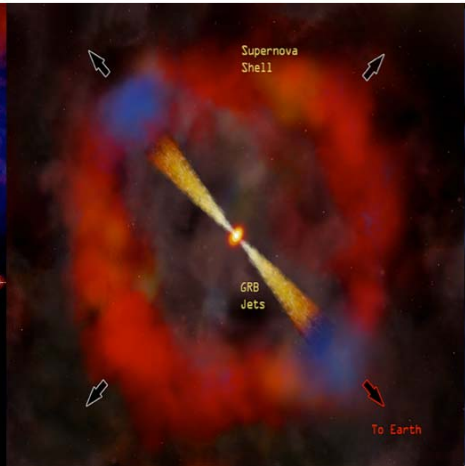
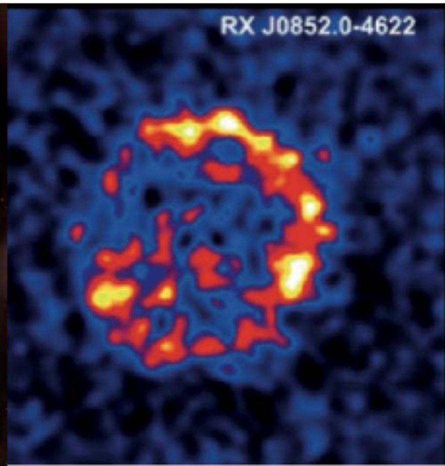
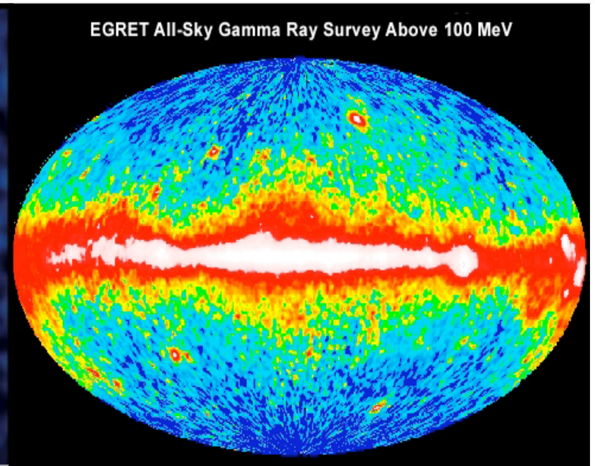
Where do cosmic rays come from?

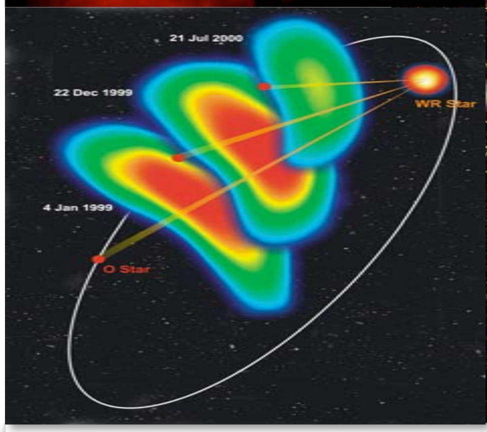
A.Neronov & T.Courvoisier
ISDC

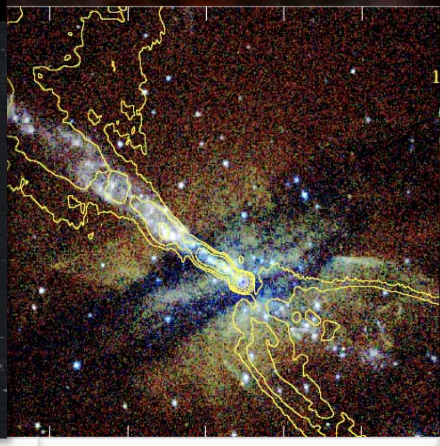
Pulsars / PWNe	GRB	SNR	The Galaxy

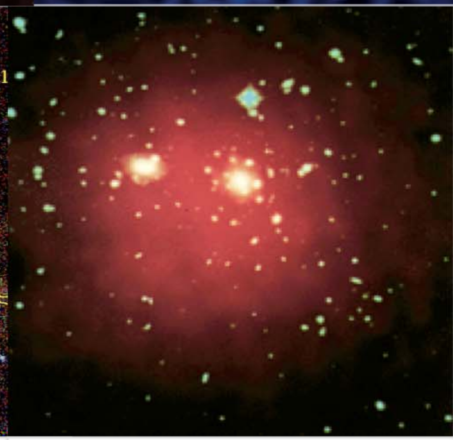


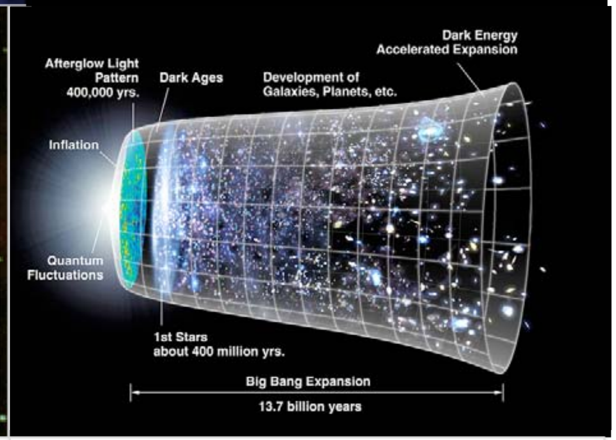












Binaries	AGN	Galaxy clusters	The Early Universe

Overview

Many faces of the problem of the origin of Cosmic rays

Astrophysical phenomena involved

- Supernovae / supernova remnants
- pulsars / pulsar wind nebulae
- active galaxies
- …

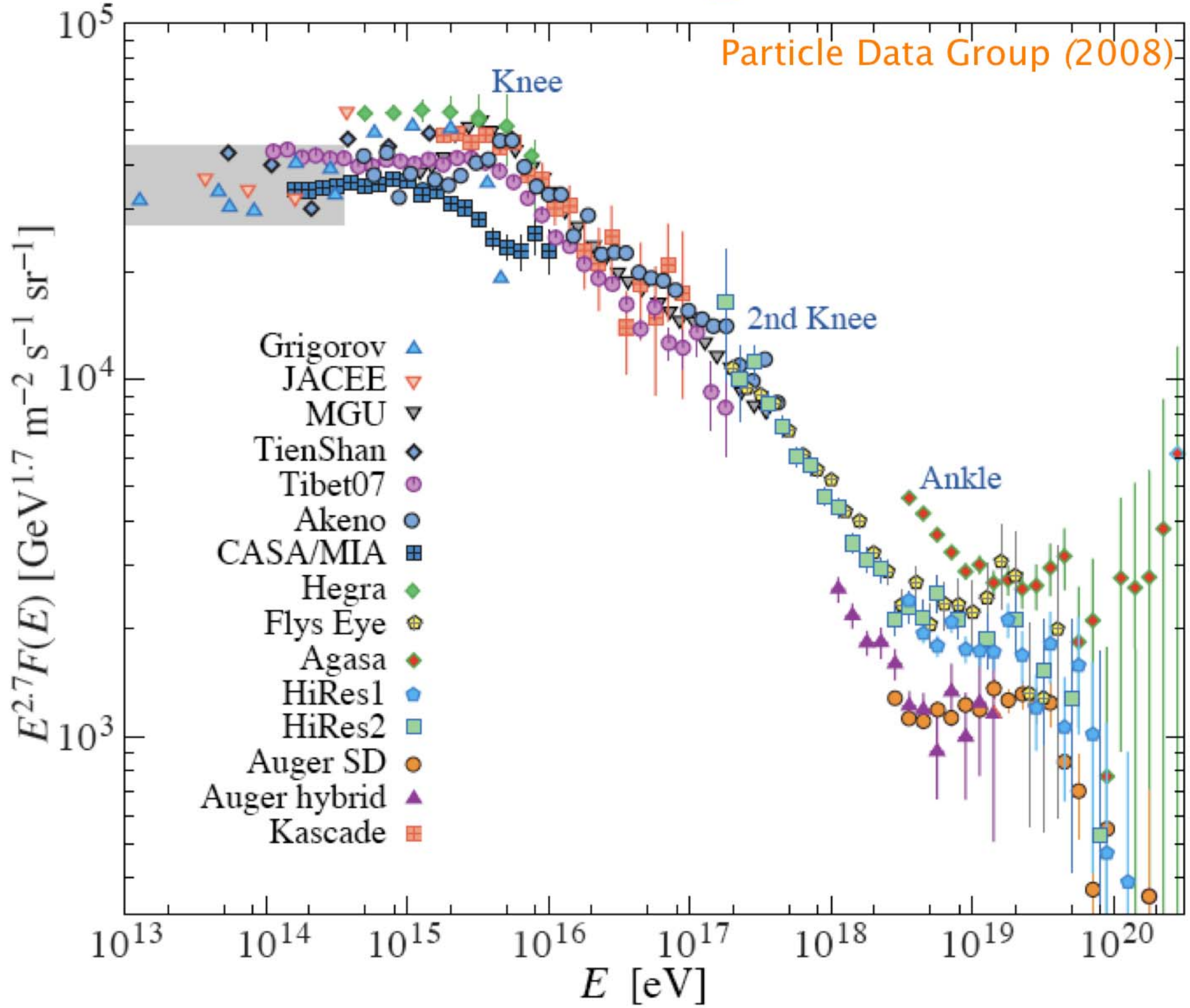
Main types of acceleration mechanisms

- shock acceleration
- acceleration by large-scale electric fields

Particle cascades

- inside cosmic ray sources
- in interstellar/intergalactic space

Problem of the origin of cosmic rays

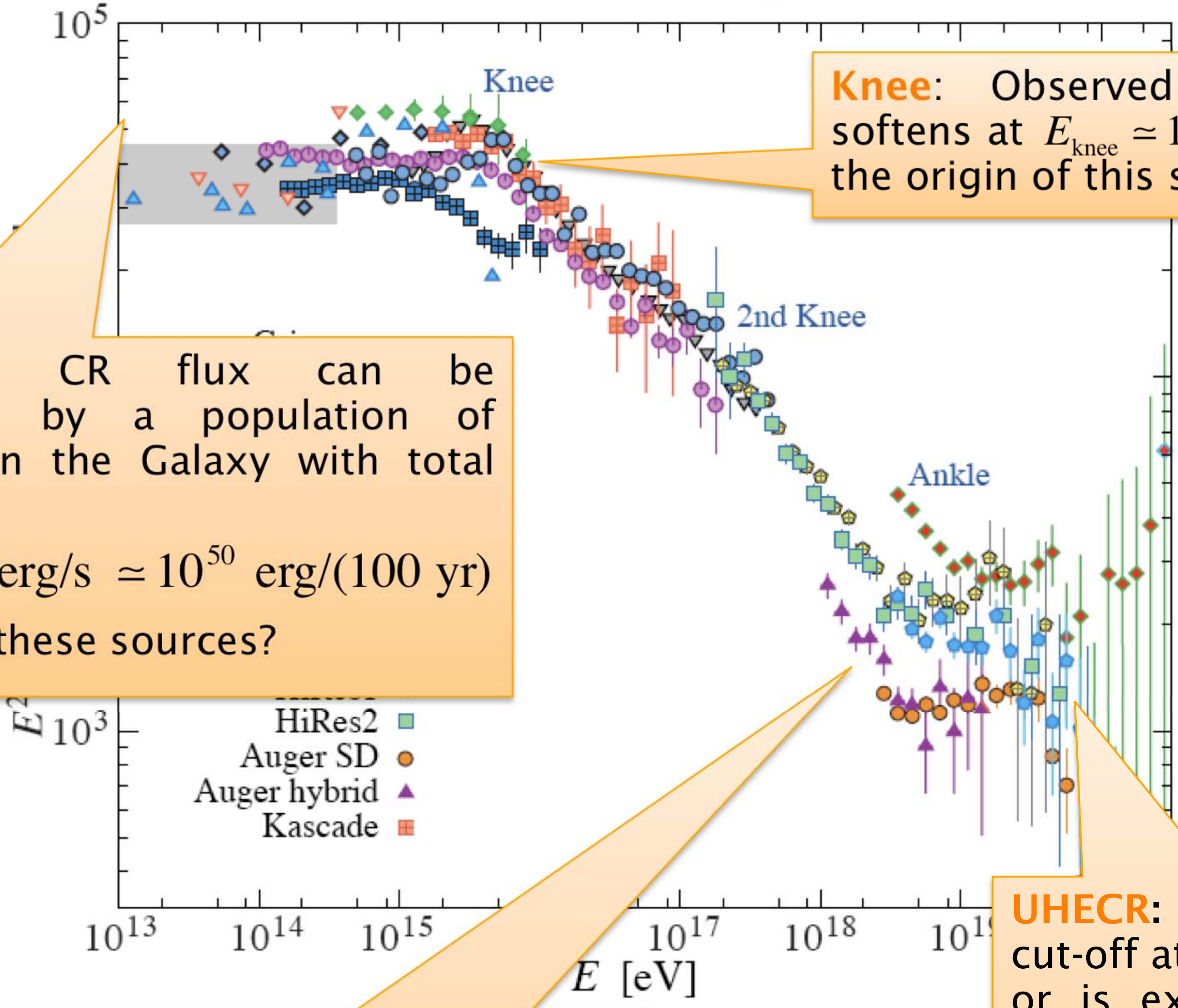


- Discovered in 1912 by V.Hess
- $dN_{CR} / dE \propto E^{-2.7..-3}$, $10^{10}\,\text{eV} \leq E \leq 10^{20}\,\text{eV}$
- Sources are unknown

➔ **Major problem of Astroparticle Physics**

Where do Cosmic Rays come from?

Problem(s) of the origin of cosmic rays



Knee: Observed CR spectrum softens at $E_{knee} \simeq 10^{15}$ eV What is the origin of this spectral feature?

Observed CR flux can be produced by a population of sources in the Galaxy with total power

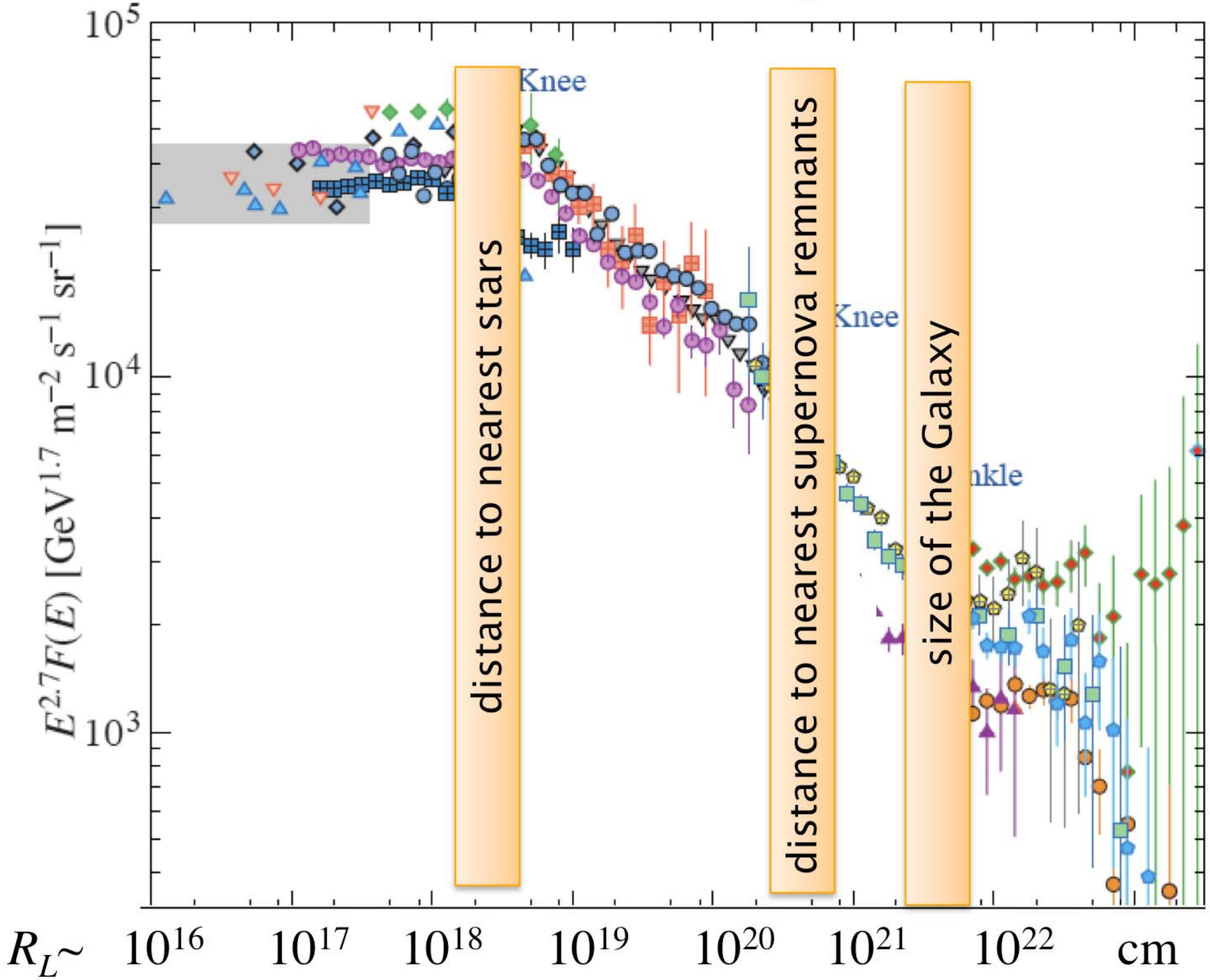
$$L \simeq 10^{40} \text{ erg/s } \simeq 10^{50} \text{ erg/(100 yr)}$$

What are these sources?

Ankle: Observed CR spectrum softens at $E_{ankle} \simeq 10^{18}$ eV What is the origin of this spectral feature? Are these CRs of Galactic or extra-galactic orgin?

UHECR: Is the spectrum cut-off at $E_{UHECR} \simeq 10^{20}$ eV or is extends to higher energies? What is the origin of the spectral feature? What are the sources of UHECR?

Problem(s) of the origin of cosmic rays

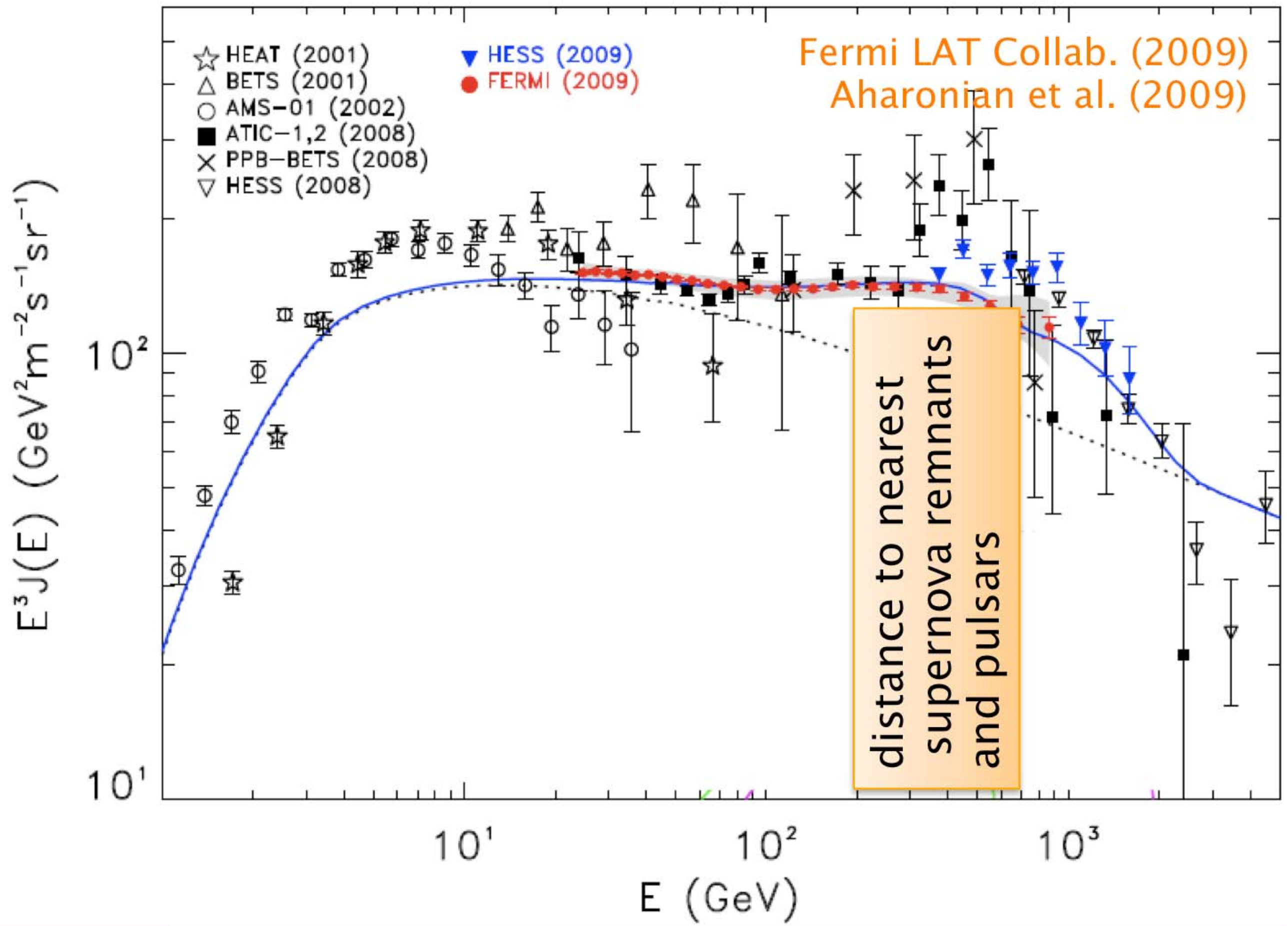


Radius of gyration in Galactic magnetic field

$$R_L = \frac{E}{ZeB} \approx 10^{18} Z^{-1} \left[\frac{E}{10^{15}\,\text{eV}}\right]\left[\frac{B}{3\times10^{-6}\,\text{G}}\right]^{-1} \text{cm}$$

➔ **CR sources at distances $R>R_L$ could not be detected directly**

… and of cosmic ray electrons



CR electrons loose their energy in $t_{synch} = \frac{9m_e^4}{4e^4B^2E} \approx 10^5 \left[\frac{E}{10^{12}\,\mathrm{eV}}\right]^{-1}\left[\frac{B}{10^{-5}\,\mathrm{G}}\right]^{-2}$ yr

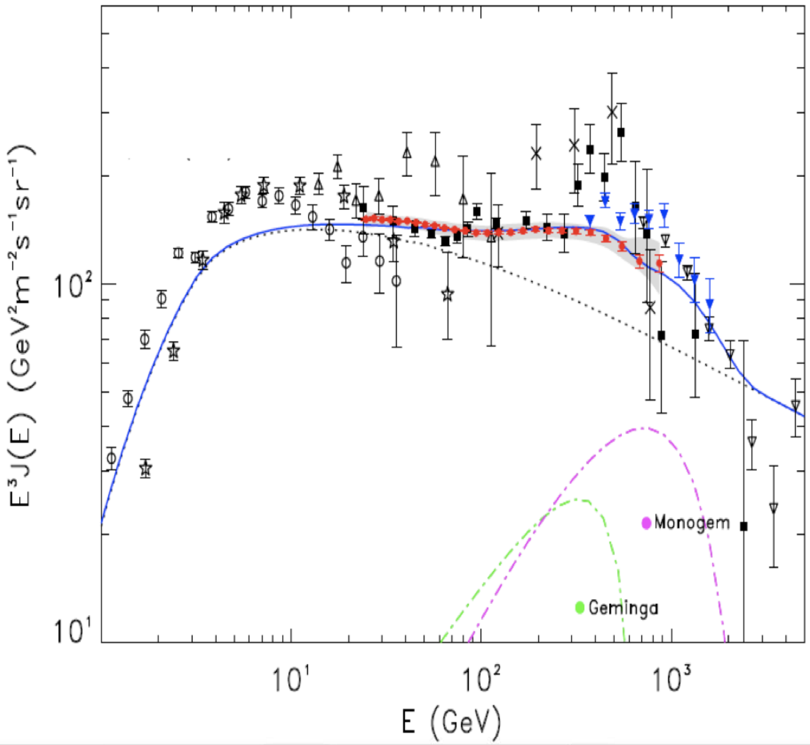
and can not diffuse further than $R \simeq \sqrt{Dt_{synch}} \approx 10^{21}\left[\frac{E}{10^{12}\,\mathrm{eV}}\right]^{1/3}$ cm from their production place

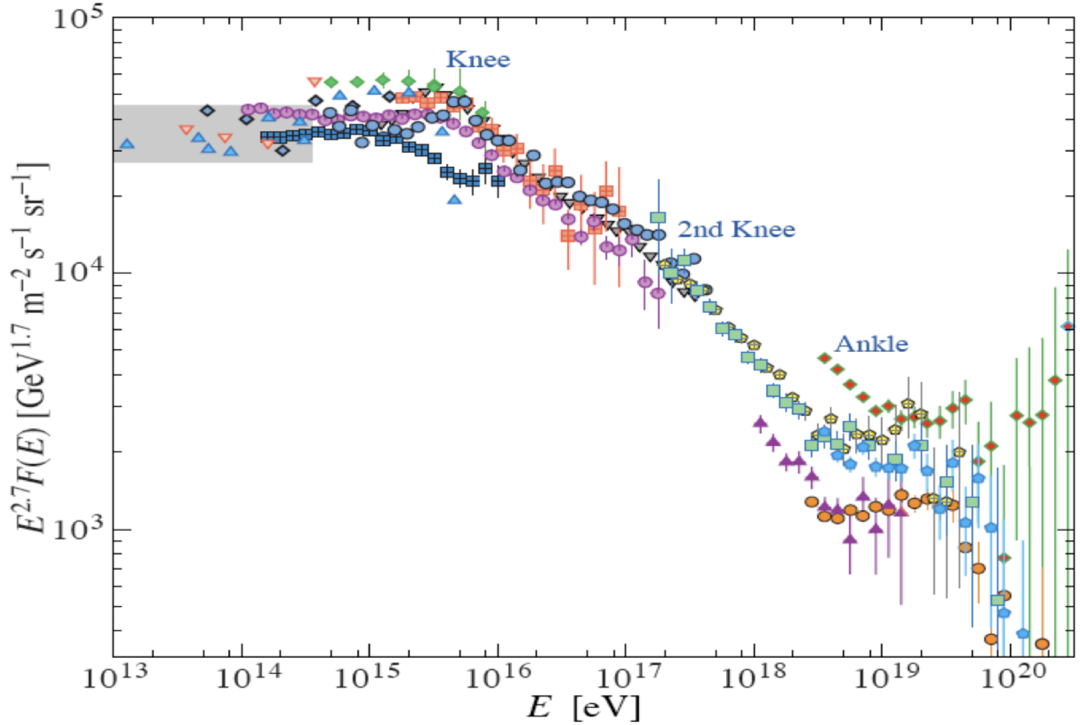
energy-dependent diffusion coefficient

➔ **CR electrons come from nearby (unknown) sources**

Where do Cosmic Rays come from?

