Origin of the most energetic particles in the Universe

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Particles and Cosmology – 2025

при поддержке гранта РНФ № 24-12-00457

Lecture 2

1. Possible Cosmic Ray sources
   - Galactic
   - Extragalactic

2. Fundamental constraints for acceleration sites

3. More realistic: escape-limited and loss-limited acceleration

Summary of Lecture 1

- Cosmic Rays extend in energy beyond 10^{20} eV.
- There are two components:
  lower-energy, likely Galactic, with $E_{\rm CR} < 5 \times 10^{18}$ eV
  higher-energy, likely extragalactic, with $E_{\rm CR} > 5 \times 10^{18}$ eV
- The highest-energy cosmic rays ($E_{\rm CR} \gtrsim 10^{20}$ eV) must come from nearby sources
- Two common acceleration mechanisms:
  shock acceleration
  shear-flow acceleration acceleration (energy boost)

Lower-energy Cosmic Rays: power budget

Source injection power $\sim 0.8 \times 10^{48}$ erg/yr ($\sim 2.5 \times 10^{40}$ erg/s)

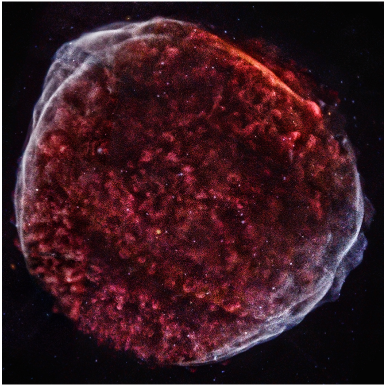
Energy density of lower-energy CRs ~ 0.3 eV/cm^3 in the volume containing $\sim 10^{10} M_\odot$ of gas with average density ~ 0.5 cm^{-3}

$\Rightarrow$ total energy of these CRs is $\sim 1.2 \times 10^{55}$ erg ,
replenished once in $t_{\rm res} \sim 15$ Myr

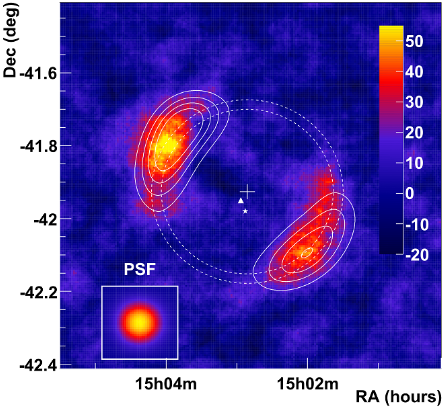
Possible sources

- Supernovae $\sim 2 \times 10^{49}$ erg/yr (one SN per 50 yr)
  — idea suggested ca. 1955 by several authors
- Pulsars ($\lesssim 0.1$ of SN power) — could be local contributors
- supermassive black hole at Galactic center, Sgr A*, now quiet, had accretion power $\gtrsim 2 \times 10^{40}$ erg/s in the recent past

Supernova remnant SN 1006

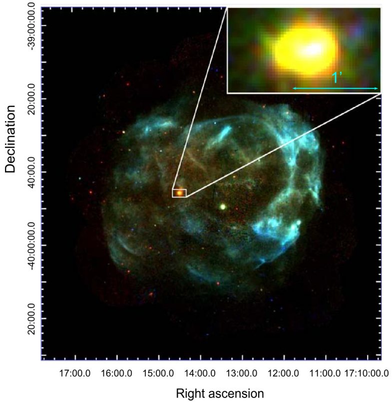


Chandra 2013

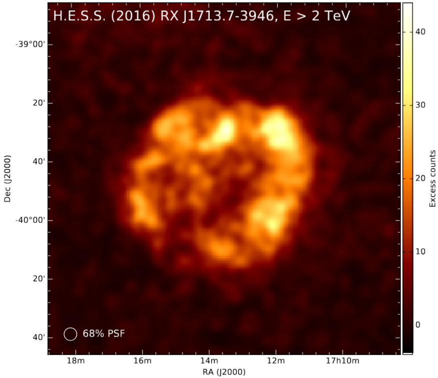


HESS Collaboration, A&A 2010

Supernova remnant RX J1713.7-3946



XMM-Newton (Tateishi et al., ApJ 2021)



