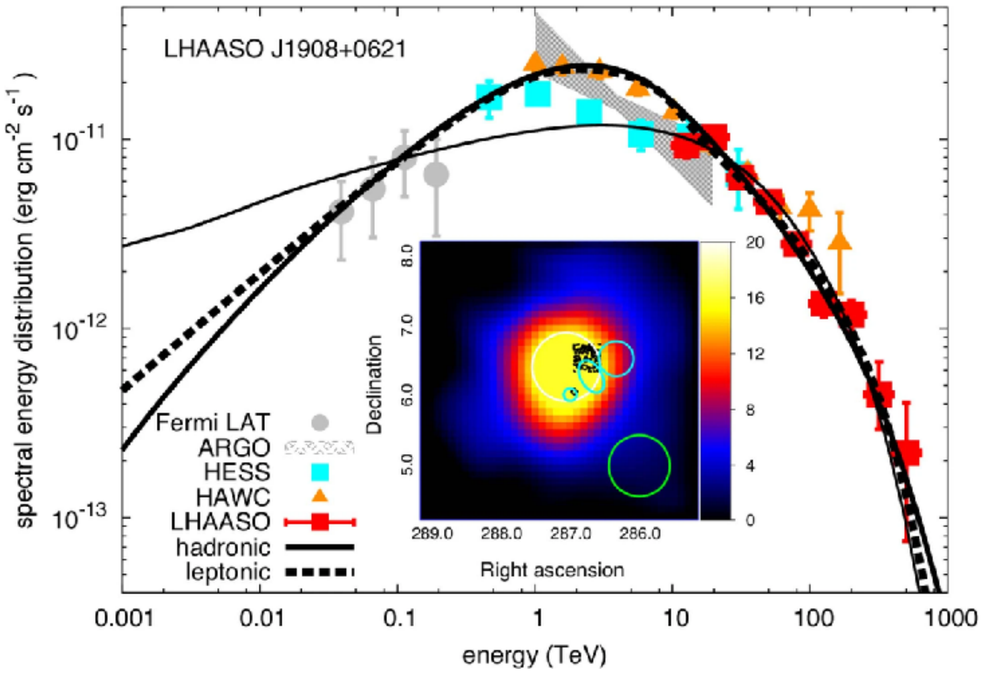
Zhen Cao, F. A. Aharonian, ... X. Zuo + Show authors

Nature **594**, 33–36 (2021) | Cite this article

17k Accesses | **71** Citations | **688** Altmetric | Metrics

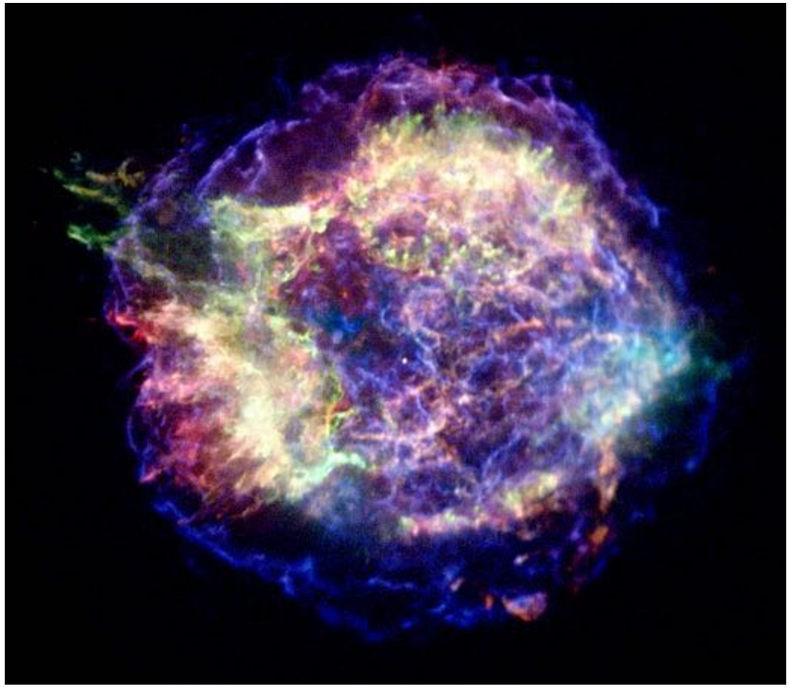
Abstract

The extension of the cosmic-ray spectrum beyond 1 petaelectronvolt (PeV; 10^{15} electronvolts) indicates the existence of the so-called PeVatrons—cosmic-ray factories that accelerate



The UHE sky is surely to give new & deeper insight (LHAASO, CTA, SWGO..)

Maximum Energy - Current estimates



We have compelling evidence for strong magnetic field amplification in SNR interiors.

But what is the relation to maximum energy?