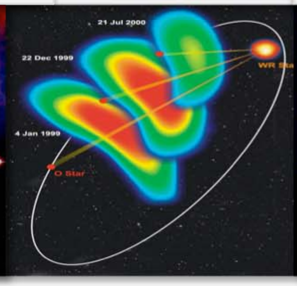
High-energy astrophysics → CR physics



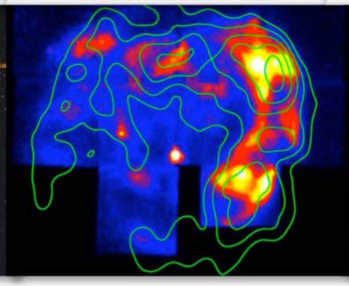


Pulsars/PWNe

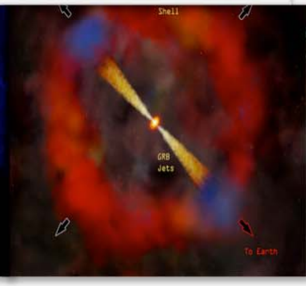
Binaries



SNR

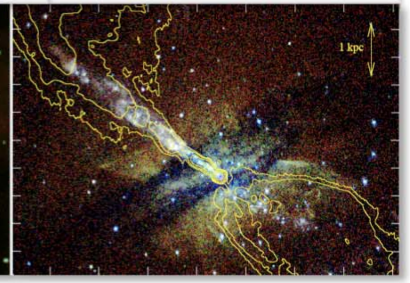


GRBs



Galaxy clusters

AGN

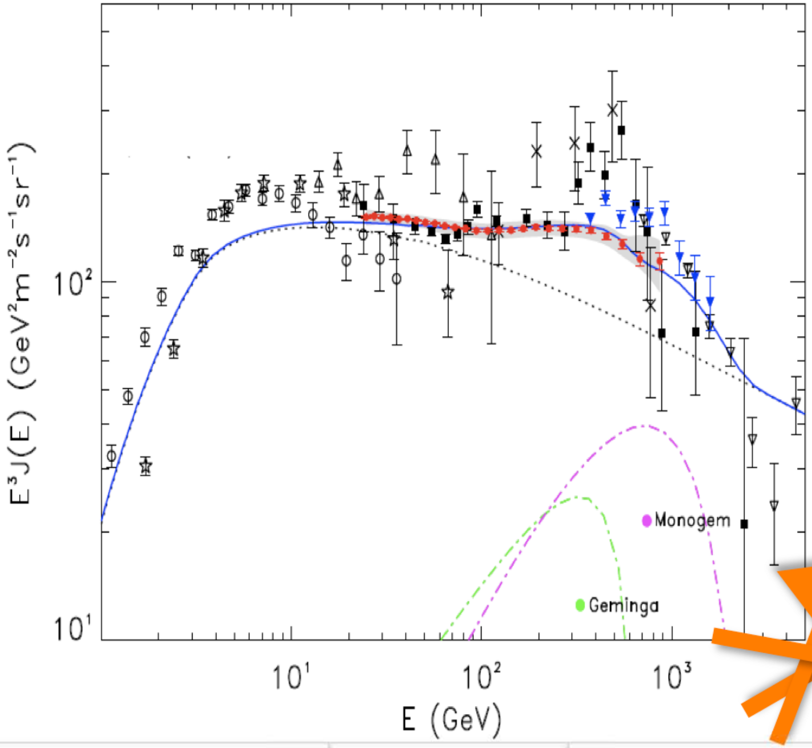


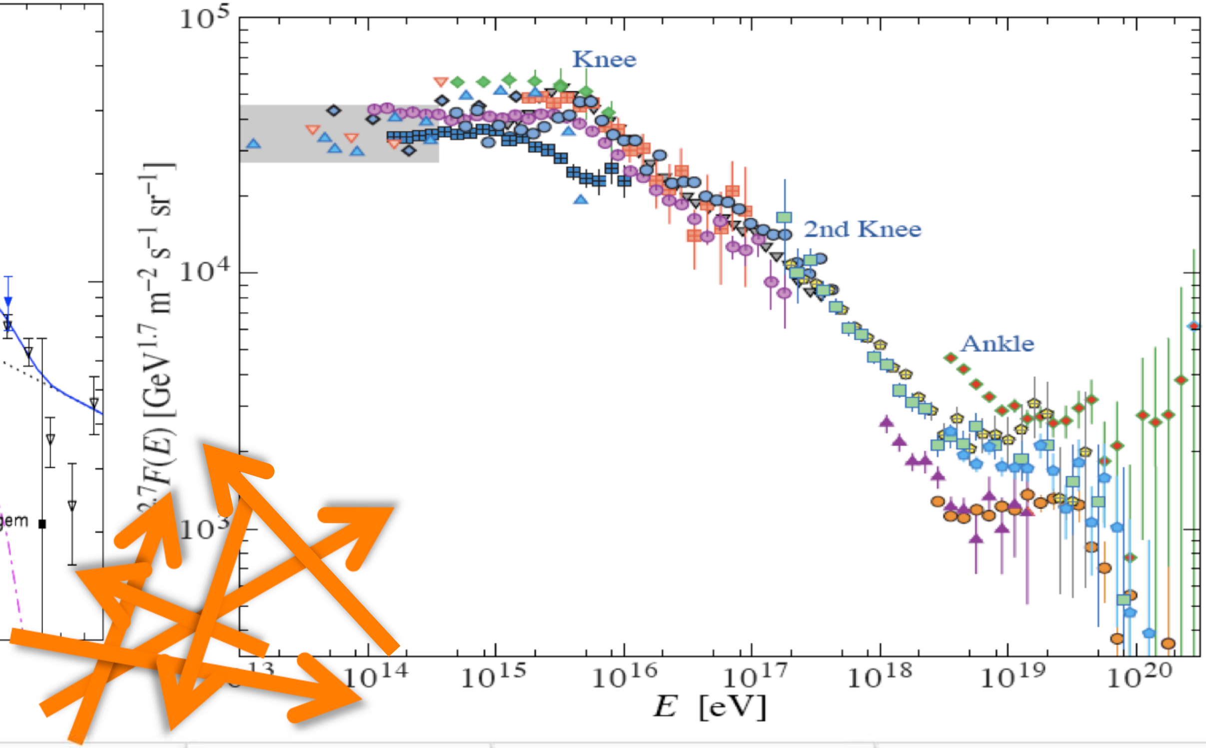
Radio, X-ray and γ-ray emission, observed from several classes of astronomical objects, is produced by particles accelerated to $E \gg m$

→ **CR source "candidates" list is well-known**

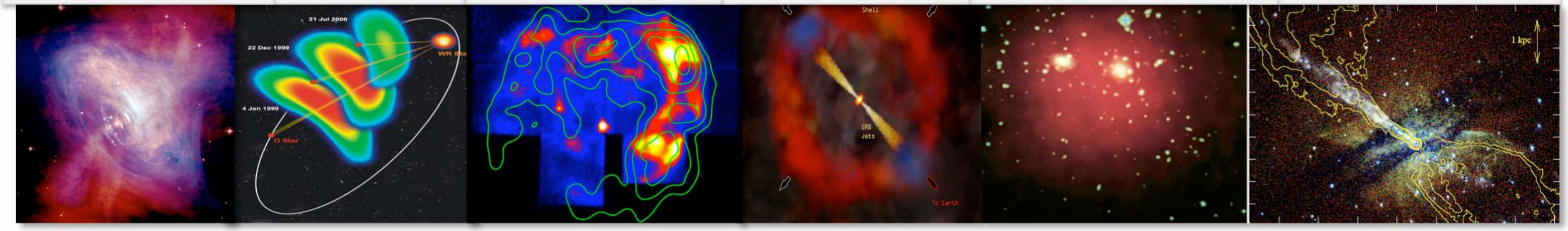
Where do Cosmic Rays come from?

High-energy astrophysics ➔ CR physics





Pulsars/PWNe	Binaries	SNR	GRBs	Galaxy clusters	AGN

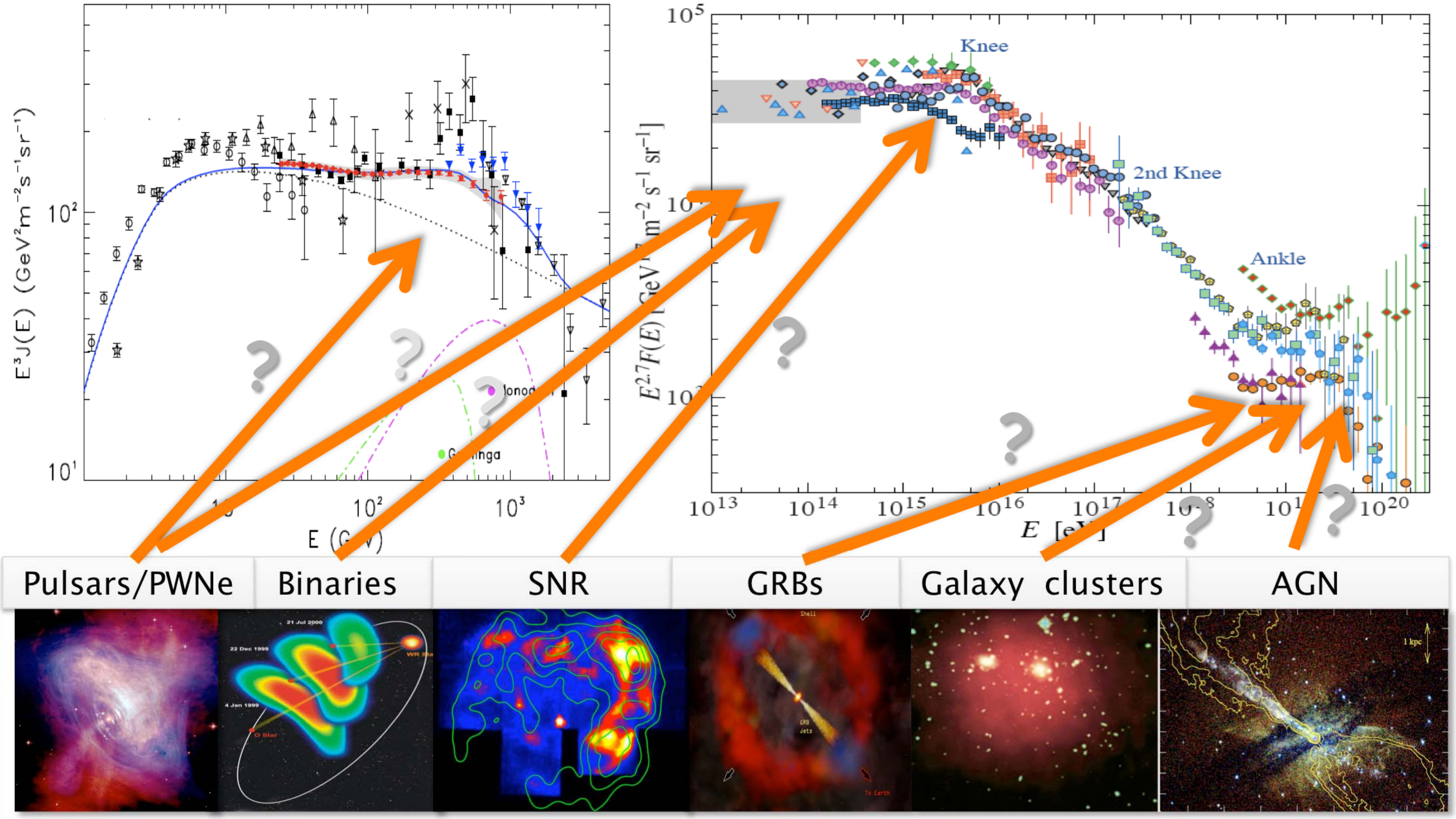


Radio, X-ray and γ-ray emission, observed from several classes of astronomical objects, is produced by particles accelerated to $E \gg m$

➔ **CR source "candidates" list is well-known**

High-energy astrophysics ➔ CR physics

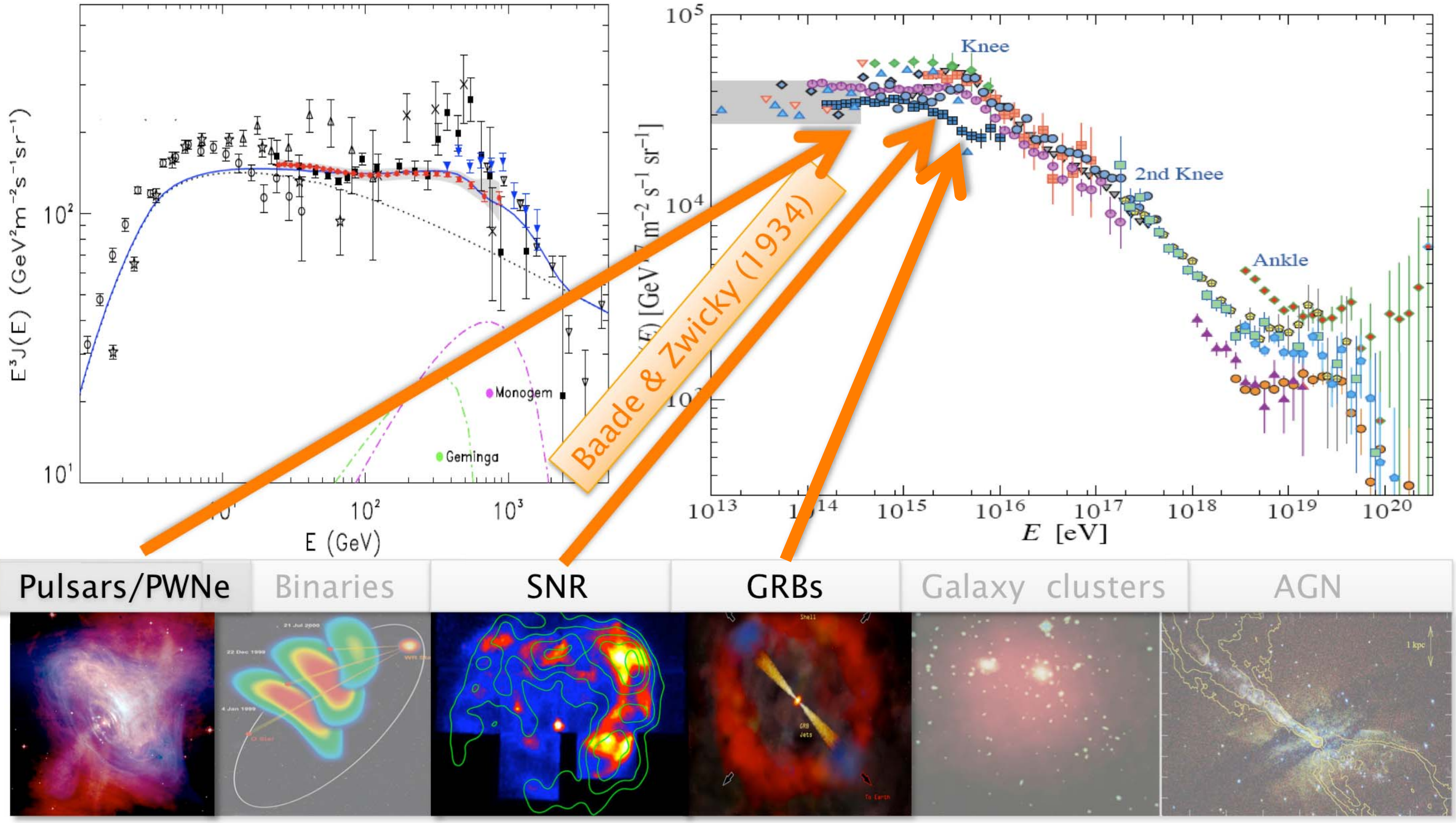
Where do Cosmic Rays come from?



Radio, X-ray and γ-ray emission, observed from several classes of astronomical objects, is produced by particles accelerated to $E \gg m$

➔ **CR source "candidates" list is well-known**

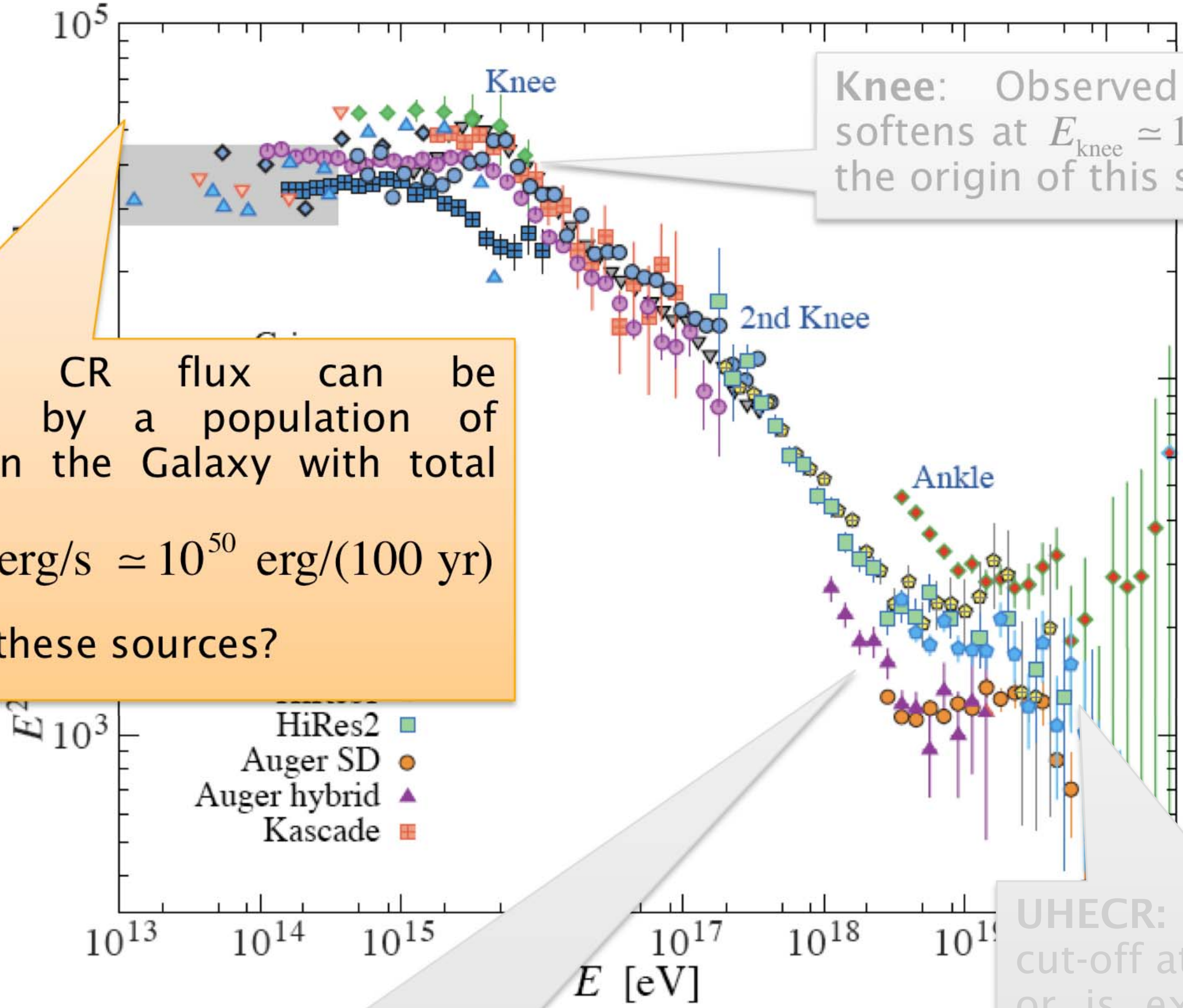
Origin of GeV-PeV cosmic rays



Where do Cosmic Rays come from?

Where do Cosmic Rays come from?

Origin of GeV-PeV cosmic rays



Knee: Observed CR spectrum softens at $E_{\rm knee} \simeq 10^{15}$ eV What is the origin of this spectral feature?

Observed CR flux can be produced by a population of sources in the Galaxy with total power
$L \simeq 10^{40}$ erg/s $\simeq 10^{50}$ erg/(100 yr)

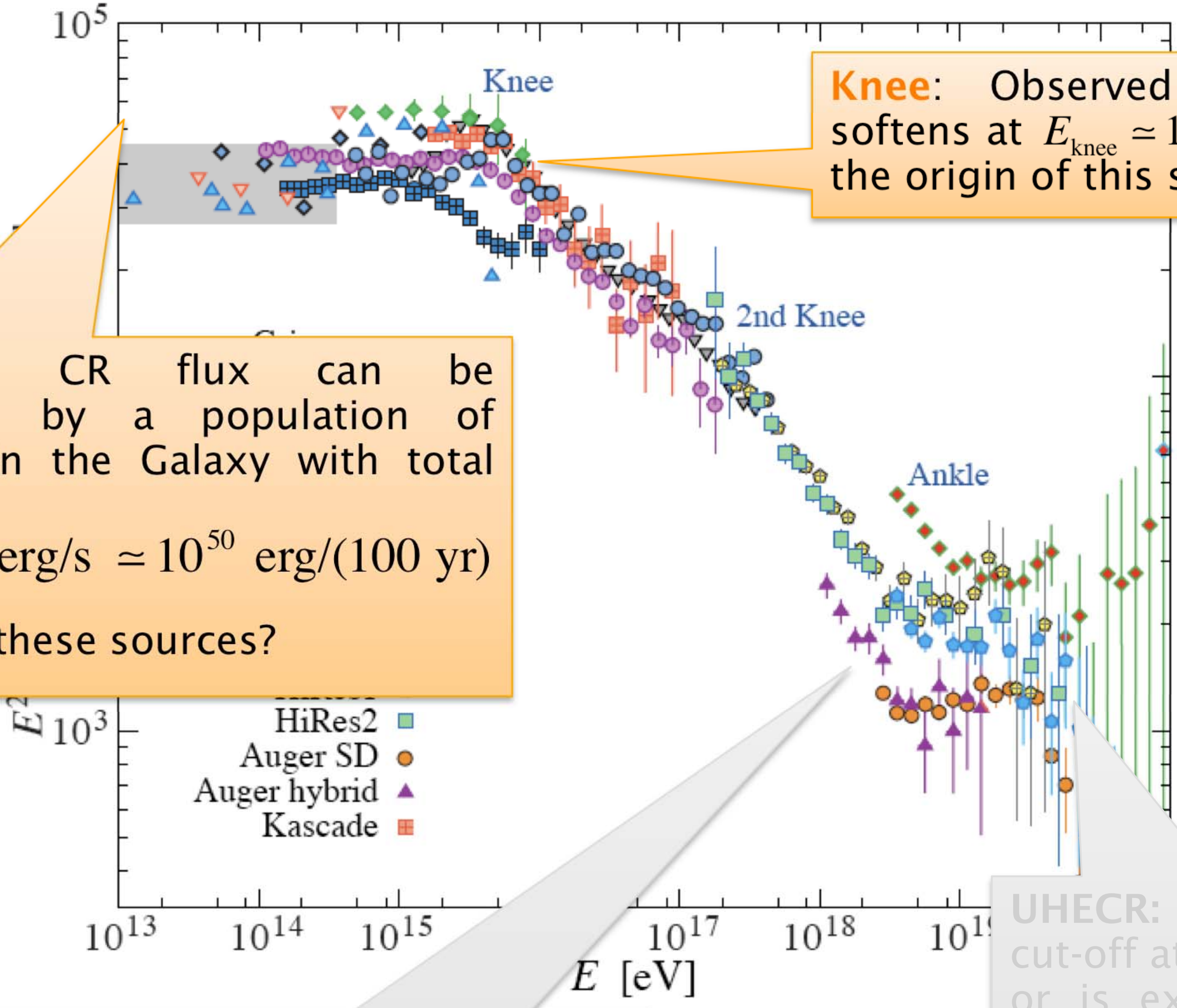
What are these sources?

Ankle: Observed CR spectrum softens at $E_{\rm ankle} \simeq 10^{18}$ eV What is the origin of this spectral feature? Are these CRs of Galactic or extra-galactic orgin?

UHECR: Is the spectrum cut-off at $E_{\rm UHECR} \simeq 10^{20}$ eV or is extends to higher energies? What is the origin of the spectral feature? What are the sources of UHECR?

Where do Cosmic Rays come from?

Origin of GeV-PeV cosmic rays



Knee: Observed CR spectrum softens at $E_{\text{knee}} \simeq 10^{15}$ eV What is the origin of this spectral feature?

Observed CR flux can be produced by a population of sources in the Galaxy with total power

$$L \simeq 10^{40} \text{ erg/s } \simeq 10^{50} \text{ erg/(100 yr)}$$

What are these sources?

Ankle: Observed CR spectrum softens at $E_{\text{ankle}} \simeq 10^{18}$ eV What is the origin of this spectral feature? Are these CRs of Galactic or extra-galactic orgin?

UHECR: Is the spectrum cut-off at $E_{\text{UHECR}} \simeq 10^{20}$ eV or is extends to higher energies? What is the origin of the spectral feature? What are the sources of UHECR?

Cosmic Rays and Supernovae

Where do Cosmic Rays come from?

Remarks on Super-Novae and Cosmic Rays

We have recently called attention to a remarkable type of giant novae.[1] As the subject of super-novae is probably very unfamiliar we give here a few more details which are not contained in our original articles.

1. Distribution of super-novae

In our calculations we made use of the assumption that on the average one super-nova appears in each galaxy every thousand years. This estimate is based on the occurrence of super-novae in the following galaxies,

Our own galaxy	in 1572
Andromeda	1885
Messier 101	1907

These three systems are located within a sphere of radius 12×10^5 light years.

In the Virgo cluster, which contains about 500 nebulae, six super-novae were found on plates taken during the last thirty years. As a curiosity we mention that in N.G.C. 4321, which is a member of Virgo, two super-novae have appeared in 1901 and 1914, respectively.

In the same interval of 30 years six additional super-novae were found in isolated nebulae.

We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has been organized only recently.

From the estimate of one super-nova per galaxy per thousand years it follows that 10^7 super-novae appear per year in the 10^{10} nebulae which are contained in a sphere of 2×10^9 years radius (critical distance derived from the red shift of nebulae). If cosmic rays come from super-novae their intensity in points far away from any individual super-nova will be essentially independent of time.

The lifetime of stars is supposed to be of the order of at least 10^{12} years. A nebula contains about 10^9 stars. These estimates, combined with the frequency of occurrence of one super-nova per galaxy per 10^3 years suggest that the super-nova process might occur to every star once in its lifetime, marking perhaps the cessation of its existence as an ordinary star. We realize that this suggestion is highly

Supernovae & end of life of stars

of our complete ignorance with respect to the evolution of the universe.

3. Ions in super-novae

If super-novae are giant analogues to ordinary novae we may expect that ionized gas shells are expelled from them at great speeds. If this assumption is correct, part of the cosmic rays should consist of protons and heavier ions. Direct tests by cloud chamber experiments at high altitudes are desirable in order to test this conclusion. Also the problem suggests itself to investigate how much energy

?

Supernovae as CR sources

4. Fluctuations of cosmic rays

In our original papers we have calculated the change in intensity of cosmic rays caused by flare-ups of super-novae in nearby galaxies. The estimates given are perhaps too optimistic in view of the fact that the velocities of different particles are different. If various particles are ejected simultaneously at the time $t=0$ from a galaxy which is 10^6 L.Y. away the times t of arrival on the earth are

$t=10^6$ years for light if its velocity does not depend on the frequency.

$t_1=10^6$ years $+410$ seconds for 10^{11} volt electrons.

$t_2=$ " $+47.6$ days " 10^9 " "

$t_3=$ " $+44$ years " 10^{11} " protons.

These time lags t_i-t would tend to smear out the change of intensity caused by the flare-up of individual super-novae. Dr. R. M. Langer in one of our seminars was the first to call attention to the straggling of simultaneously ejected particles.

5. The super-nova process

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware

Supernovae ↔ Neutron stars

F. Zwicky

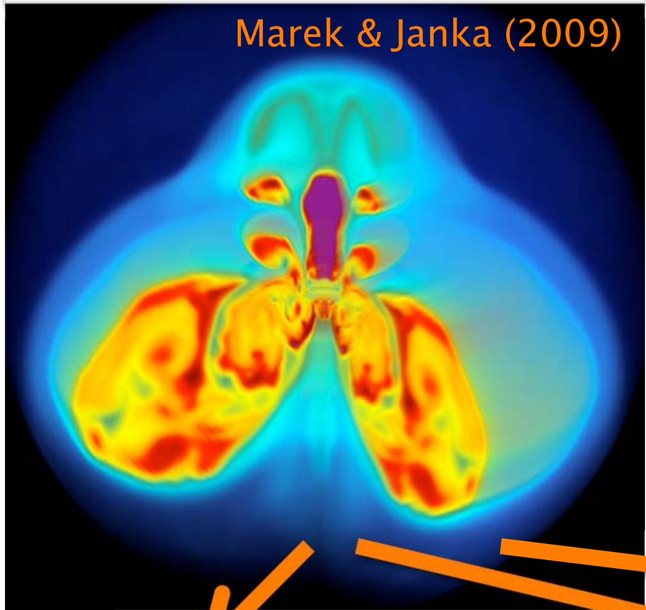
Mt. Wilson Observatory and
California Institute of Technology, Pasade[na]
May 28, 1934.

Baade & Zwicky (1934)

Where do Cosmic Rays come from?

Cosmic Rays and Supernovae

Supernova explosion



Marek & Janka (2009)

Supernova explosions give rise to several classes of sources.

Supernova remnants and pulsar wind nebulae are known to be sources of multi-TeV γ-rays.