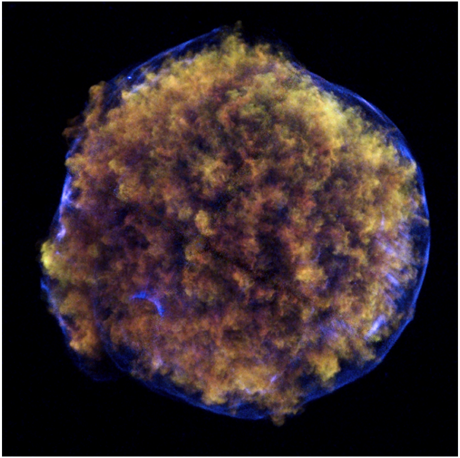
HESS Collaboration, A&A 2018

red — 0.2–1.0 keV

green — 1.0–2.0 keV

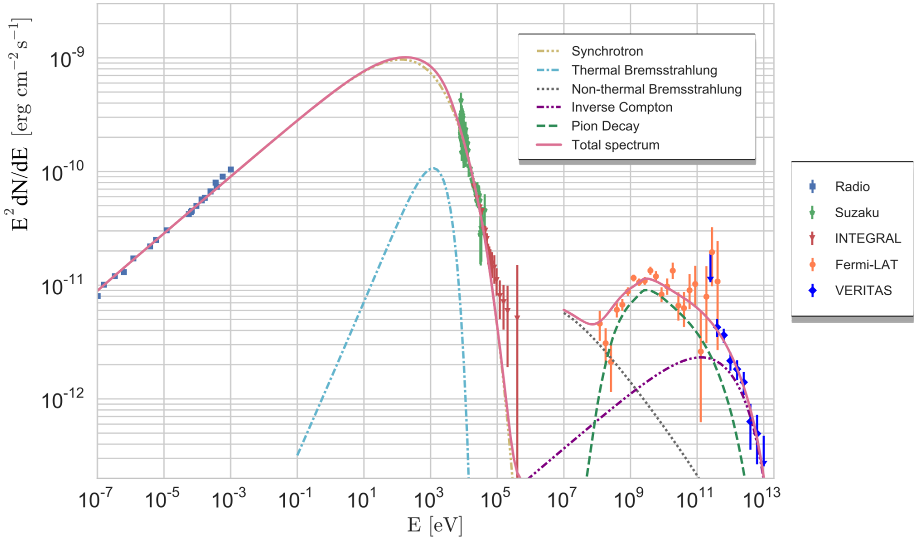
blue — 2.0–4.5 keV

Tycho supernova remnant



Chandra 2011

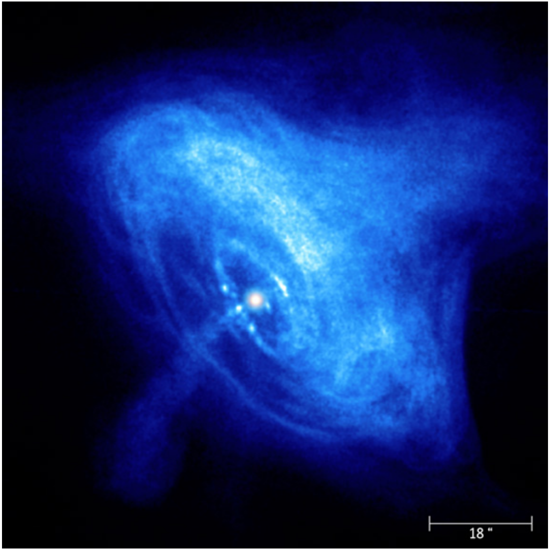
Spectral model for Cas A supernova remnant



