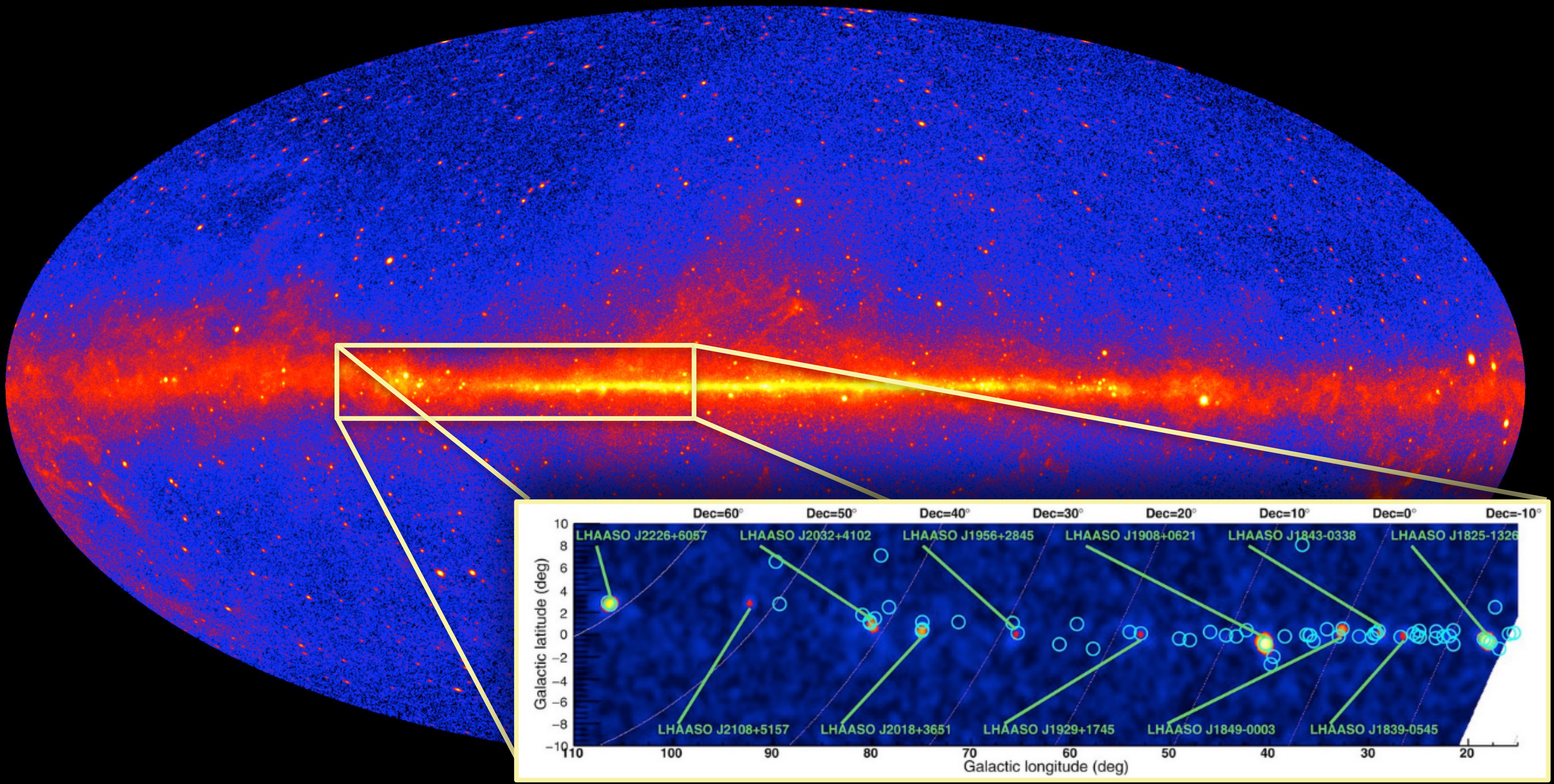

The search of Galactic PeVatrons

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INAF/Oss. Astrofisico di Arcetri

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NATIONAL INSTITUTE FOR ASTROPHYSICS

“Hands-on the Extreme Universe with High Energy Gamma-ray Data” - Sexten school 18-22 Aug. 2022

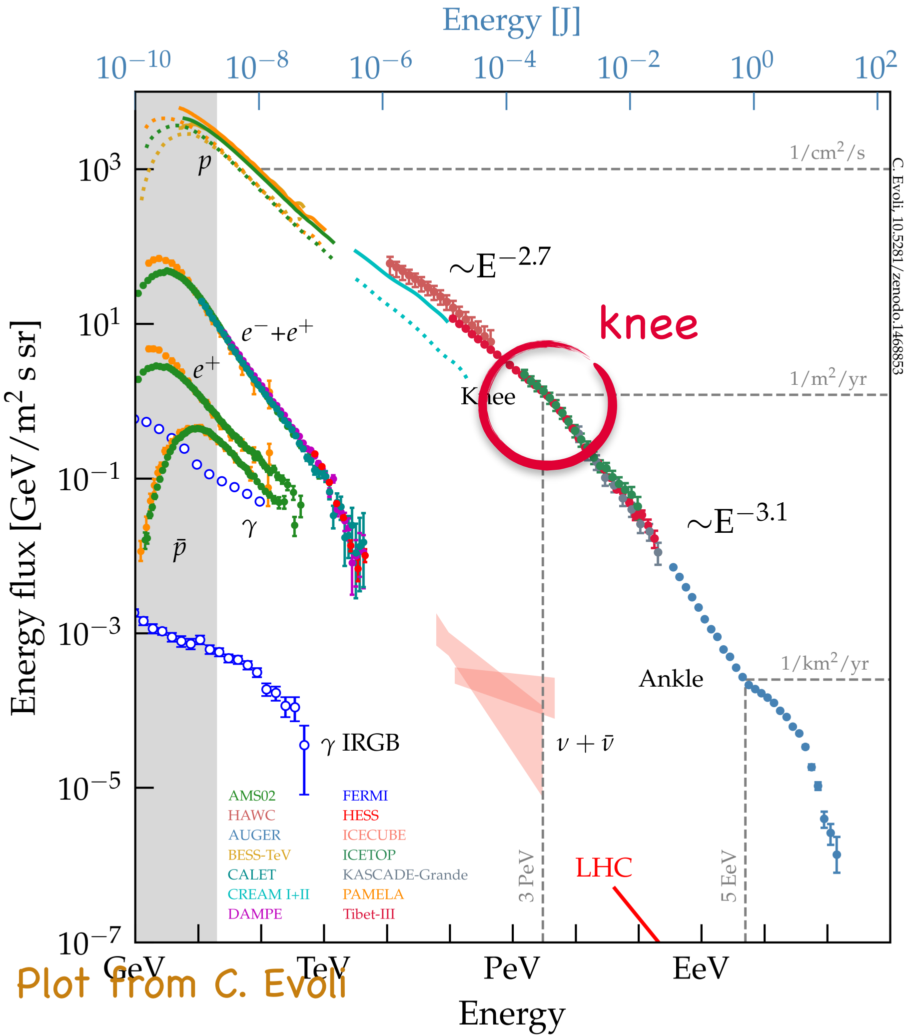
Summary

- Connection between *PeVatrons* and *Cosmic Rays*
- The VHE gamma-ray sky today
- Sources candidate to be PeVatrons:
  - past: SNRs
  - present: SNRs, supernovae, young stellar clusters, super-bubbles, PSR/PWNe
- Observational strategies
  - gamma-rays and CTAO

Some additional material:
- S. Gabici: "Theory and phenomenology of PeVatrons" CDY Talk 2022
- P. Cristofari: "The hunt for PeVatrons: the case of SNRs", Universe, 2021
- Workshop: "The role of CTAO in PeVatrons searches", May 2022

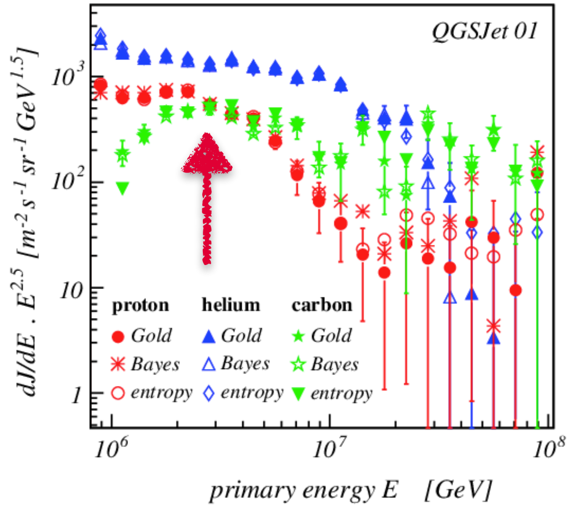
Why are PeV cosmic ray important?

Protons need to be accelerated up to ~ 1 PeV

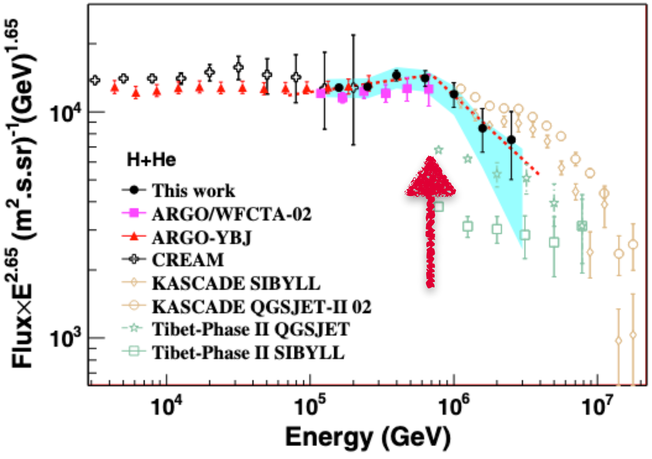


Plot from C. Evoli

Still not completely clear where the proton knee is: different experiments provide different values between 0.5-3 PeV



KASCADE coll. (2005)

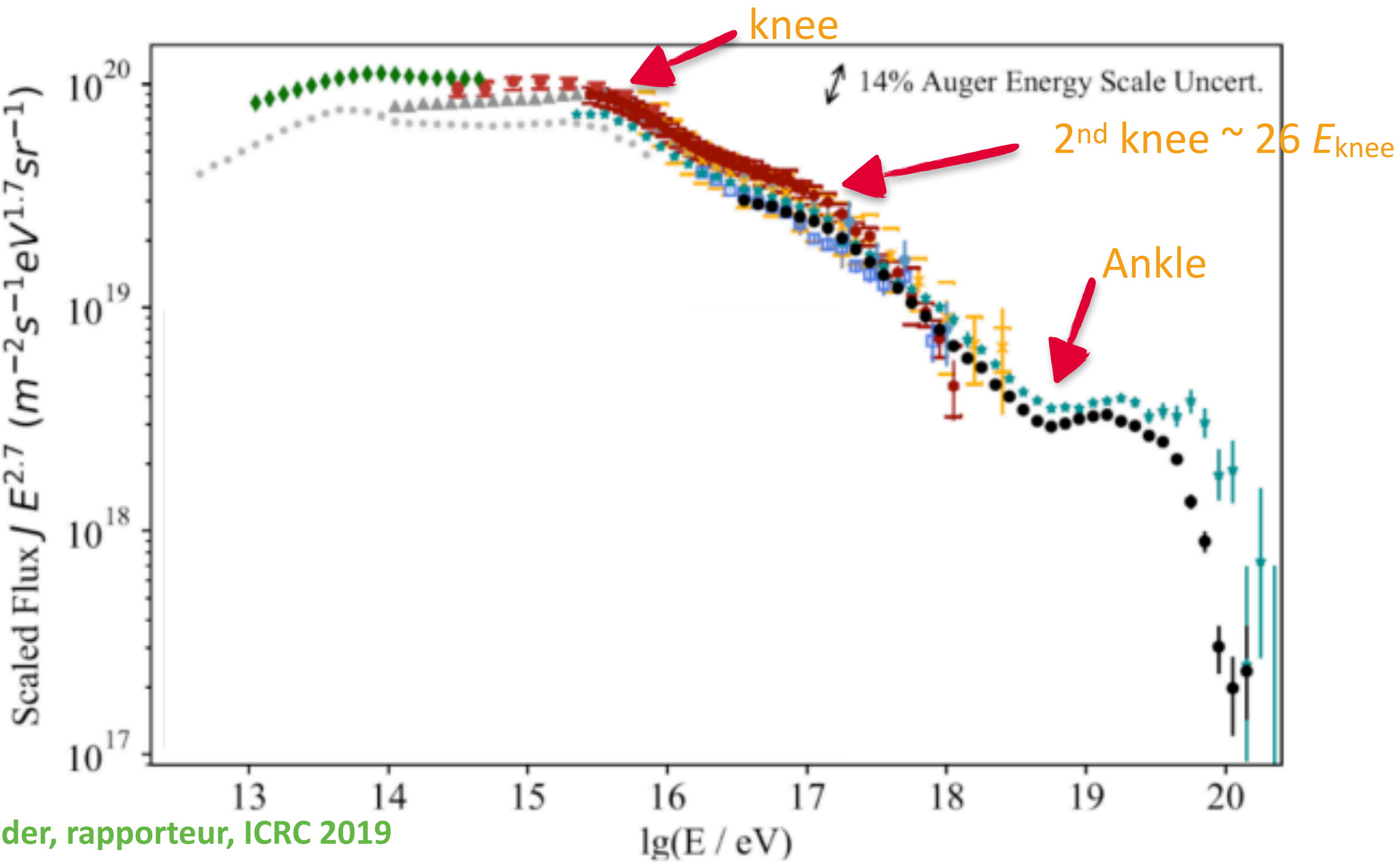


ARGO coll. (2015)

PeVatrons in the context of Galactic CRs

The cutoff shape is important to understand the knee region and the Galactic-extraGalactic transition region

distinguish between cutoff and steep spectra of broken spectra: requires to detect flux over several decades



F. G. Schroder, rapporteur, ICRC 2019

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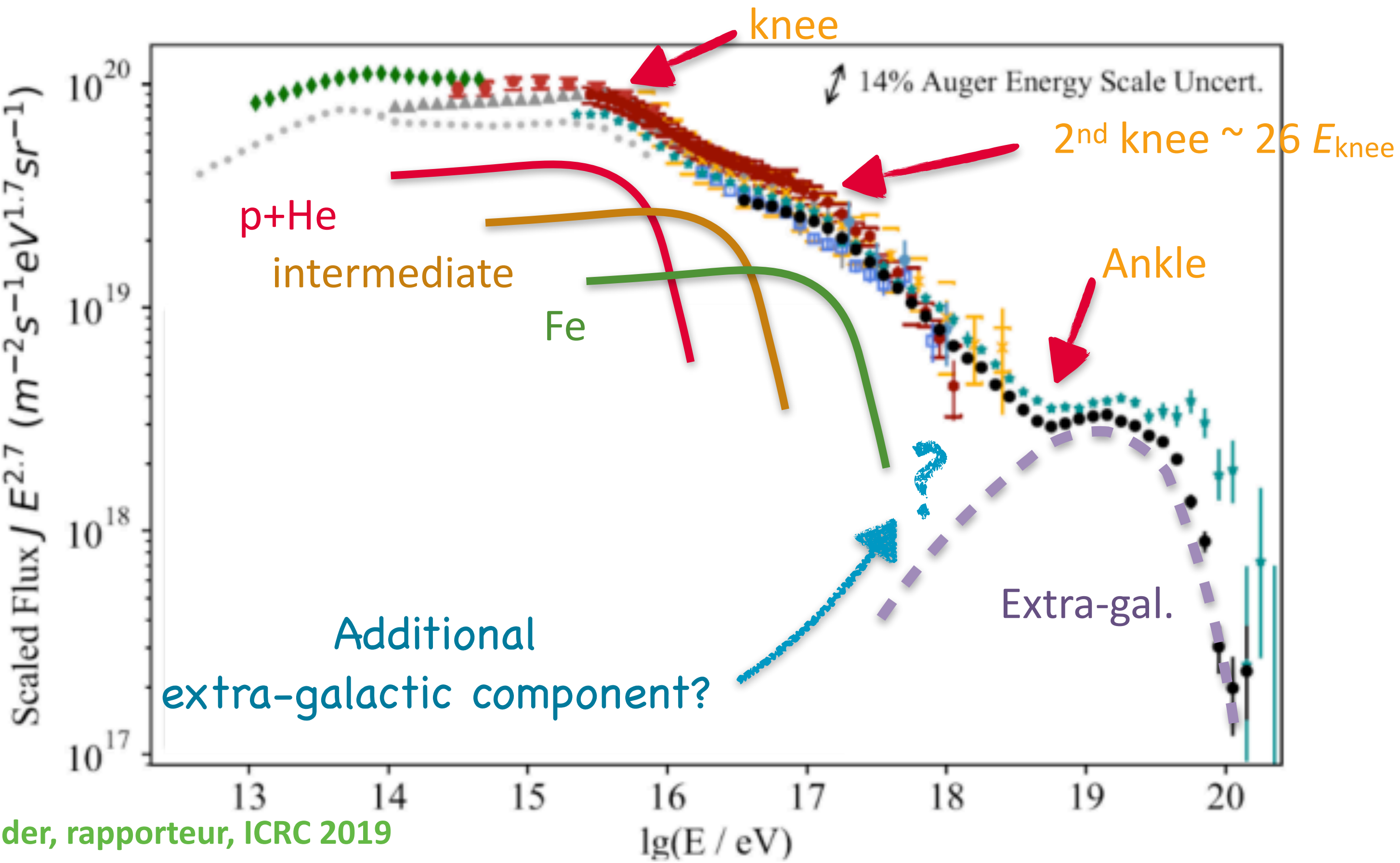