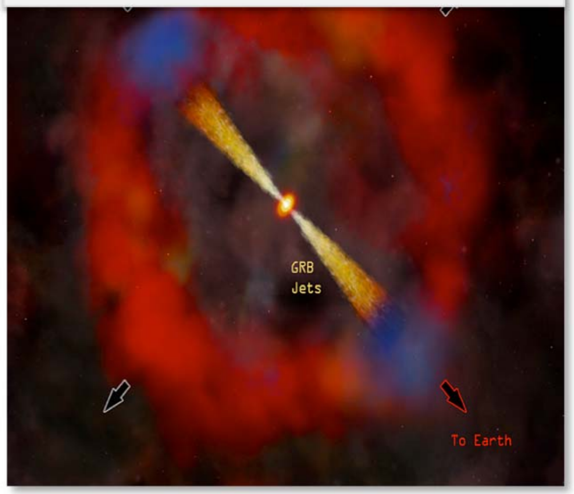
γ–ray bursts are known to be sources of multi-GeV γ-rays.

➔Particle acceleration is taking place in supernova-related sources

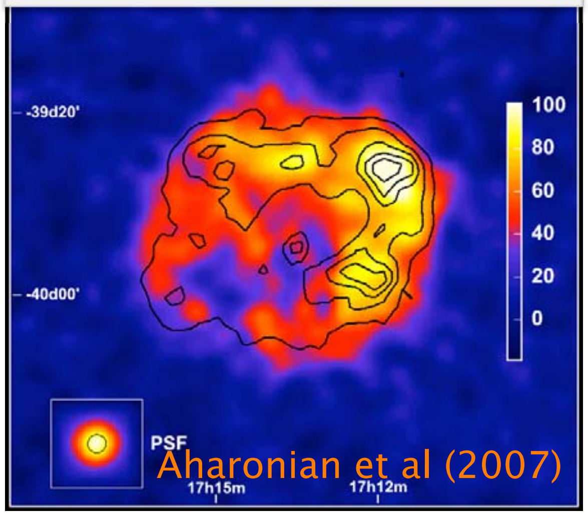
Pulsars/Pulsar wind nebula (PWN)

Weisskopf et al (1999)

gamma-ray burst (GRB)



Supernova remnant (SNR)

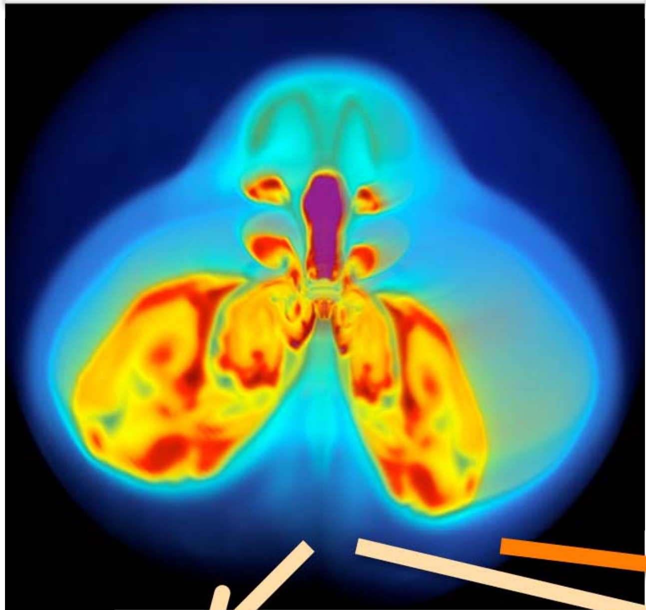


Aharonian et al (2007)

Where do Cosmic Rays come from?

Cosmic Rays and Supernovae

Supernova explosion



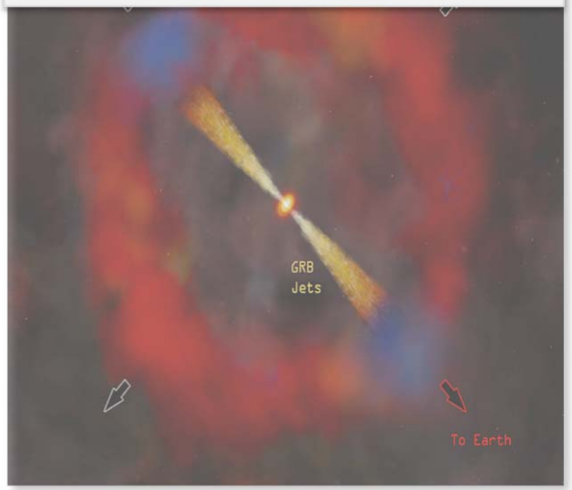
Supernova explosions give rise to several classes of sources.

Supernova remnants and pulsar wind nebulae are known to be sources of multi-TeV γ-rays

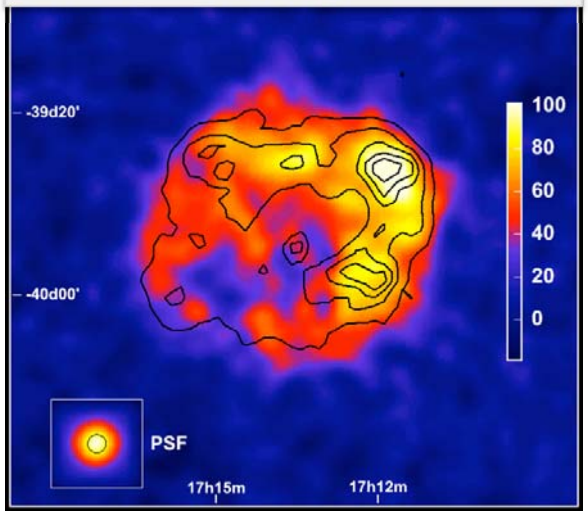
In the case of SNR multi-TeV γ-rays are possibly produced in CR interactions $(pp \to p\pi^0; \pi^0 \to 2\gamma)$

Pulsars/Pulsar wind nebula (PWN)

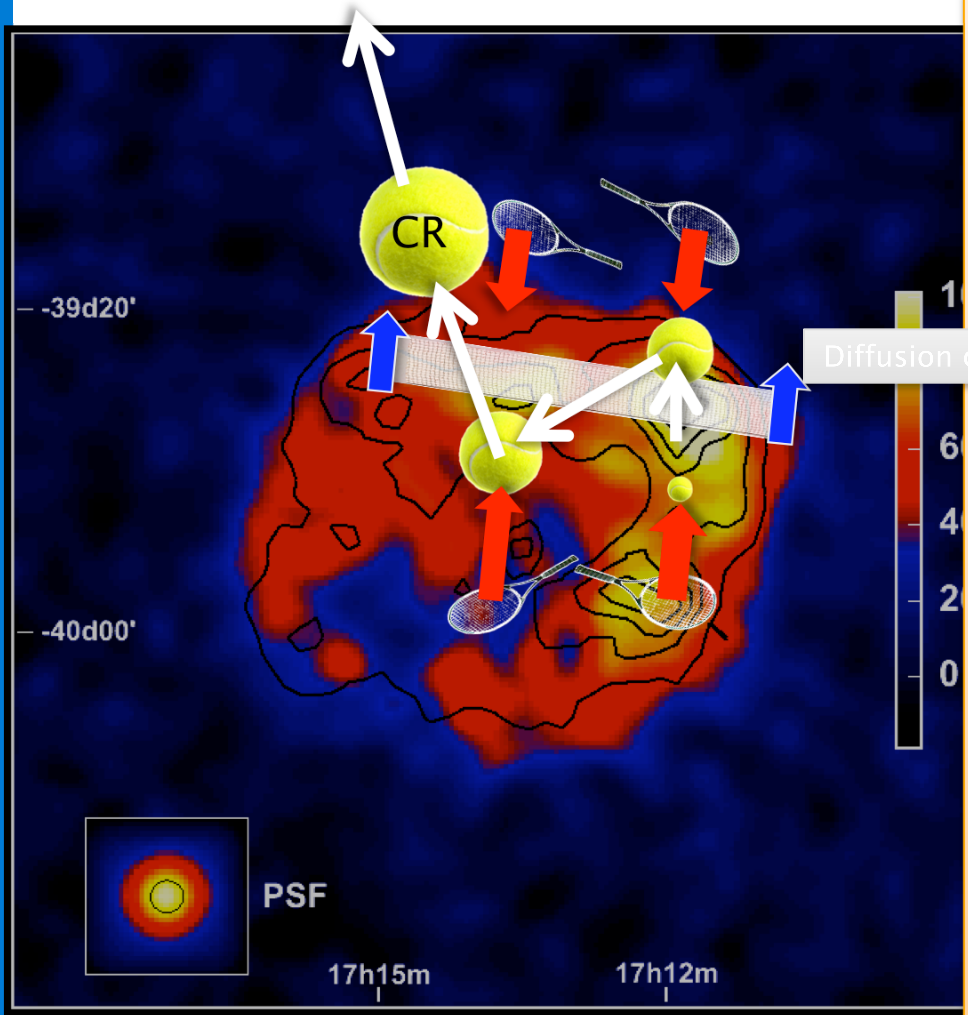
gamma-ray burst (GRB)



Supernova remnant (SNR)



Diffusive shock acceleration



- Particles gain energy

(change of) velocity of the flow at the shock

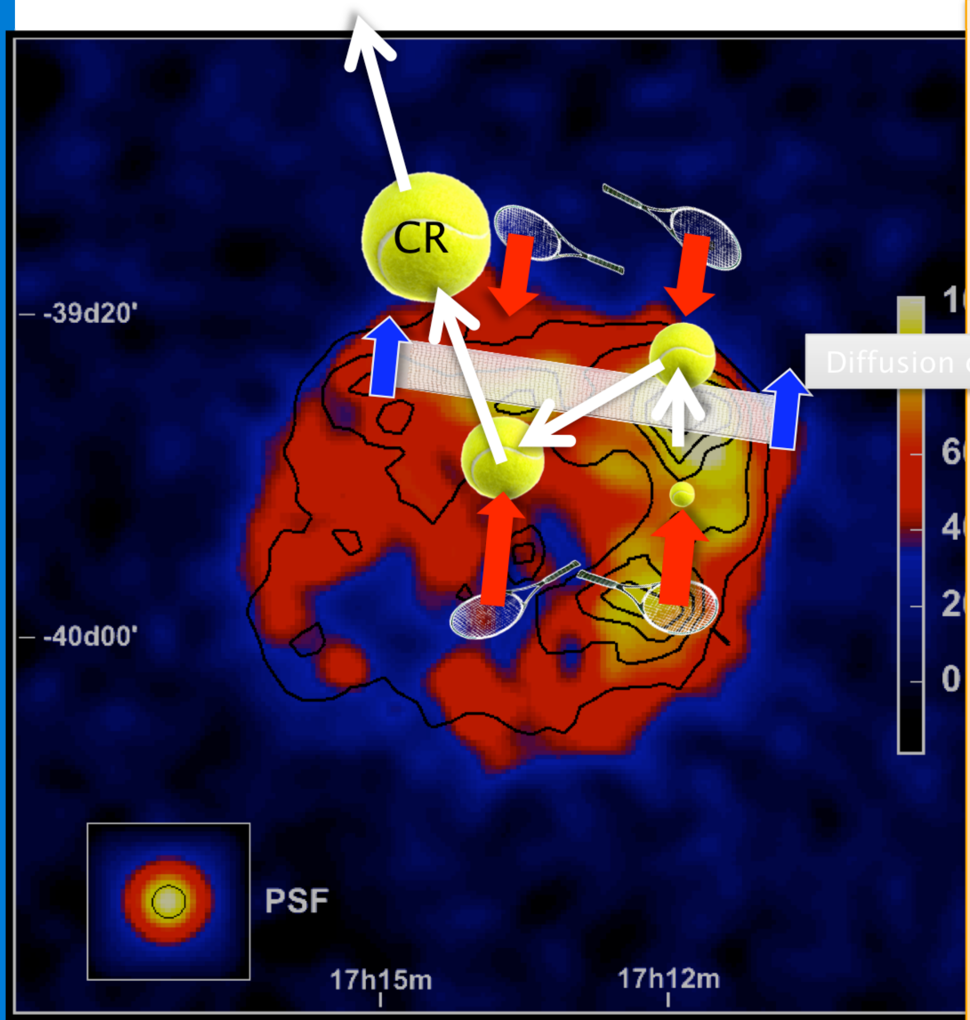
$$\Delta E \simeq \beta E \quad (\beta \sim \delta V < 1)$$

each time they diffuse through the **shock** on the time scale

Diffusion coefficient

$$\Delta t \simeq \frac{D}{V} \sim \frac{R_L}{3V} = \frac{E}{3eBV}$$

Diffusive shock acceleration



(change of) velocity of the flow at the shock

- Particles gain energy

$$\Delta E \simeq \beta E \quad (\beta \sim \delta V < 1)$$

each time they diffuse through the shock on the time scale

Diffusion coefficient

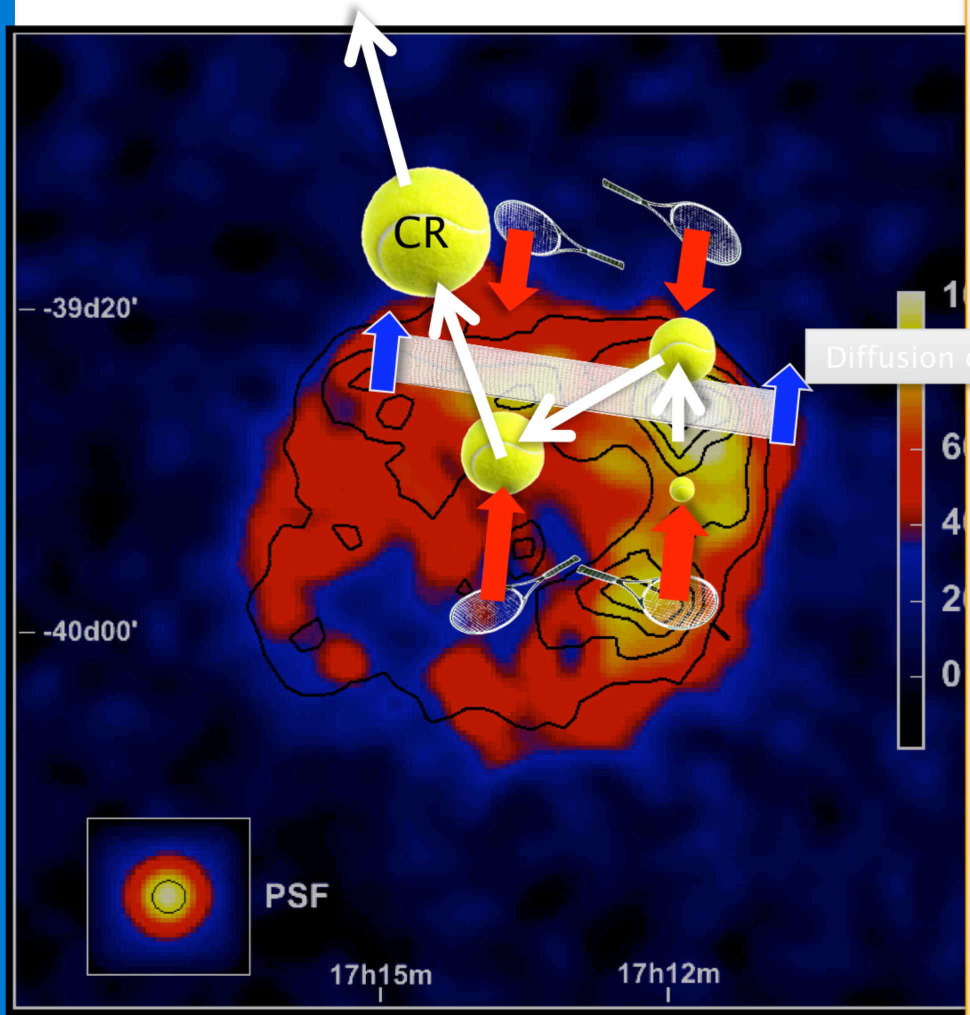
$$\Delta t \simeq \frac{D}{V} \sim \frac{R_L}{3V} = \frac{E}{3eBV}$$

- Acceleration time

acceleration "efficiency"

$$T_{\rm acc} = \frac{E}{\Delta E / \Delta t} \simeq \frac{E}{\kappa e B}, \quad \kappa \simeq V^2 \ll 1$$

Diffusive shock acceleration



- Particles gain energy

(change of) velocity of the flow at the shock

$$\Delta E \simeq \beta E \quad (\beta \sim \delta V < 1)$$

each time they diffuse through the shock on the time scale

Diffusion coefficient

$$\Delta t \simeq \frac{D}{V} \sim \frac{R_L}{3V} = \frac{E}{3eBV}$$

- Acceleration time

acceleration "efficiency"

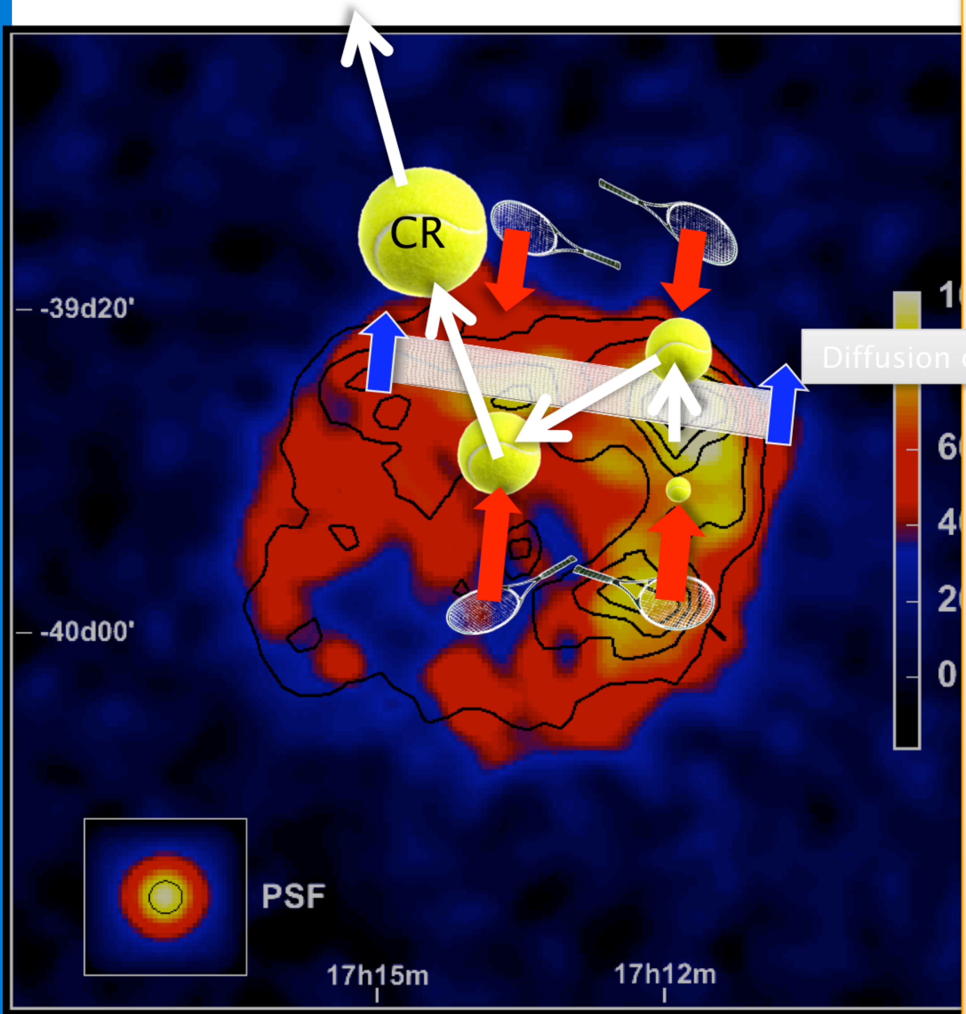
$$T_{\rm acc} = \frac{E}{\Delta E / \Delta t} \simeq \frac{E}{\kappa e B}, \quad \kappa \simeq V^2 \ll 1$$

- Particle energies are limited by finite life time of the source

$$T_{\rm acc} \simeq \frac{E}{\kappa e B} \leq T_{\rm source} \Rightarrow$$

$$E < 2 \times 10^{14} \left[\frac{V}{10^{-2} c}\right]^2 \left[\frac{B}{10^{-5}\,{\rm G}}\right] \left[\frac{T_{\rm source}}{10^3\,{\rm yr}}\right] {\rm eV}$$

Diffusive shock acceleration



- Particles gain energy

(change of) velocity of the flow at the shock

$$\Delta E \simeq \beta E \quad (\beta \sim \delta V < 1)$$

each time they diffuse through the shock on the time scale

Diffusion coefficient

$$\Delta t \simeq \frac{D}{V} \sim \frac{R_L}{3V} = \frac{E}{3eBV}$$

- Acceleration time

acceleration "efficiency"

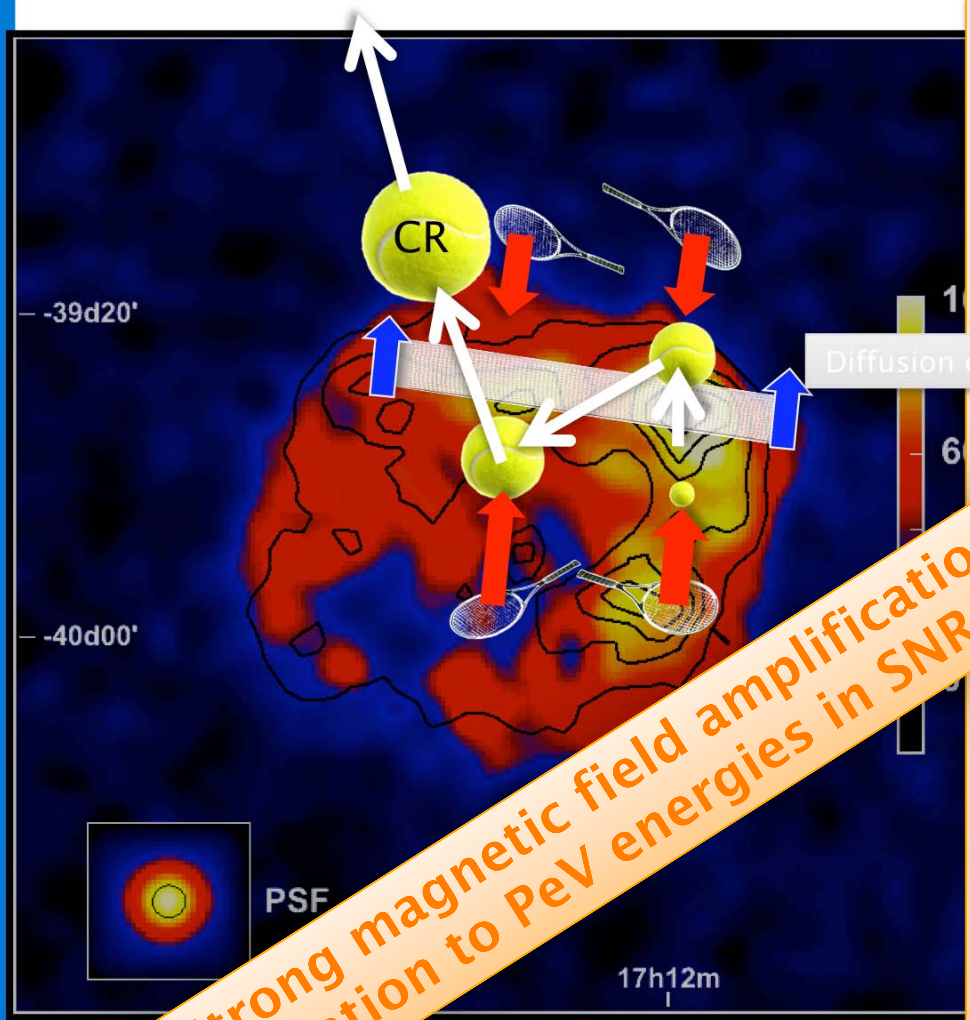
$$T_{\rm acc} \simeq \frac{E}{\kappa eB}, \quad \kappa \simeq V^2 \ll 1$$

- Particle energies are limited by escape of particles from the source

$$T_{\rm acc} \leq T_{\rm escape} \simeq \frac{R_{\rm source}^2}{R_L} \Rightarrow$$

$$E < 10^{13} \left[\frac{V}{10^{-2}c}\right]^2 \left[\frac{B}{10^{-5}\,{\rm G}}\right]\left[\frac{R_{\rm source}}{10\ {\rm pc}}\right] {\rm eV}$$

Diffusive shock acceleration



(change of) velocity of the flow at the shock

- Particles gain energy

$$\Delta E \simeq \beta E \quad (\beta \sim \ldots < 1)$$

each time they d... ough the shock on th... ale

$$\ldots \frac{R_L}{3V} = \frac{E}{3eBV}$$

...eration time

acceleration "efficiency"

$$T_{\text{acc}} \simeq \frac{E}{\kappa e B}, \quad \kappa \simeq V^2 \ll 1$$

- Particle energies are limited by

$$E < 2 \times 10^{14} \left[\frac{V}{10^{-2} c}\right]^2 \left[\frac{B}{10^{-5}\,\text{G}}\right] \left[\frac{T_{\text{source}}}{10^3\,\text{yr}}\right] \text{eV}$$

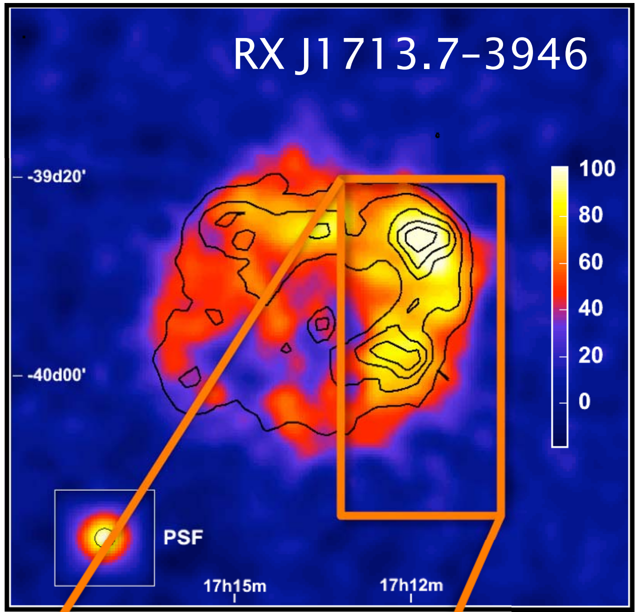
$$E < 10^{13} \left[\frac{V}{10^{-2} c}\right]^2 \left[\frac{B}{10^{-5}\,\text{G}}\right] \left[\frac{R_{\text{source}}}{10\,\text{pc}}\right] \text{eV}$$

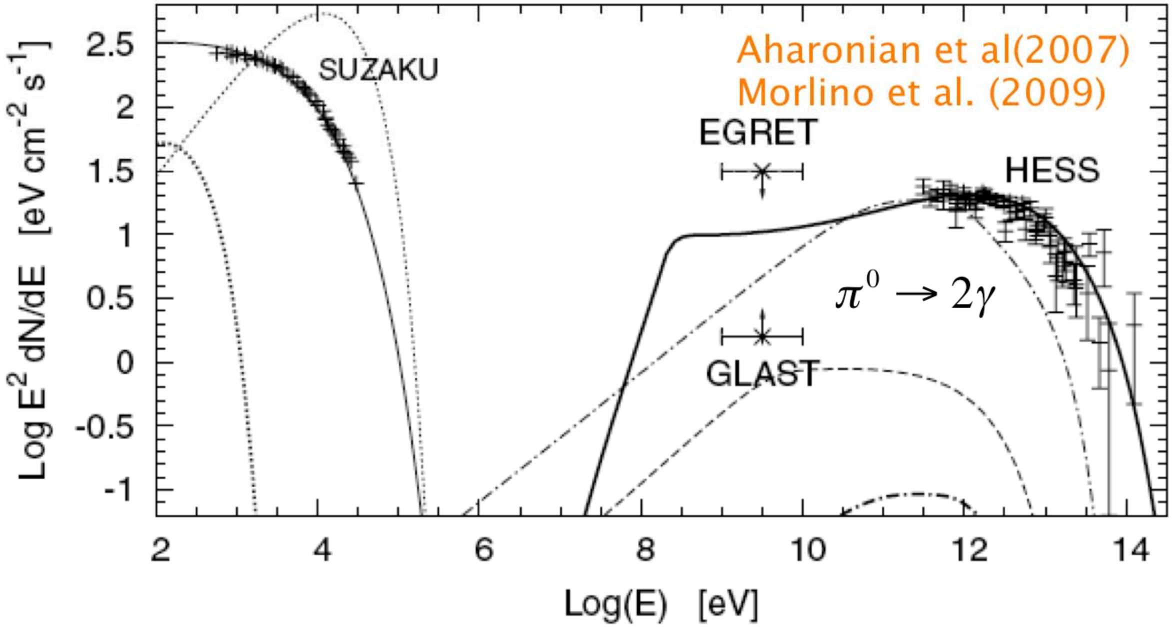
→ Strong magnetic field amplification is required to allow acceleration to PeV energies in SNR free expansion time

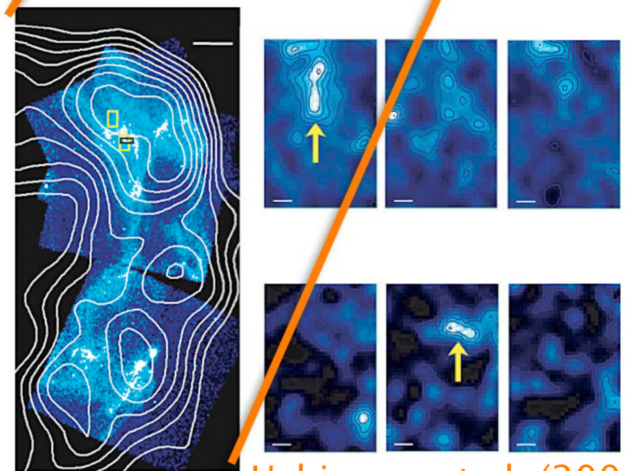
Cosmic Rays and Supernovae

Where do Cosmic Rays come from?