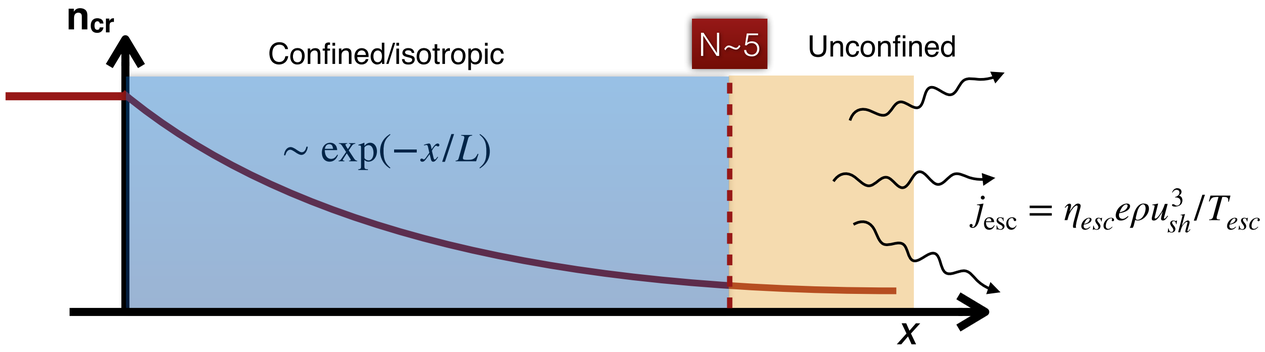
Hillas says $\varepsilon_{\mathrm{max}} < \varepsilon_{\mathrm{Hillas}} = quBR/c$

Lagage & Cesarsky say $\varepsilon_{\mathrm{max}} \lesssim \varepsilon_{\mathrm{Hillas}}$ **(only if** $\lambda \approx r_{\mathrm{g}}$**)**

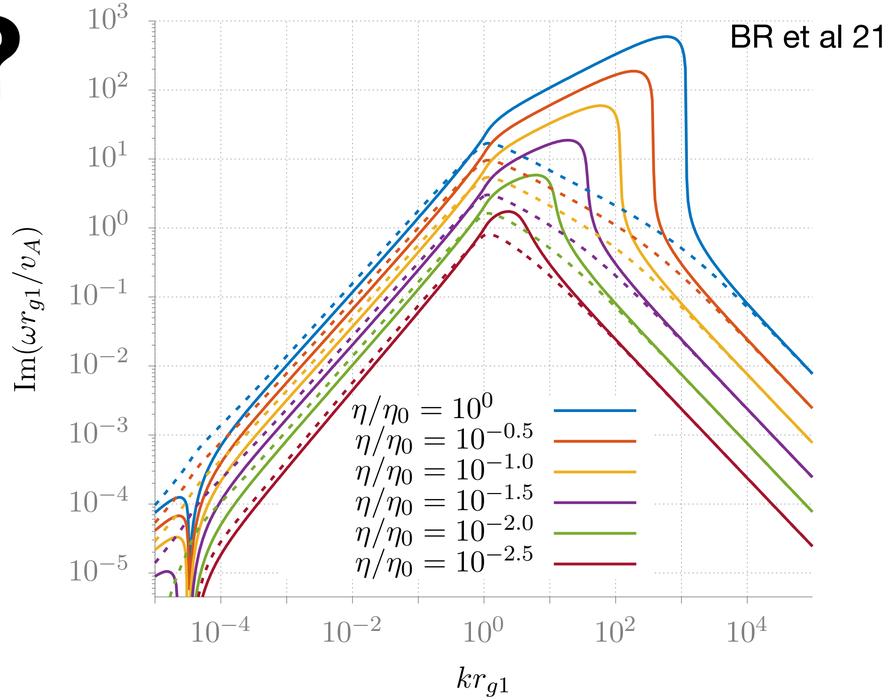
What value should we take for B here?

What sets maximum energy?

Need time to generate large scale non-linear fields $N = \int \omega_{\max} dt \propto \int_x^\infty j_{cr} dx'$