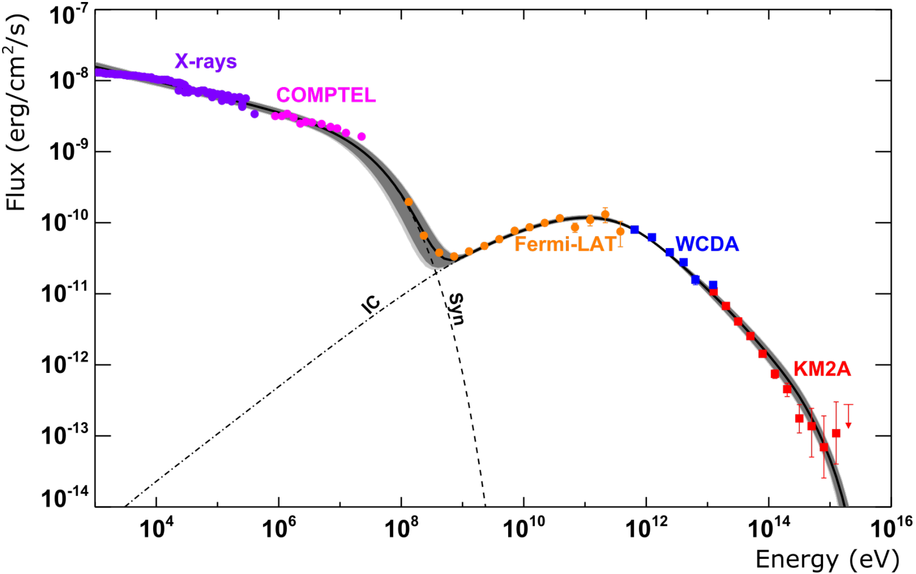
Abeysekara et al., ApJ 2020

Crab pulsar's X-ray nebula

NASA/CXC/ASU/Hester et al.



Crab pulsar spectrum extends to PeV



LHAASO Collab., Science 2021

Higher-energy Cosmic Rays: power budget

Source power $\sim 3 \times 10^{43}$ erg/yr/Mpc^3 (efficiency ~ 0.6 eV/nucleon)

Energy density of extragalactic CRs $\sim 10^{-8}$ eV/cm^3, accumulated over Hubble time

Universe's critical density is ≈ 5.6 keV/cm^3,

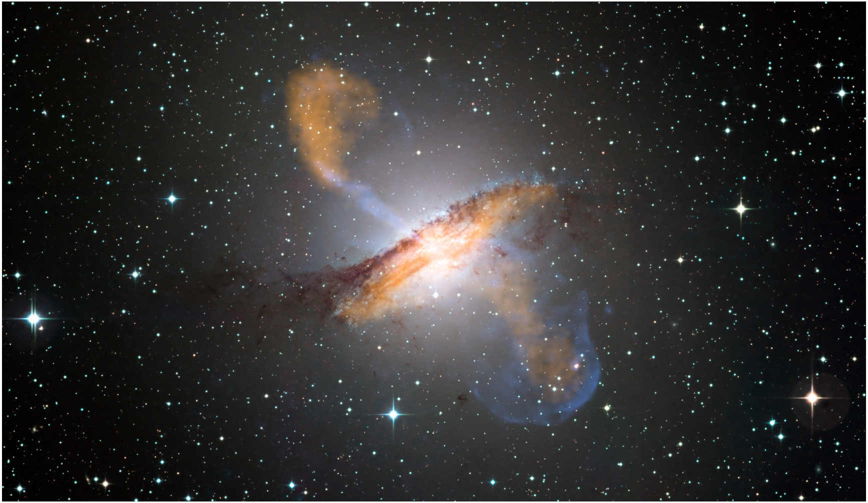
a fraction $\Omega_{\rm stars} \approx 0.003$ of which is in galaxies (mostly in form of stars)

$\Rightarrow$ extragalactic CRs comprise $\sim 0.6 \times 10^{-10}$ of the matter's rest energy