Problem close to being resolved?







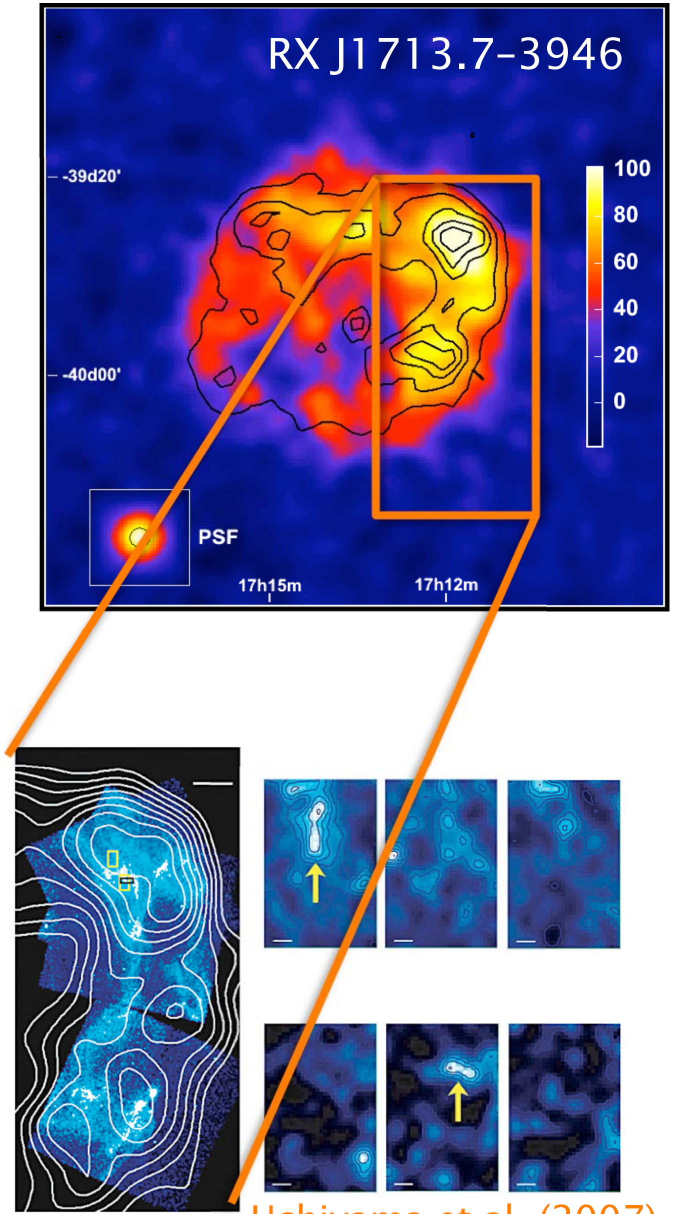
Uchiyama et al. (2007)

✷strong magnetic fields (**B~0.1-1 mG**) are found in SNR shells

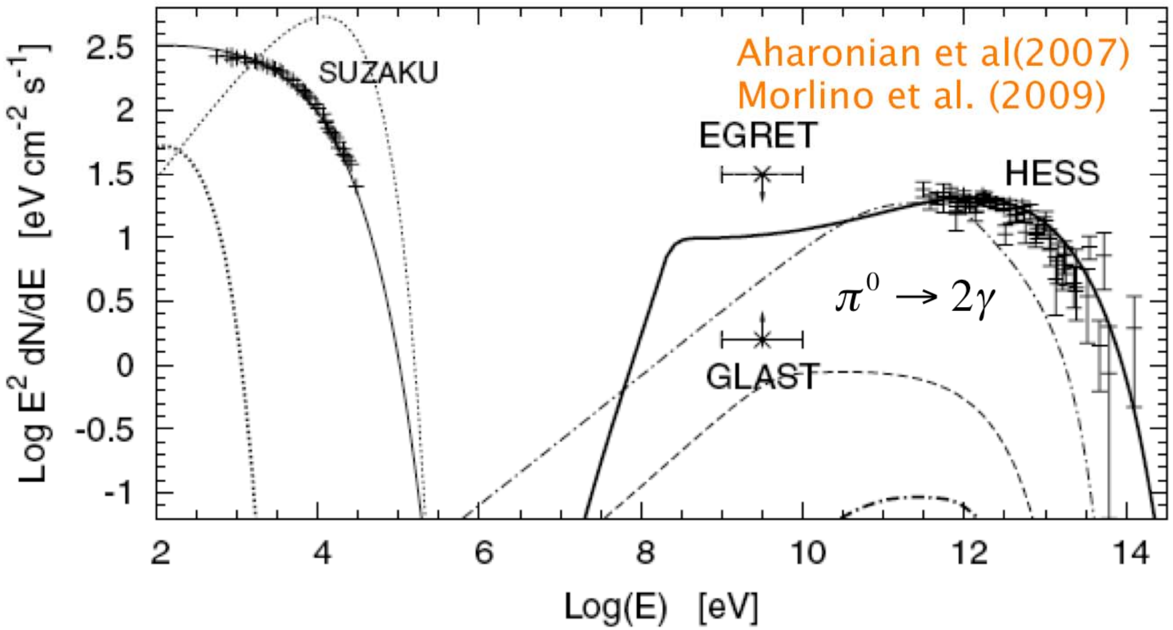
Where do Cosmic Rays come from?

Cosmic Rays and Supernovae

Problem close to being resolved?



Uchiyama et al. (2007)

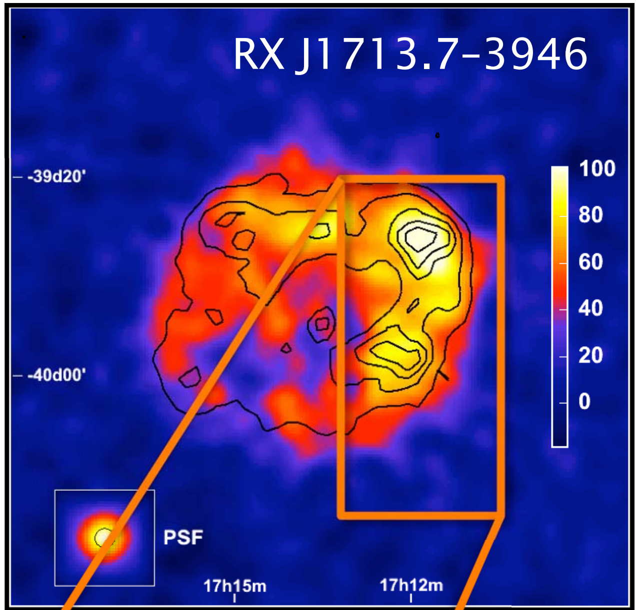


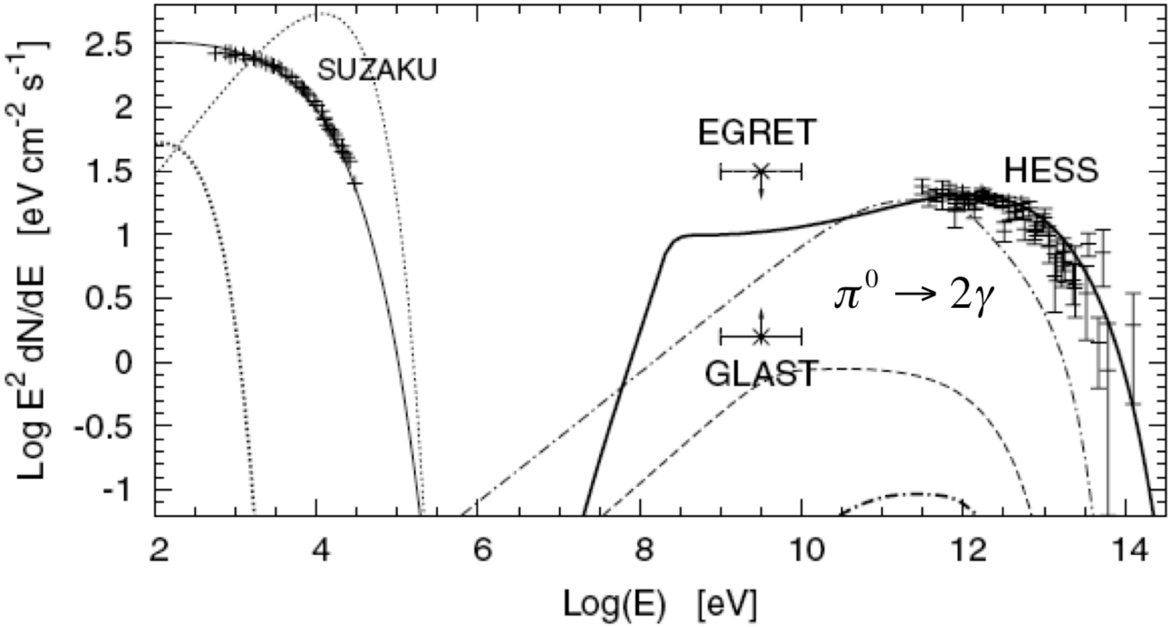
- ✷strong magnetic fields (**B~0.1-1 mG**) are found in SNR shells
- ✷γ-rays with energies **>10 TeV** from SNRs are observed

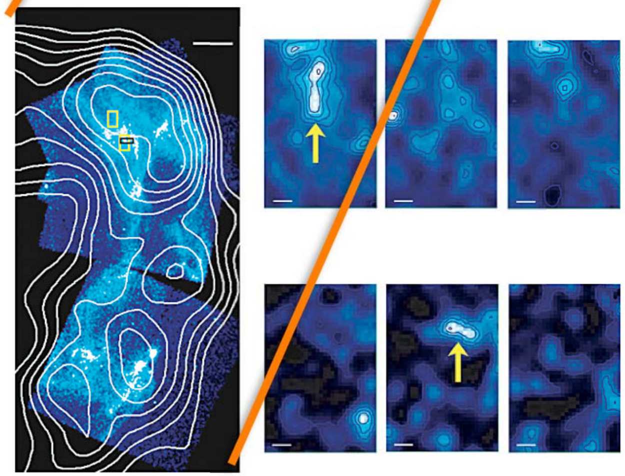
Cosmic Rays and Supernovae

Where do Cosmic Rays come from?

Problem close to being resolved?





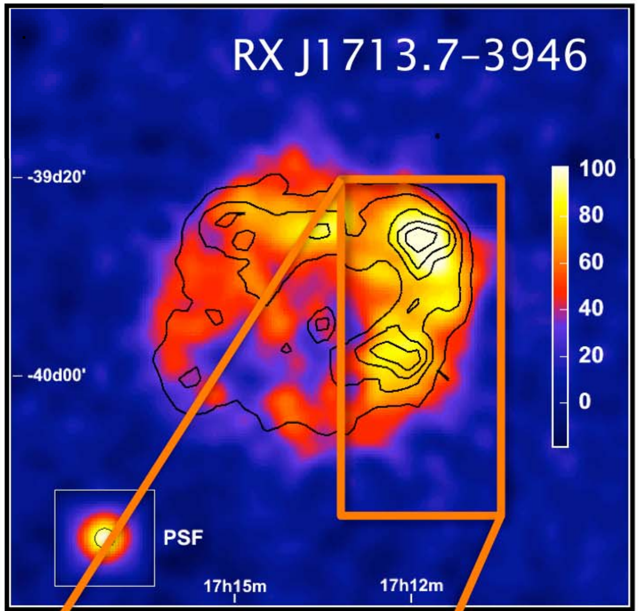


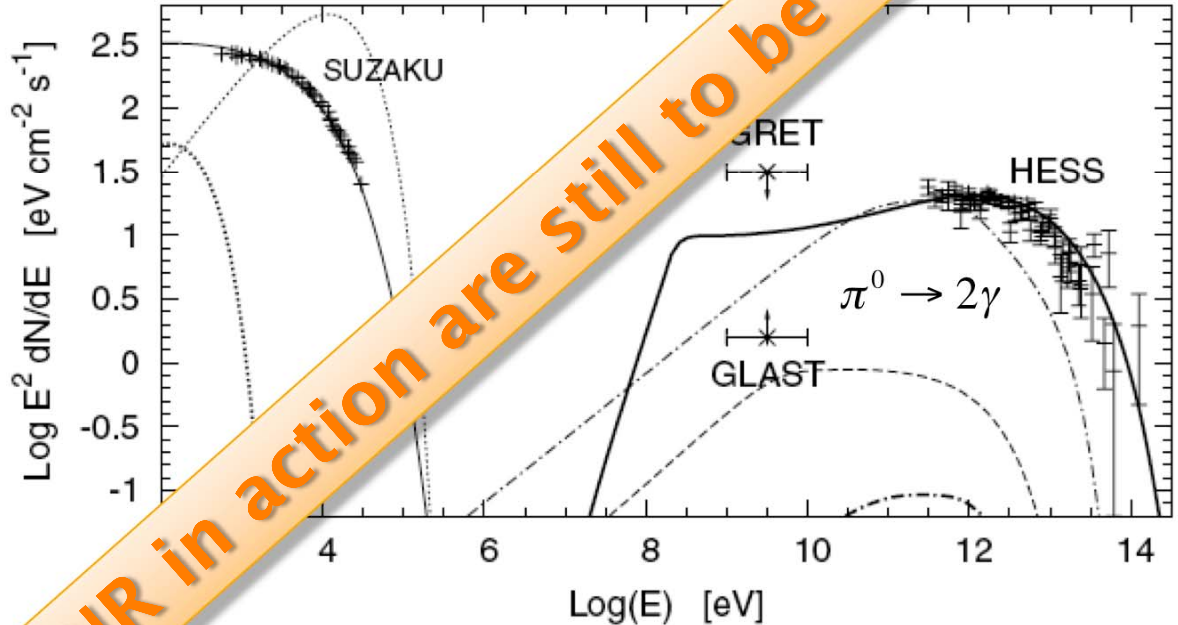
- ✸strong magnetic fields (0.1-1 mG) are found in SNR shells
- ✸γ-rays with energies >10 TeV from SNRs are observed
- ✸**Purely "leptonic" models of the origin of γ-ray emission are not fully ruled out**
- ✸**No observational evidence for proton acceleration up to the "knee" energy so far**
- ✸**It is difficult to estimate the fraction of the SN energy in the cosmic rays**

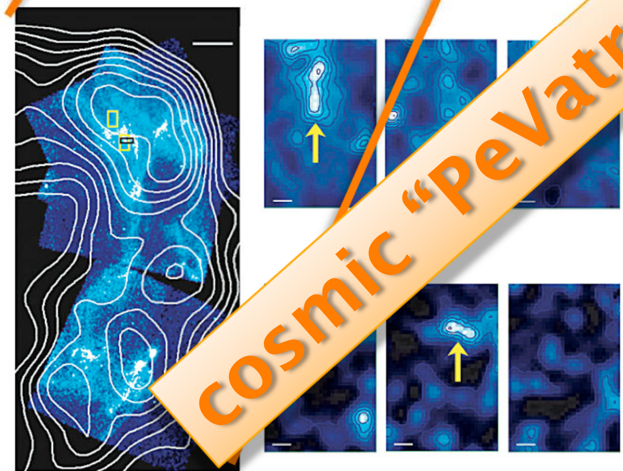
Where do Cosmic Rays come from?

Cosmic Rays and Supernovae

Problem close to being resolved?





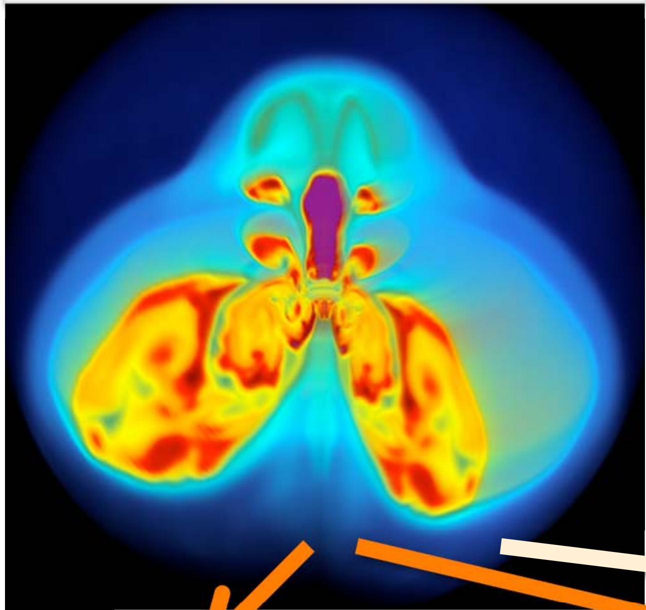


cosmic "PeVatron" SNR in action are still to be found

- ✸strong magnetic fields (0.1-1 mG) are found in SNR shells
- ✸γ-rays with energies >10 TeV from SNRs are observed
- ✸**Purely "leptonic" models of the origin of γ-ray emission are not fully ruled out**
- ✸**No observational evidence for proton acceleration up to the "knee" energy so far**
- ✸**It is difficult to esctimate the fraction of the SN energy in cosmic rays**

Supernovae → GRBs, pulsars

Supernova explosion



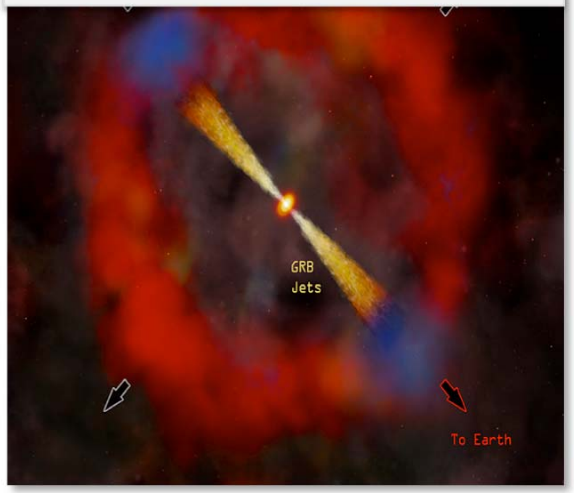
Supernova explosions give rise to several classes of sources.

Supernova remnants and pulsar wind nebulae are known to be sources of multi-TeV γ-rays

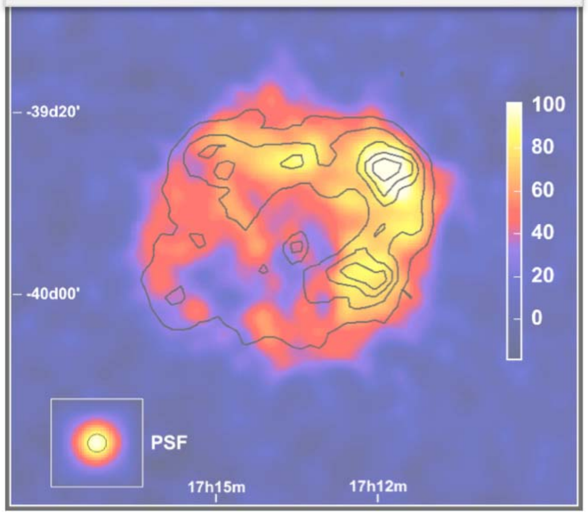
Highest energy CRs are produced at early stages of SNR evolution…
…or right at the moment of explosion?

Pulsars/Pulsar wind nebula (PWN)

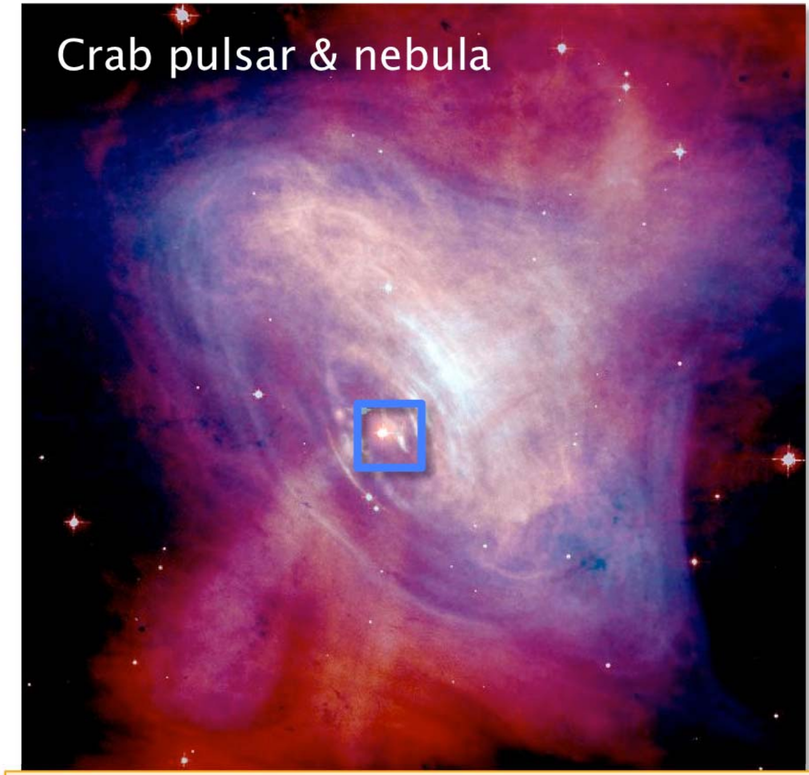
gamma-ray burst (GRB)



Supernova remnant (SNR)



Particle acceleration in pulsars

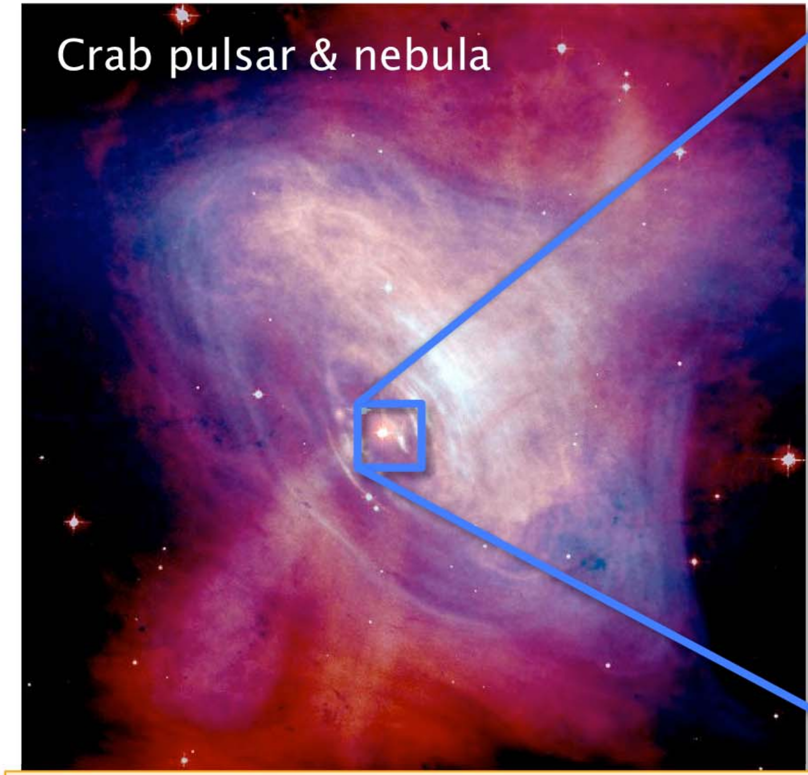


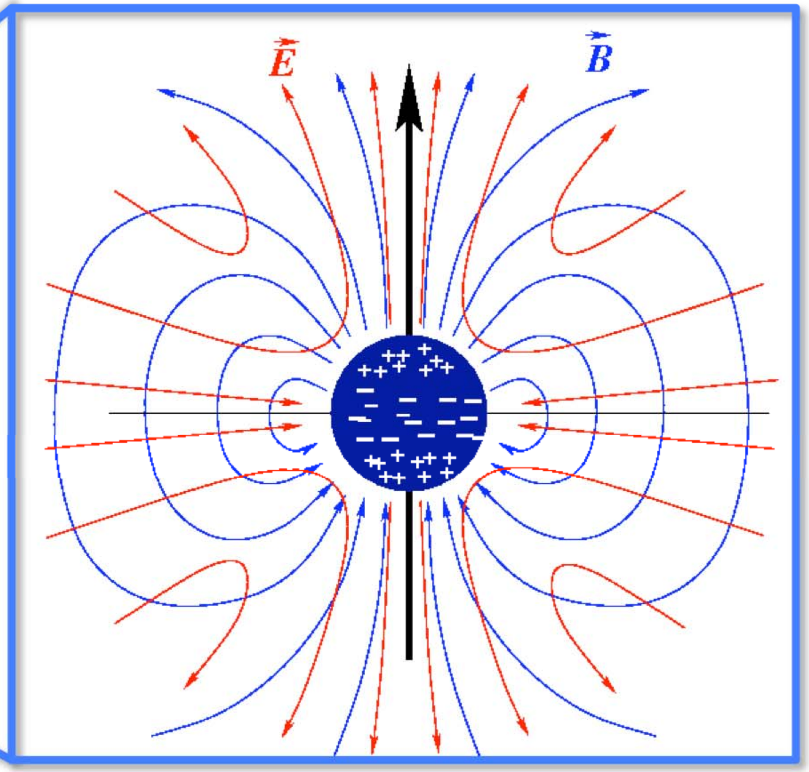
Rotating neutron star stores energy

$$E_{\text{rotation}} = \frac{I\Omega^2}{2} \simeq 2 \times 10^{50} \left[\frac{P}{10\ \text{ms}} \right]^{-2} \text{erg}$$

NS rotation period

Particle acceleration in pulsars





Rotating neutron star stores energy

$$E_{\text{rotation}} = \frac{I\Omega^2}{2} \simeq 2 \times 10^{50} \left[\frac{P}{10\ \text{ms}}\right]^{-2} \text{erg}$$