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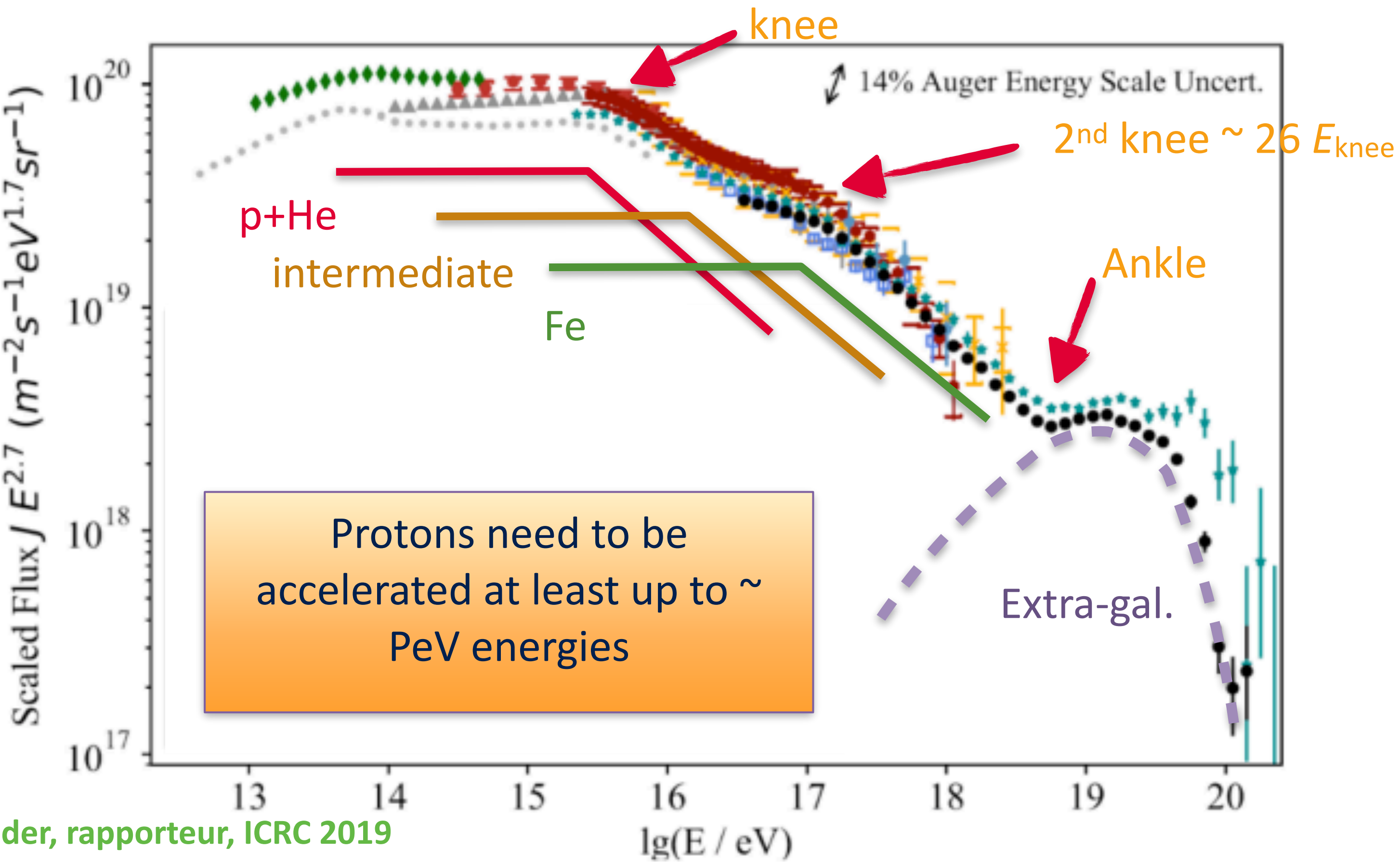
PeVatrons in the context of Galactic CRs

The cutoff shape is important to understand the knee region and the Galactic-extraGalactic transition region

distinguish between cutoff and steep spectra of broken spectra: requires to detect flux over several decades Do we need super-PeVatrons to fill the gap with extraGalactic CR?



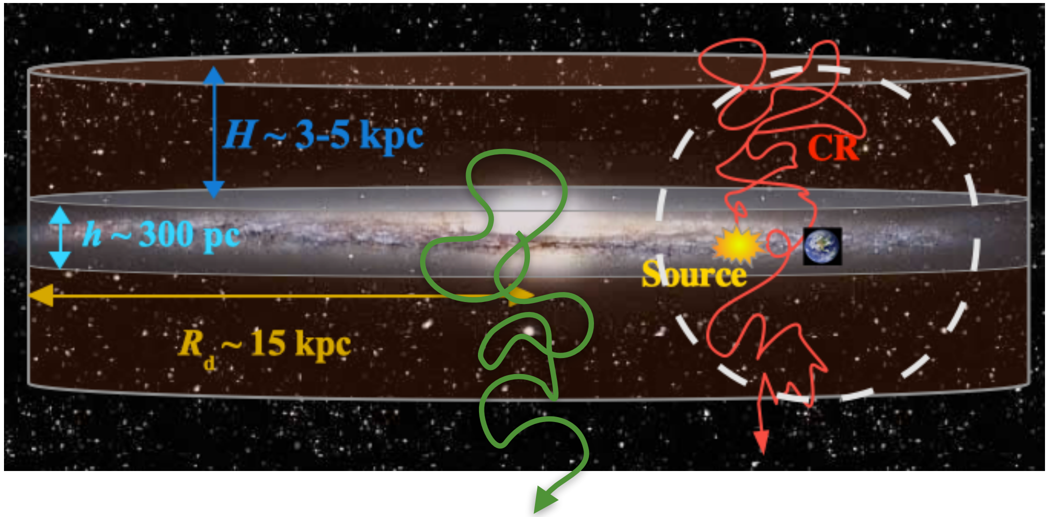
Protons need to be accelerated at least up to ~ PeV energies

F. G. Schroder, rapporteur, ICRC 2019

How close PeVatrons should be?

Sources should be located within few kpc from the Sun

- If diffusion is isotropic maximum distance ~ halo size $(H \lesssim 5\ \mathrm{kpc})$
- Propagation mainly along Galactic disc not allowed due to grammage
- Possible PeVatrons in the Galactic Centre may hardly contribute to the CR flux at Earth



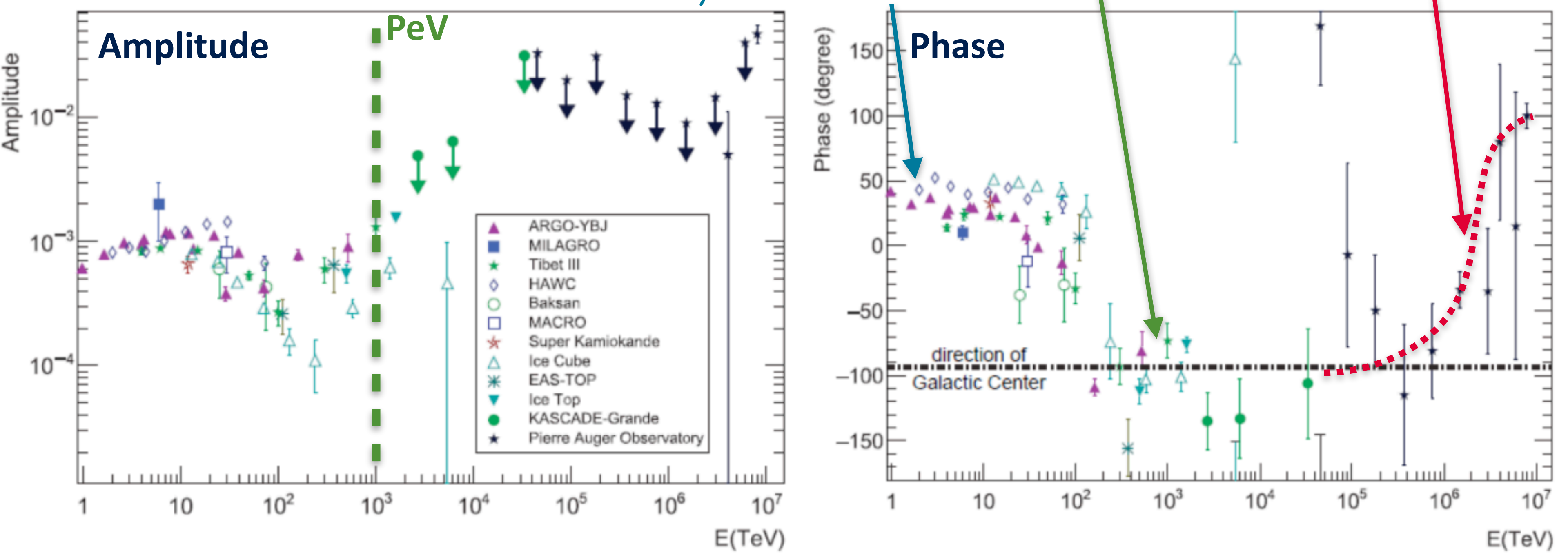
The escape of particle occurs mainly in the vertical direction

How many PeVatrons we need?

Anisotropy constraints

- At ~PeV anisotropy ~ 10^{-3} ⇒ Few sources cannot account for anisotropy
- # of sources depends on the local diffusion

$$\delta = \frac{\text{diffusive flux}}{\text{ballistic flux}} = \frac{3D\nabla f}{c\,f}$$



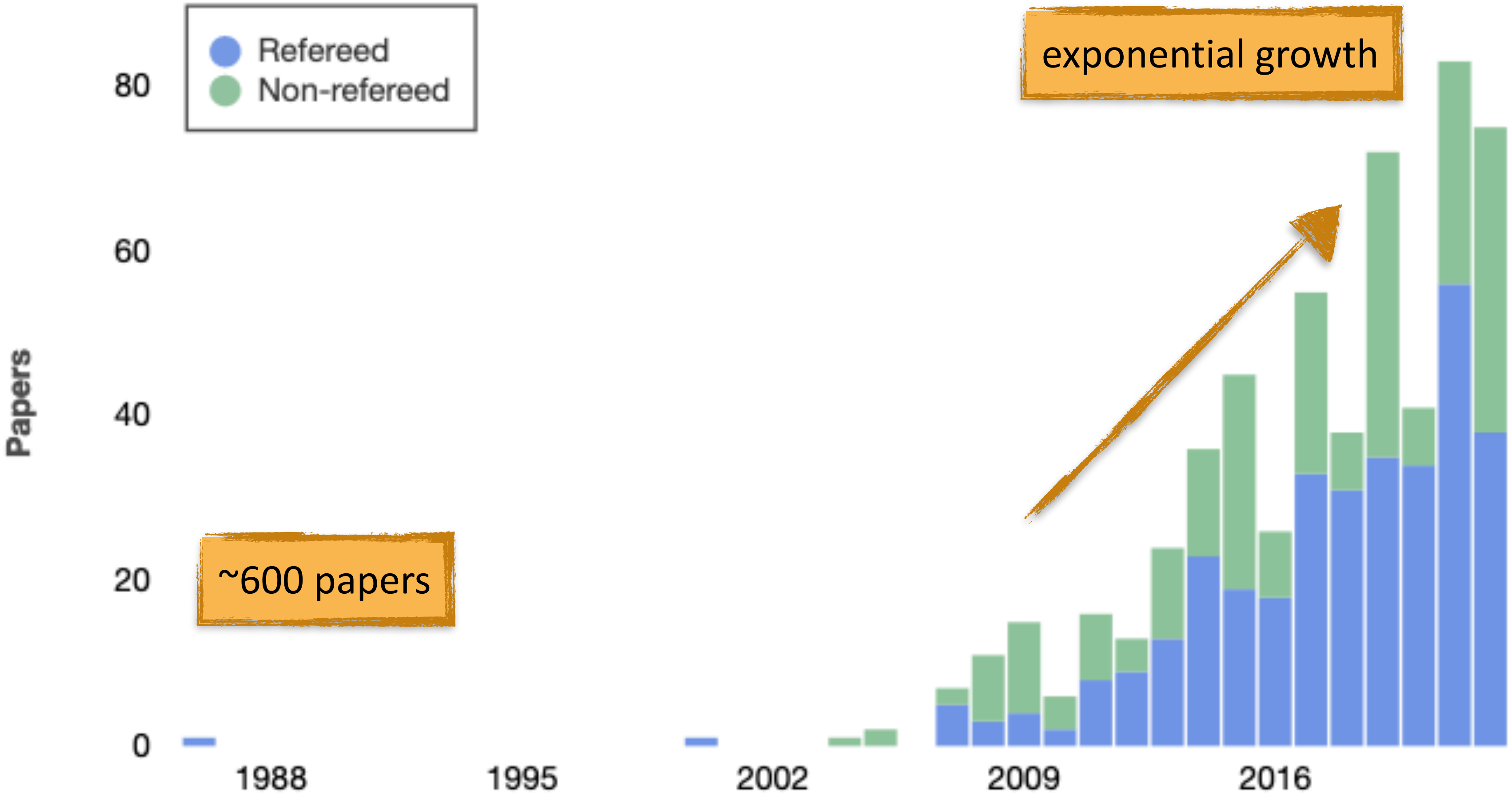
Anisotropy dominated
by distante sources

Anisotropy dominated
by local sources

Evidence of transition from
Galactic to extra-galactic

When did the word “Pevatron” appeared?

Idea borrowed from S. Gabici



exponential growth

~600 papers

ASD search for “Pevatron” or “Pevatrons”

When did the word "Pevatron" appeared?