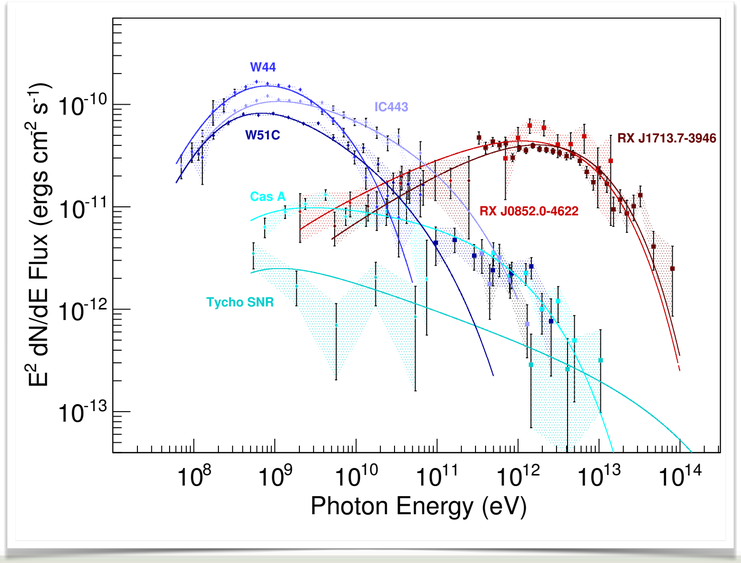


Bell et al. 2013 picture



Shock in constant density environment, one finds

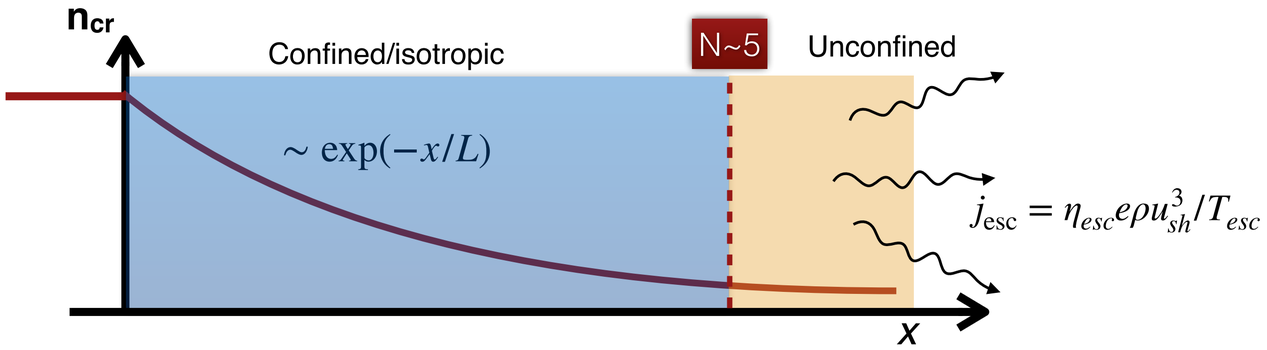
$$\varepsilon_{\max} \approx 30 \left(\frac{P_{\rm cr}}{\rho u_{\rm sh}^2}\right) \left(\frac{n_{\rm gas}}{0.1 {\rm cm}^{-3}}\right)^{0.5} \left(\frac{u_{\rm sh}}{5{,}000 \text{ km s}^{-1}}\right)^3 \left(\frac{t_{\rm snr}}{100 \text{ yrs}}\right) \text{TeV}$$

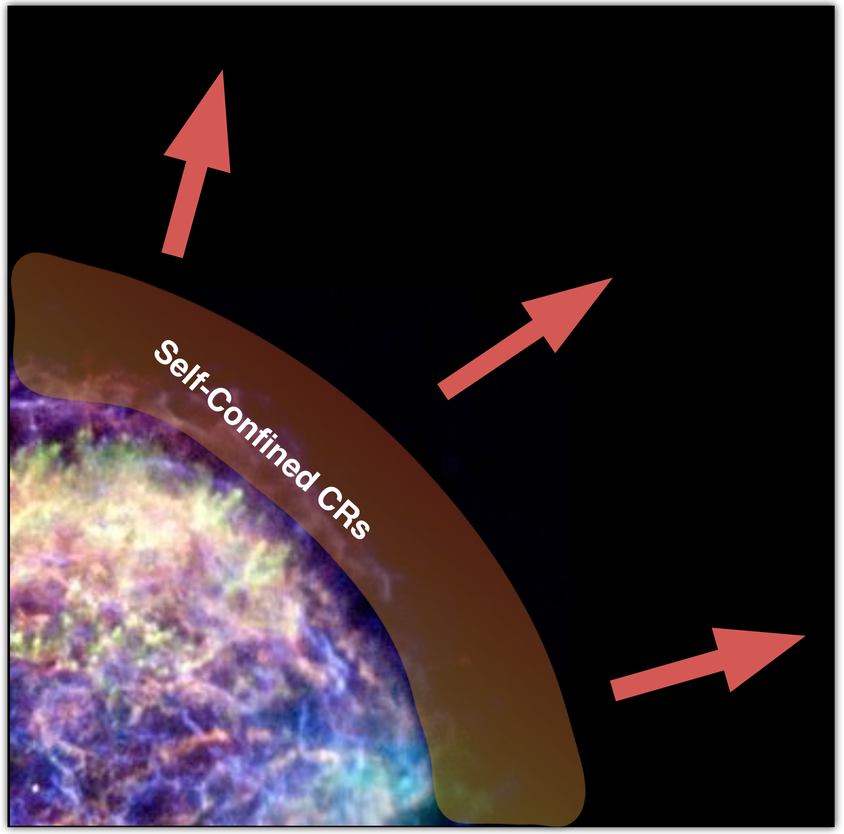


PeV sources need fast shocks in high density environments, e.g. young SNR in dense stellar wind

What sets maximum energy?

