HONEST Workshops: Hot Topics in High Energy Astrophysics

PeVatrons and their environments: Concluding Remarks

Emma de Oña Wilhelmi & Ruben Lopez-Coto

Motivation of this workshop

HONEST: Hot Topics in High Energy Astrophysics

- **DISCLAIMER**: will try to summarise the main discussion points. This contains surely a very biased view and will not cover much of todays session => Keep for the discussion.

  But before: Thanks to all speakers and participants for the excellent contributions and lively discussions, to all participants for joining (even at sometime not convinient time), to all the chairs and specially to the technical team: Julia Eckert, Sonal Patel, Mabel Bernardos and Jonas Kramer for facilitating this Workshop with an excellent technical support.

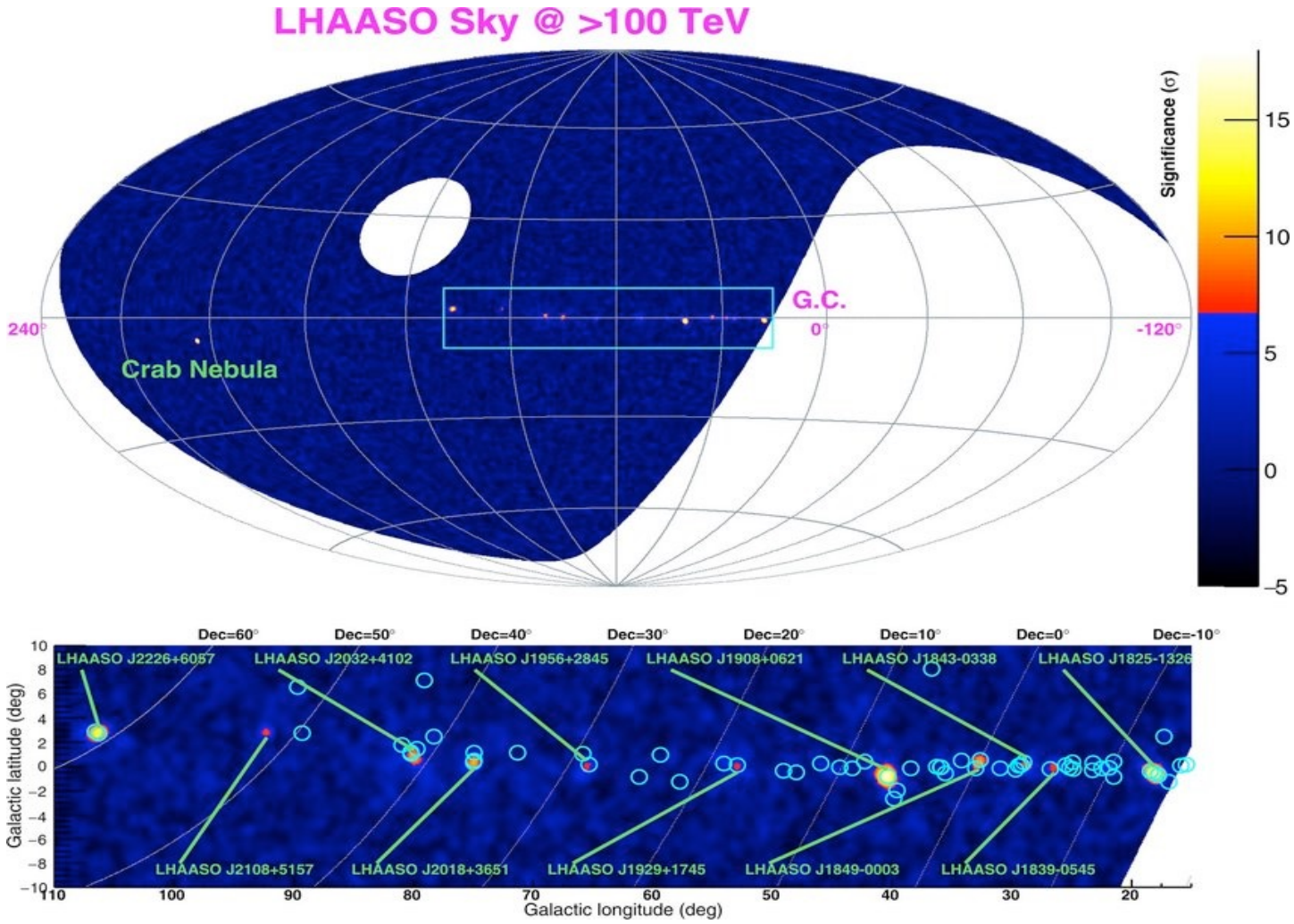
Motivation of this workshop

HONEST: Hot Topics in High Energy Astrophysics

Why now? many observational pieces have been put together:

- GeV / TeV observations
- Hard X-rays
- New detectors in the mutli-TeV regime

Definitely a Hot Topic in the field

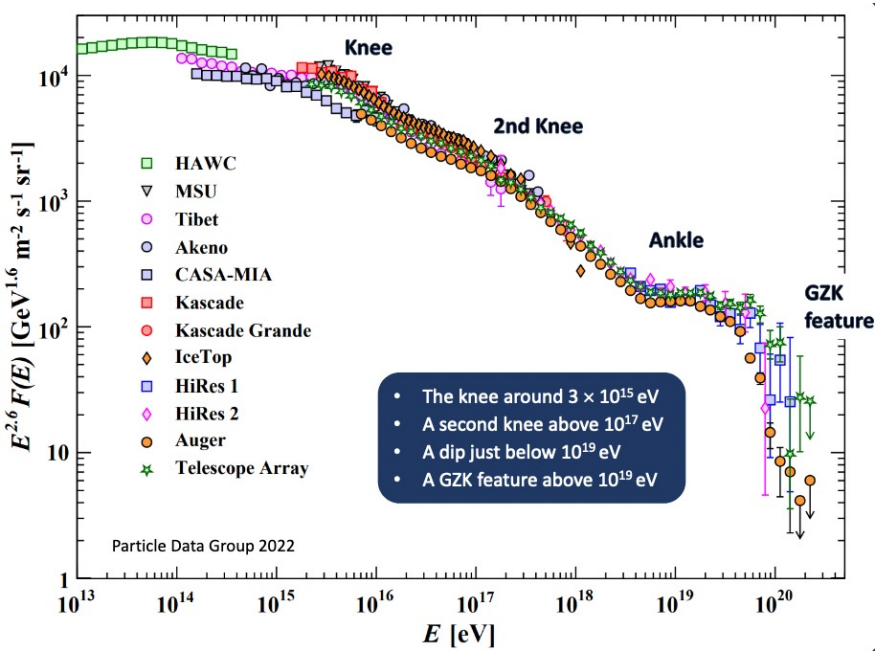


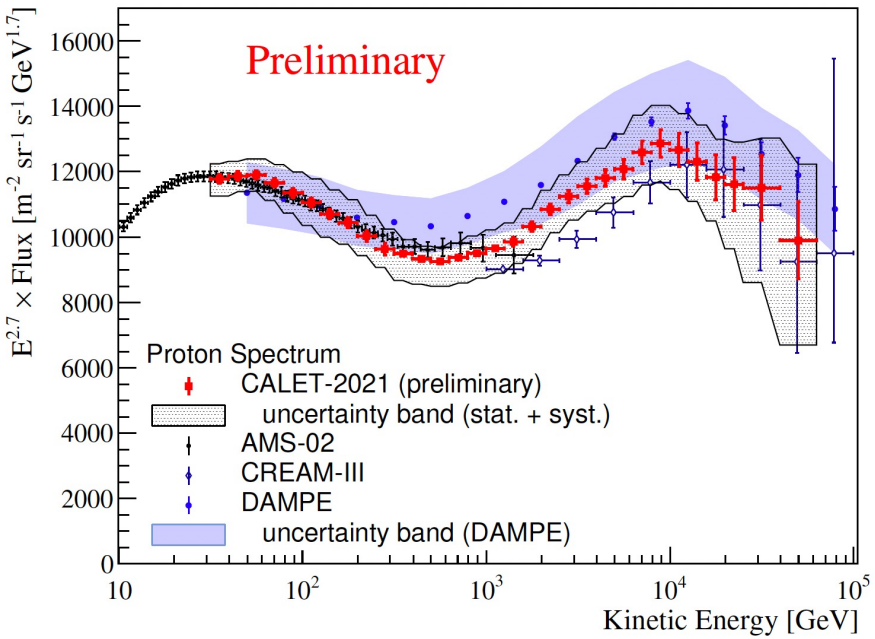
What's the fuss with PeV particles

The CR spectrum and the origin of the highest energy particles

Particle spectrum shows general trends, but the proton spectrum is subjected to statistics and systematic errors: this could broaden the range of possible PeVatrons.

Latest results from CALET/DAMPE show that the region below 1 PeV may not be as featureless as we thought