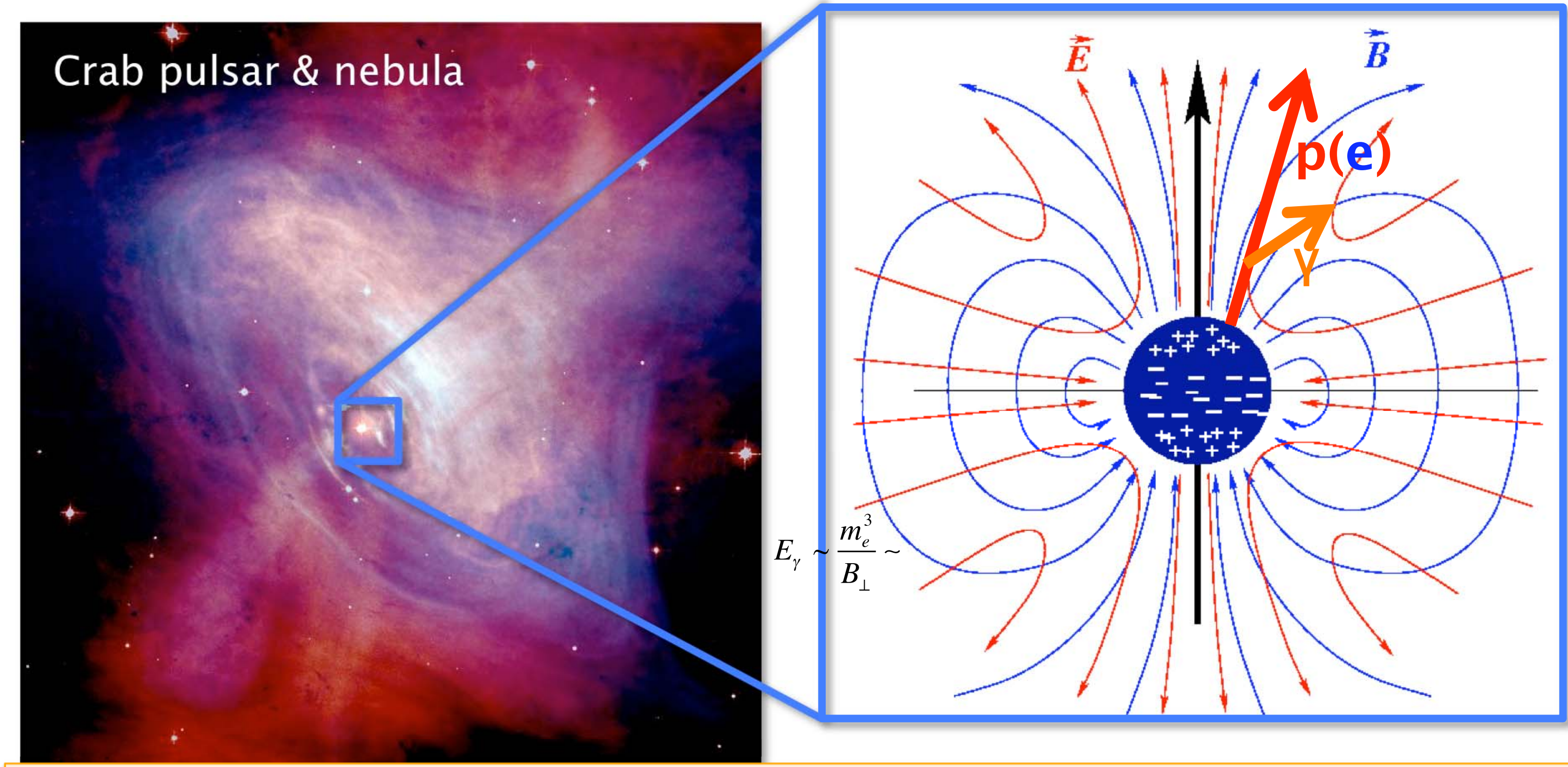
NS rotation period

Ordered electric field induced by the NS rotation can accelerate protons up to energies

$$E \sim e\ \Omega\ B\ R_{NS}^2 \simeq 10^{17} \left[\frac{B}{10^{12}\,\text{G}}\right] \left[\frac{P}{10\ \text{ms}}\right]^{-1} \text{eV}$$

$$\Rightarrow \kappa = \Omega R_{NS} \sim 1 \left[\frac{P}{0.2\ \text{ms}}\right]$$

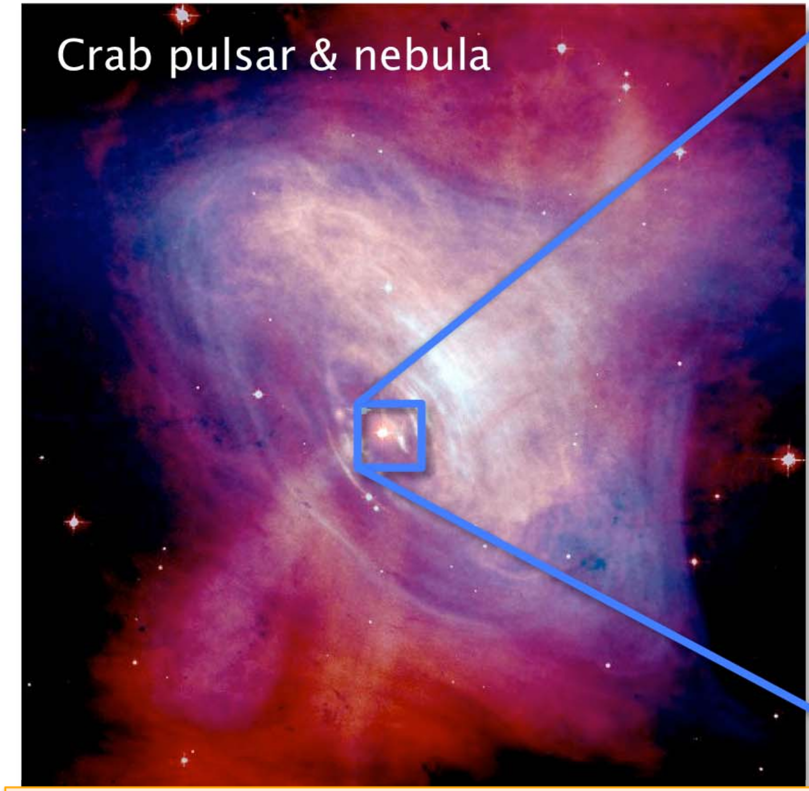
Particle acceleration in pulsars

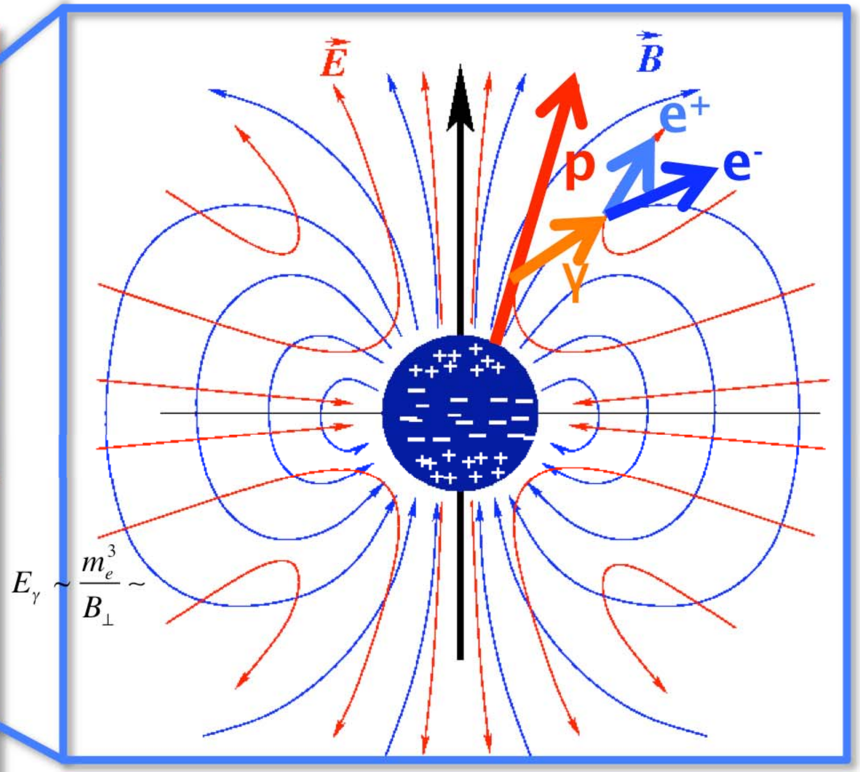


Accelerated protons and/or electrons emit curvature radiation

$$E_\gamma \simeq \frac{E^3}{R_{NS} m^3} \simeq 5 \times 10^9 \left[\frac{E}{10^6 m}\right]^3 \mathrm{eV}$$

Particle acceleration in pulsars





Accelerated protons and/or electrons emit curvature radiation

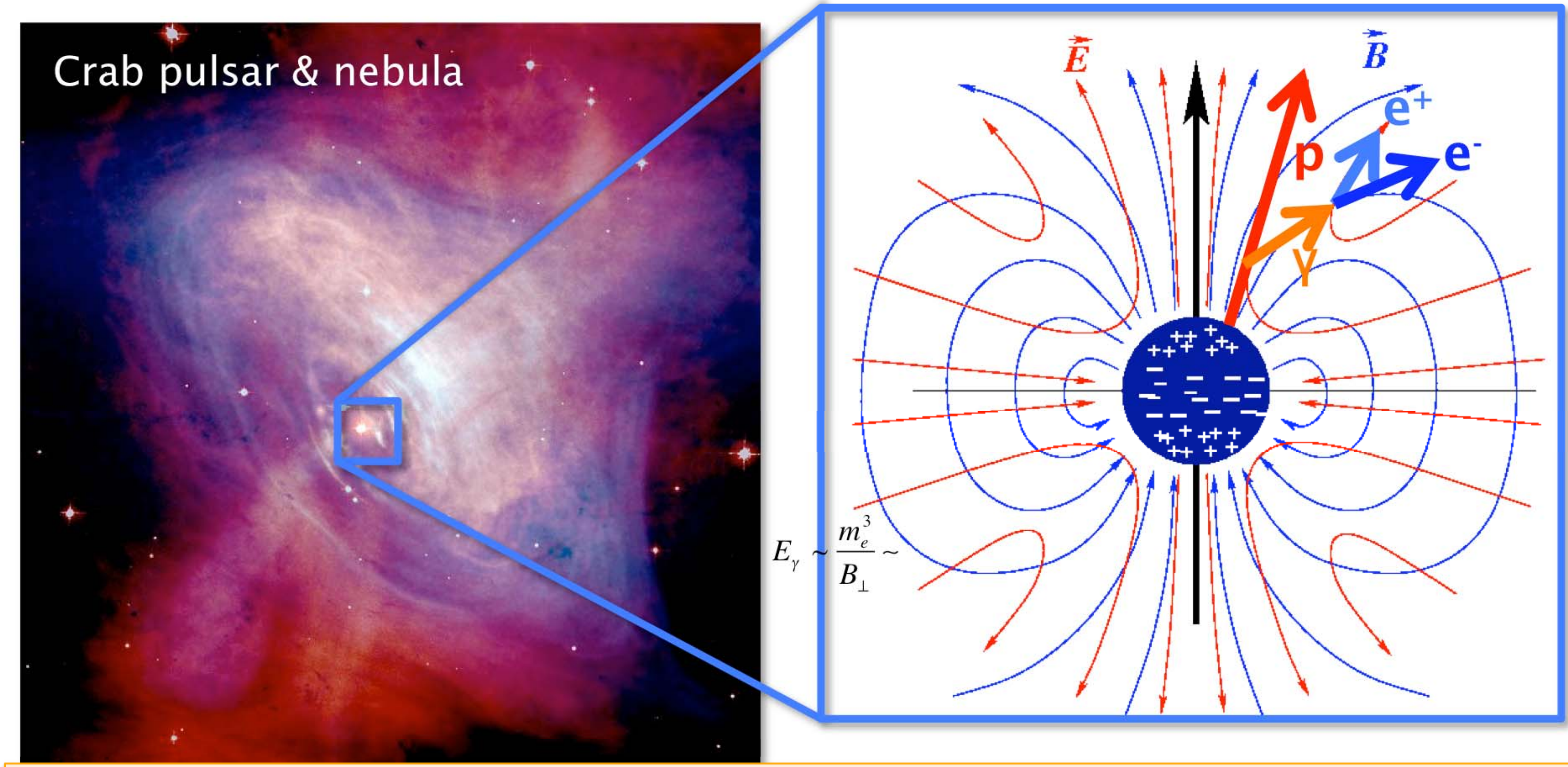
$$E_\gamma \simeq \frac{E^3}{R_{NS} m^3} \simeq 5 \times 10^9 \left[\frac{E}{10^6 m} \right]^3 \text{eV} \leq 10 \text{ GeV}$$

which interacts with magnetic field and/or X-ray photons

Fermi
MAGIC

$$E_e \sim 1 \text{ TeV}; \; E_p \sim 1 \text{ PeV}$$

Problem of pulsar wind formation



Accelerated protons and/or electrons emit curvature radiation

$$E_\gamma \simeq \frac{E^3}{R_{NS} m^3} \simeq 5 \times 10^9 \left[\frac{E}{10^6 m}\right]^3 \text{eV} \leq 10\ \text{GeV}$$

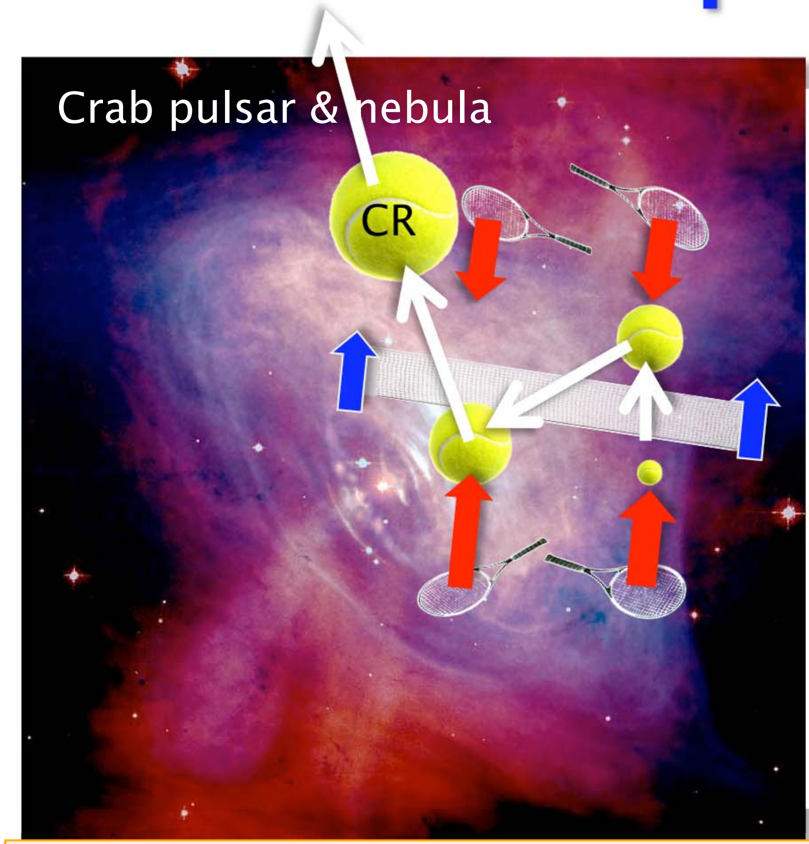
Fermi
MAGIC

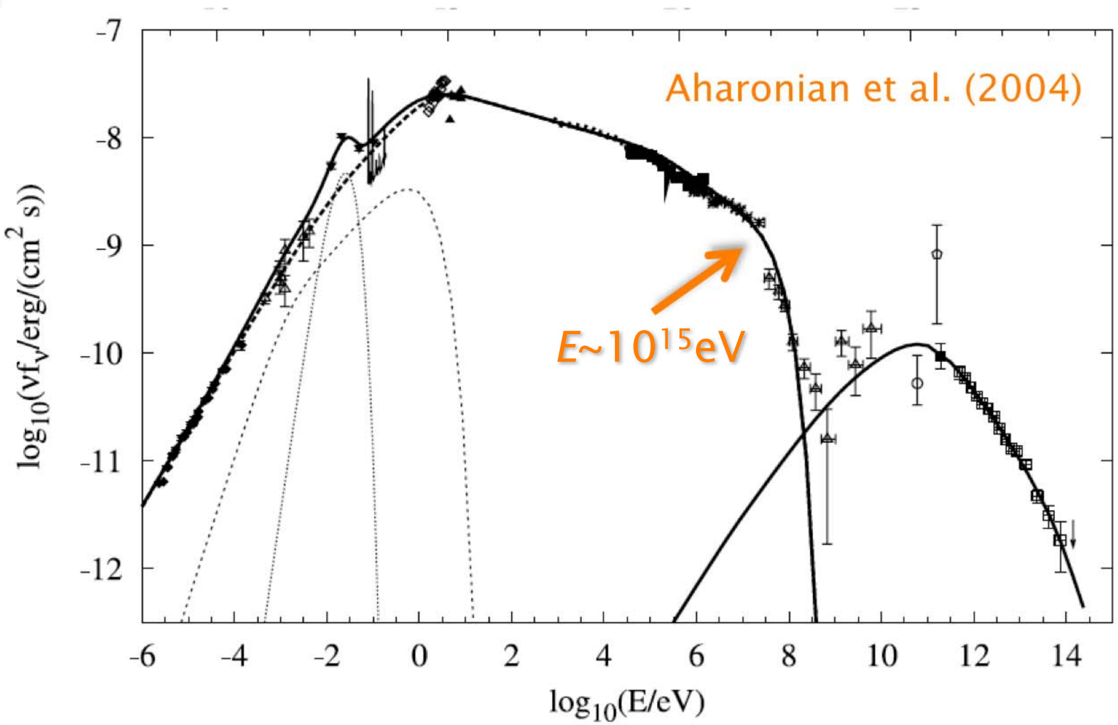
which interacts with magnetic field and/or X-ray photons

$$E_e \sim 1\ \text{TeV};\ \ E_p \sim 1\ \text{PeV}$$

Neutron star generates a relativistic particle-loaded “wind”.
Mechanism of wind formation and its Lorentz factor are uncertain.

… and in pulsar wind nebulae





Particle acceleration to >PeV energies in Crab (nebula and/or parent pulsar) is observed

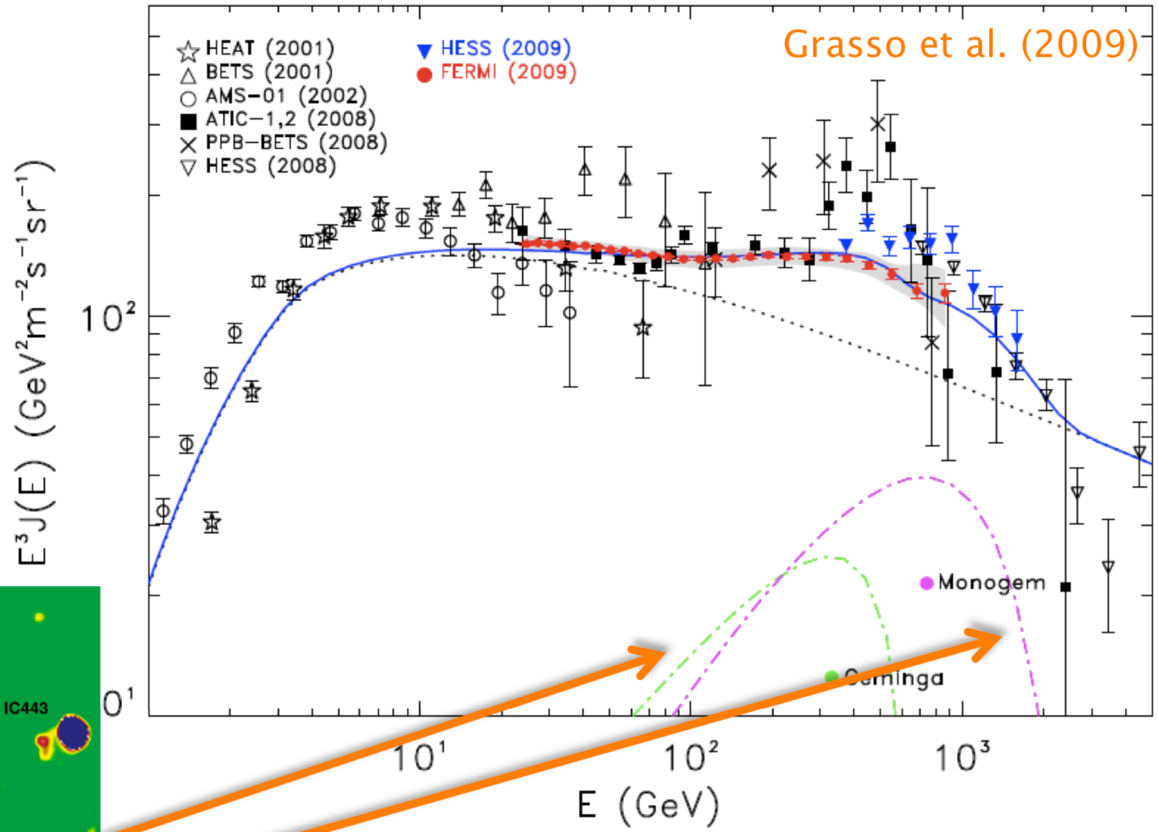
$$E_{\rm synch} \simeq \frac{eBE^2}{m_e^3} \simeq 4\left[\frac{B}{10^{-4}\ \rm G}\right]\left[\frac{E}{10^{15}\,\rm eV}\right]^2 \rm MeV$$

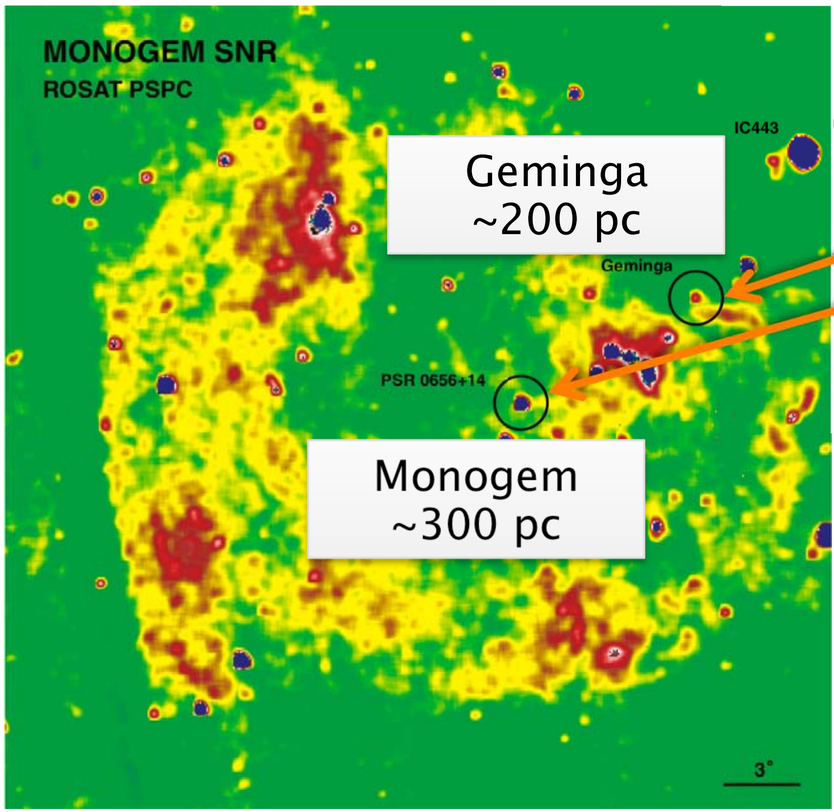
acceleration is highly efficient: $T_{\rm acc} \leq T_{\rm escape} \Rightarrow E < 3\times10^{15}\left[\frac{V}{c}\right]^2\left[\frac{B}{10^{-4}\,\rm G}\right]\left[\frac{R_{\rm shock}}{10^{17}\ \rm cm}\right]\rm eV$

PWNe (and/or their parent pulsars) are "confirmed PeVatrons"

Where do Cosmic Rays come from?

CR electron sources

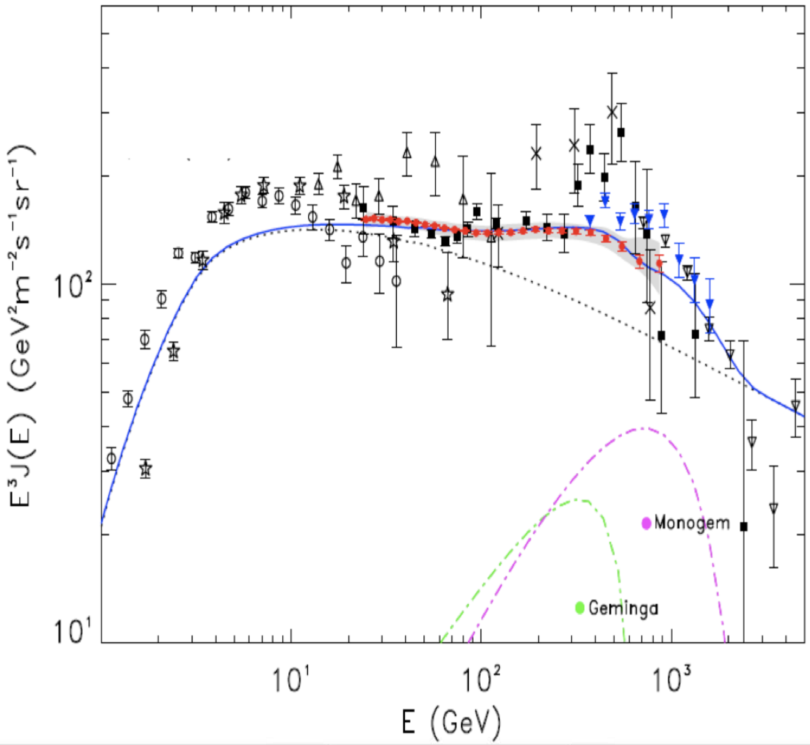


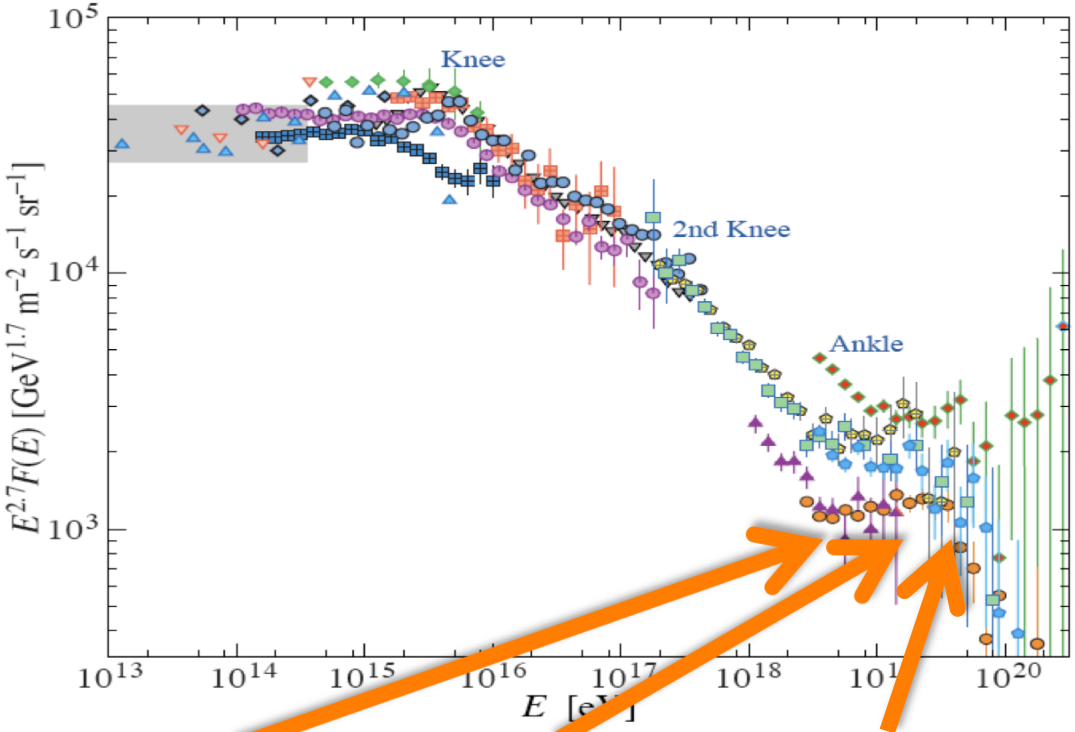


Nearby pulsars/PWNe could be responsible for the highest energy cosmic ray electrons

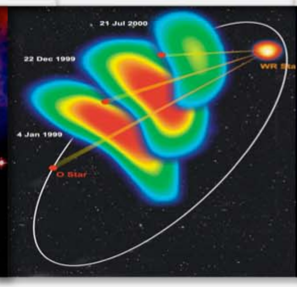
Where do Cosmic Rays come from?