Need time to generate large scale non-linear fields $N = \int \omega_{\max} dt \propto \int_x^\infty j_{cr} dx'$





For shocks expanding into stellar winds: $4\pi r^2 \rho v_w = \dot{M}$

$$\varepsilon_{\max} \approx 0.8Z \left(\frac{\eta_{esc}}{0.03}\right) \left(\frac{u_{\rm sh}}{10{,}000\ {\rm km\ s^{-1}}}\right)^2 \sqrt{\frac{\dot{M}/(10^{-5} M_\odot {\rm yr}^{-1})}{v_w/(10\ {\rm km/s})}}\ {\rm PeV}$$

Bell et al. '13

If true, a shock like the one of SN1987A could have produced PeV protons. Can we test it?

Testing the maximum energy in the wind model

The VHE gamma-ray detection of the recurring nova RS Ophiuchi by HESS & MAGIC

Insights from a nova source

- White dwarf - Red giant binary system
- Recurrent nova, explosions occurring every 10-20 years
- Previous outburst revealed highly asymmetric outburst, with shock velocity of several thousand km/s lasting for several weeks
- Shock expands into the wind of the red super giant.

$$\dot{M} \approx 10^{-7} M_{\odot}/\mathrm{yr}$$

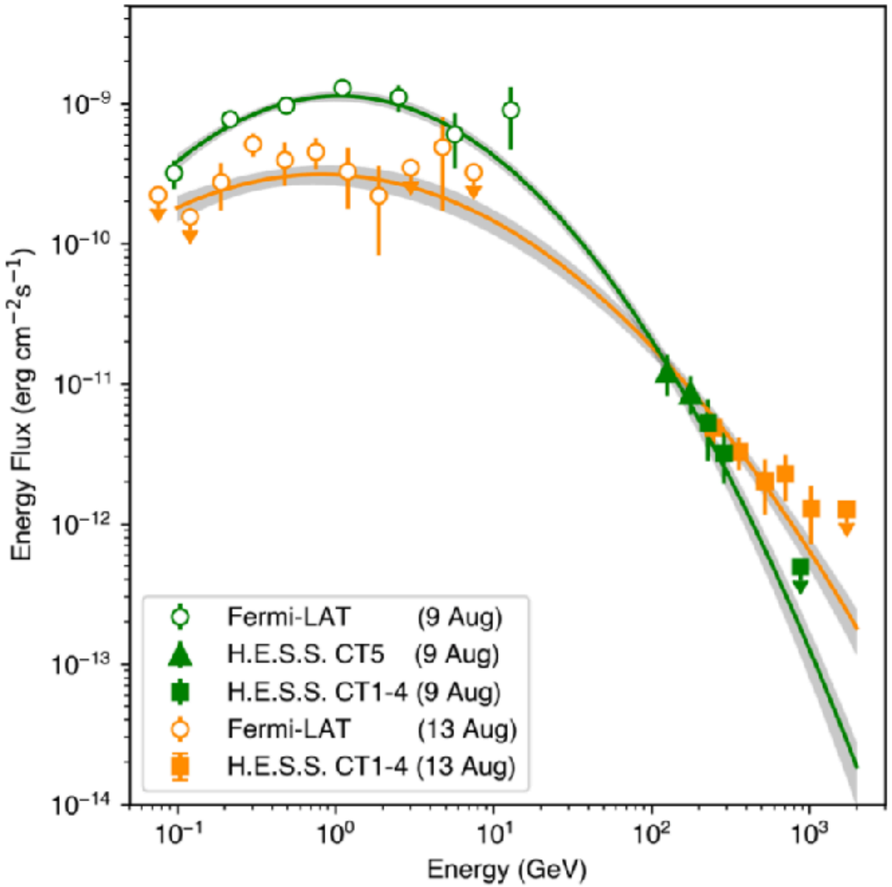
$$v_{wind} \approx 10 - 30 \text{ km/s}$$