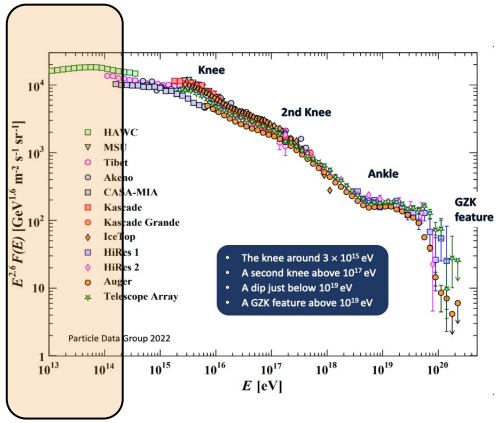




See talk by Donghwa Kang, Nov 29

The origin of the Galactic Cosmic Rays

Sub-PeV regime

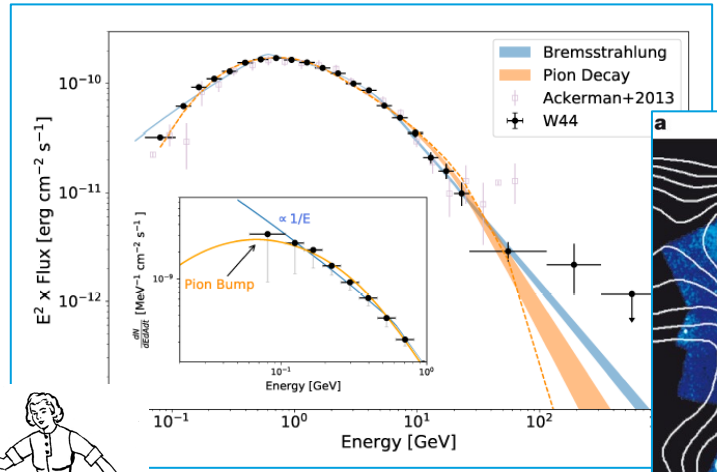


~100 MeV to ~0.5 PeV

General agreement: most of the **low energy particles** comes from SN

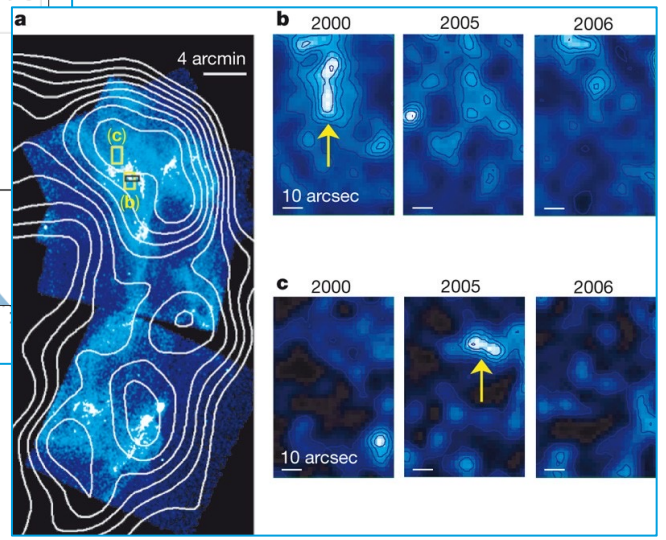
- Experimental evidences & theoretically comfortable