Possible sources

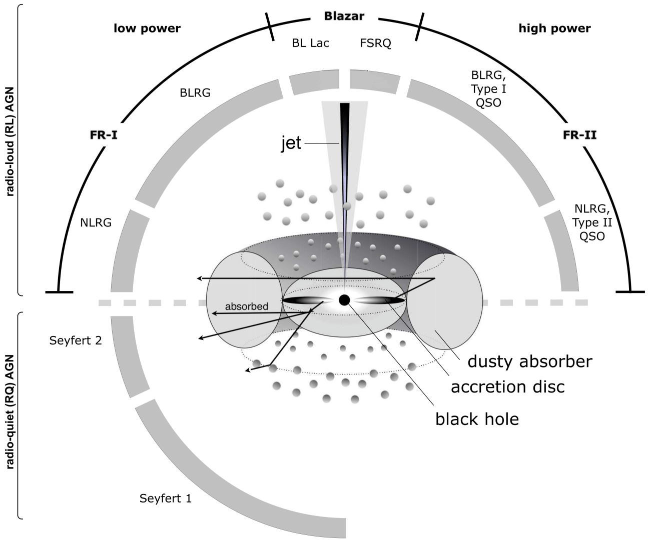
- Active Galactic Nuclei life-time average efficiency ~ 50 keV/nucleon — assuming $M_{\rm BH}/M_* \sim 10^{-3}$ SMBH to host galaxy mass ratio
- Gamma-Ray Bursts. Need $E_{\rm GRB} > 2\times10^{52}$ erg (rate $\sim$1.5 Gpc^{-3}yr^{-1})
- accretion onto galaxy clusters has efficiency ~ 10 keV/nucleon

Centaurus A — the nearest active galaxy



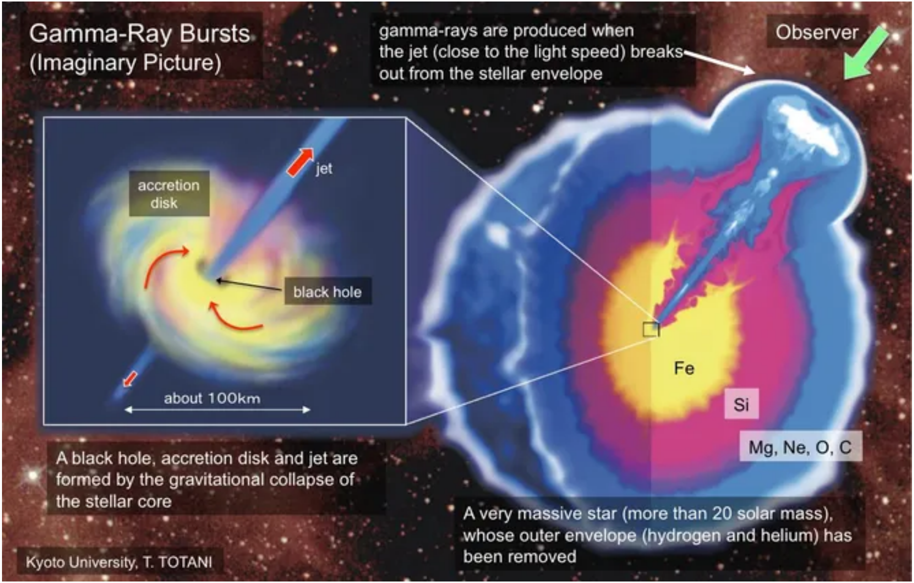
optical (true color)	ESO/WFI
submillimetre (orange)	MPIfR/ESO/APEX/A.Weiss et al.
X-ray (blue)	NASA/CXC/CfA/R.Kraft et al.

Schematic view of Active Galactic Nucleus

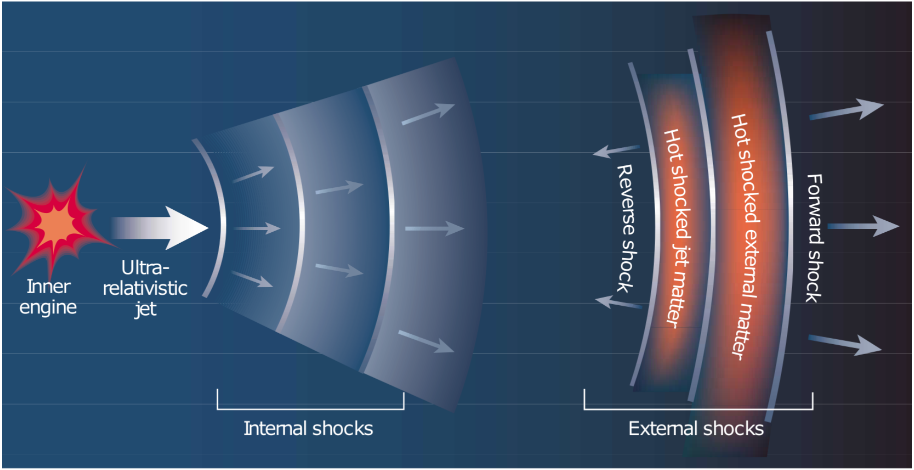


after Beckmann & Shrader, PoS 2012

Gamma Ray Burst



Gamma Ray Burst



Piran, Nature (2003)