H.E.S.S. Collaboration 2022

MAGIC Collaboration 2022

Gamma-ray detection reveals extreme acceleration

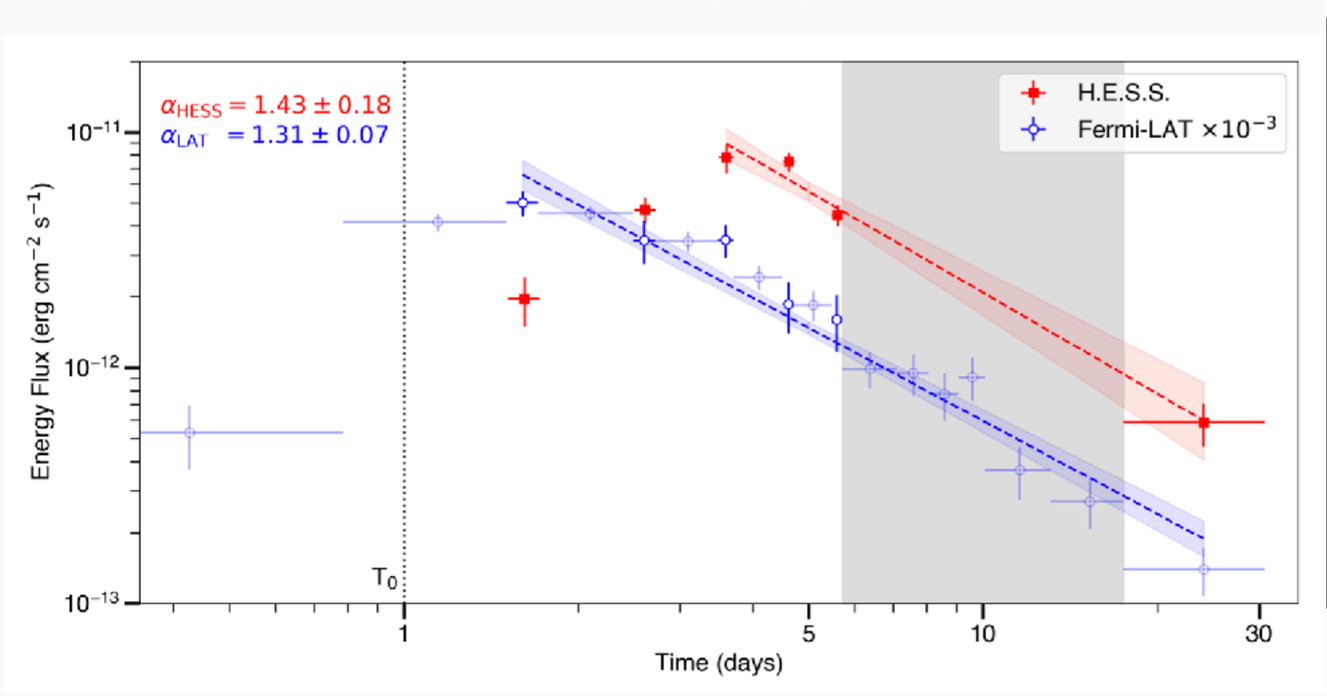
$$\varepsilon_{\max} \approx 5Z \left(\frac{\eta_{esc}}{0.01}\right) \left(\frac{u_{\rm sh}}{5{,}000\ \mathrm{km\ s^{-1}}}\right)^2 \sqrt{\frac{\dot{M}/(10^{-7} M_\odot \mathrm{yr}^{-1})}{v_w/(10\ \mathrm{km/s})}}\ \mathrm{TeV}$$



H.E.S.S. Collaboration 2022

Gamma-rays detected up to ~ TeV consistent with the maximum particle energy prediction

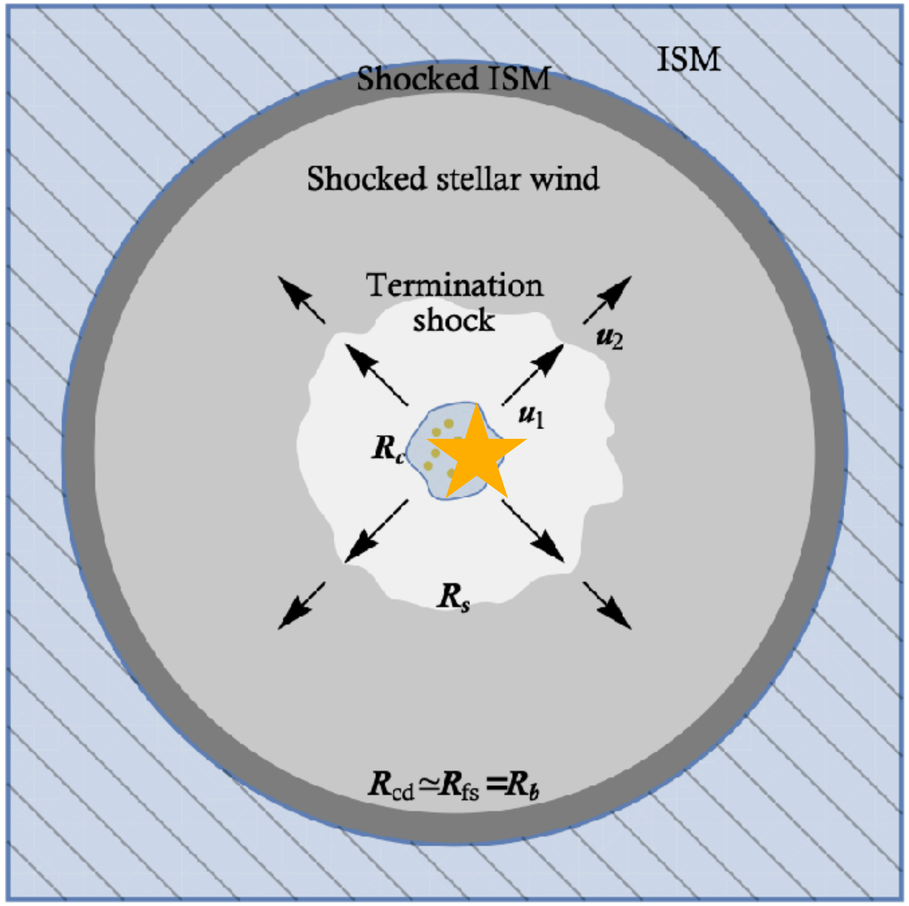
Spectrum can **not** be explained without strong magnetic field amplification