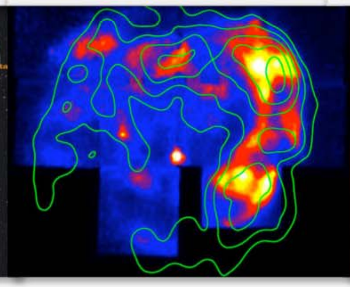
High-energy astrophysics → CR physics

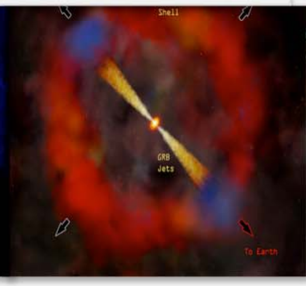


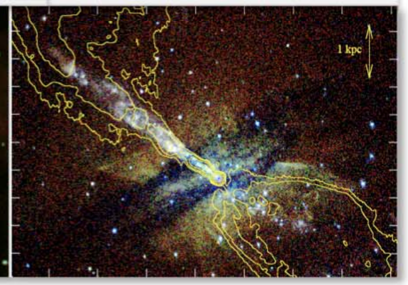


Pulsars/PWNe | Binaries | SNR | GRBs | Galaxy clusters | AGN





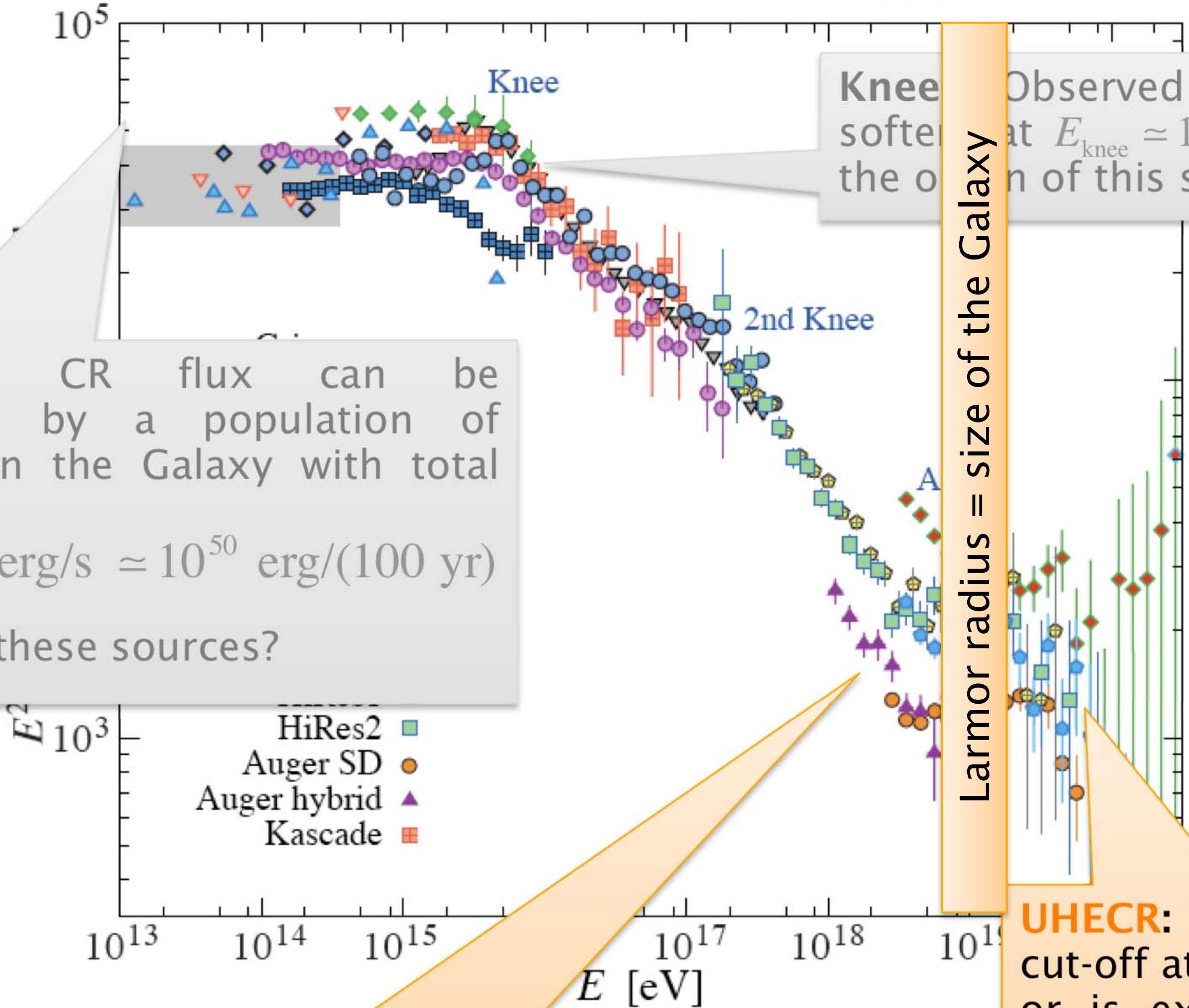




Radio, X-ray and γ-ray emission, observed from several classes of astronomical objects, is produced by particles accelerated to $E \gg m$

→ CR source "candidates" list is well-known

Origin of highest energy cosmic rays



Larmor radius = size of the Galaxy

Knee: Observed CR spectrum softens at $E_{\rm knee} \simeq 10^{15}$ eV What is the origin of this spectral feature?

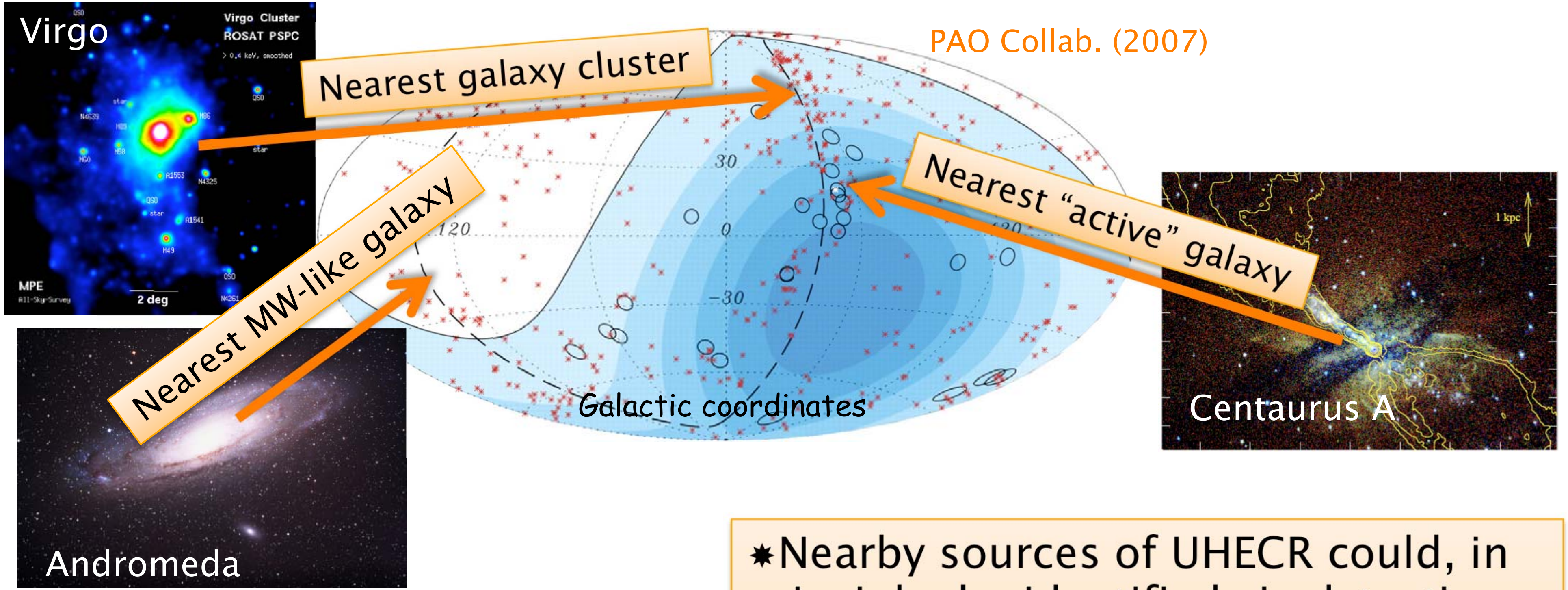
Observed CR flux can be produced by a population of sources in the Galaxy with total power $L \simeq 10^{40}$ erg/s $\simeq 10^{50}$ erg/(100 yr)

What are these sources?

Ankle: Observed CR spectrum softens at $E_{\rm ankle} \simeq 10^{18}$ eV What is the origin of this spectral feature? Are these CRs of Galactic or extra-galactic orgin?

UHECR: Is the spectrum cut-off at $E_{\rm UHECR} \simeq 10^{20}$ eV or is extends to higher energies? What is the origin of the spectral feature? What are the sources of UHECR?

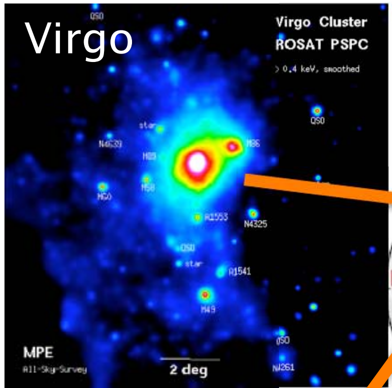
Nearby UHECR sources?

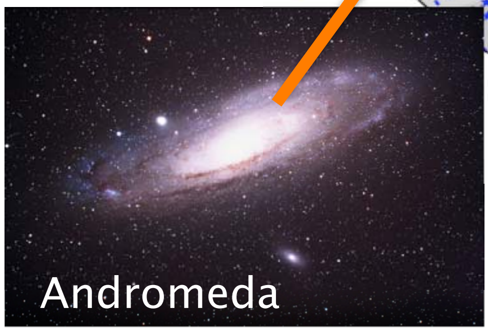


- ✷Nearby sources of UHECR could, in principle, be identified via detection "excess" of CR events in the source direction
- ✷ Correlation of arrival directions of UHECR events with nearby AGN was claimed by Pierre Auger Observatory
- ✷The nearest radio galaxy Centaurus A is an "UHECR hot-spot"

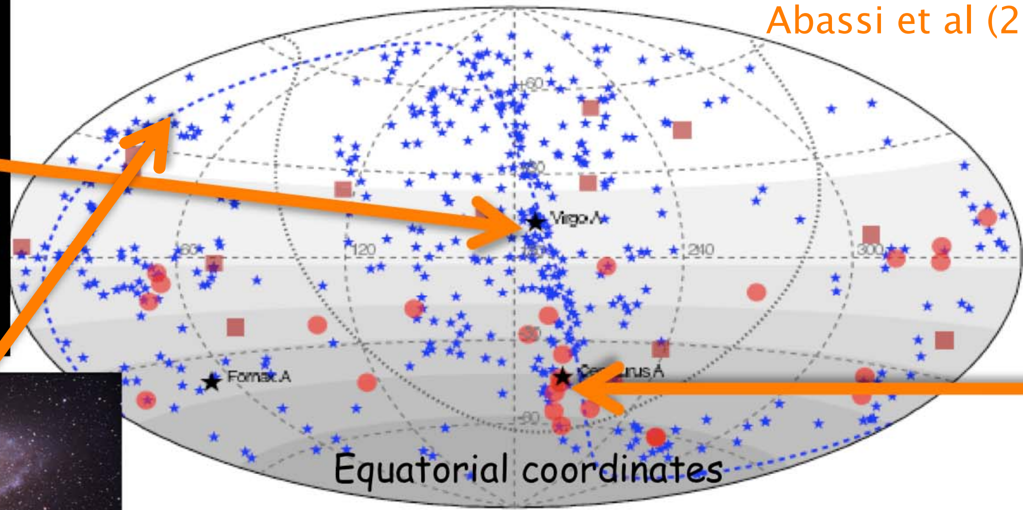
Where do Cosmic Rays come from?

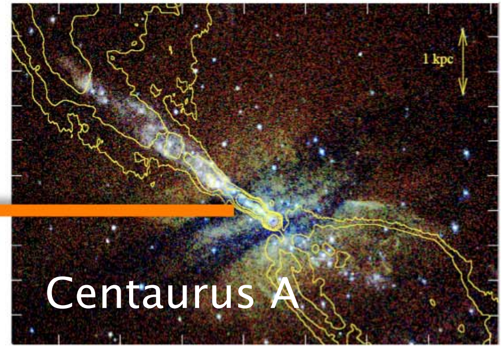
Nearby UHECR sources?

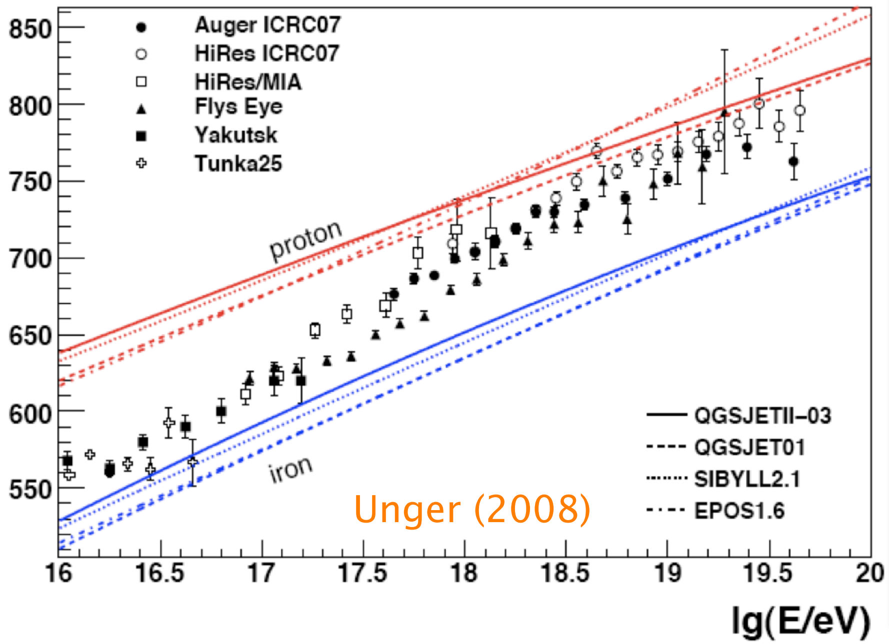




Abassi et al (2008)





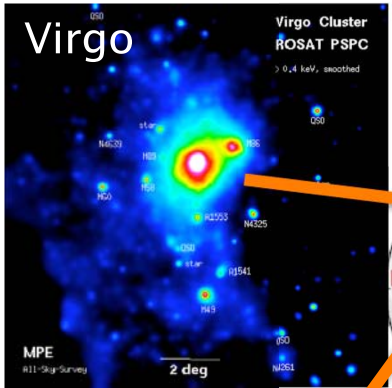


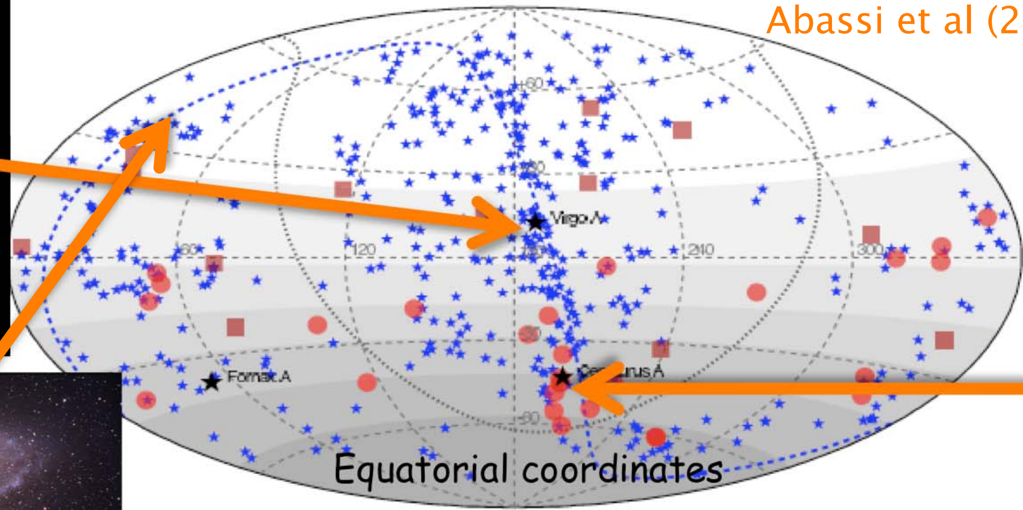
Unger (2008)

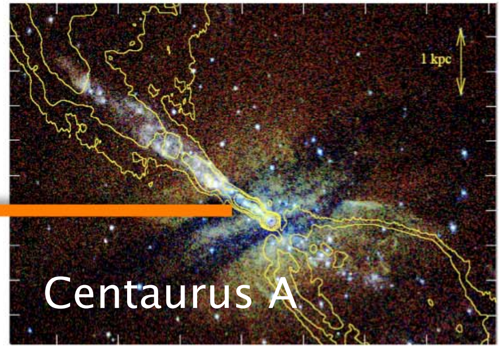
- ✸Nearby sources of UHECR could, in principle, be identified via detection “excess” of CR events in the source direction
- ✸ Correlation of arrival directions of UHECR events with nearby AGN was claimed by Pierre Auger Observatory
- ✸The nearest radio galaxy Centaurus A is an “UHECR hot-spot”
- ✸**HiRes data?**
- ✸**Heavy nuclei component?**

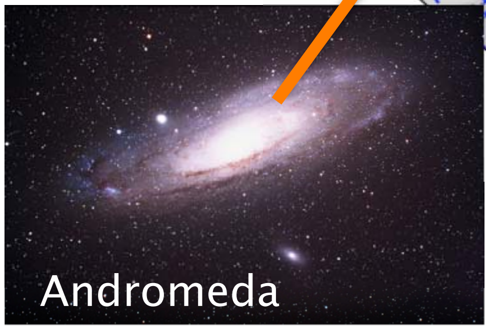
Where do Cosmic Rays come from?

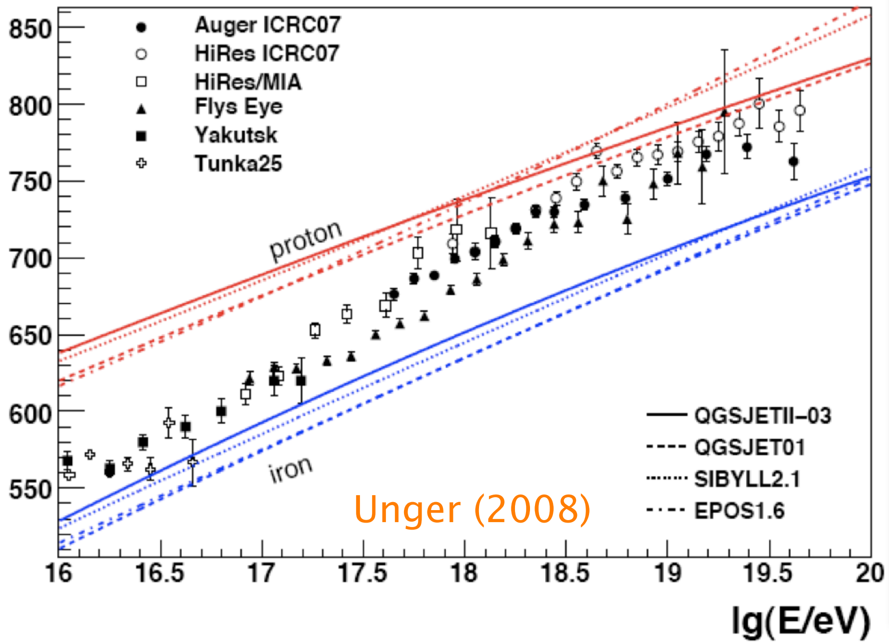
Nearby UHECR sources?







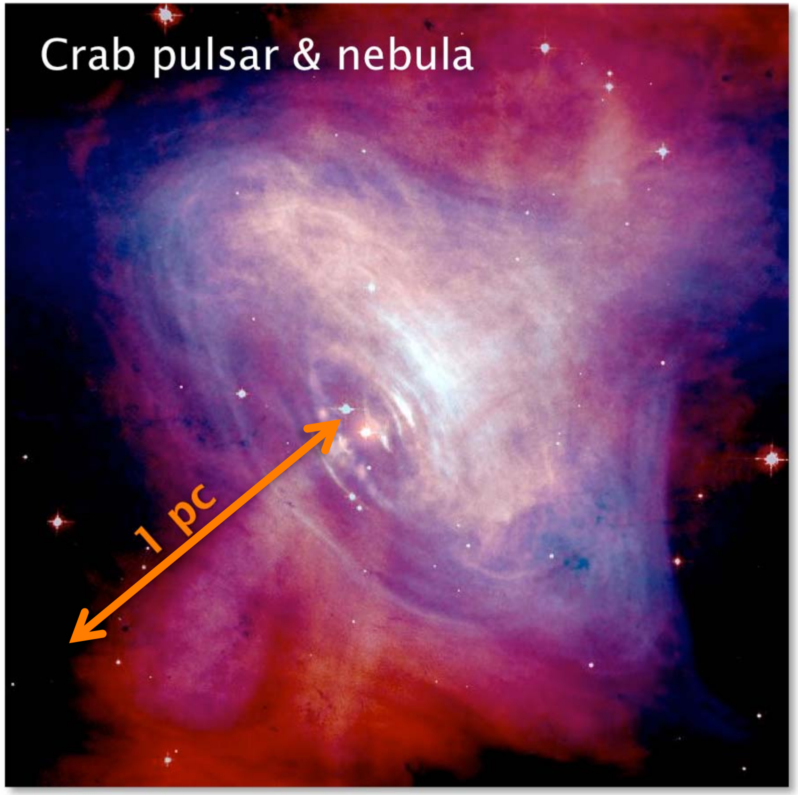


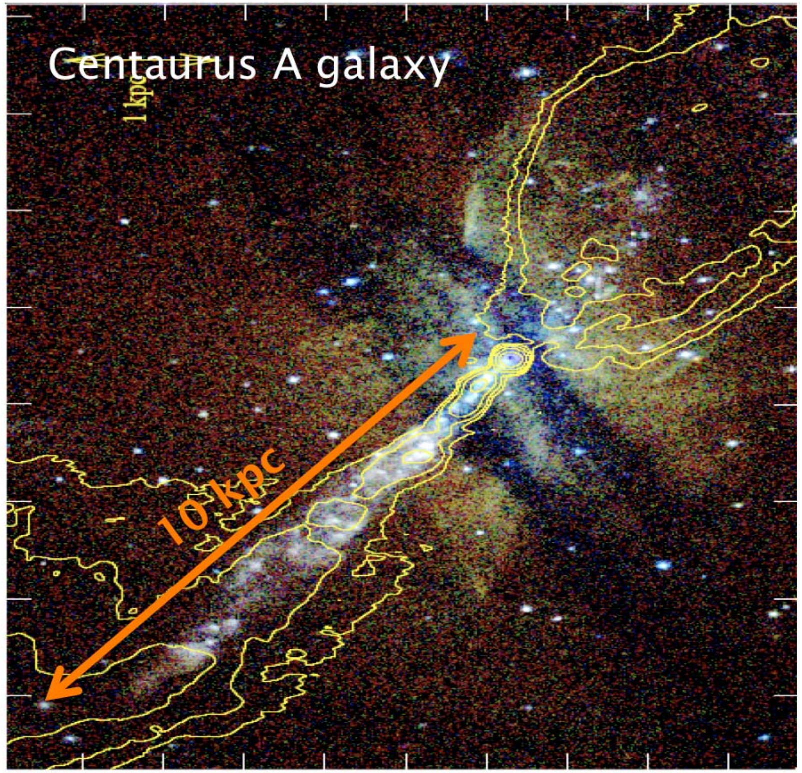


- ✷Nearby sources of UHECR could, in principle, be identified via detection "excess" of CR events in the source direction
- ✷ Correlation of arrival directions of UHECR events with nearby AGN was claimed by Pierre Auger Observatory
- **✷The nearest radio galaxy Centaurus A is an "UHECR hot-spot"**
- ✷HiRes data?
- ✷Heavy nuclei component?

Where do Cosmic Rays come from?

stellar → galaxy-scale accelerators



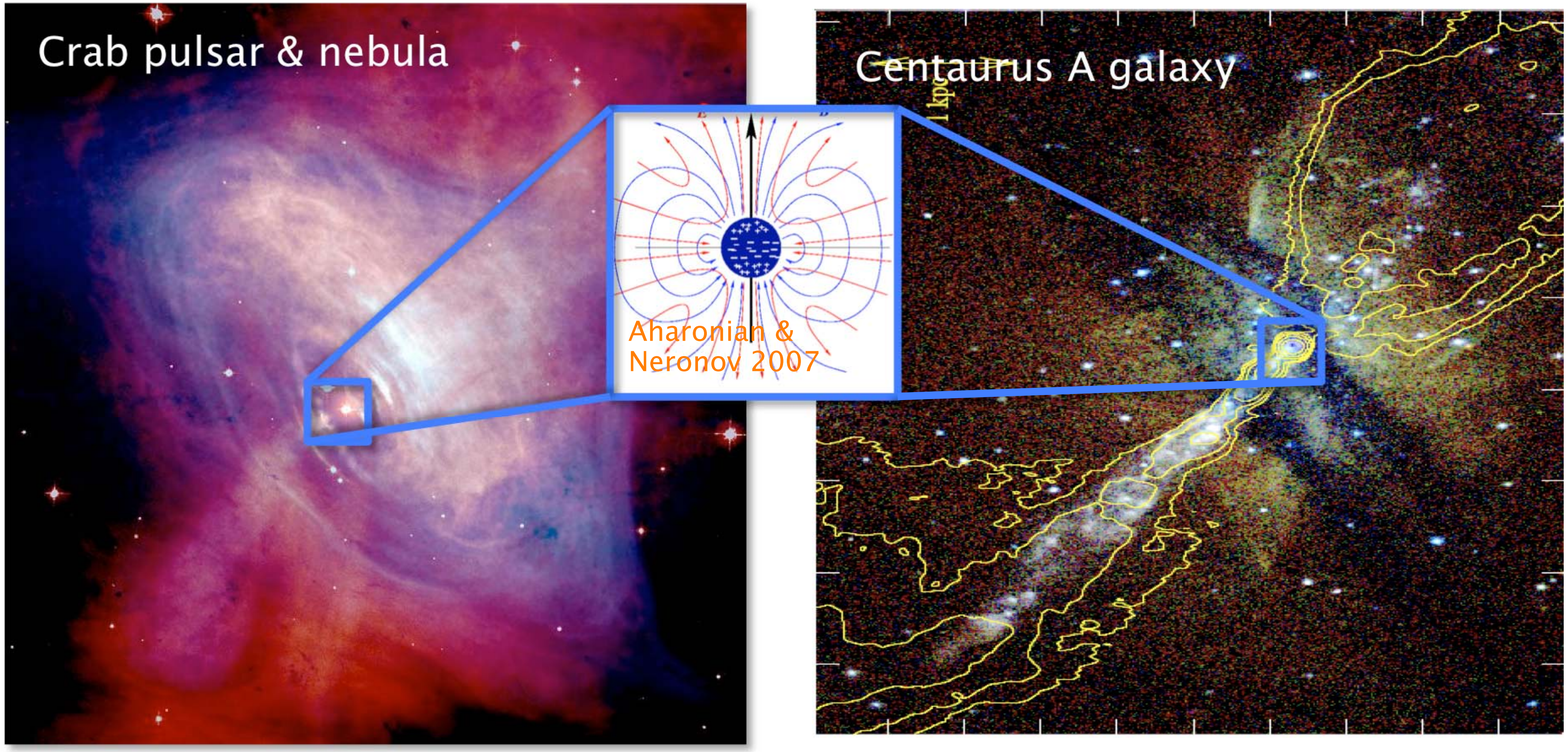


Relativistic outflows are generated not only by neutron stars, but also by black holes (e.g. in active galactic nuclei, AGN).

Jet-emitting AGN are sources of TeV γ-rays. Detection of X-ray synchrotron emission from jets implies presence of ~100 TeV electrons.