External shock decelerates from $\Gamma_0 \sim 500$

Fundamental constraints for acceleration sites

1. Particles should be confined with the acceleration site $E_{\rm max} < qBR$ — Hillas criterion (due to Greisen, 1965)

lower limit on magnetic energy in the accelerator

$$W_{\rm m} > \frac{R}{6}\left(\frac{E_{\rm max}}{q}\right)^2$$

2. Energy gain rate $\dot{E} = \eta q B c$ should balance at least the minimum possible losses — curvature radiation

$$\Rightarrow \quad \eta q B c > \dot{E}_{\rm rad} = \frac{2}{3}\left(\frac{E_{\rm max}}{mc^2}\right)^4 \frac{q^2}{R^2} c$$

lower limit on magnetic energy in the accelerator

$$W_{\rm m} > \frac{2}{27}\frac{q^2}{R}\left(\frac{E_{\rm max}}{mc^2}\right)^8 \frac{1}{\eta^2}$$

Fundamental constraints for acceleration sites

Equating the two lower limits on the the amount of electromagnetic energy stored in the acceleration region we find the optimal (the minimum possible) estimate:

$$W_{\rm m}^{\rm (opt)} \simeq \frac{1}{9\,\eta}\,\frac{E_{\rm max}^5}{(mc^2)^4}$$

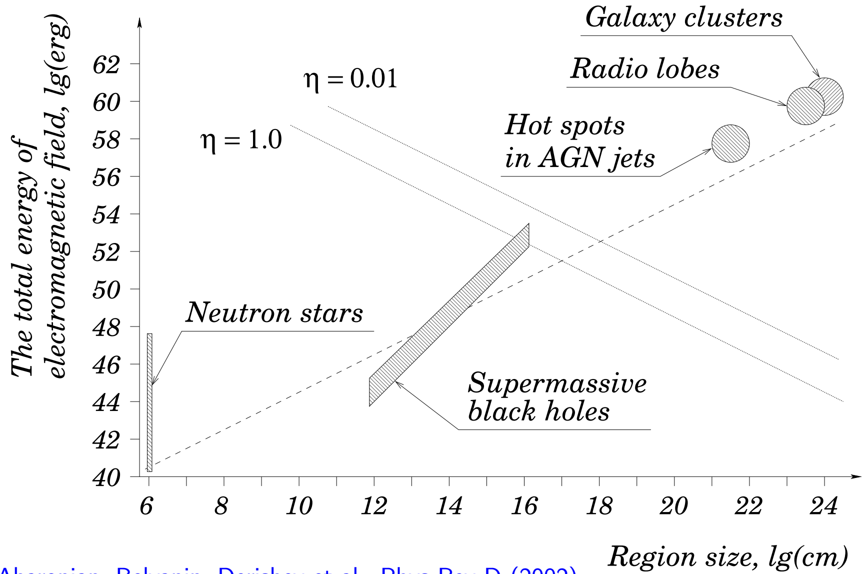
The corresponding optimal size is

$$R^{\rm (opt)} \simeq \frac{2}{3\,\eta}\,\frac{q^2 E_{\rm max}^3}{(mc^2)^4}$$

The optimal magnetic field strength is

$$B^{\rm (opt)} \simeq \frac{3}{2}\eta\,\frac{\left(mc^2\right)^4}{q^3 E_{\rm max}^2}$$

Fundamental constraints for acceleration sites



Aharonian, Belyanin, Derishev et al., Phys Rev D (2002)