Lessons from RS Oph

- Maximum energy photon detected consistent with maximum energy prediction in wind
- If shock was 10 times faster and mass loss 100 times larger, PeV protons achievable
- Note that both Cas A and SN1987A are thought to have had a late stage with much faster winds (several 100 km/s), evacuating a lower density bubble close to star.
- Acceleration in RS Oph followed shock from WD propagating into wind of companion (could SNR in other binary systems play a role not yet considered?)

SNRs in compact (wind blowing) stellar clusters



Morlino et al. 21

A conglomeration of massive stars with high kinetic power output in a small volume creates a unique environment for particle acceleration - so-called **superbubbles**

Commonly perceived that some “collective processes” could be at work that facilitates acceleration to energies > PeV

Can supernova remnants still be the answer?

See Vieu et al 22 for overview of collective processes

Compact Massive Stellar Clusters (Superbubbles)

Weaver et al ‘77

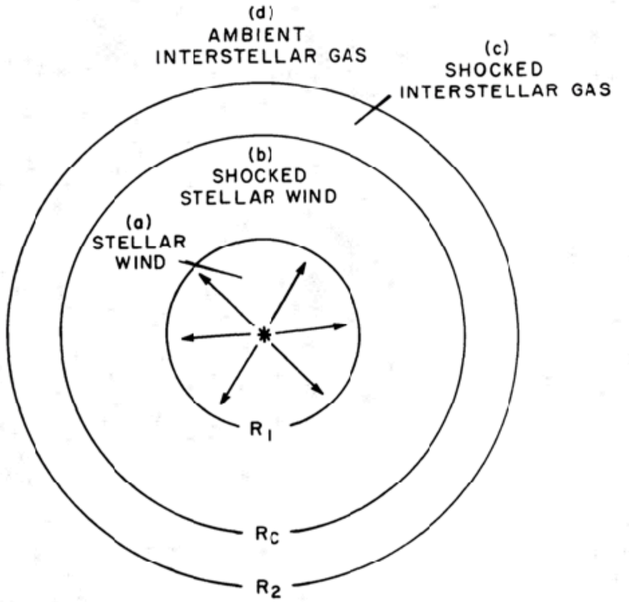
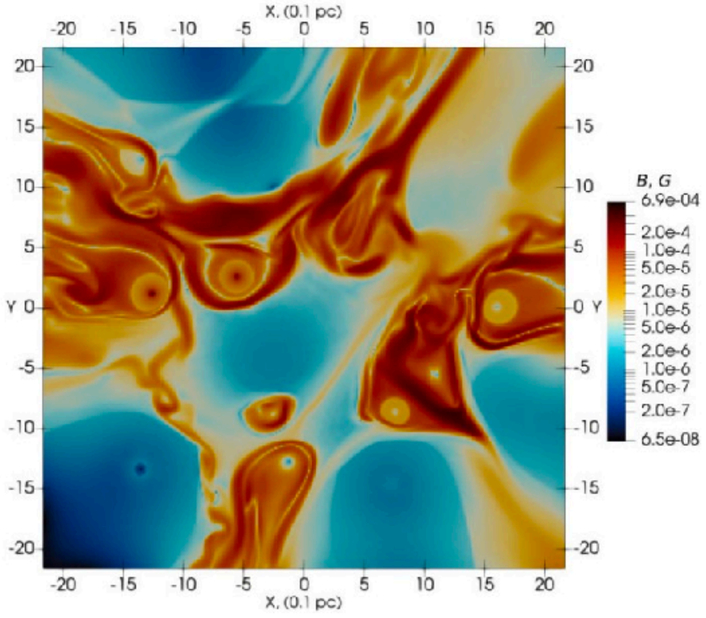


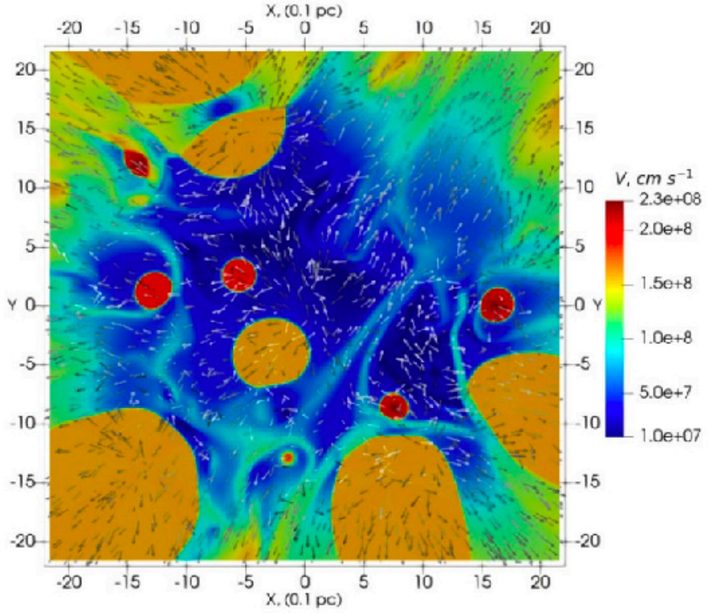
FIG. 1.—Schematic sketch indicating the regions and boundaries of the flow.