Peron 2021



Pion decay

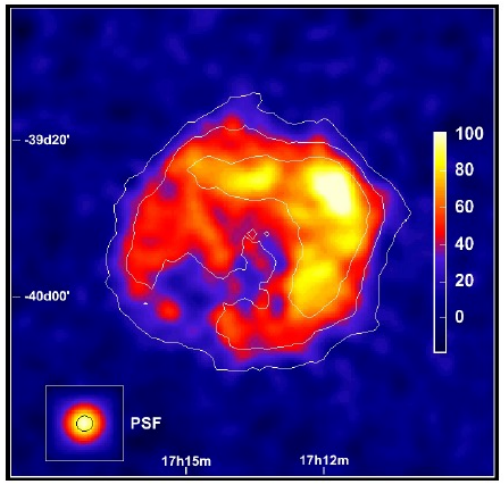
Amplified magnetic field

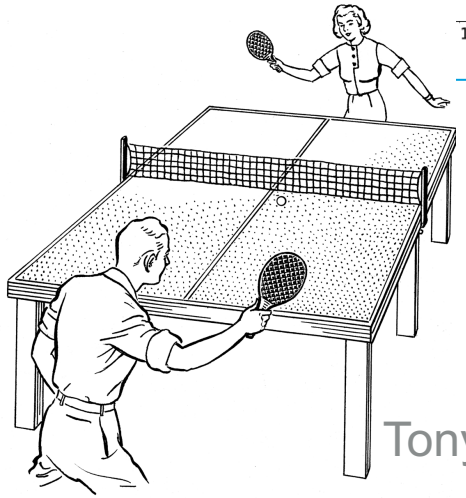


Uchiyama 2007

Morphology

Felix Aharonian talk

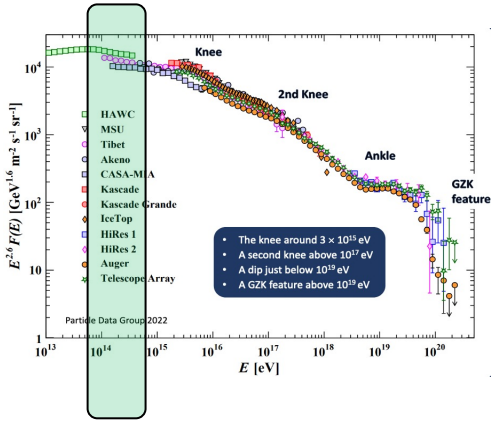




Tony Bell talk

The origin of the Galactic Cosmic Rays

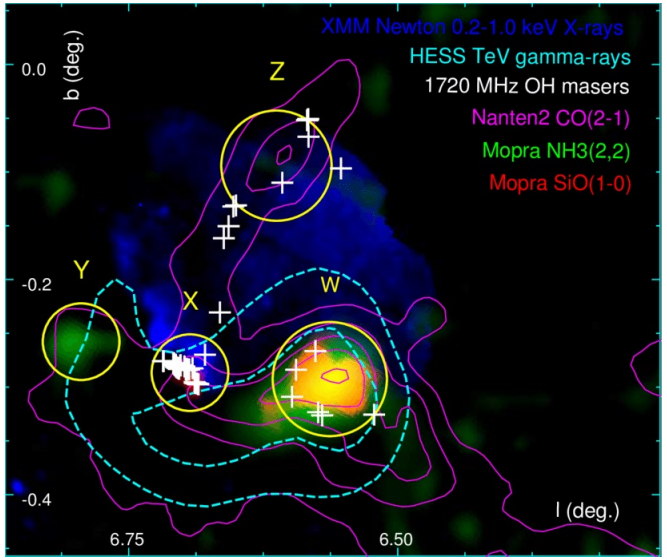
~hundreds of TeV to the PeV regime

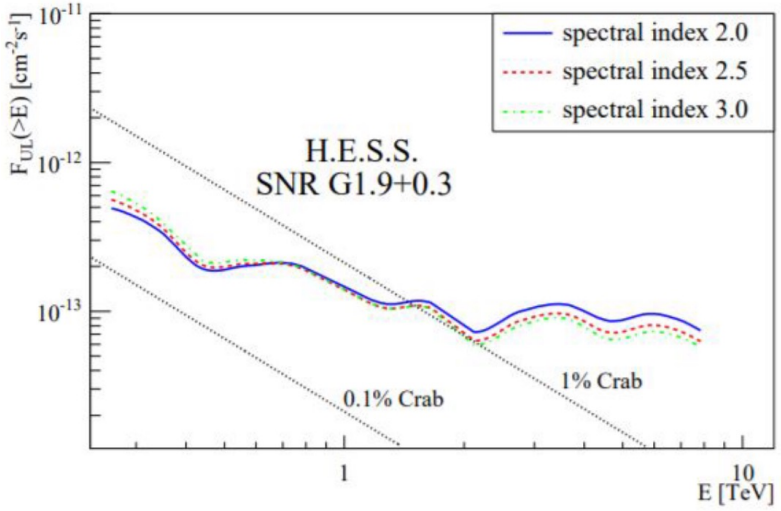


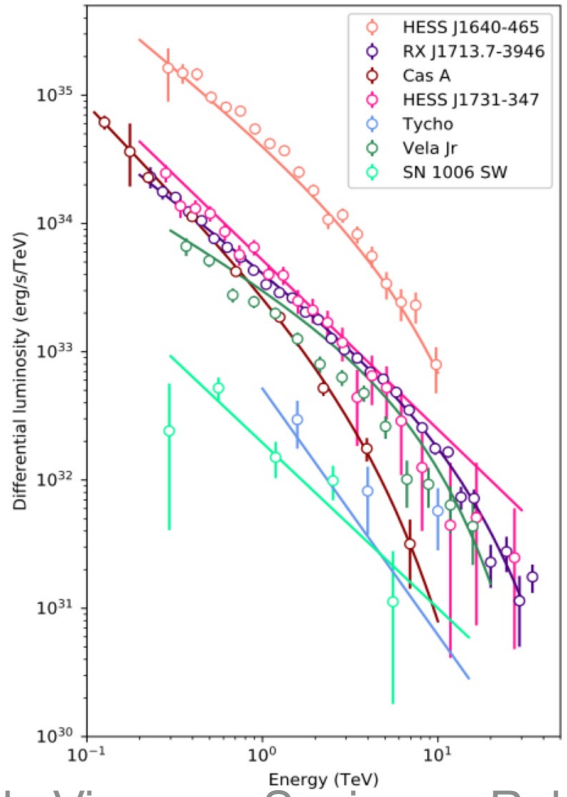
~0.5 PeV to few PeV

The challenge to the standard paradigm: known young SNRs seems not to be PeVatrons at present