Constraints for relativistically-moving accelerators

Lorentz transformations

$E = \Gamma E', \quad W = \Gamma W', \quad B = \Gamma B'$

primed quantities are measured in the comoving frame,

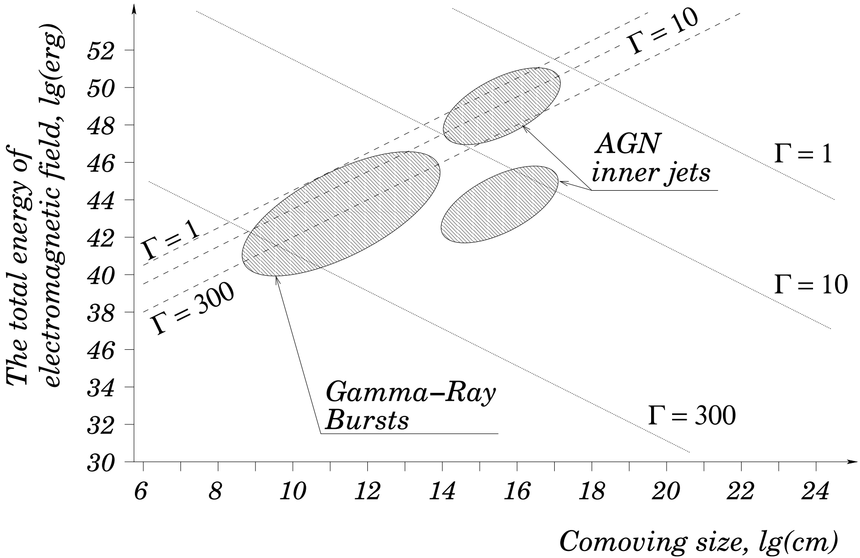
Γ is Lorentz factor of bulk motion

The minimum possible magnetic energy: $$W_{\rm m}^{\rm (opt)} \simeq \frac{1}{9\,\Gamma^4}\,\frac{1}{\eta}\,\frac{E_{\rm max}^5}{(mc^2)^4}$$

The corresponding optimal size is $$R'^{\rm (opt)} \simeq \frac{2}{3\,\Gamma^3}\,\frac{1}{\eta}\,\frac{q^2 E_{\rm max}^3}{(mc^2)^4}$$

The optimal magnetic field strength is $$B'^{\rm (opt)} \simeq \frac{3\,\Gamma^2}{2}\,\eta\,\frac{(mc^2)^4}{q^3 E_{\rm max}^2}$$

Constraints for relativistically-moving accelerators



Aharonian, Belyanin, Derishev et al., Phys Rev D (2002)

Possible UHECR ($E_{\mathrm{cr}} \gtrsim 10^{20}$ eV) acceleration sites

Non-relativistic objects

- Accretion shocks in clusters of galaxies
- Giant radio lobes
- Accretion discs around supermassive black holes

Objects with relativistic jets/shocks (reviewed in the next lectures)

- Jets in Active Galactic Nuclei
- Gamma-Ray Bursts (note tough constraint on the energy efficiency)

Escape-limited acceleration

Input

- escape time $t_{\rm esc} = \dfrac{R^2}{r_g c}$ (assume Bohm diffusion)
- particle's gyroradius $r_g = E/(qB)$
- acceleration rate $\dot{E} = \eta q B c$

Equation for maximum energy $E_{\rm max} = \dot{E}\, t_{\rm esc} = \eta (qB)^2 \dfrac{R^2}{E_{\rm max}}$

$$E_{\rm max} = \sqrt{\eta}\, qBR$$

similar to Hillas criterion, but smaller

Loss-limited acceleration

Input

- Available acceleration time is limited by attenuation distance $D_{\rm att}$:
  $t_{\rm acc} < t_{\rm max} = D_{\rm att}/c$
- acceleration rate $\dot{E} = \eta qBc$

$$E_{\rm max} = \dot{E}\, t_{\rm max} = \eta\, qBD_{\rm att}$$

Summary 2

- Several object types meet fundamental criteria for proton acceleration up to 10^{20} eV and even more so for iron nuclei
- Considering more realistic (actually model-dependent) limitations may result in substantially lower energy limit for Cosmic Rays