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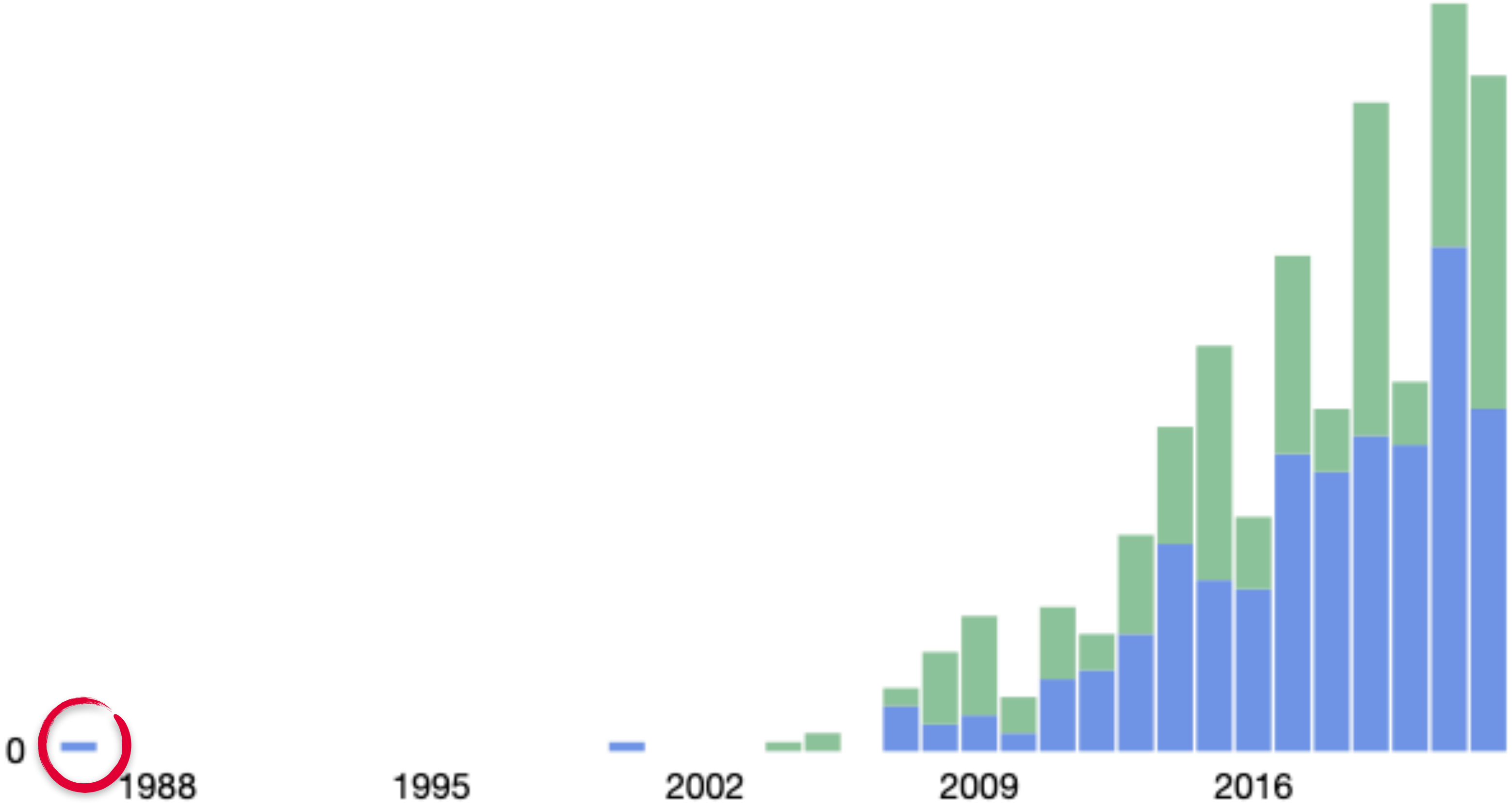

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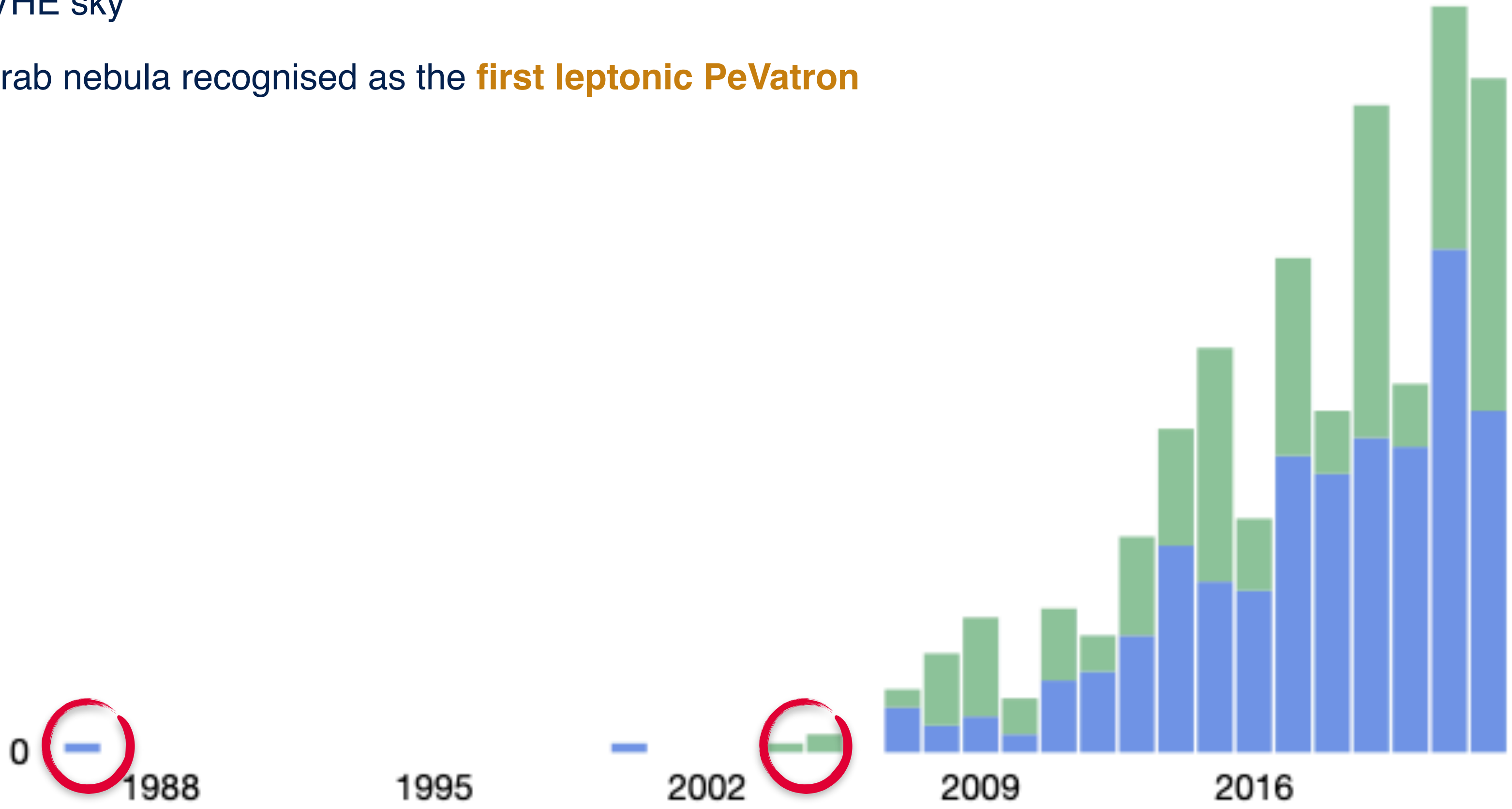

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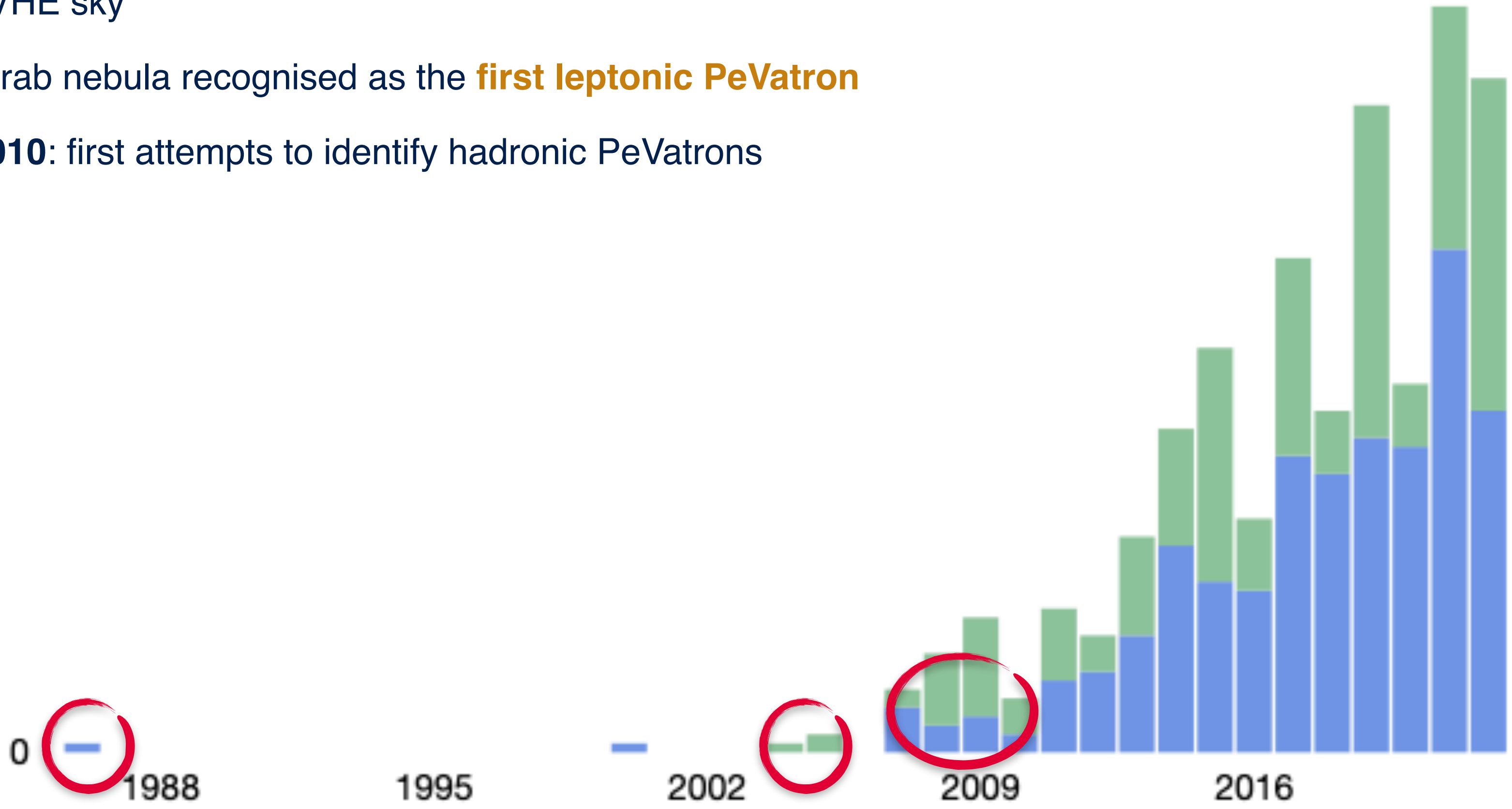

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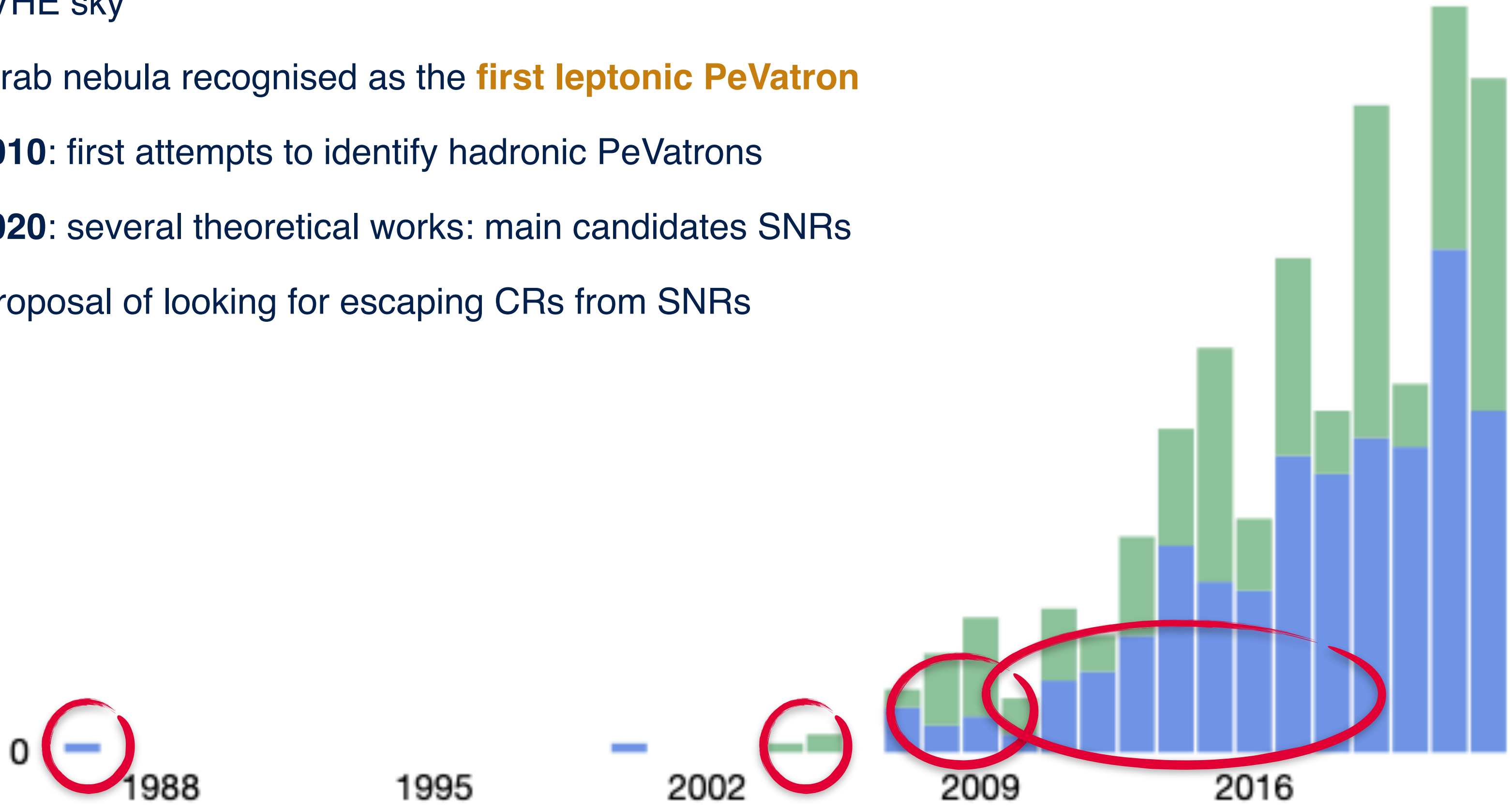