Experimentally





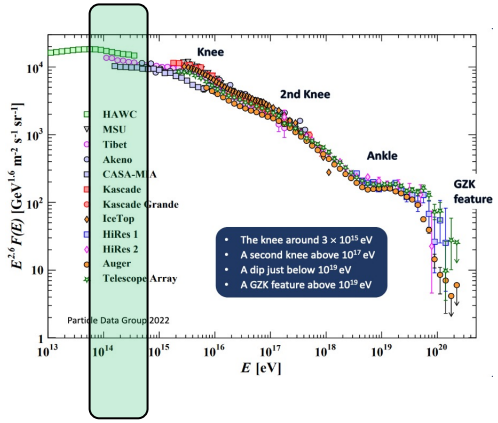


Maxted 2016

See Ruizhi Yang, Samar Safi-Harb talk, Vincenzo Sapienza, Roberta Giuffrid

The origin of the Galactic Cosmic Rays

~hundreds of TeV to the PeV regime



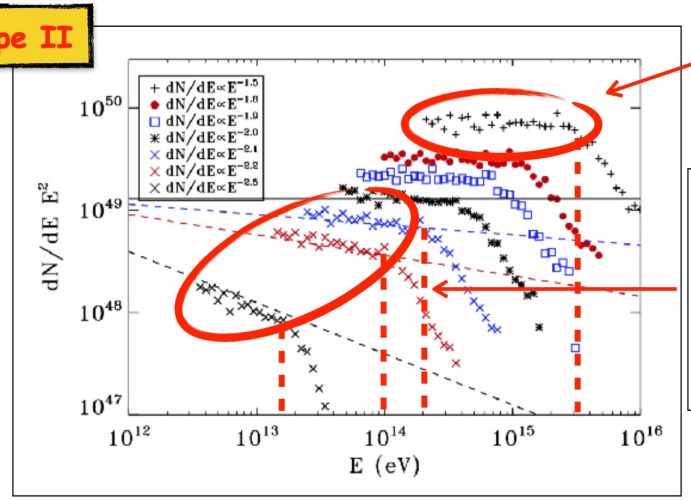
~100 MeV to ~0.5 PeV

The challenge to the standard paradigm: known young SNRs seems not to be PeVatrons at present

And theoretically:

- We need young SNRs in dense winds (type II)

type II



Schure & Bell 2014

knee at the right place

—> injection too hard

injection spectrum slightly steeper than 2

—> not enough to reach the knee

- We need escape of particles upstream to excite self-confining fluctuating magnetic fields:

$$\epsilon_{max} \sim \left(\frac{\eta_{\rm CR,max}}{3\%}\right)\left(\frac{n_e}{\rm cm^{-3}}\right)^{1/2}\left(\frac{R}{\rm pc}\right)\left(\frac{u_s}{10^7 \rm m\ s^{-1}}\right)^2 80\ \rm TeV$$

See talks from Tony Bell, Stefano Gabici, Brian Reville, Giovanni Morlino, Jacco Vink, Robert Brose, Alexandre Marcowith

The origin of the Galactic Cosmic Rays

~hundreds of TeV to the PeV regime

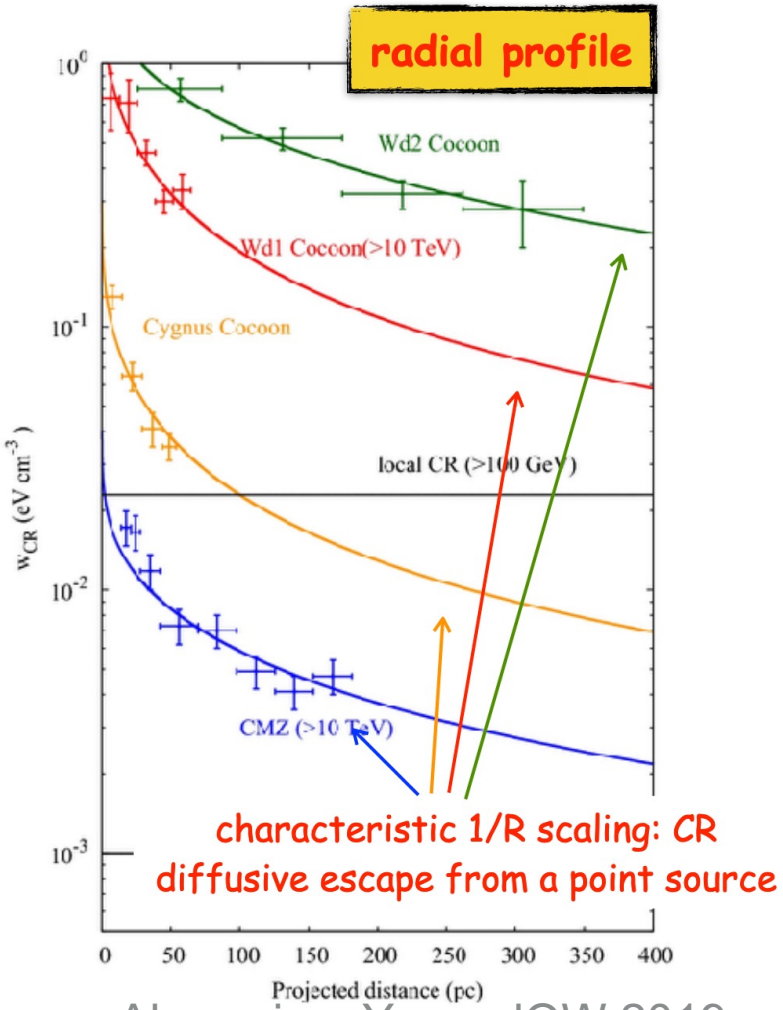
(not so) New ideas:

- Early phase in the <100 yrs (highest density / fastest shock velocity)
- SNRs we don’t know? which observations do we need to do?
- Some candidates like Boomerang or Eel?
- Other accelerators: Stellar clusters / SNRs in Stellar clusters / Galactic Center / Pulsar wind Nebula / ...