It is well known that the collective winds can inflate bubble.

If sufficiently compact, they can drive a strong collective (super sonic) wind, terminating at a reverse shock (See Giovanni’s talk)

What about the magnetic field?





3D MHD simulations of Badmaev et al. 22

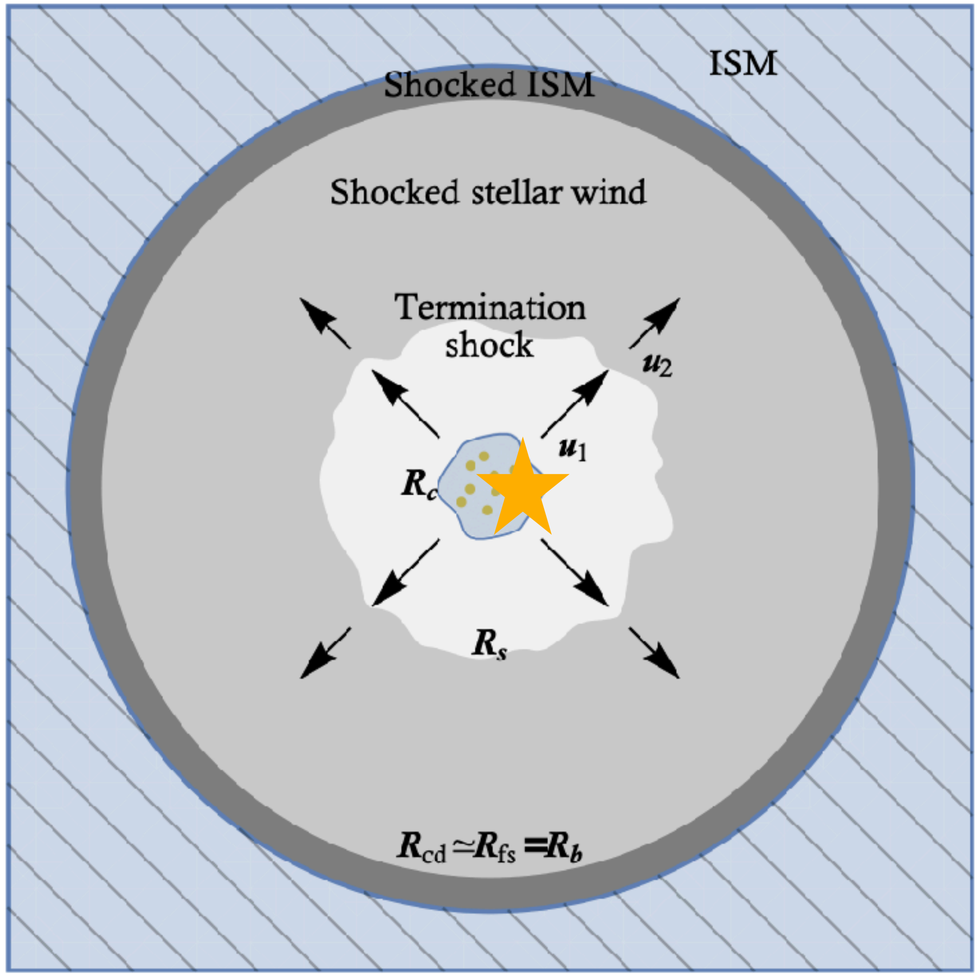
If each star on average outputs

$L_{\rm kin} \sim 10^{36}{\rm erg/s}$

can in principle generate ~100 μG fields*
in the core (turbulent and isotropic)