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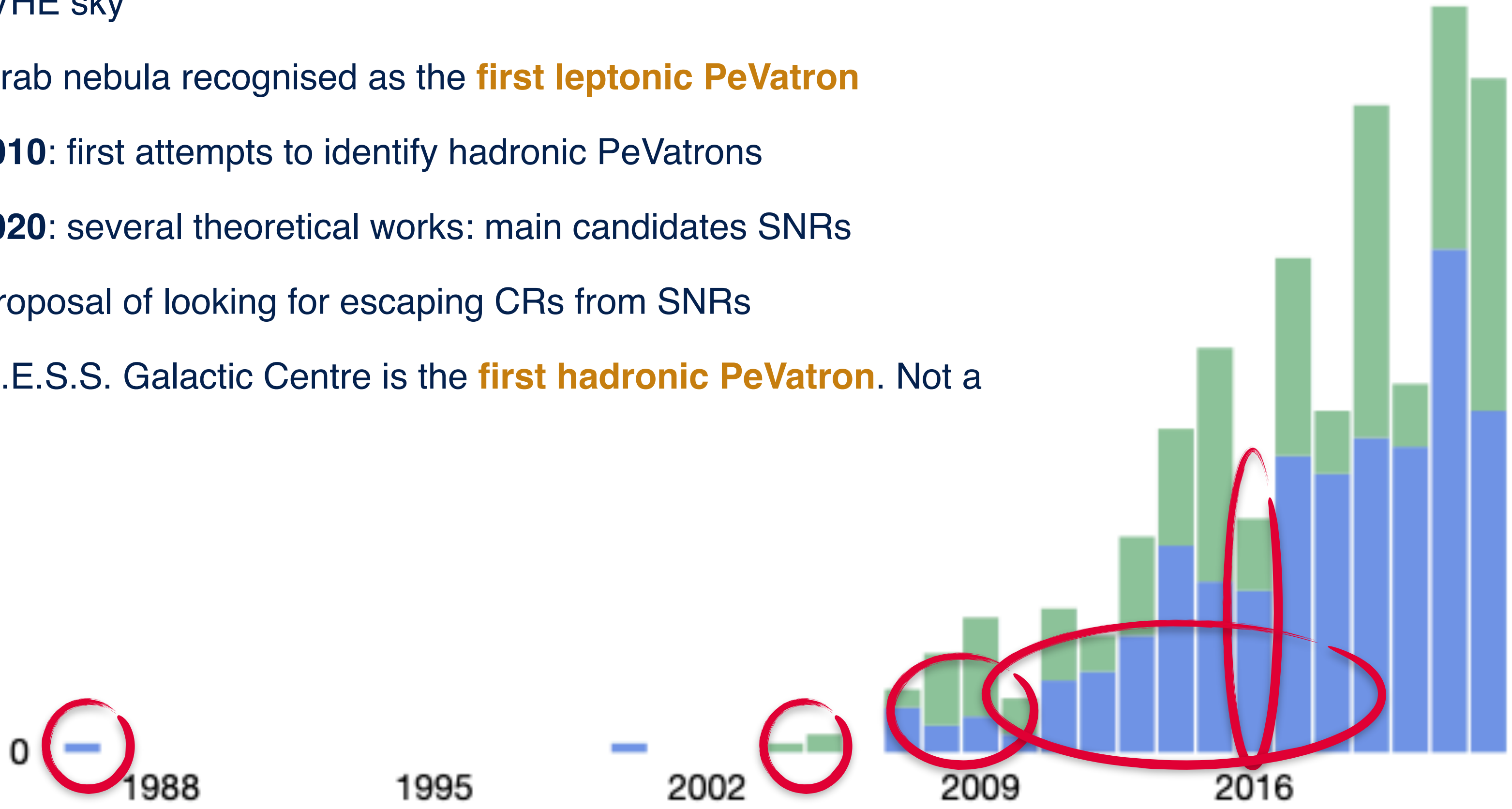

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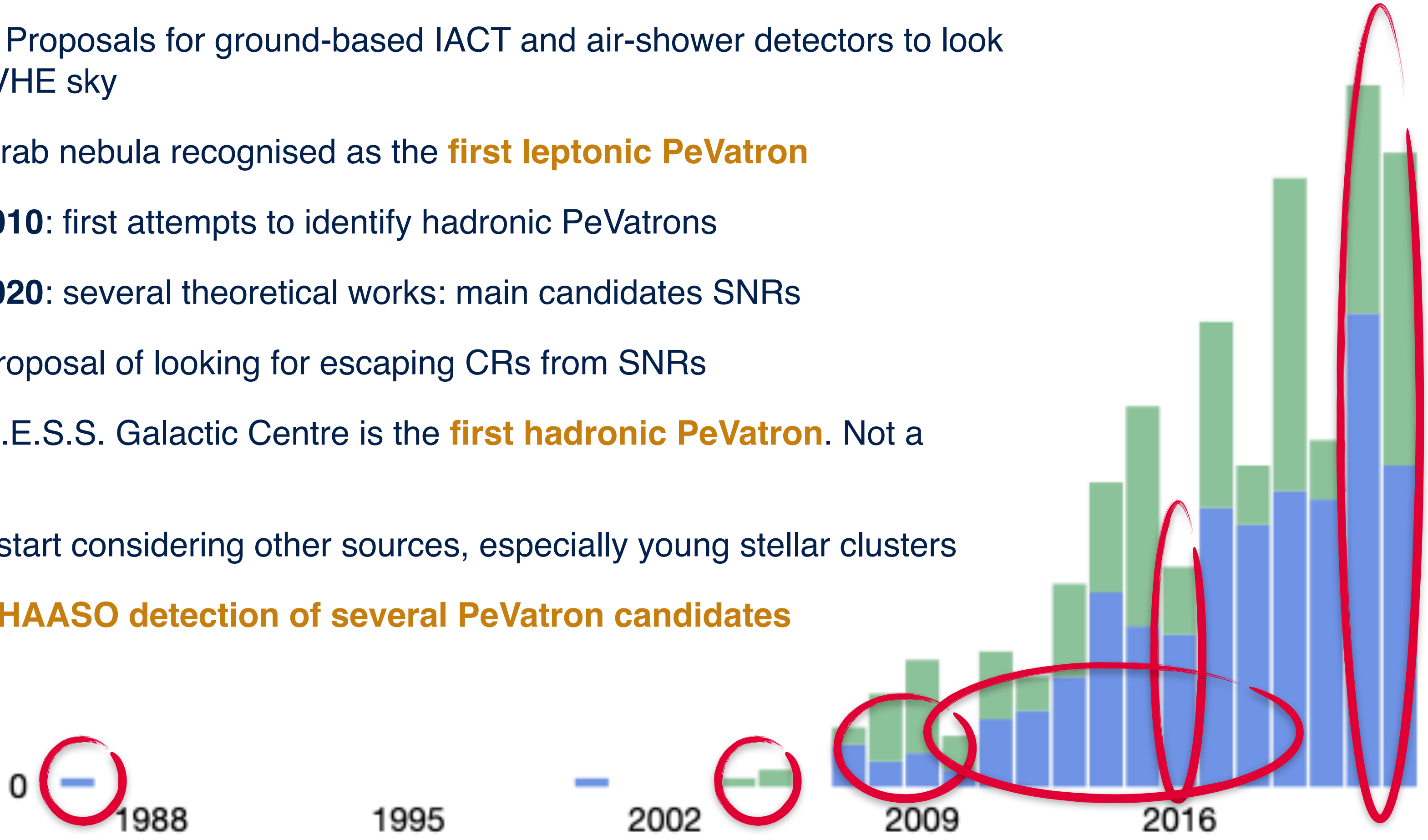
- **2010**: proposal of looking for escaping CRs from SNRs
- **2016**: H.E.S.S. Galactic Centre is the **first hadronic PeVatron**. Not a SNR!
- **>2019**: start considering other sources, especially young stellar clusters
- **2021**: **LHAASO detection of several PeVatron candidates**

Data-driven era



ASD search for "Pevatron" or "Pevatrons"

The most popular scenario: DSA@SNRs

- Why SNRs are so popular?
  1. Enough power to sustain the entire CR flux:

$$P_{\rm CR} \sim \frac{U_{\rm CR} V_{\rm CR}}{\tau_{\rm esc}(1\,{\rm GeV})} \sim 10^{40}\,{\rm erg} \qquad \left[\tau_{\rm esc} \simeq H^2/D(E)\right]$$

$$P_{\rm SN} \sim R_{\rm SN} E_{\rm SN} \sim 3 \times 10^{41} \frac{R_{\rm SN}}{(100\,{\rm yr})^{-1}} \frac{E_{SN}}{10^{51}{\rm erg}}\ {\rm erg/s}$$

$$\Rightarrow \boxed{P_{\rm CR} \simeq 1 - 10\,\%\,P_{\rm SN}}$$

  2. Enough sources:

$$N(<d, E) \sim {\rm R}_{\rm SN}\,\left(d/R_d\right)^2 \tau_{\rm esc}(E) = \frac{1}{100yr}\left(\frac{5{\rm kpc}}{15{\rm kpc}}\right)^2 2\,{\rm Myr} \simeq 7000$$

  3. A well studied theory for particle acceleration: DSA
  4. Observations show the presence of relativistic particles

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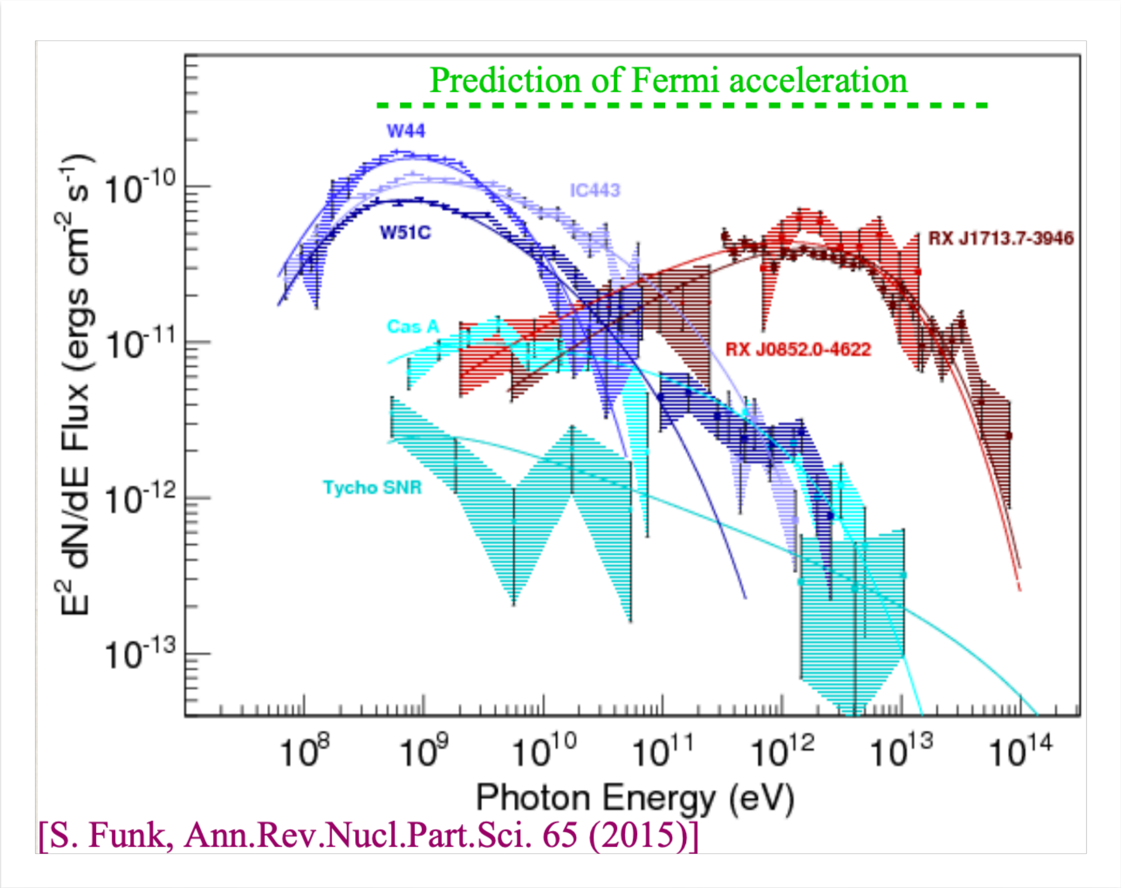
  3. A well studied theory for particle acceleration: DSA
  4. Observations show the presence of relativistic particles

- However:
  - No evidence for acceleration > 100 TV even in young SNRs
  - From theory only very powerful and rare SNRs can reach PeV

SNR in gamma-rays

No evidence of acceleration beyond ~100 TeV

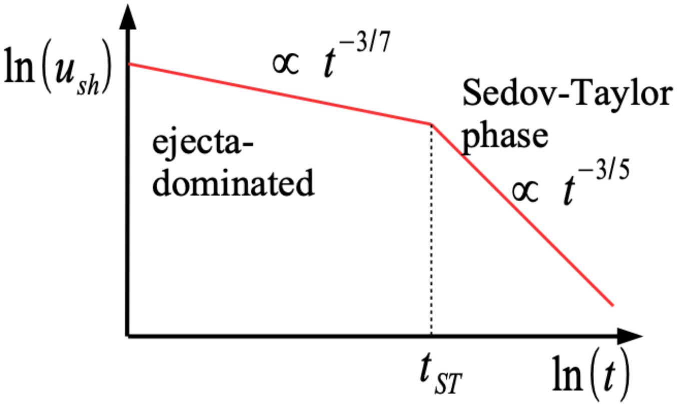
$$p \to \pi^0 \to \gamma\,\gamma \qquad\qquad E_\gamma \simeq 0.1\, E_p$$



[S. Funk, Ann.Rev.Nucl.Part.Sci. 65 (2015)]

Maximum energy in shock acceleration theory applied to SNRs

Maximum energy can only increase during the ejecta dominated phase of the SNRs because $u_{\rm sh} \sim {\rm const}$.



Shock radius $\begin{cases} R_{\rm sh} \propto t^{4/7} & \text{ejecta-dominated} \\ R_{\rm sh} \propto t^{2/5} & \text{Sedov-Taylor phase} \end{cases}$

But particle diffuse ahead of the shock: $d \propto \sqrt{Dt}$

↓

During the ST phase the highest energy particles cannot be reached by the shock and escape towards upstream

Estimate of the beginning of the ST phase: $M_{swept-up} = M_{ejecta}$

$$\begin{cases} t_{ST} = R_{ST}/u_{sh} \\ E_{SN} = 1/2\, M_{ej} u_{sh}^2 \end{cases} \Rightarrow t_{ST} \simeq 50 \left(\frac{M_{ej}}{M_\odot}\right)^{5/6} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{-1/2} \left(\frac{n_{\rm ism}}{{\rm cm}^{-3}}\right)^{-1/3} {\rm yr}$$

Maximum energy in shock acceleration theory applied to SNRs

Maximum energy obtained from the condition $t_{\rm acc} = t_{\rm ST}$

$$t_{\rm acc} = \frac{\tau_{\rm cycle}}{\Delta E/E} \approx 8\frac{D}{u_{\rm sh}^2}$$

Using the diffusion coefficient from quasi-linear theory:
$$\begin{cases} D = \dfrac{1}{3}\dfrac{r_L v}{\mathscr{F}(k_{\rm res})} \\ \mathscr{F}(k) = \left(\dfrac{kP(k)}{B_0^2/8\pi}\right) \end{cases}$$

Normalised energy density per unit logarithmic bandwidth

$$E_{\rm max} \simeq 5\times 10^{13}\mathscr{F}(k_{\rm max})\left(\frac{B_0}{\mu G}\right)\left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1/6}\left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{1/2}\left(\frac{n_{\rm ism}}{{\rm cm}^{-3}}\right)^{-1/3} {\rm eV}$$

$E_{\rm max}$ is weakly dependent on all parameters but the magnetic field

PeV energies requires $\mathscr{F} \gg 1$

Need of magnetic field amplification

How to amplify the magnetic field

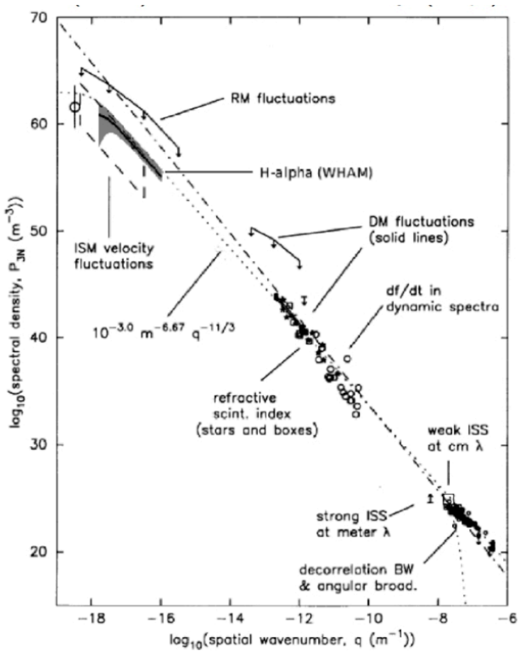
For reviews see: Drury (1994); Blasi (2013, 2019); Gabici et al (2019)