The origin of the Galactic Cosmic Rays

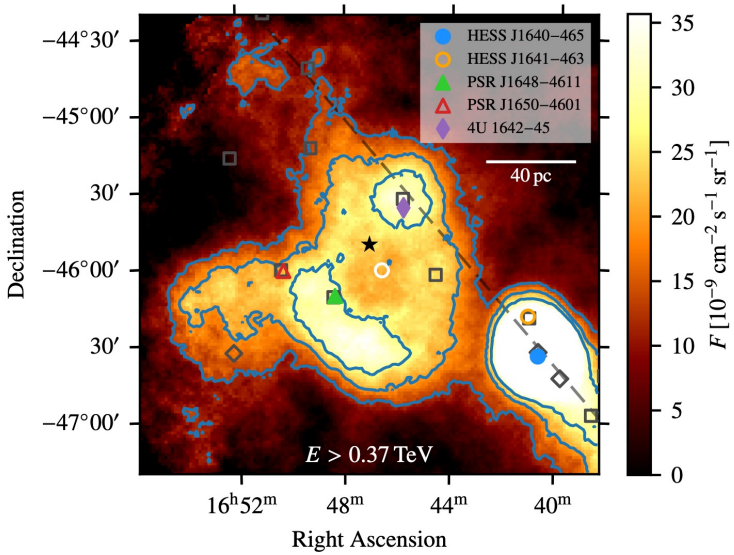
Stellar Clusters

Exciting observations reviving stellar clusters as PeVatrons

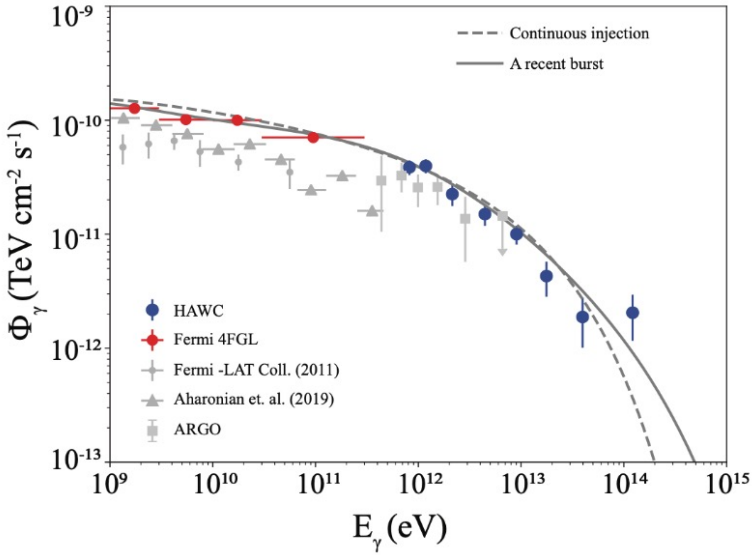


Aharonian, Yang, dOW 2019

HESS Col. 2022



HAWC Col. 2020



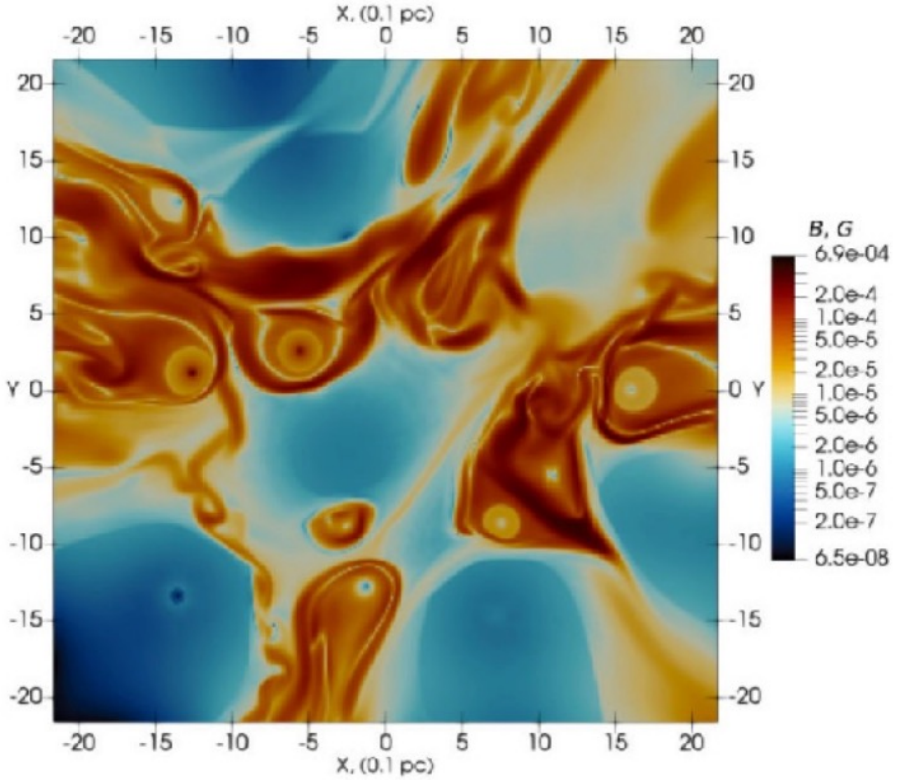
+LHAASO > PeV!!