→ AGN (radio galaxies and blazars) work as particle accelerators

stellar → galaxy-scale accelerators

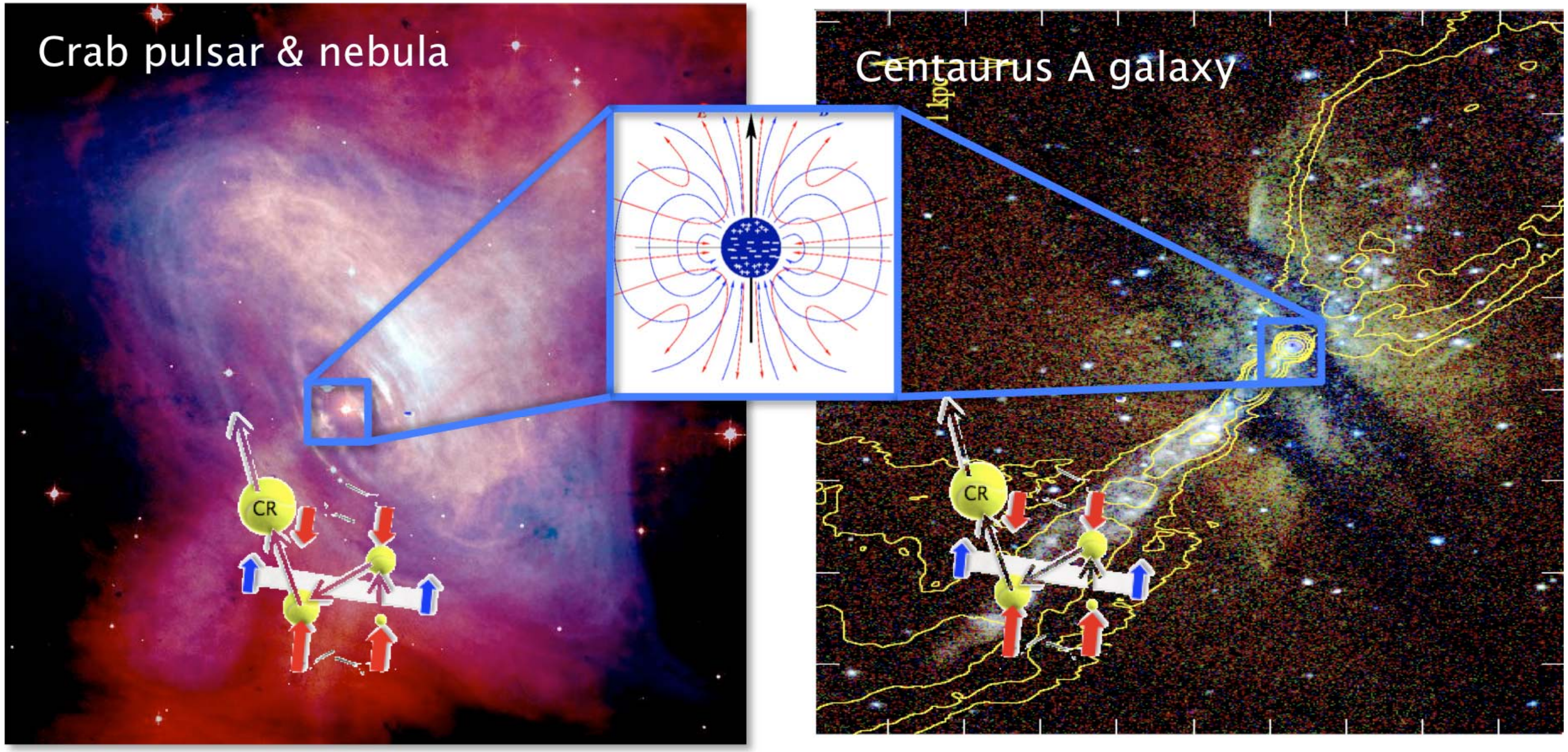


Relativistic outflows are generated not only by neutron stars, but also by black holes (e.g. in active galactic nuclei, AGN).

Jet-emitting AGN are sources of TeV γ-rays. Detection of X-ray synchrotron emission from jets implies presence of ~100 TeV electrons.

→ AGN (radio galaxies and blazars) work as particle accelerators

stellar ➔ galaxy-scale accelerators

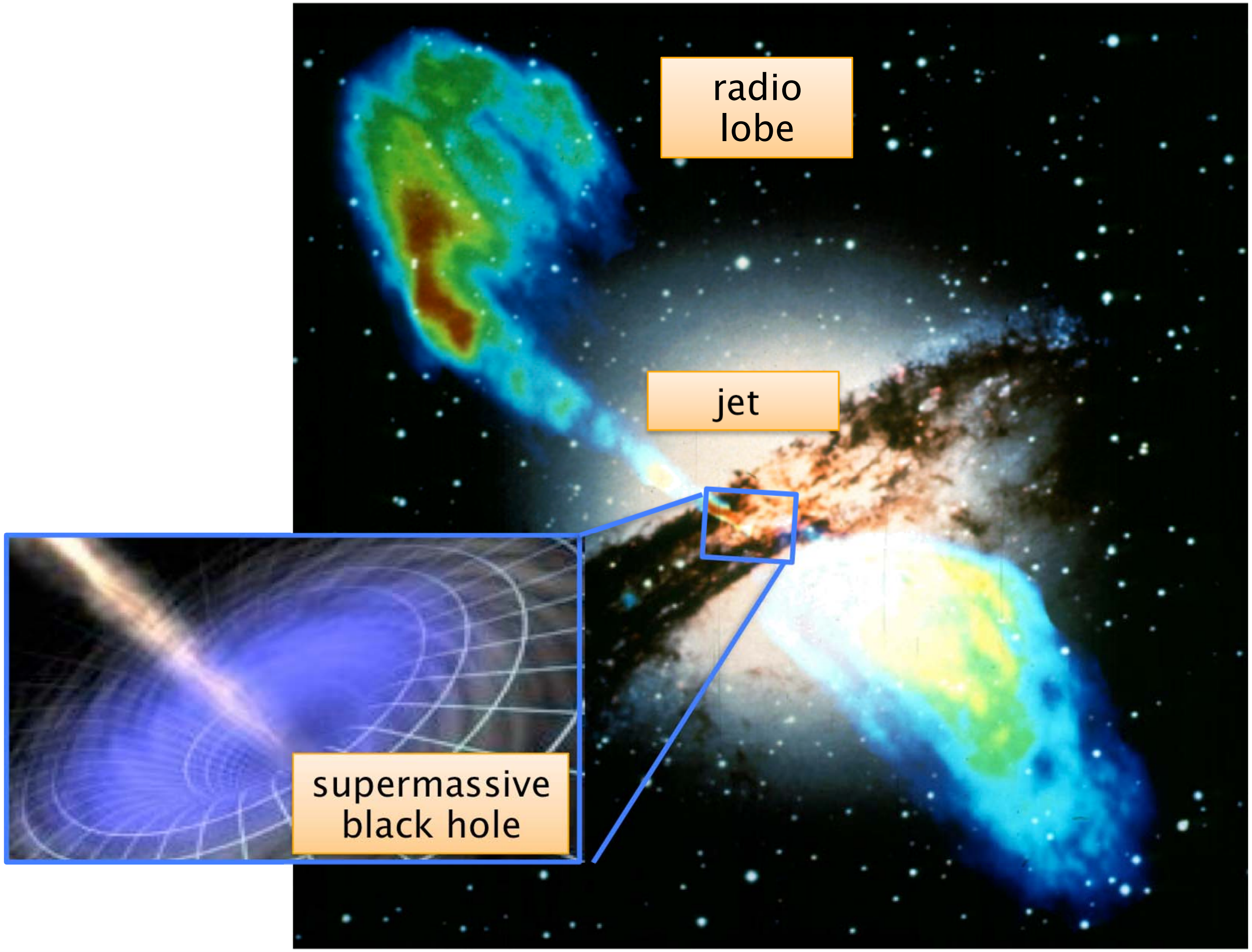


Relativistic outflows are generated not only by neutron stars, but also by black holes (e.g. in active galactic nuclei, AGN).

Jet-emitting AGN are sources of TeV γ-rays. Detection of X-ray synchrotron emission from jets implies presence of ~100 TeV electrons.

➔ AGN (radio galaxies and blazars) work as particle accelerators

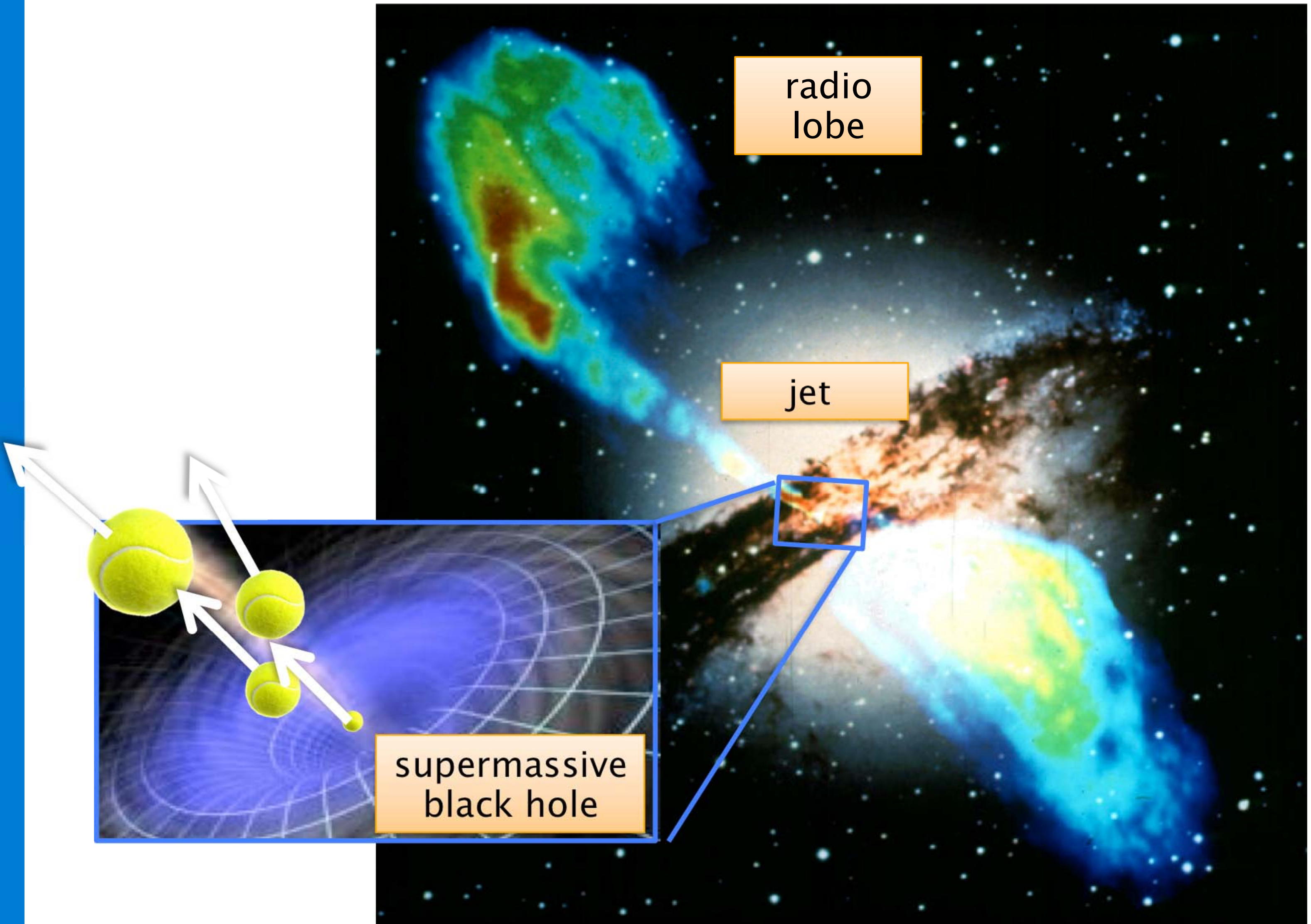
Where do AGN jets come from?



Understanding of the mechanism(s) of particle acceleration in radio galaxies could help to resolve the **long-standing (since 1918) problem** of the origin of AGN jets

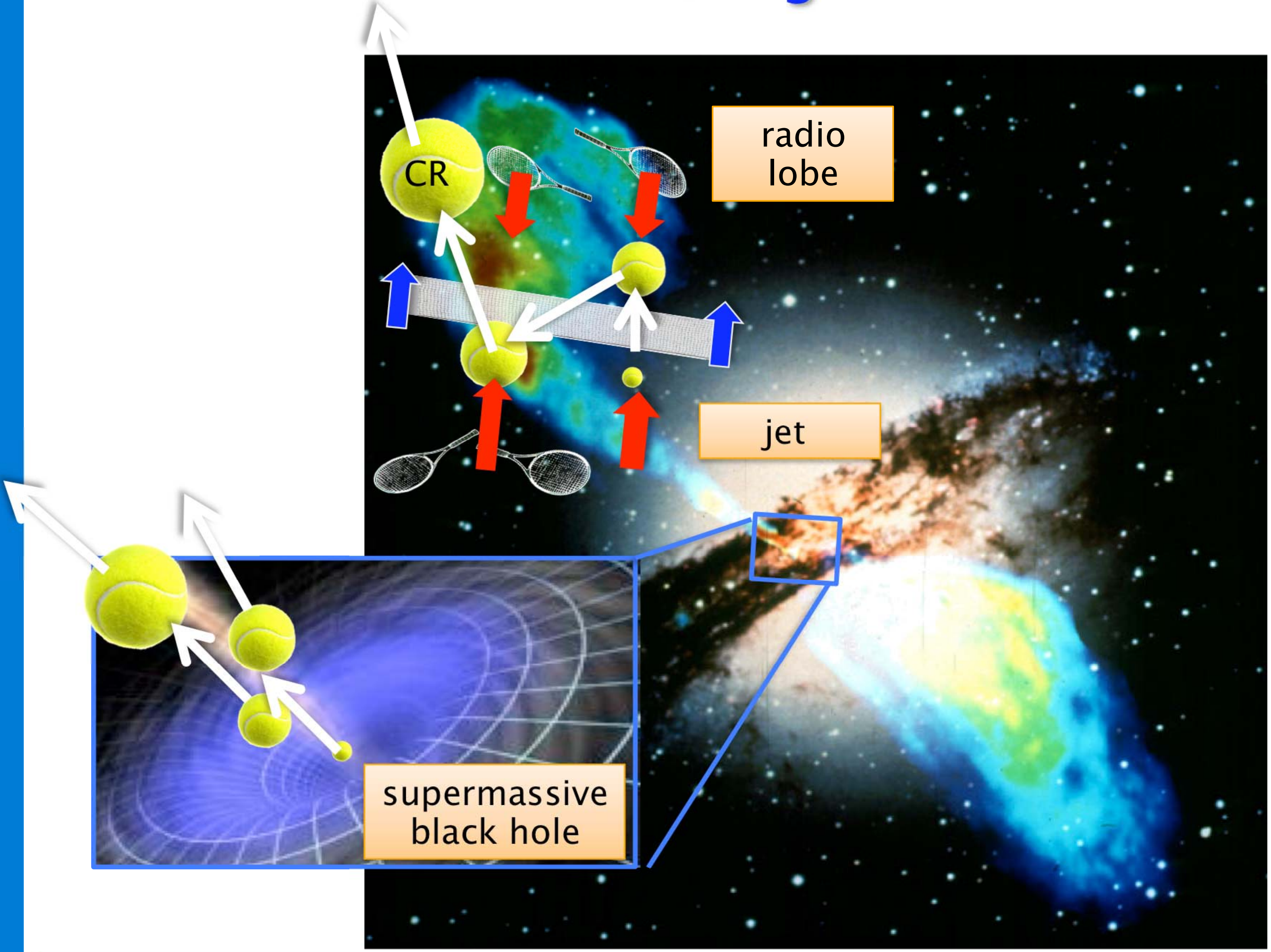
Where do Cosmic Rays come from?

Where do AGN jets come from?



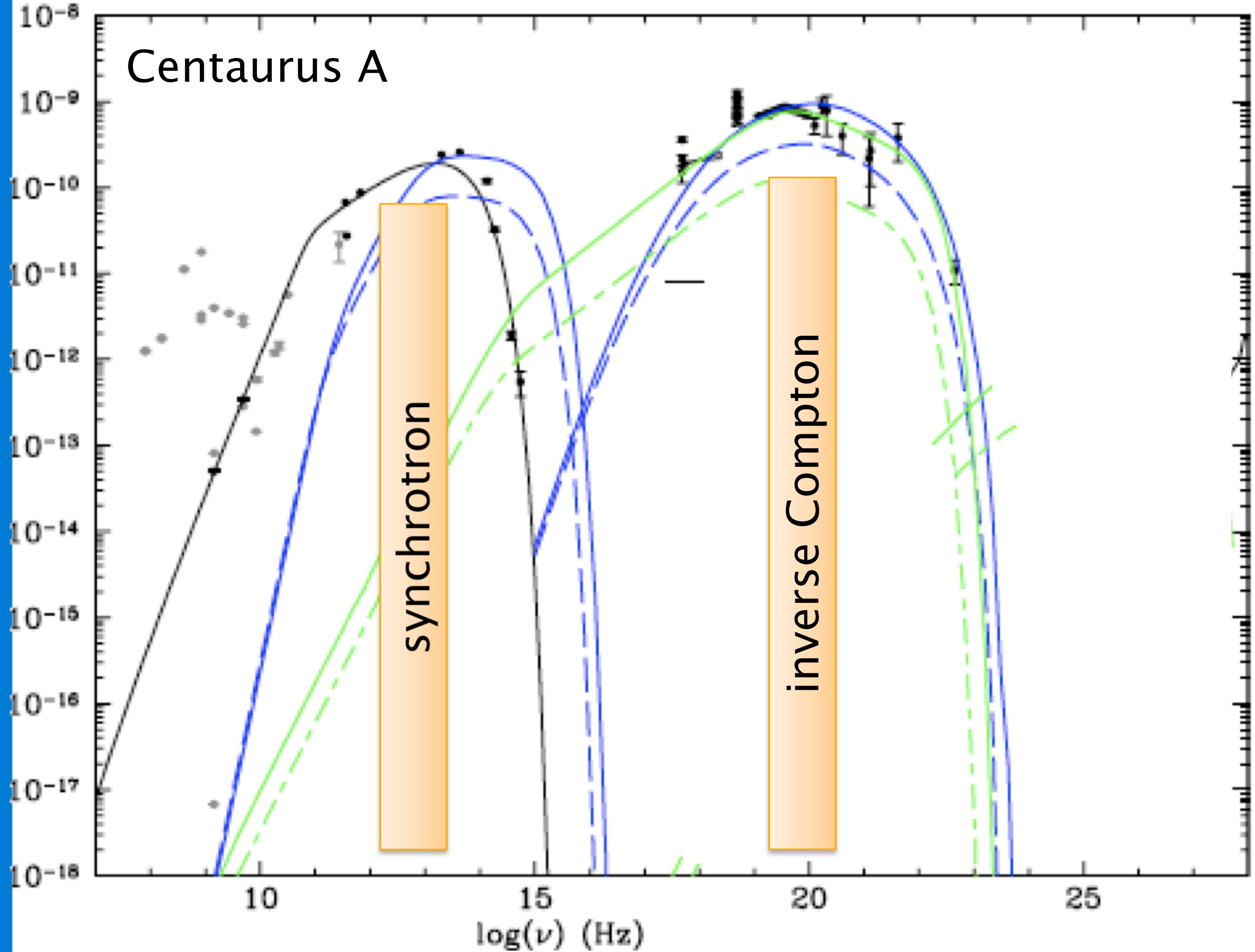
Understanding of the mechanism(s) of particle acceleration in radio galaxies could help to resolve the **long-standing (since 1918) problem** of the origin of AGN jets

Where do AGN jets come from?



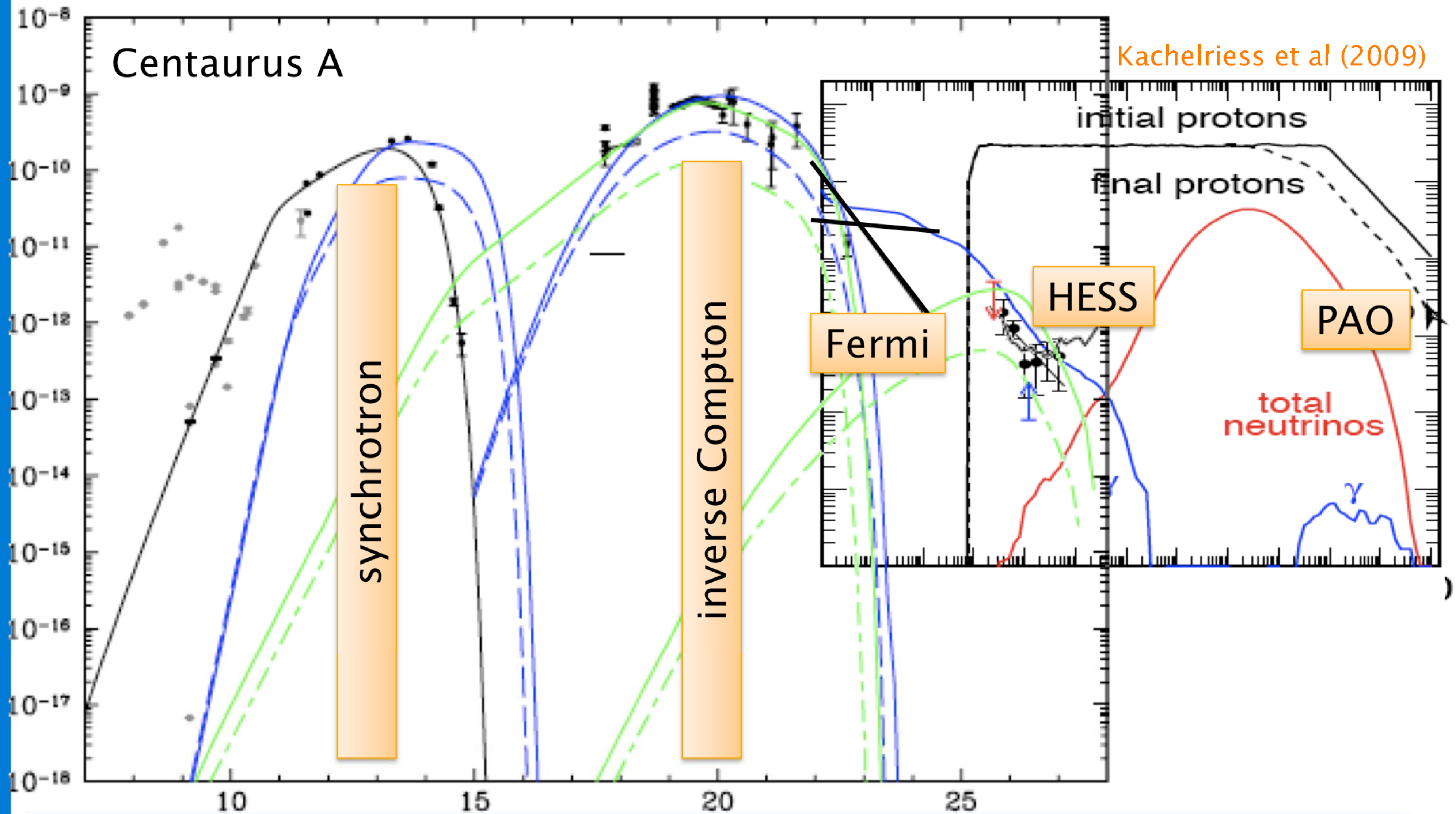
Understanding of the mechanism(s) of particle acceleration in radio galaxies could help to resolve the **long-standing (since 1918) problem** of the origin of AGN jets

Where do AGN jets come from?



Conventional models of radio-to-γ-ray emission from radio galaxies and blazars involve synchrotron + inverse Compton emission from electrons

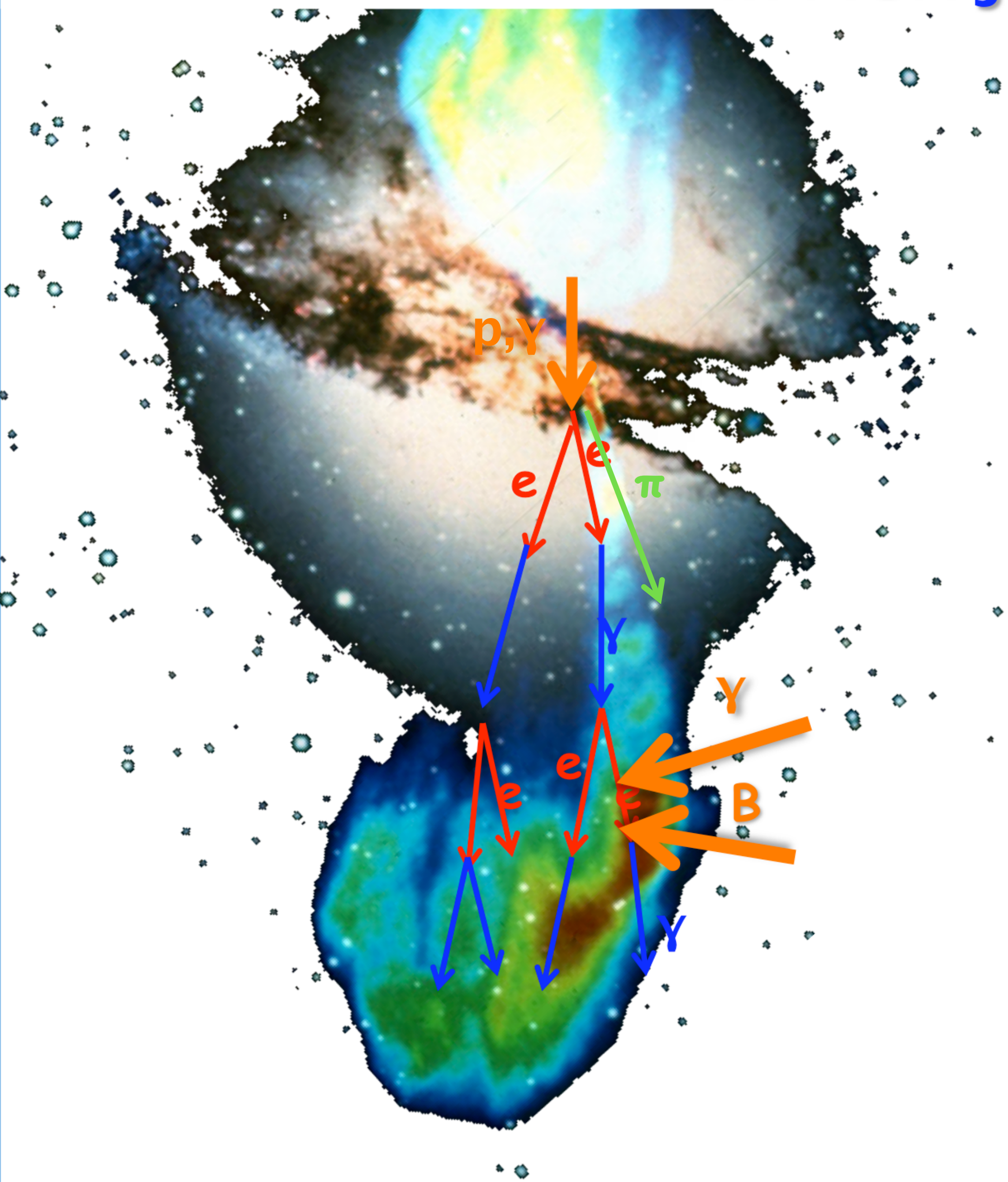
Where do AGN jets come from?