- In the regular ISM turbulence is injected by SNR and stellar winds:
  - Kolmogorov power spectrum $\mathscr{F}(k) = k \frac{\langle \delta B(k) \rangle^2}{B_0^2} = \frac{2}{3} \eta_B \left(L_{\rm tur} k \right)^{-2/3}$
  - Injection scale $L_{\rm tur} \sim 10 - 100$ pc
  - Total power in turbulence $\eta_B \sim 0.01 - 0.1$

→ $\mathscr{F}\left(1/r_L(1{\rm PeV})\right) \sim 10^{-3}$

$E_{\rm max} \sim few$ GeV

Electron density fluctuation in the ISM
[Armstrong et al.(1995) ApJ 443, 209]

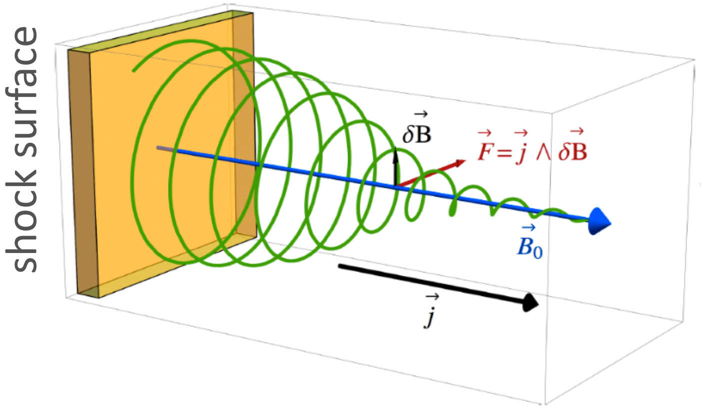


- Proposed magnetic field amplification mechanisms:
  - Resonant streaming instability [Skilling (1975)] → $\mathscr{F} \lesssim 1$
  - MHD instability due to density perturbation [Giacalone & Jokipii (2007)]
  - Acoustic instability [Drury & Falle (1983)]
  - Non-resonant streaming instability [Bell (2004)] → $\mathscr{F} \gtrsim 1$

} → $\mathscr{F} \sim 1$
in realistic conditions

Non-resonant streaming instability

Bell (2004); Bell et al. (2013), Schure at al. (2014)



The instability is excited by the Lorentz force

$$\vec{j}_{CR}\times\delta\vec{B}$$

where the current is due to escaping particles upstream.

Condition to trigger the instability: $\mathbf{j}\times\mathbf{B}$ **force > magnetic tension**

$$\frac{\vec{j}_{CR}}{c}\times\delta\vec{B}>\frac{1}{4\pi}\left(\nabla\times\vec{B}\right)\times\vec{B} \quad\Longrightarrow\quad j_{CR}>\frac{B_0 c}{4\pi L}$$

The minimum and maximum scales where the amplification works are:

$$\begin{cases} L_{\rm min}=\dfrac{1}{k_{\rm max}}=r_L(p_{\rm min})\dfrac{c}{v_d}\dfrac{U_{B_0}}{U_{\rm CR}} \\ L_{\rm max}=\dfrac{1}{k_{\rm min}}=r_L(p_{\rm min}) \end{cases}$$

The maximum growth occurs at $k=k_{max}\ll 1/r_L(p_{\rm min})$

The amplification saturates when: $\vec{j}_{CR}=\dfrac{Bc}{4\pi r_L(p_{\rm min})}$

The current can be written as: $j_{\rm CR}=ev_d n_{\rm CR}\simeq ev_d\, U_{\rm CR}/(p_{\rm min}c)$

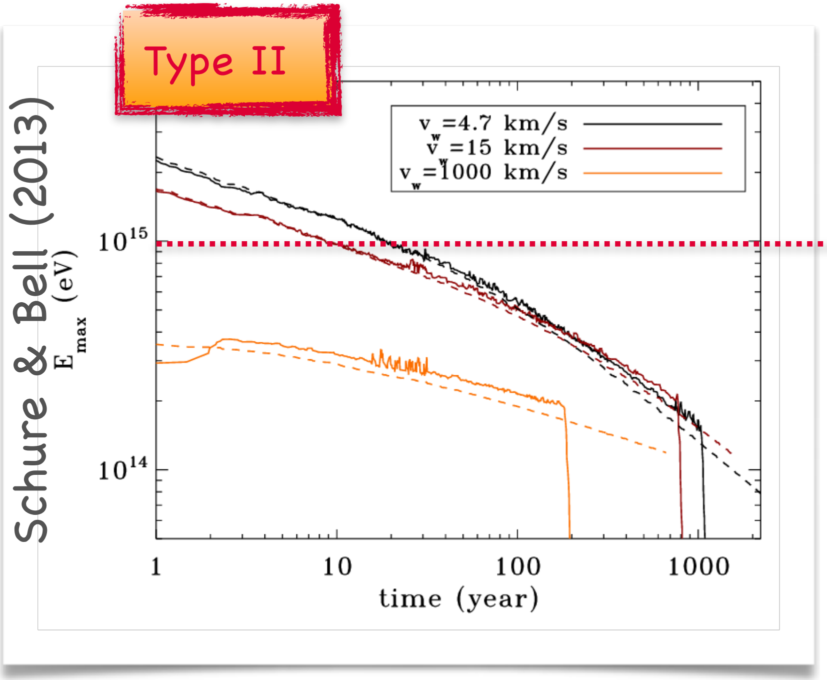
$$\Longrightarrow\quad \boxed{\frac{B_{\rm sat}^2}{B_0^2}\sim\frac{U_{\rm CR}}{U_{B_0}}\frac{v_d}{c}}$$

can be >> 1

Only very young SNRs can accelerate to PeV

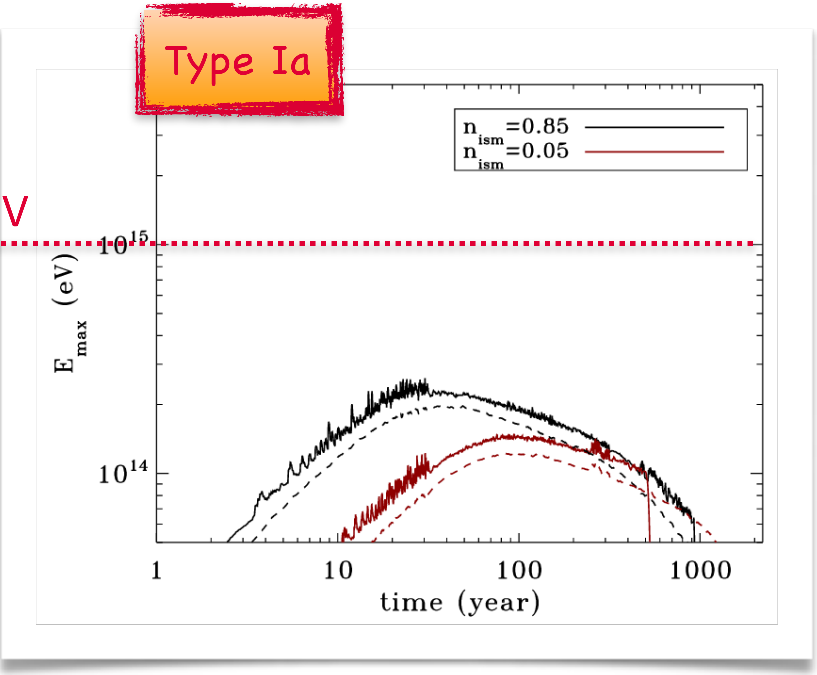
$$\frac{B_{\rm sat}^2}{B_0^2} \sim \frac{U_{\rm CR}}{U_{B_0}}\frac{v_d}{c} \propto n_0 v_{sh}$$

Efficient amplification requires:
- large densities
- large shock speed



Schure & Bell (2013)

1 PeV

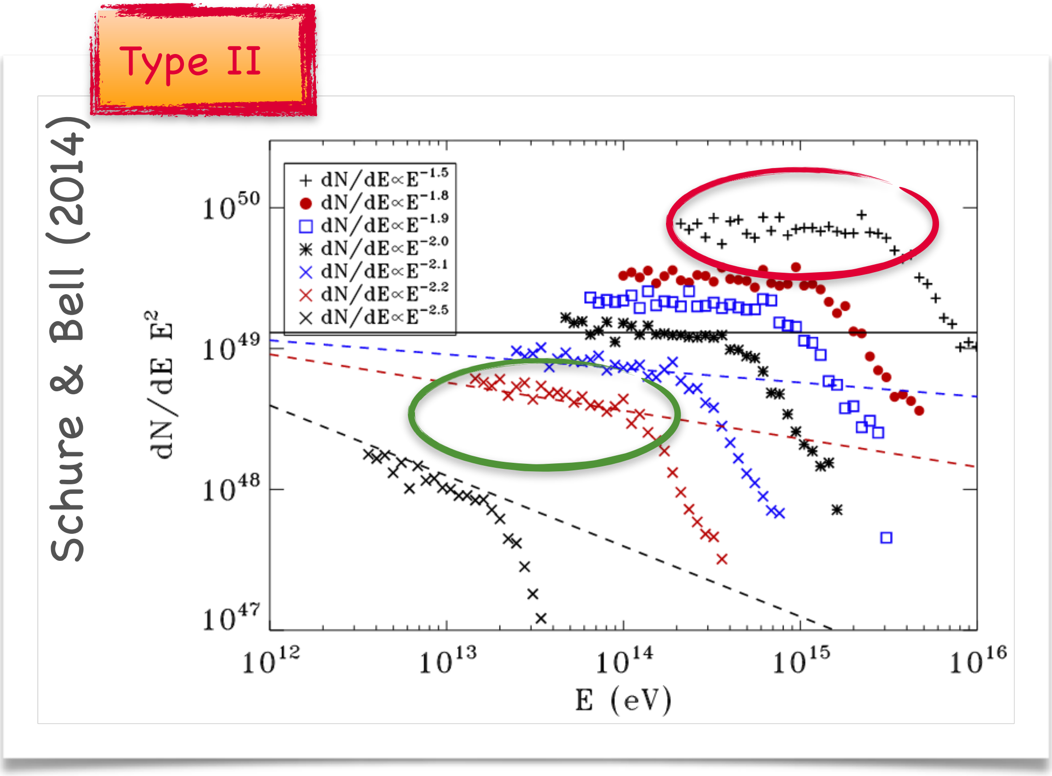


PeV energies can be reached:

- Only by core-collapse SN expanding into dense environment (slow and dense progenitor's wind)
- During the very early phase (age $\lesssim 50$ years)

Maximum energy vs. slope

Spectrum of CRs released by the SNR during its entire lifetime



Schure & Bell (2014)

Knee at the right place

injected spectrum too hard

Right spectrum

low maximum energy

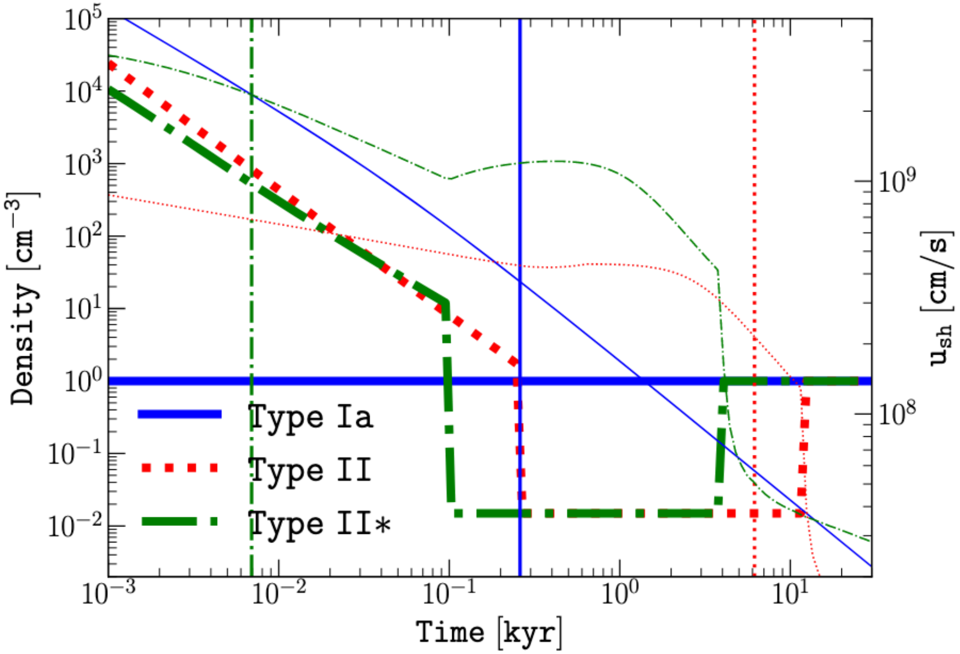
Exploring different SNR models

Cristofari, Blasi & Amato (2020)

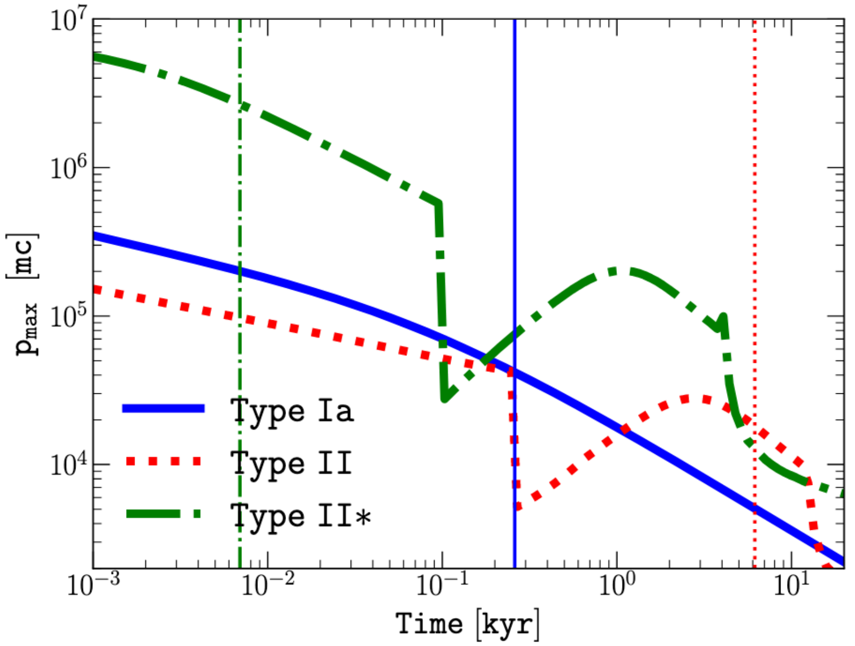
Parameters for different type of SNRs

Type	Ia	II	II*
M_{ej} $[M_\odot]$	1.4	5	1
E_{SN} $[10^{51}$ erg$]$	1	1	10
$\dot{M}$ $[10^{-5}$ $M_\odot/yr]$	–	1	10
u_w $[10^6$ cm/s $]$	–	1	1
r_1 [pc]	–	1.5	1.3