See talks Lars Mohrmann, Ruizhi Yang

The origin of the Galactic Cosmic Rays

Stellar Clusters

Backup up by theoretical works:



Badmaev+ 2022

Large magnetic fields
Fast outflows as in SNRs
Energetics << than in SNRs

We need 10^{41} erg/s at > 1 PeV (assuming injection spectrum 2.3)

Large size

Hillas criterium

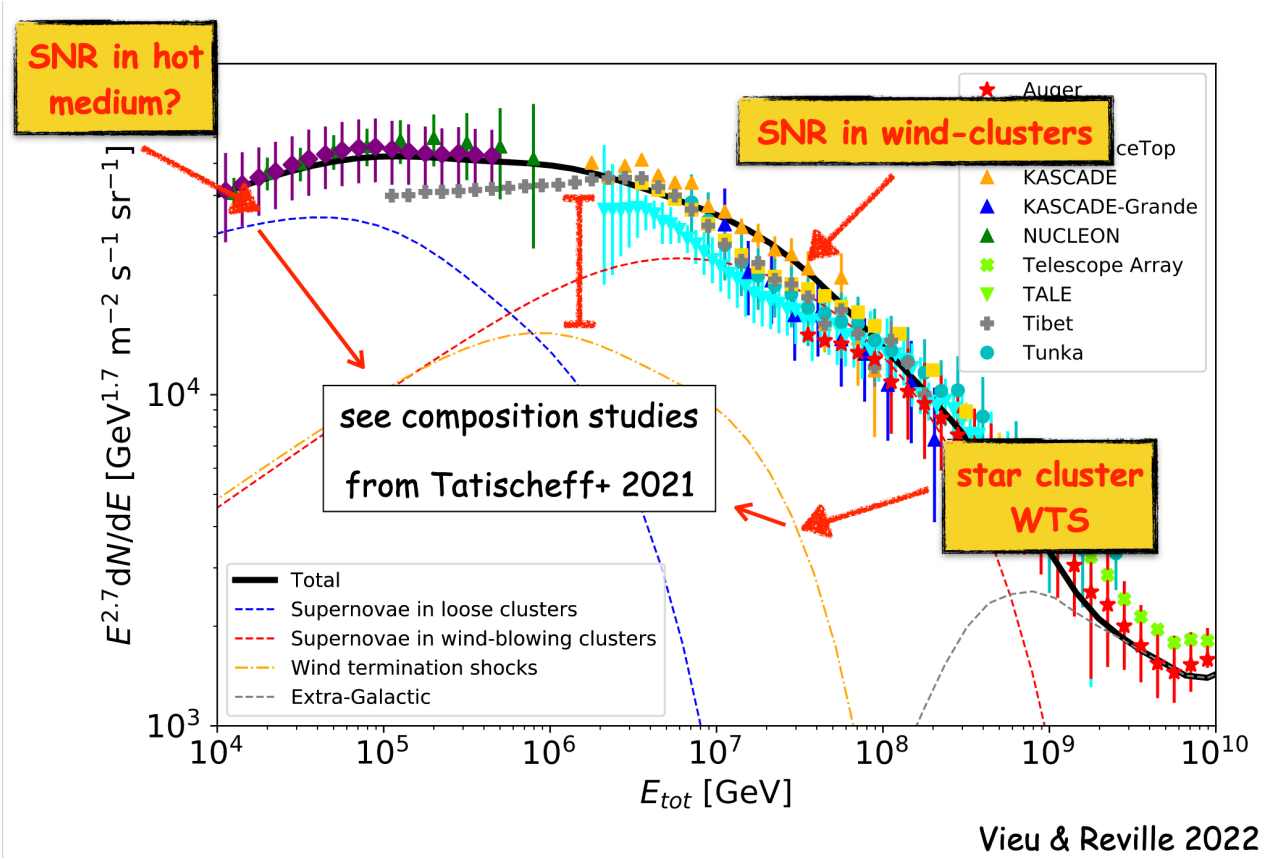
$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

* Needs Bohm scattering

The origin of the Galactic Cosmic Rays

SNRs in loose clusters, in wind-blowing clusters, wind termination shocks

Backup up by theoretical works:



- Based on Gaia observations
- Fits CRs composition
- From “source populations” to shocks in different conditions
- **But still to be proven**