* assuming approx 10% efficiency

Bootstrapping the cluster wind



Morlino et al. 21

Magnetic field is entrained in the wind: $B \propto r^{-s}$
Where s~ 1 - 4/3

$$\varepsilon_{\rm Hillas} \approx quBr = quB_c r_c (r_c/r)^{s-1}$$

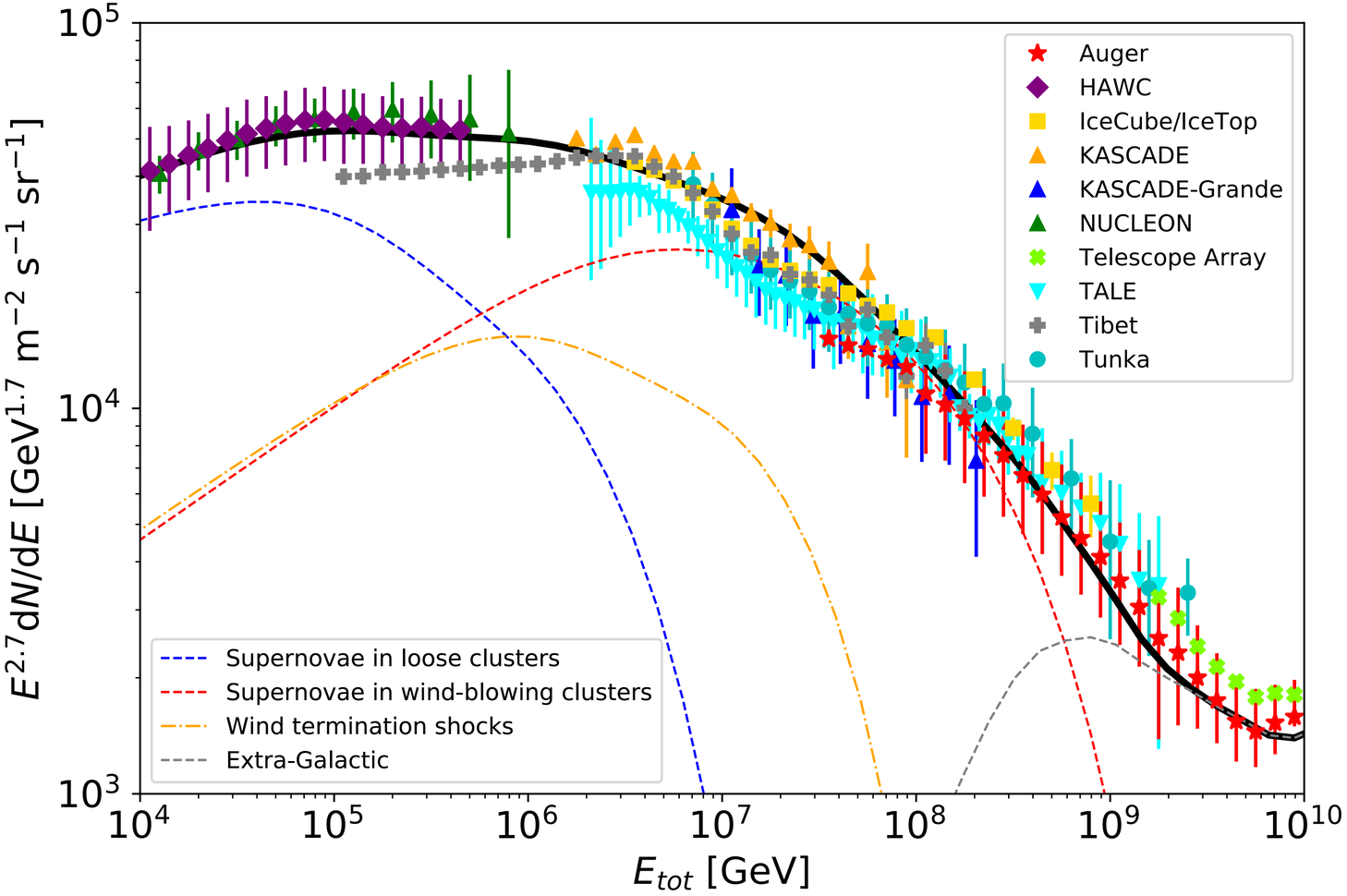
$$\varepsilon_{\rm max} \approx Z \left(\frac{u_{sh}}{5000\ \text{km/s}}\right)\left(\frac{B_c}{100\ \mu\text{G}}\right)\left(\frac{r_c}{1\ \text{pc}}\right)\ \text{PeV}$$

$$(\text{if}\ \ \lambda \sim r_{\rm g})$$

CCSN can launch fast shock, ~10 000 km/s
Accelerating protons **above** the knee and high Z nuclei close to the ankle.

Vieu, BR, Aharonian, 2022

MSCs as the primary source of GCRs > PeV



Using Gaia data it is estimated that ~15% of nearby MSCs can blow collective winds

Rate of favourable CCSN in compact clusters $\lesssim 6$ % of galactic CCSN rate

Contribution from compact MSCs takes over GCRs above a few 100 TeV, creating a knee-like feature

Provides also a good fit to composition.

More details in Vieu & Reville, MNRAS accepted, (arXiv:2211.11625)

Conclusions

- New gamma-ray discoveries are changing how we think of cosmic ray origin problem.
- We expect exciting discoveries with the next generation of UHE gamma ray facilities
- The plasma physics of CRs and their self-generated fields are broadly consistent with observations, but can't solve the >PeV problem alone (maybe)
- A model of CR acceleration in stellar clusters provides a compelling fit to the galactic CR spectrum close to and above the knee
- Future simulations will shed light on the multi-scale aspects (turbulence, binary systems, large scale field structure)