Environmental properties



Maximum energy

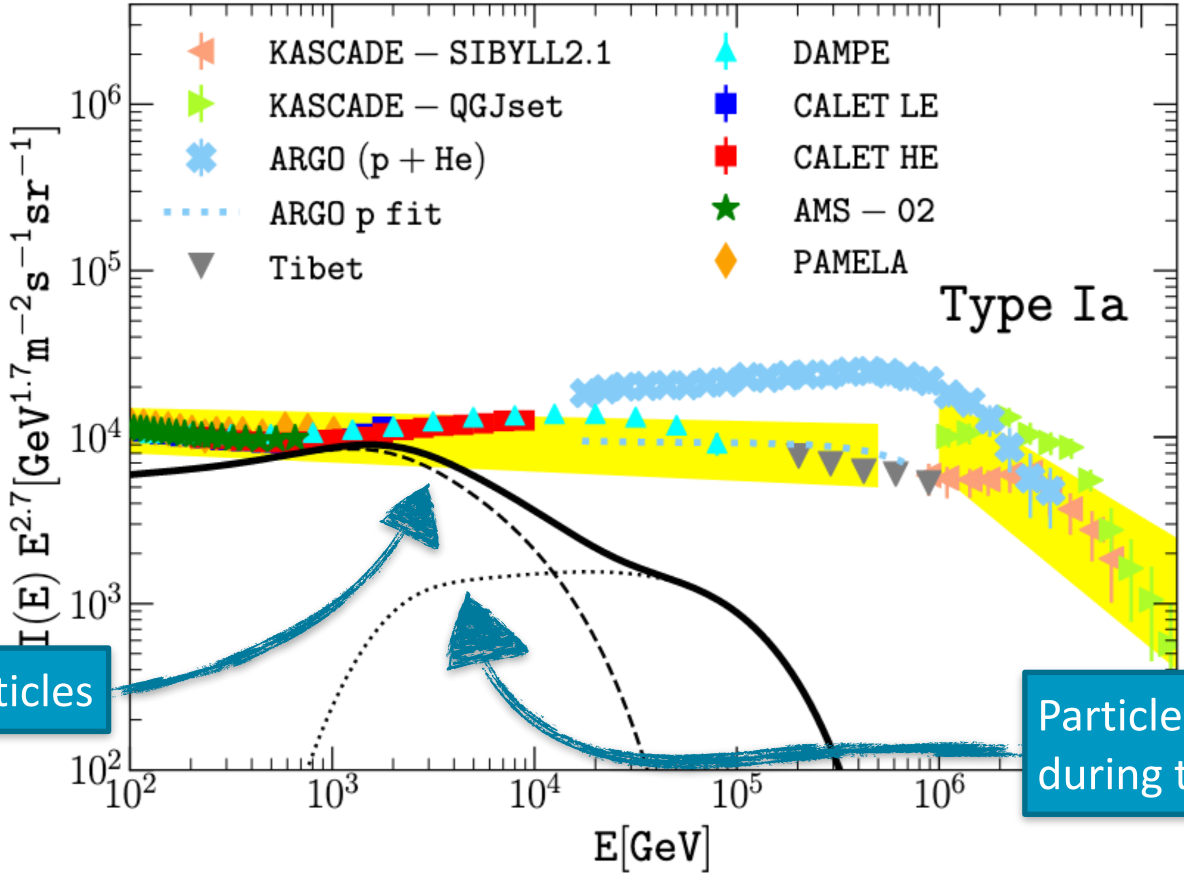


Accounting for Galactic propagation

Cristofari, Blasi & Amato (2020)

$$\mathrm{Rate} = \frac{1}{100\ \mathrm{yr}}\ ;\ \xi_{\mathrm{CR}} = 0.1$$

COMPARISON WITH THE CR SPECTRUM DETECTED AT THE EARTH



Confined particles

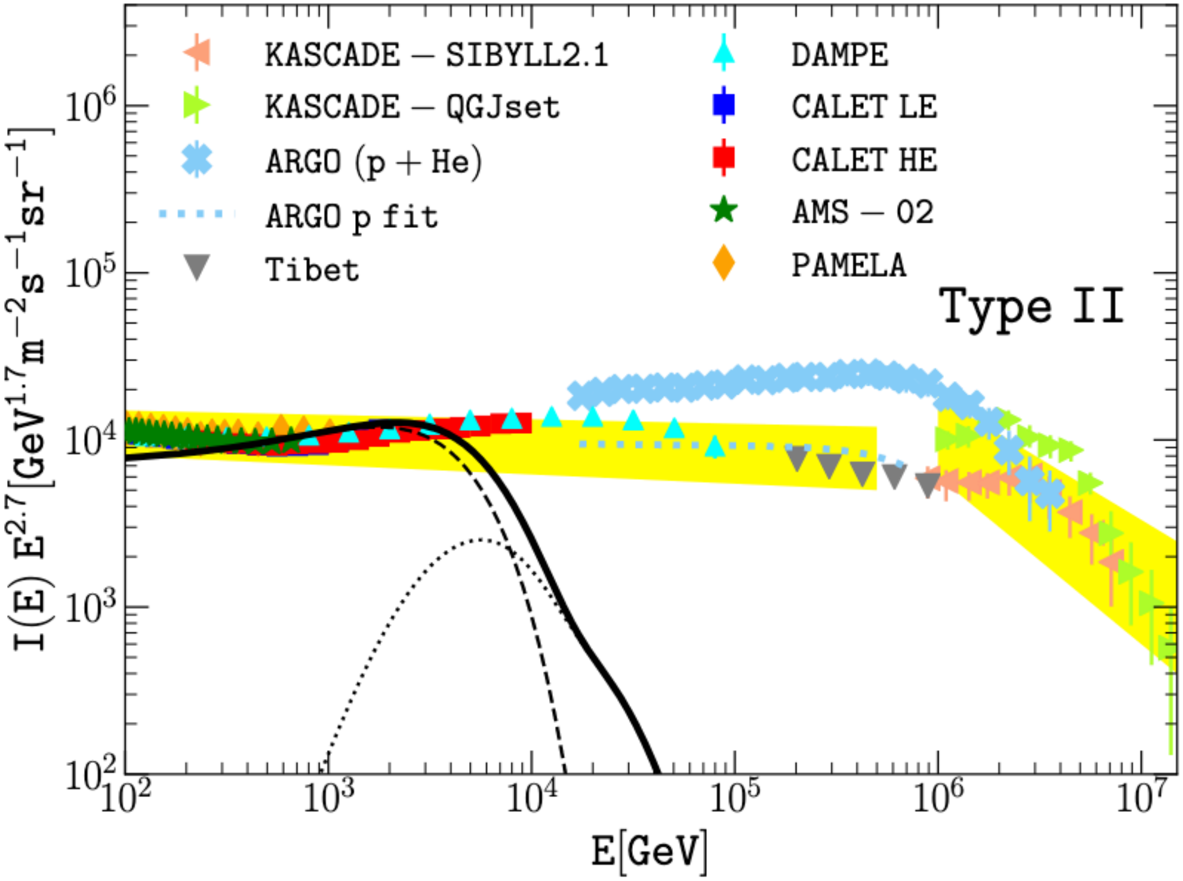
Particles escaping during the acceleration

Accounting for Galactic propagation

Cristofari, Blasi & Amato (2020)

$$\text{Rate} = \frac{2}{100\ \text{yr}}\ ;\ \xi_{\rm CR} = 0.06$$

COMPARISON WITH THE CR SPECTRUM DETECTED AT THE EARTH

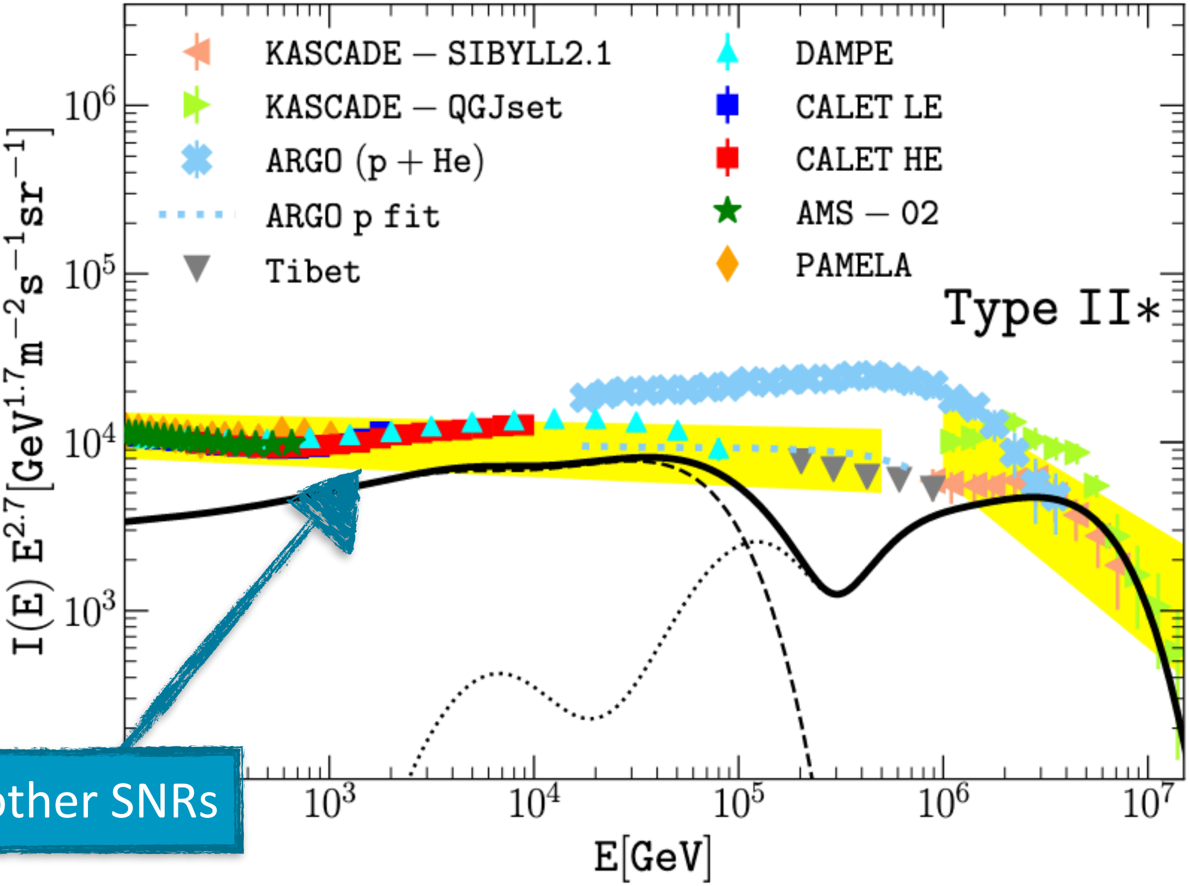


Accounting for Galactic propagation

Cristofari, Blasi & Amato (2020)

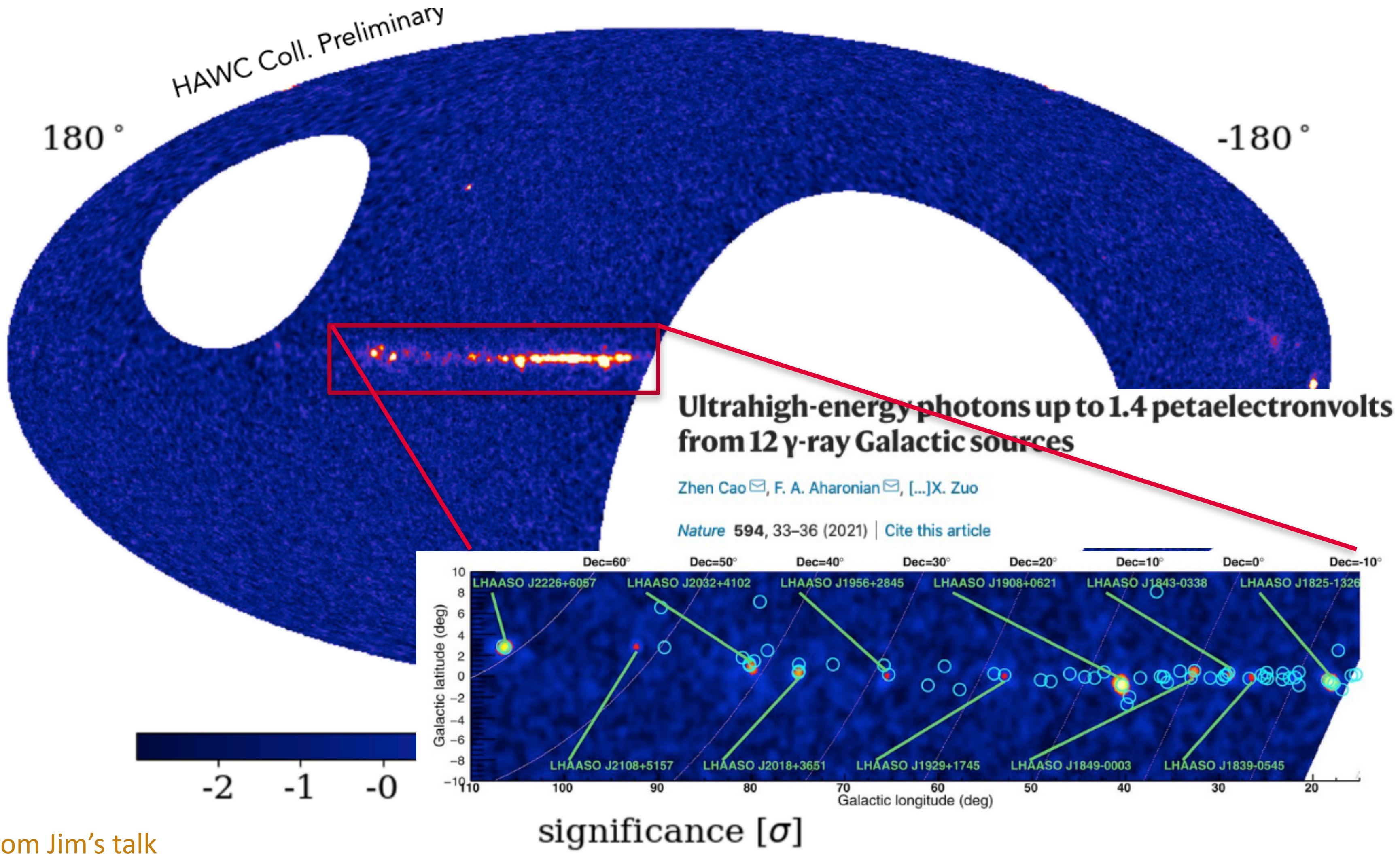
$$\mathrm{Rate} = \frac{3}{10000\ \mathrm{yr}}\ ;\ \xi_{\mathrm{CR}} = 0.1$$