If UHECR association with Cen A is confirmed, revision of the conventional model of activity of radio galaxies will be needed
➔ **insight into the problem of formation of jets?**

Particle cascades

in AGN jets



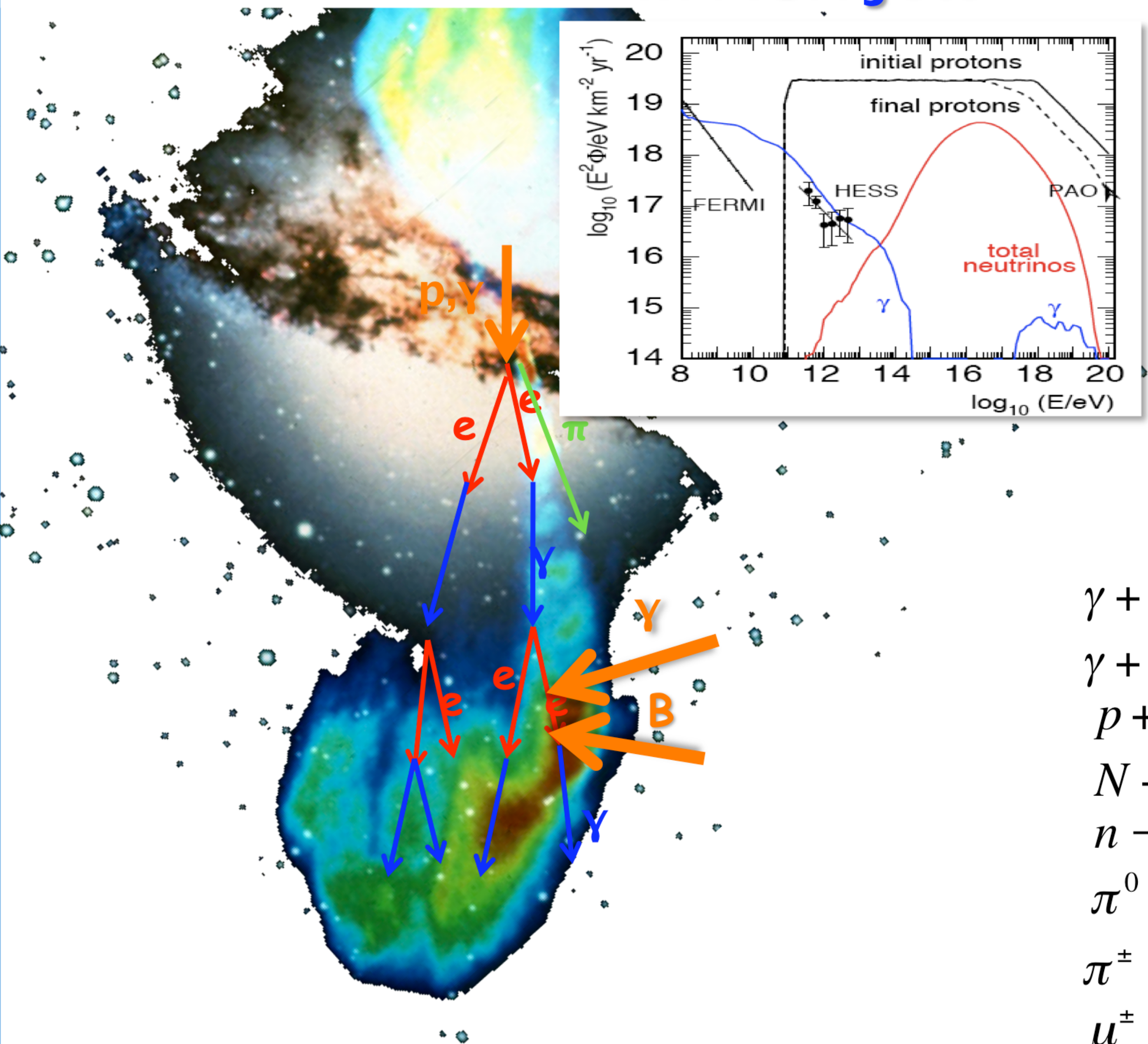
Neronov et al. (2002)

$$\gamma + e^- \rightarrow \gamma + e^-$$
$$\gamma + \gamma \rightarrow e^+ + e^-$$
$$p + \gamma \rightarrow p + e^+ + e^-$$
$$N + \gamma \rightarrow N + \underline{n}\pi$$
$$n \rightarrow p + e^- + \nu_e$$
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$
$$\mu^\pm \rightarrow e^\pm + \nu_e(\overline{\nu}_e) + \nu_\mu(\overline{\nu}_\mu)$$

Particle cascades

in AGN jets

Where do Cosmic Rays come from?



$$\gamma + e^- \rightarrow \gamma + e^-$$

$$\gamma + \gamma \rightarrow e^+ + e^-$$

$$p + \gamma \rightarrow p + e^+ + e^-$$

$$N + \gamma \rightarrow N + \underline{n}\pi$$

$$n \rightarrow p + e^- + \nu_e$$

$$\pi^0 \rightarrow \gamma + \gamma$$

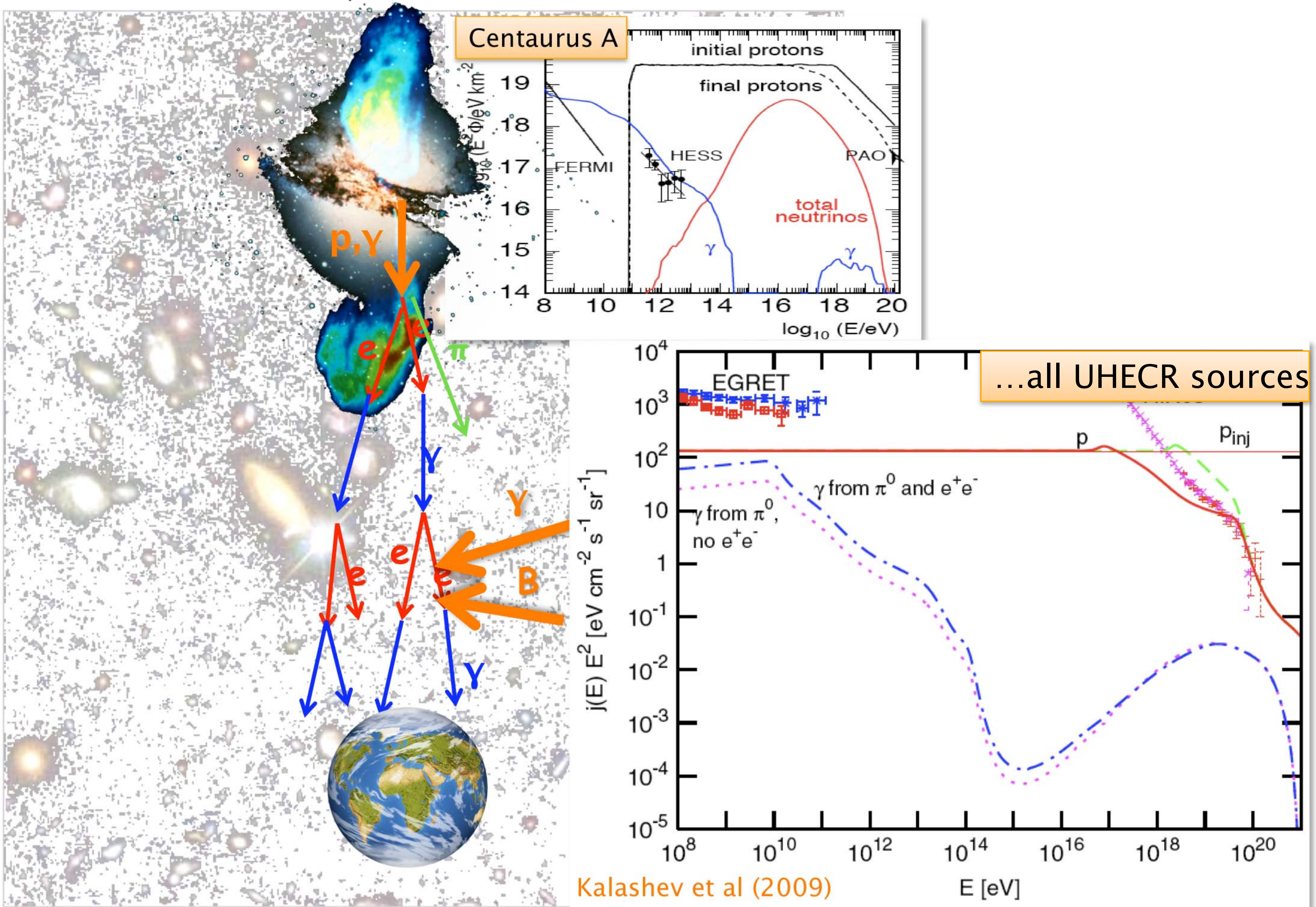
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$

$$\mu^\pm \rightarrow e^\pm + \nu_e(\overline{\nu}_e) + \nu_\mu(\overline{\nu}_\mu)$$

Neronov et al. (2002)

Particle cascades:

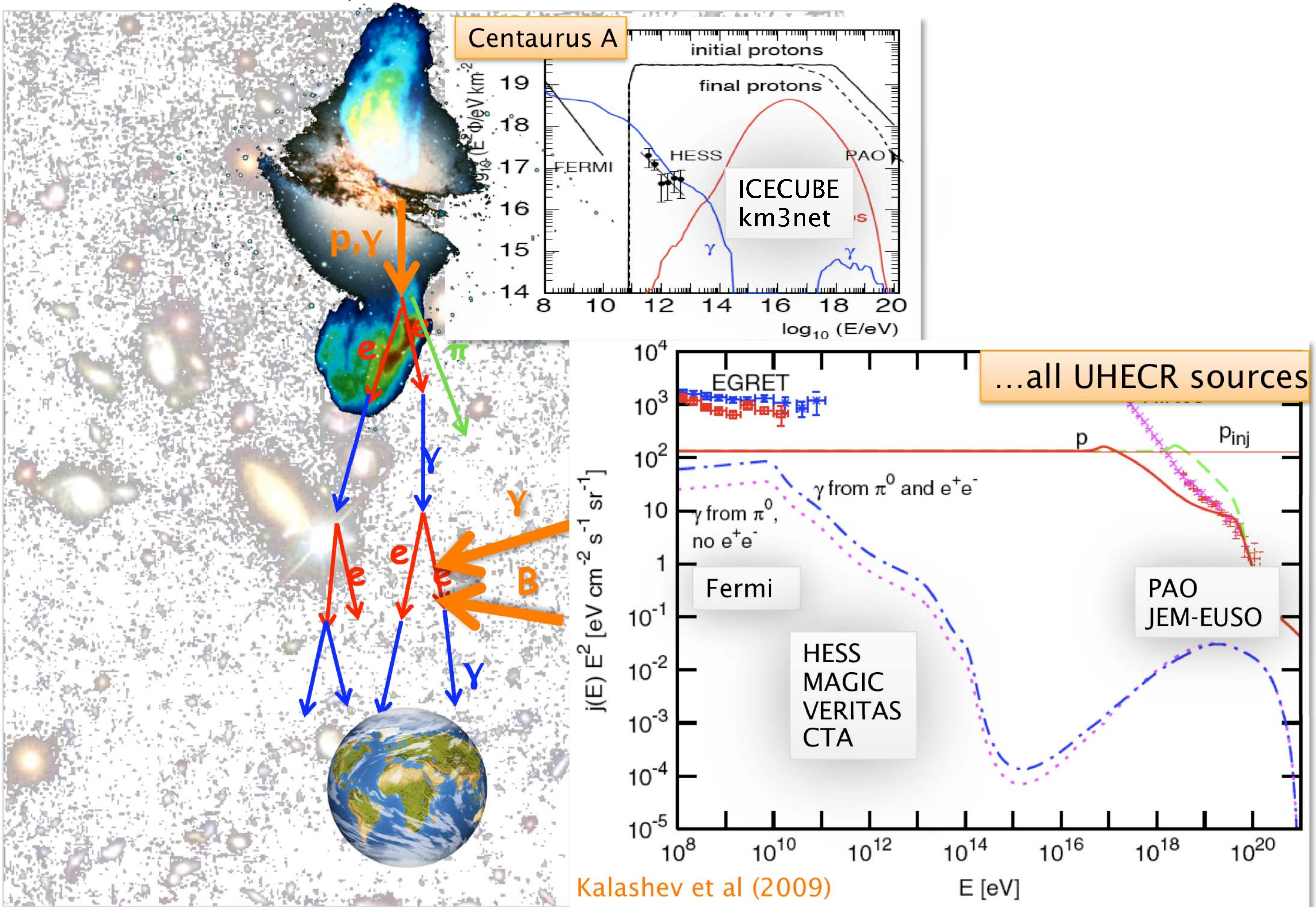
in CR sources and in the Universe



Kalashev et al (2009)

Particle cascades:

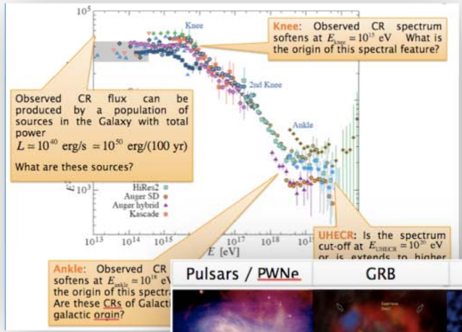
in CR sources and in the Universe

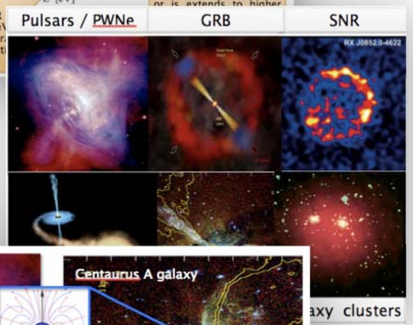


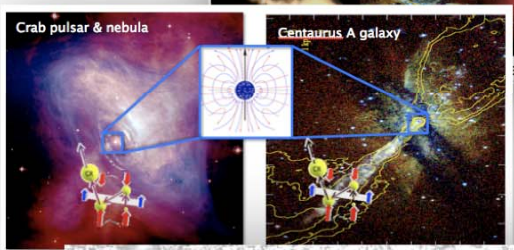
Kalashev et al (2009)

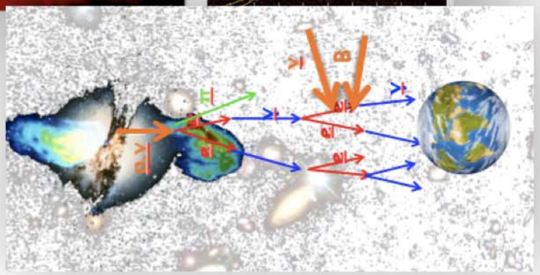
Where do Cosmic Rays come from?

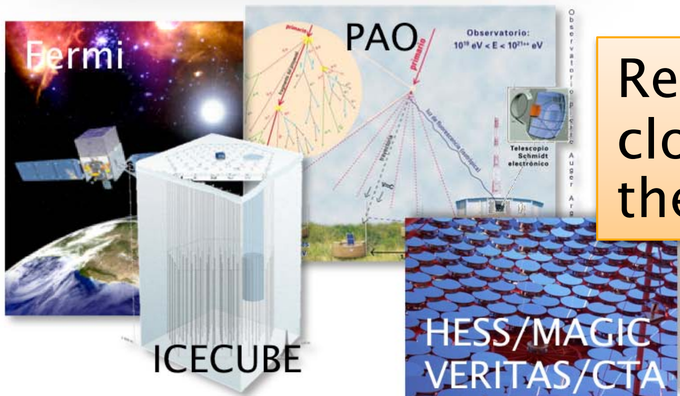
Summary











Many faces of the problem of the origin of Cosmic rays

Rich astrophysical phenomena involved

Supernovae, SNR, pulsars, PWN, GRB, AGN,…

Two main type of acceleration mechanisms

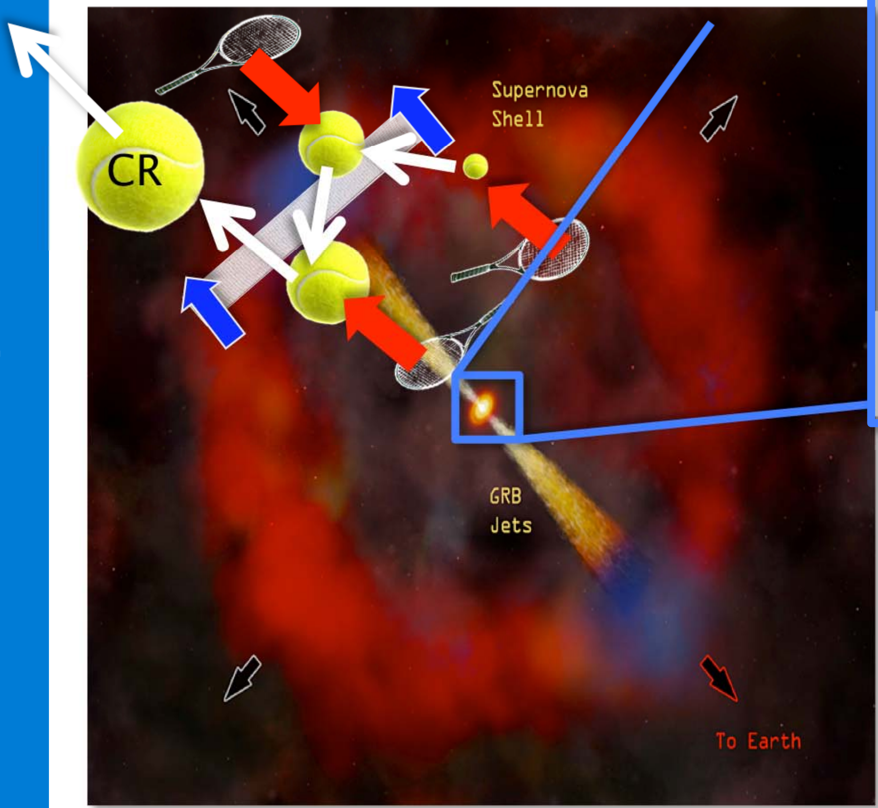
shock acceleration vs. acceleration by large-scale electric fields

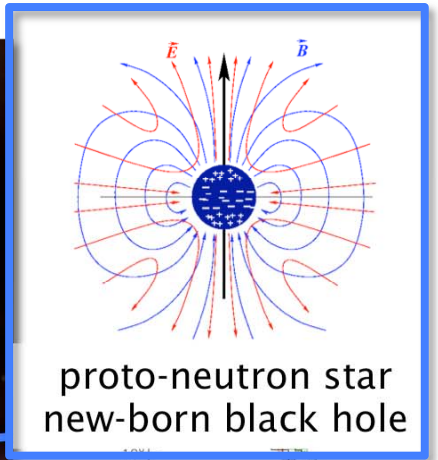
CR source properties determined not only by acceleration mechanism(s), but also by particle cascades in and/or outside the sources

Recent advances in instrumentation bring us close to solution of (some of) the problem(s) of the origin of CRs

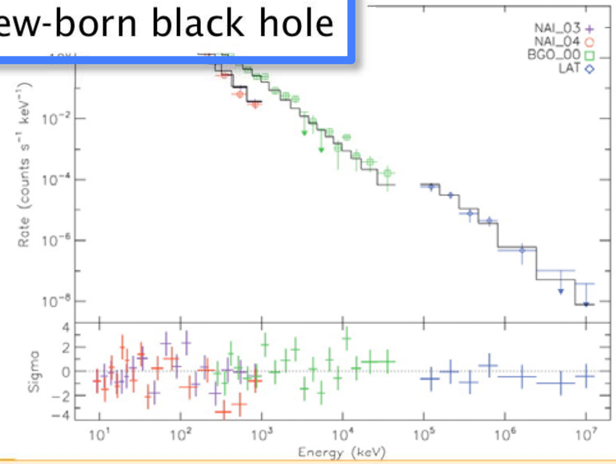
Where do Cosmic Rays come from?

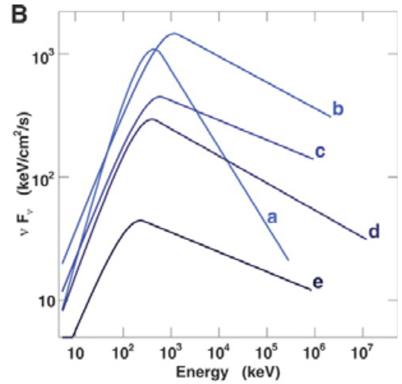
Particle acceleration in GRBs





Fermi LAT & GBM Collab. (2009)





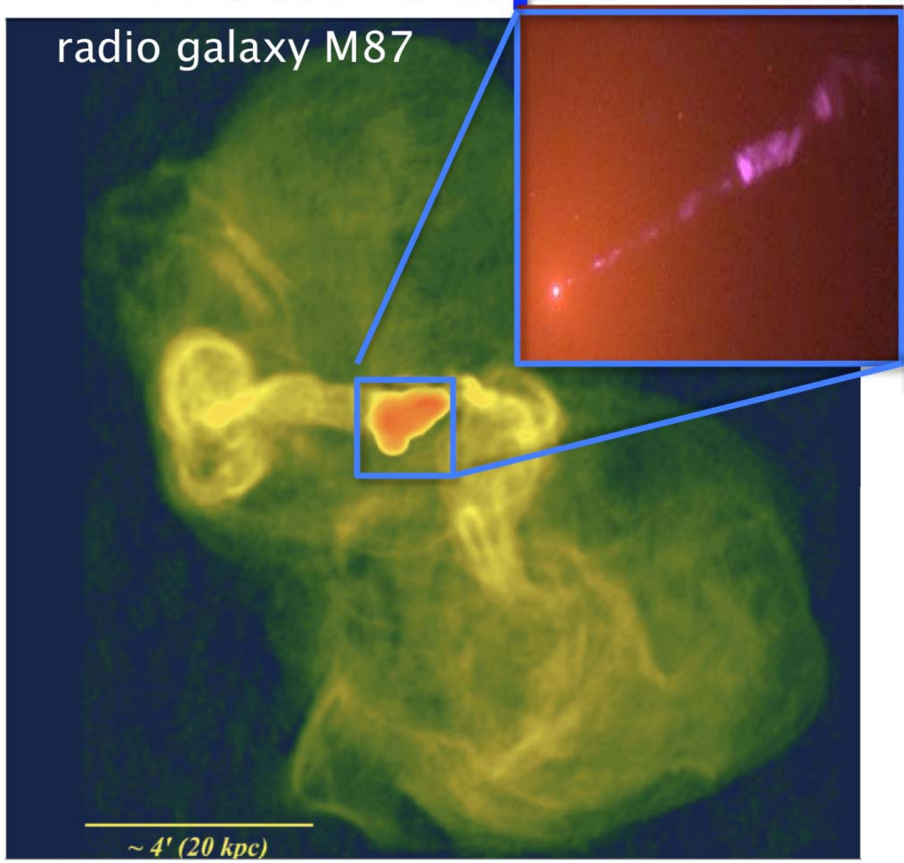
Long (10-100 s) gamma-ray bursts associated to the collapse of massive star and/or supernova explosion.

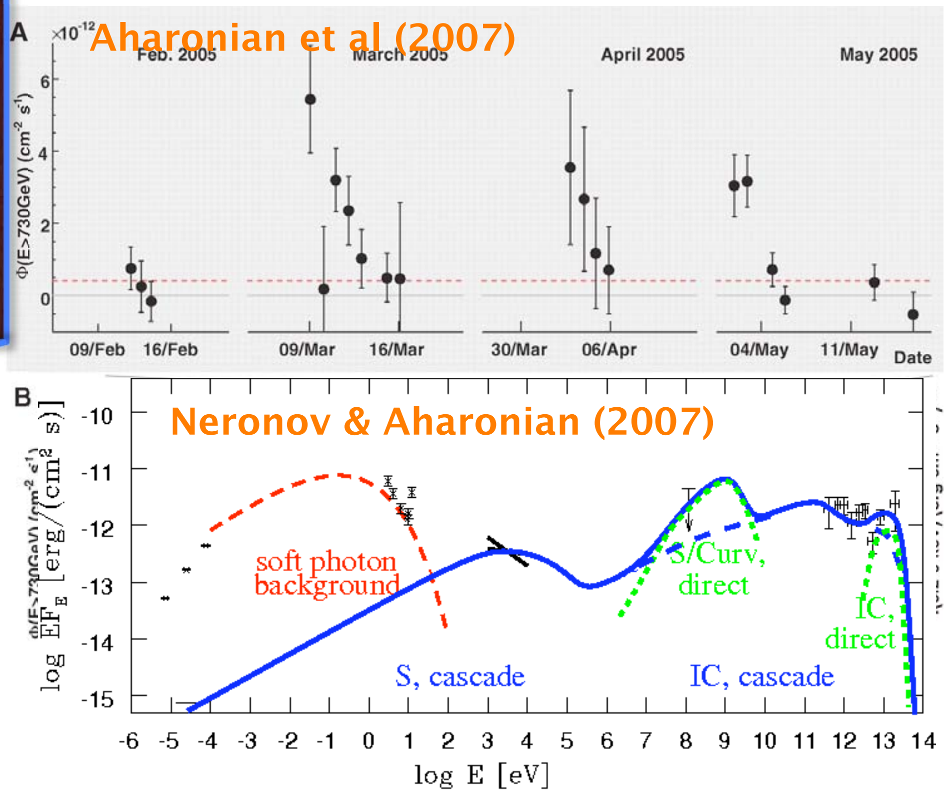
Emission is produced by relativistic (~10^2-10^3) outflow (jet) from newly formed neutron star or black hole

Spectrum of the "prompt" GRB emission extends to multi-GeV band

Mechanisms of particle acceleration in the GRB "central engine" and in the outflow are not clear

Particle acceleration near supermassive black holes



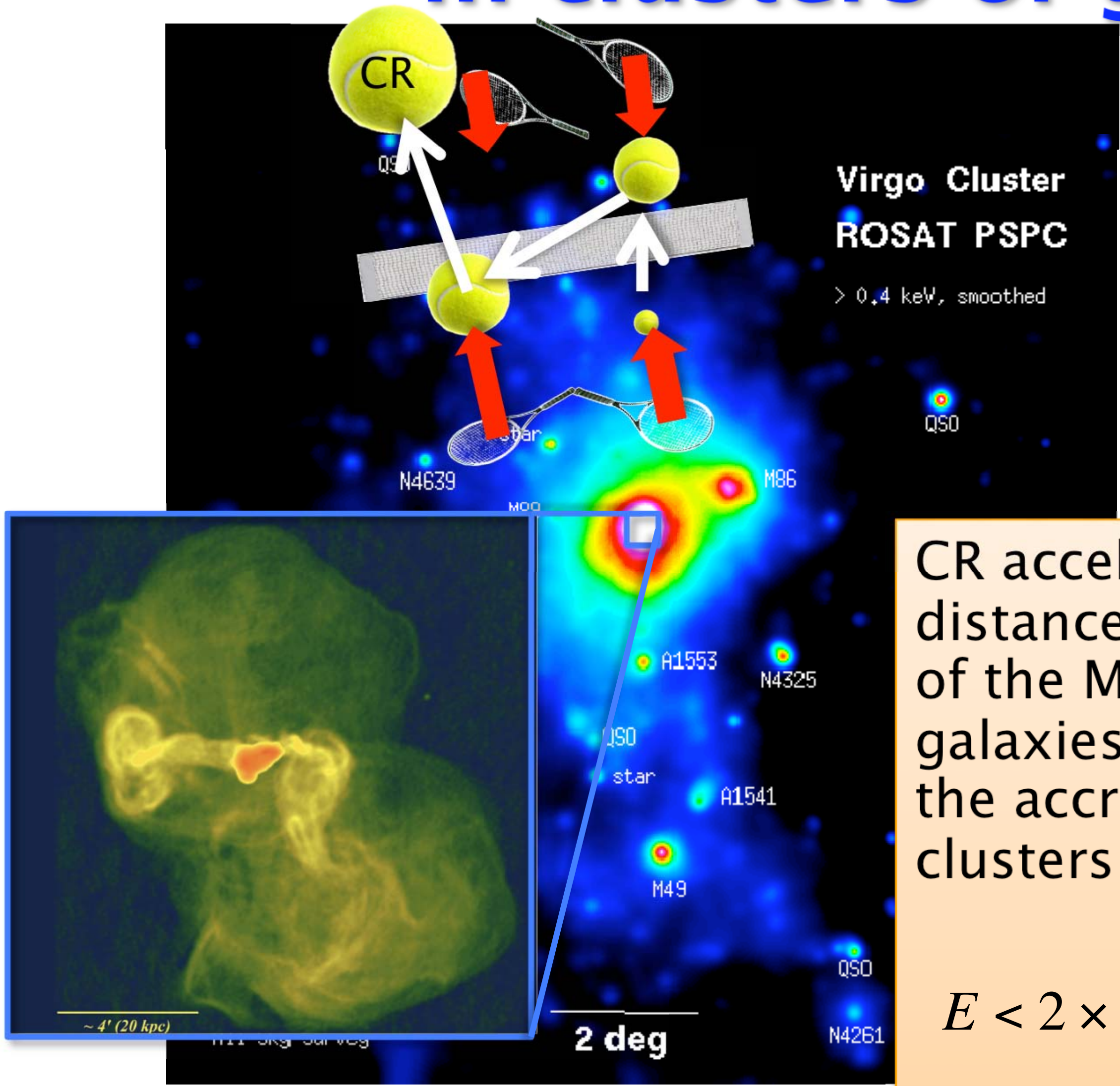


Variability time scales of TeV emission are close to the “fundamental” time scale(s) of the “central engine” (supermassive black hole):

$$R_{\rm lso} = \frac{4\pi G_N M_{BH}}{c^3} \simeq 2.2 \left[\frac{M_{BH}}{3\times 10^9 M_{\rm Sun}} \right] \mathrm{d}$$

➔ **Particle acceleration takes place close to black hole horizon**

Particle acceleration in clusters of galaxies



CR acceleration can take place at distance scales even larger than that of the Mpc-scale lobes of radio galaxies. Acceleration is possible at the accretion shocks of (still forming) clusters of galaxies

$$E < 2\times 10^{18}\left[\frac{V}{10^{-3}c}\right]^2\left[\frac{B}{10^{-6}\,\mathrm{G}}\right]\left[\frac{T_{\mathrm{source}}}{10^{10}\,\mathrm{yr}}\right]\mathrm{eV}$$

$$E < 10^{16}\left[\frac{V}{10^{-3}c}\right]^2\left[\frac{B}{10^{-6}\,\mathrm{G}}\right]\left[\frac{R_{\mathrm{source}}}{10\ \mathrm{Mpc}}\right]\mathrm{eV}$$