SNRs and clusters as PeVatrons

Some problems

BUT:

$$F_\gamma(r) \propto n(r) \times w_{CR}(r)$$

- **Radial profile sometimes does not follow 1/r**
  Product of CRs x gas distribution -> Might not have to follow (or advection dominant – See Giovanni Morlino's talk)
  Depends on the center of gravity
- **Massive clusters are large and messy** – difficult to prove the association with the stellar cluster. We need:
  - Better gamma-ray instruments (of course) and neutrino detectors

  Maybe we should not worry so much about finding The PeVatron, or the Super-PeVatron, or the Ankeltron, but rather understand fully shocks in different media:

Observations

See talks Anne Lemiere, Andrew Taylor, Giada Peron, Felix Aharonian

Understanding shocks in different media

- Smaller objects in cleaner environments? Where? Non-thermal protostars?
- Can we use novae and other transients (time connection!) to understand better winds and shocks?
- Understanding CR propagation:
  - the Galactic center still provides lots of information (central source, Galactic ridge, Femi bubbles), but again, a busy complex region
  - Isolated molecular clouds as clean labs to interaction with no acceleration
- Other accelerators:
  - Shocks in Pulsar winds and binary systems
  - Microquasars
  - In another Galaxies… (careful about neutrinos!)

Leptonic (and hadronic?) accelerators

Pulsar Wind Nebulae & Binary systems

- PWNe: the Crab nebula as the most powerful accelerator known (2-3 PeV)

- Crab: Lots of observations, lots of theoretical works, still lots to understand:
  - PWN variability
  - Sigma problem – still a problem?
  - Magnetic field B < 600 uG
  - Protons in the wind: energetically sub-dominant
- Acceleration in Pulsar Wind Nebulae: the non-thermal extreme accelerators, relativistic shocks!
- Binary systems seem to extended >> 10 TeV (and some cases > 100 TeV)

Lots of questions to continue during the discussion time

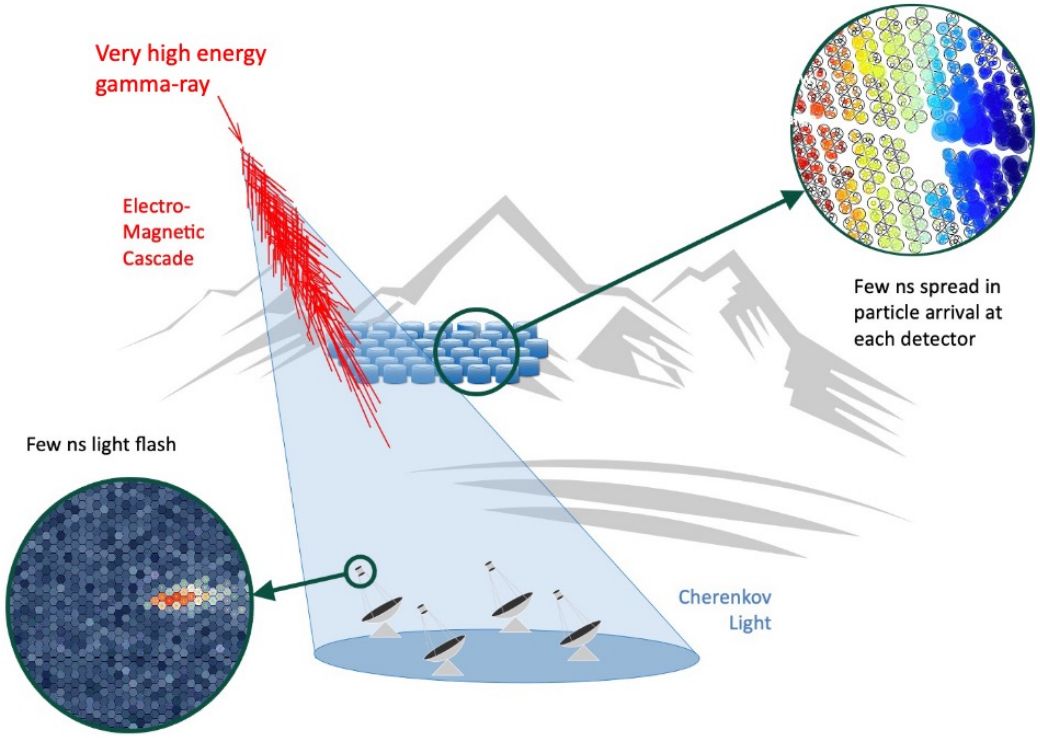
See talks Barbara Olmi, Elena Amato, Dmitry Khangulyan, Philipp Mertsech, Gwenael Gianti

Into the future: Surveys and Future Instruments

- Surveys: Improve the analysis techniques to see the most energetic energy band accessible
- Hybrid approach extremely successful ! (see LHAASO)

- We need high resolution instruments

- CTA, ASTRI, SWGO



See talks Jim Hinton, Mathieu de Naurois , Zhen Cao, Martina Cardillo

Thanks again

and see you in two years for the 3rd HONEST Edition