If only Tipe II* are PeVatrons
⇒probability to detect ~ 0



No room for other SNRs

The VHE sky in the present



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

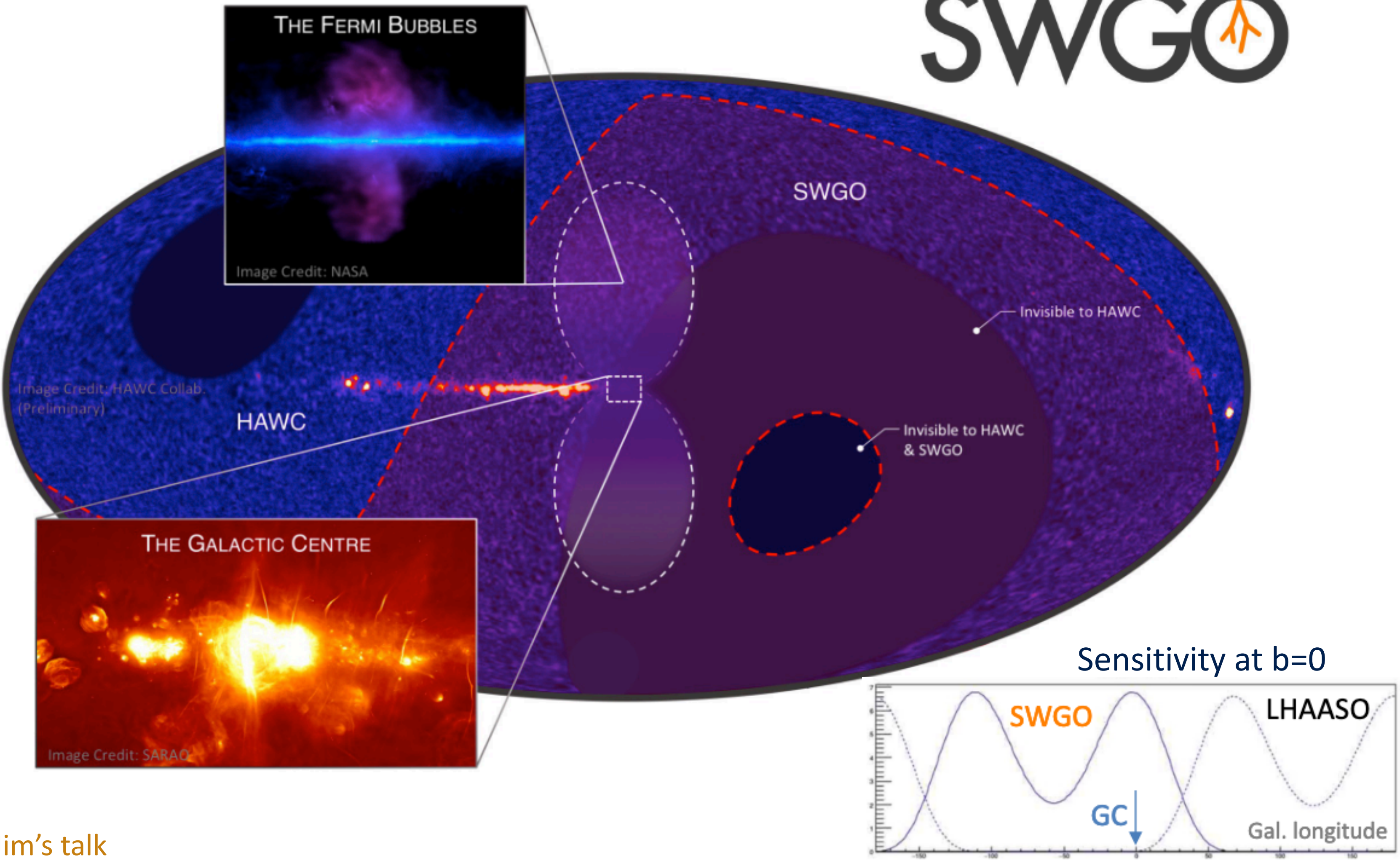
Zhen Cao, F. A. Aharonian, [...]X. Zuo

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

Slide from Jim’s talk

The VHE sky in the future

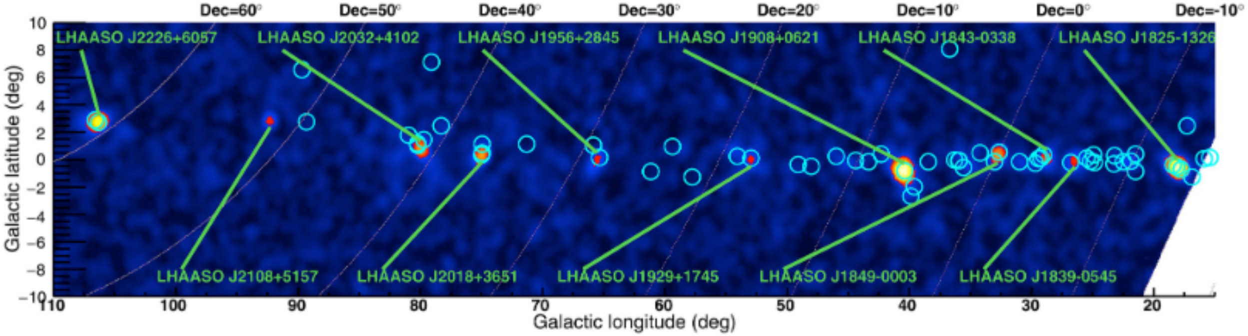
www.swgo.org



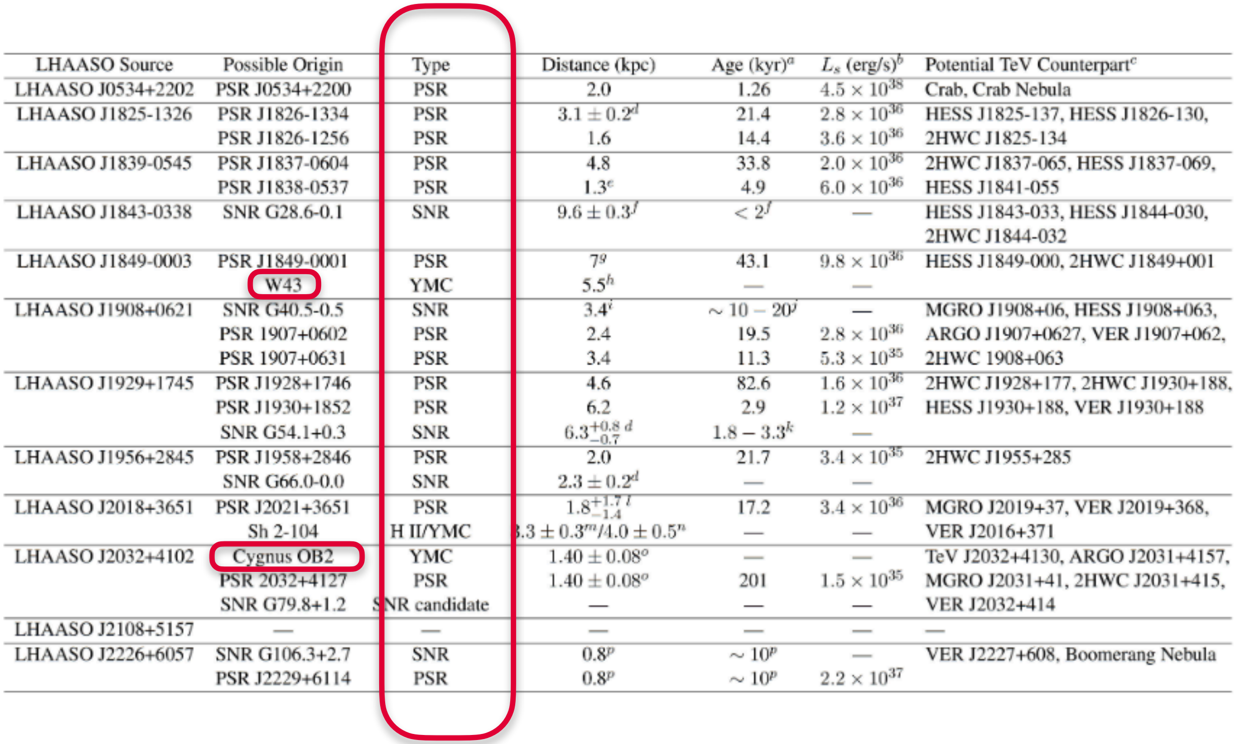
Sensitivity at b=0

Slide from Jim’s talk

LHAASO sources



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.



LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

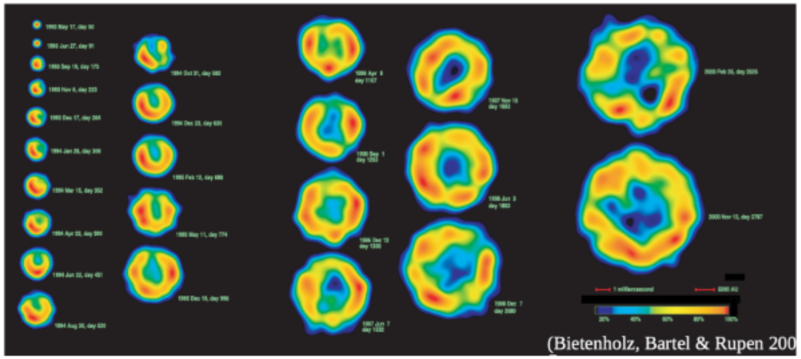
Uncertain nature of sources due to poor angular resolution

- **Not many SNRs**
- **Many PSRs** **(not a surprise: probability of one PSR in LHAASO PSF ~1)**
- **2 young massive SC**

Which are the alternatives?

❖ ***Hadronic sources***

- Core-collapse supernovae
  - gamma-rays in the first days after SN explosion [see P. Cristofari et al. (2020,2022)]



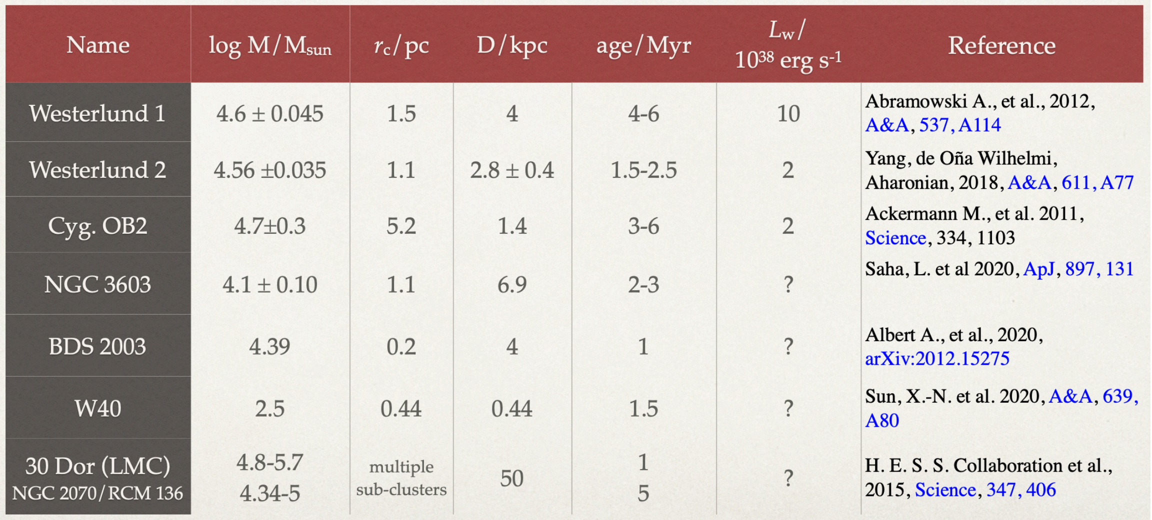
(Bietenholz, Bartel & Rupen 200

The potential for detection with CTA (Consortium paper in preparation)
F. Acero, C. Boisson, J. Devin, V. Dwarkadas, G. Giacinti, N. Komin, A. Marcowith, M. Renaud, S. Ohm, J. Vink, H. Sol, T. Stolarczyk, V. Tatischeff

Which are the alternatives?

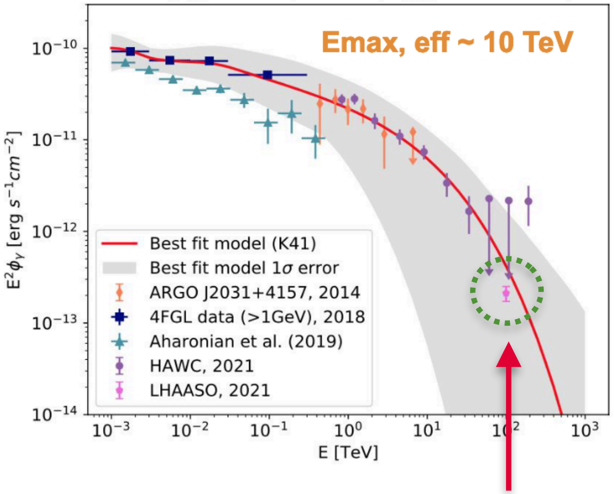
❖ *Hadronic sources*

- Core-collapse supernovae
- Massive young stellar clusters
  - Several YSC have been associated to gamma-rays
  - LHAASO detected ~1.4 PeV photon in coincidence with Cygnus OB2
  - Theoretical models not very advanced yet



Name	log M/M_{sun}	r_c/pc	D/kpc	age/Myr	L_w/ 10^{38} erg s^{-1}	Reference
Westerlund 1	4.6 ± 0.045	1.5	4	4-6	10	Abramowski A., et al., 2012, A&A, 537, A114
Westerlund 2	4.56 ±0.035	1.1	2.8 ± 0.4	1.5-2.5	2	Yang, de Oña Wilhelmi, Aharonian, 2018, A&A, 611, A77
Cyg. OB2	4.7±0.3	5.2	1.4	3-6	2	Ackermann M., et al. 2011, Science, 334, 1103
NGC 3603	4.1 ± 0.10	1.1	6.9	2-3	?	Saha, L. et al 2020, ApJ, 897, 131
BDS 2003	4.39	0.2	4	1	?	Albert A., et al., 2020, arXiv:2012.15275
W40	2.5	0.44	0.44	1.5	?	Sun, X.-N. et al. 2020, A&A, 639, A80
30 Dor (LMC) NGC 2070/RCM 136	4.8-5.7 4.34-5	multiple sub-clusters	50	1 5	?	H. E. S. S. Collaboration et al., 2015, Science, 347, 406

Cygnus Cocoon spectrum



Emax, eff ~ 10 TeV

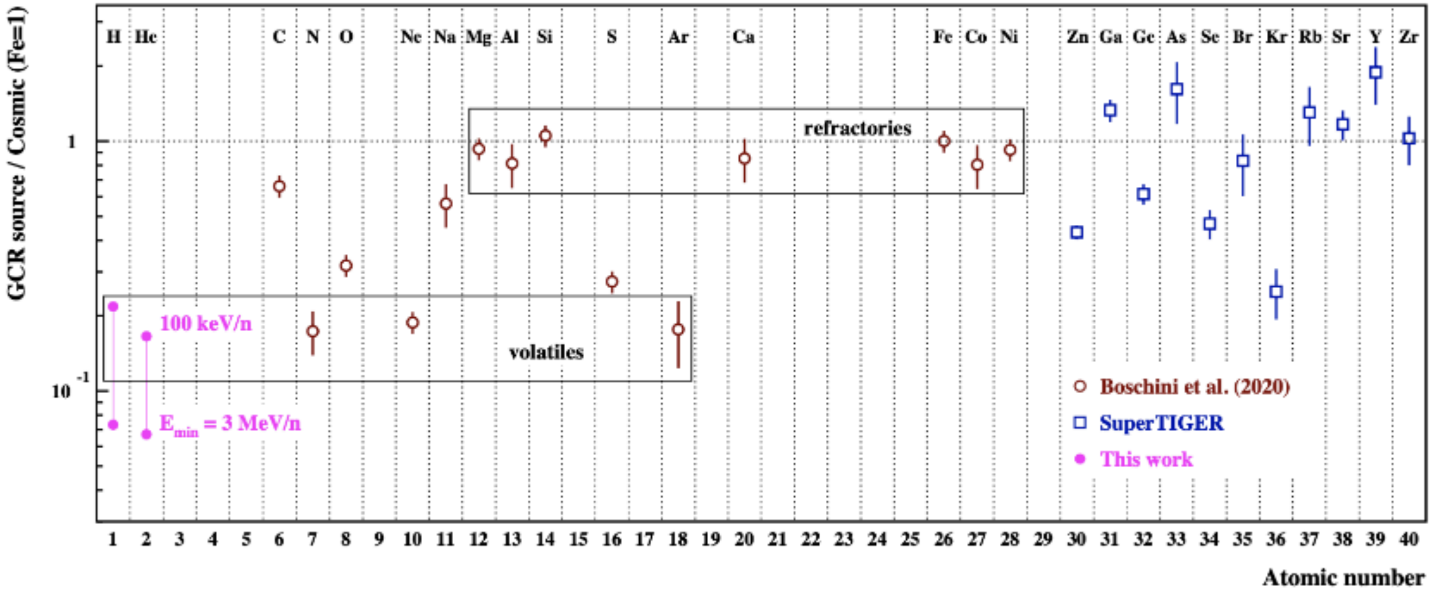
LHAASO flux: no correction for the extraction area

Which are the alternatives?

❖ ***Hadronic sources***

- Core-collapse supernovae
- Massive young stellar clusters
- Super bubbles
  - At least a fraction of CRs need to be accelerated from winds material
  - see eg. Parizot et al. (2004); Ferran & Marcowith (2010); Vieu, Gabici & Tatisheff (2021, 2022)

Tatischeff + (2021)

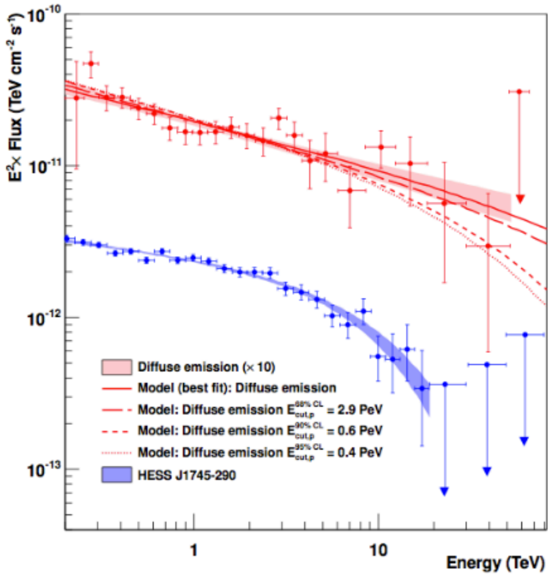


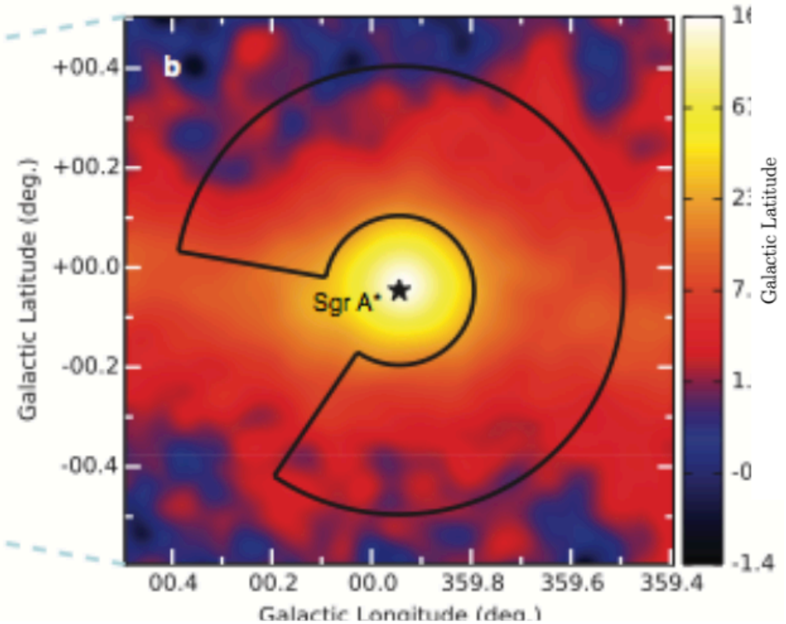
DSA -> preferential injection of high A/Q ions [Meyer, Drury & Ellison 1998]
SBs are hot-> A/Q ~2 for all elements -> flat abundances

Which are the alternatives?

- ***Hadronic sources***
  - Core-collapse supernovae
  - Massive young stellar clusters
  - Super bubbles
  - Galactic centre
    - Sgr A* or stellar clusters?
    - Remember: difficult to contribute to local PeV CRs

H.E.S.S. coll. 2016





Which are the alternatives?

- ***Hadronic sources***
  - Core-collapse supernovae
  - Massive young stellar clusters
  - Super bubbles
  - Galactic centre
  - Giant magnetic islands
    - Purely theoretical proposal [Pezzi, Blasi, Matthaeus (2022)]
    - Particle trapping and energisation in a Fermi I-like process
    - Acceleration sites difficult to identify
    - No clear correlation with gas

→ **difficult detection**

Which are the alternatives?

❖ ***Hadronic sources***

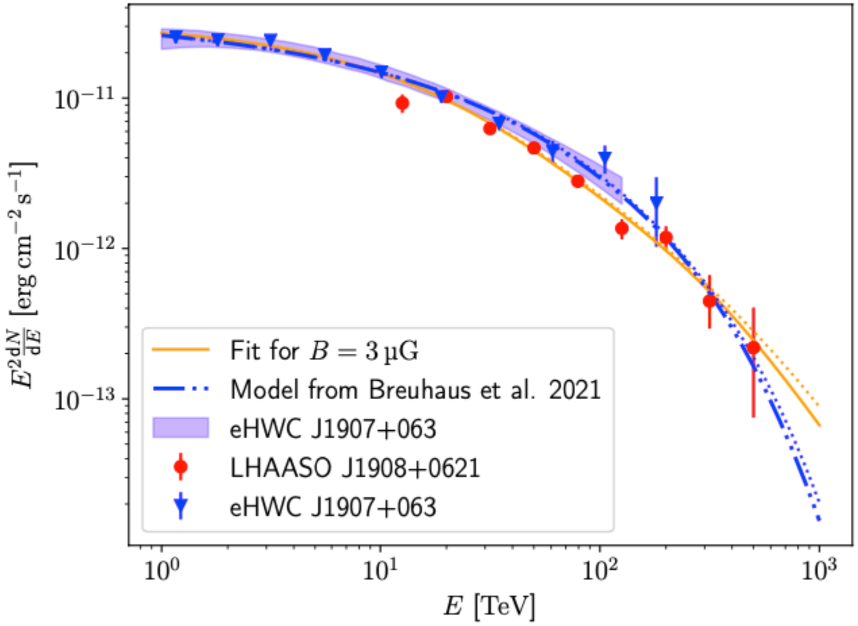
- Core-collapse supernovae
- Massive young stellar clusters
- Super bubbles
- Galactic centre
- Giant magnetic islands

❖ ***Leptonic sources***

- Pulsars and PWNe
  - PWNe as hadronic accelerators?

Pulsars & PWNe

- Leptonic origin of gamma-rays > 100 TeV is possible
    - requires low magnetic field ($\lesssim 3\mu G$)
        - not easy to accomodate for young PWNe
        - need to separate acceleration from cooling zones
    - detailed MWL analysis is required
    - All LHAASO sources are close to pulsars (not a surprise due to the large angular resolution)



e.g.
M. Breuhaus, B. Reville, J. Hinton (2022) A&A 660, A8

Pulsars & PWNe

- Leptonic origin of gamma-rays > 100 TeV is possible
- Acceleration is limited by the maximum pulsar potential drop

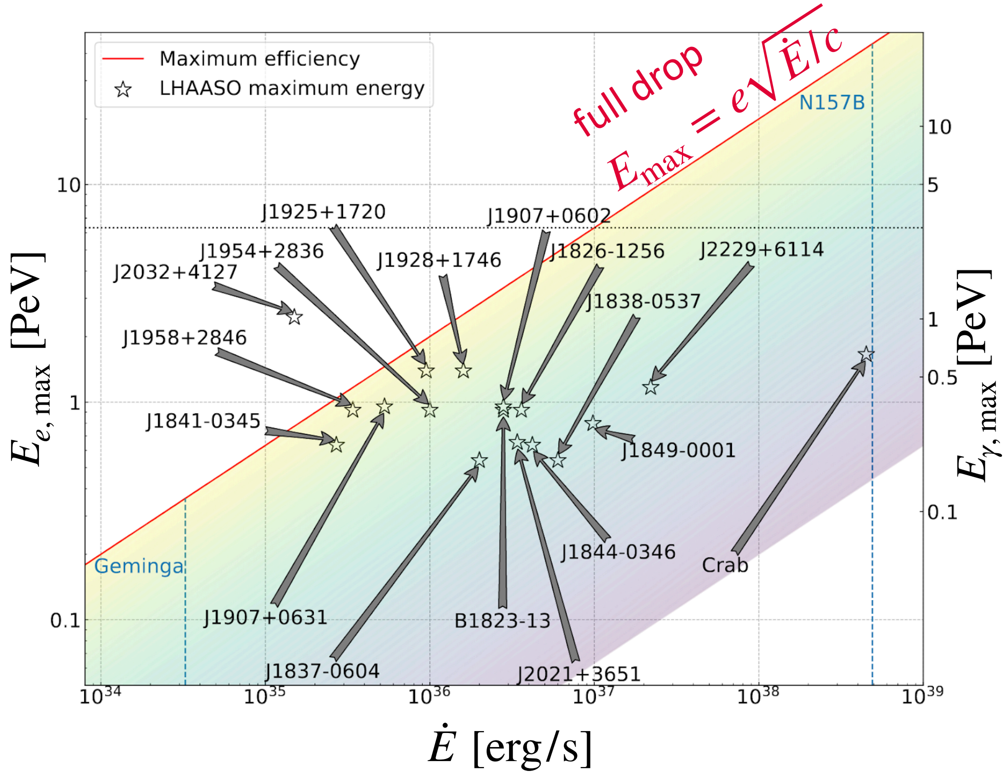
$$\Phi_{\rm PSR} = \sqrt{\dot{E}/c}$$

$$E_{\max} \approx e\Phi_{\rm PSR} = \xi_e\, e\, B_{TS}\, R_{TS}$$

$$\frac{B_{TS}^2}{4\pi} = \xi_b \frac{\dot{E}}{4\pi R_{TS}^2\, c}$$

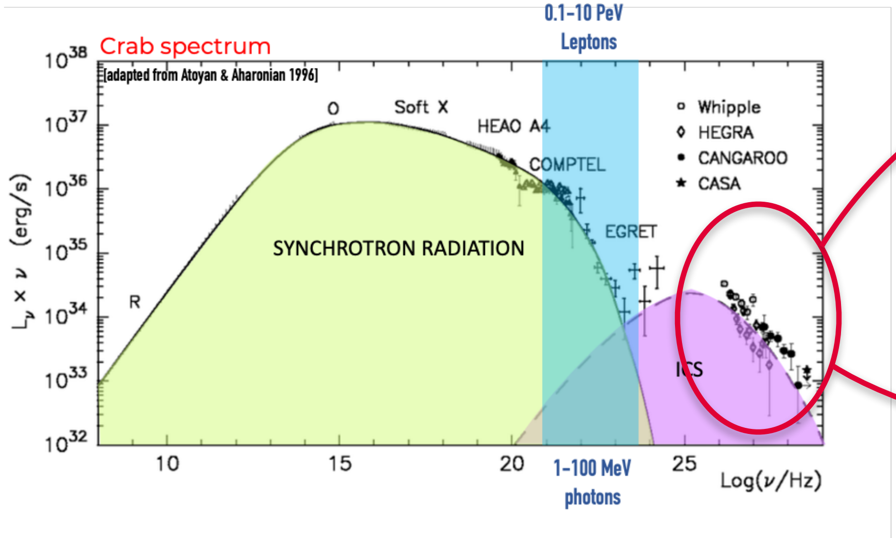
$$\boxed{E_{\max} \simeq 1.8\ \xi_e\ \xi_b^{1/2} \left(\frac{\dot{E}}{10^{36}\mathrm{erg/s}}\right)^{1/2}\ \mathrm{PeV}}$$

$[\xi_e, \xi_b] < 1$

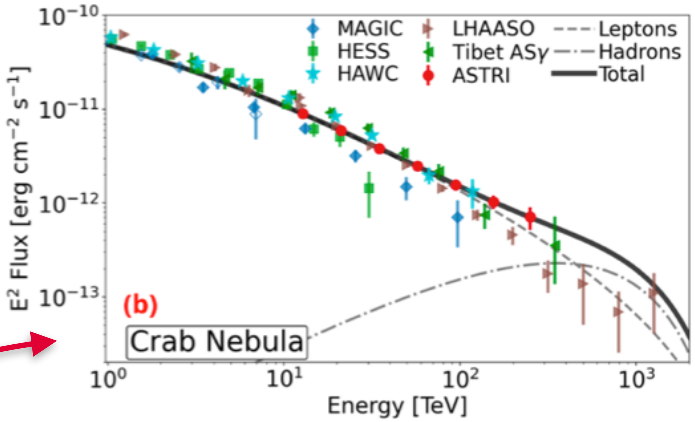


Pulsars & PWNe

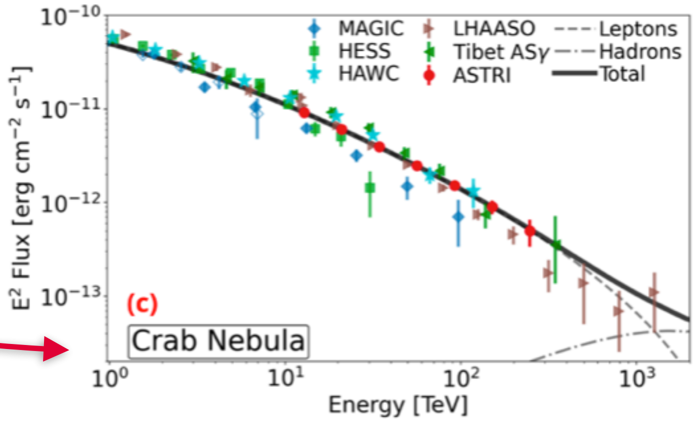
- Leptonic origin of gamma-rays > 100 TeV is possible
- Acceleration is limited by the maximum pulsar potential drop
- Theoretically PWNe can be hadronic PeVatrons as well
  - If protons (hadrons) are stripped from the NS surface and accelerated like electrons, we expect ~few % of the total energy channelled into accelerated hadrons [Guepin, Cerutti & Kotera, 2020]
  - pp emission may show up in the high energy tale of IC emission



4% protons with γ=5x10⁶



4% protons with γ=2x10⁷



Role of CTAO

CTAO does not have the sensitivity of air-shower particle detectors like LHAASO at PeV energies, BUT

- large energy coverage (with good sensitivity!)
- excellent angular resolution/energy resolution

➡ CTAO will be crucial to “make sense” out of LHAASO PeVatron discoveries by providing in-depth observations!

Possible observational strategies

- Play the strength of the instrument:
  - Excellent angular resolution:
    - energy-dependent morphology
    - correlation studies with gas
    - identify the acceleration regions(e.g. composite SNR+PWN)
    - MWL comparisons
  - Wide energy band coverage and energy resolution:
    - precise determination of spectral shape
    - distinguish between leptonic and hadronic

Key points to identify sources and to understand the physics

- (relatively) Narrow field of view:
  - survey not optimal; a few deep pointing (with all telescopes) can catch a good fraction of our Galaxy's most interesting objects (similar strategy will be used by ASTRI-MA)
- Follow-up of PeVatron candidate sources
  - Northern sky: from LHAASO and relatively soon from ASTRI-MA
  - Southern sky: from HESS, from SWGO and CTA GPS

Object-oriented strategies

- If PeVatrons are SNRs (at age $\lesssim$ tens of ys as suggested by theory)
  - Look for emission from close-by clouds illuminated by escaping PeV particles
  - Look for young SNe in close-by galaxies to check for TeV-PeV emission
- Stellar Clusters
  - Very extended sources: require deep observations
- PWNe
  - High spatial resolution + high energy resolution
  - Hadronic contribution: combined analysis with ASTRI, LHAASO (or SWGO) only for powerful pulsars
- Giant magnetic islands
  - the most difficult case to detect: probably only diffuse emission will be detected
- Super-PeVatrons
  - Search of synchrotron emission due to secondaries with LSTs (in possible synergy with Fermi-LAT) [F. Aharonian suggestion]
- For PeVatron candidates High Night sky background deep observations can be done: they do not subtract observation time from other KSPs)
- Overlap with other KSPs: GC and Star-forming regions

Conclusions

- The PeVatrons science case is today reacher and more puzzling than what was in the past
- Gamma-ray VHE-UHE measurements are a powerful tool for understanding particle acceleration up to and beyond PeV
  - ✦ Huge step forward in sensitivity at UHE with LHAASO
- CTAO and ASTRI-MA will make the difference
  - ✦ Small angular and energy resolution
  - ✦ Wide energy range

→ needed to identify sources and understand physics

- Best observational strategy
  - ✦ Deep pointing of few selected targets