Lecture 2

Multi-messenger Astronomy

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Summary of previous lecture

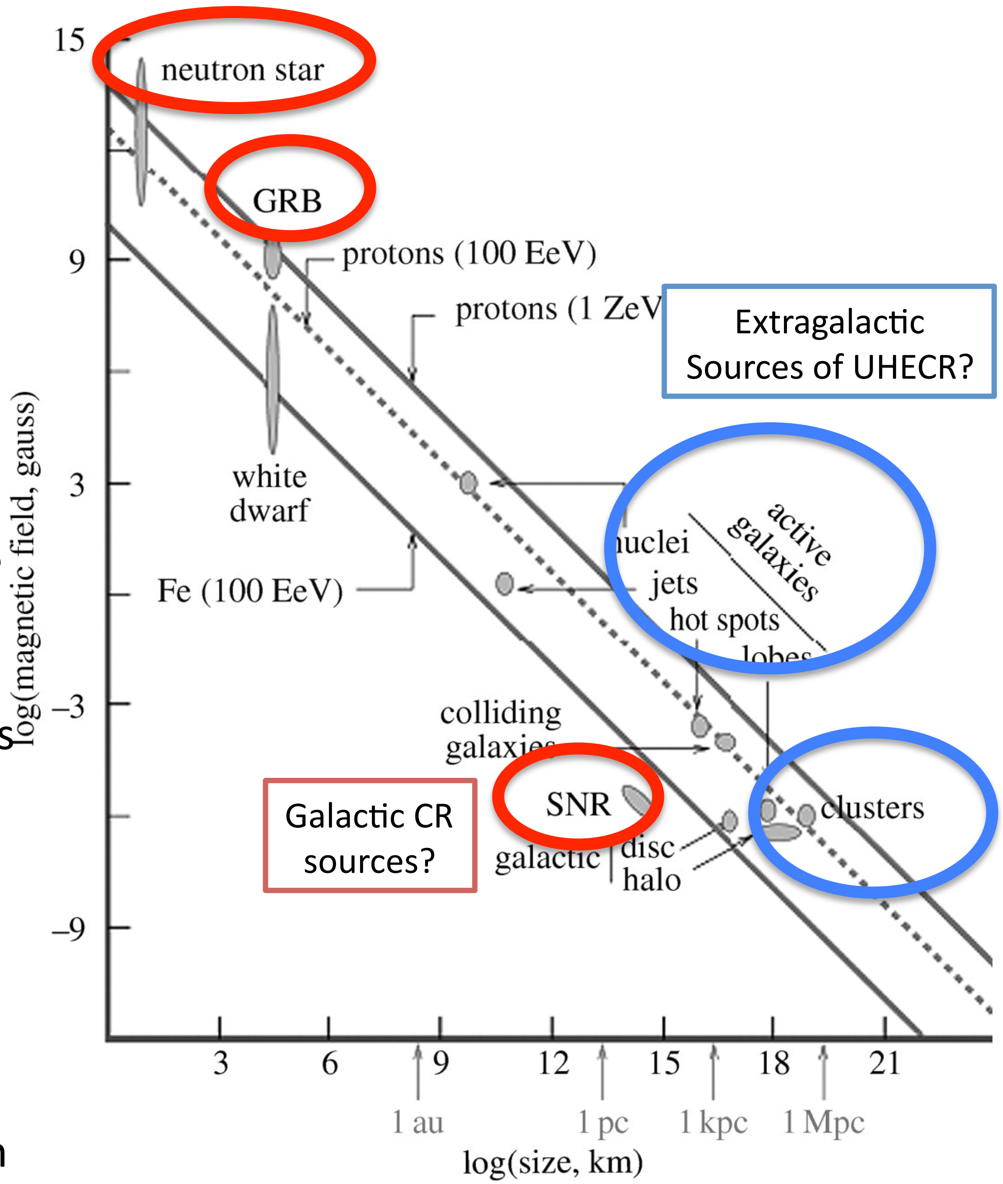
Problem of the origin of Cosmic Rays:

- of GeV energies
- of PeV energies ("knee" of the CR spectrum)
- of EeV energies ("ankle" of the CR spectrum)
- of UHECR ($\sim 10^{20}$ eV)

CRs with energies below ~10^{18} eV propagate in a diffusive way through the Galactic magnetic field. Direct identification of CR sources via tracing back the arrival directions of individual CRs is not possible.

Complementary information from astronomical observations is needed to identify sites of particle acceleration in and outside the Galaxy.

"Multi-messenger approach" to the problem of identification of CR sources.



Overview of Lecture 2

1) Electromagnetic emission from CR particle accelerators

2) Astronomical observations in High-energy and very-high-energy gamma-ray bands: direct signatures of on-going particle acceleration in astronomical objects.

3) Multi-wavelength approach for the study of astronomical sources.

4) Crab source example across the wavebands

5) From multi-wavelength to multi-messenger astronomy: astronomical observations in the very-high-energy neutrino channel.

Electromagnetic emission from particle accelerators

Particle acceleration is accompanied by the energy loss, e.g. synchrotron

$$\frac{dE}{dt} = -P_{synch} \approx \frac{e^4 B^2 E^2}{m^4}$$

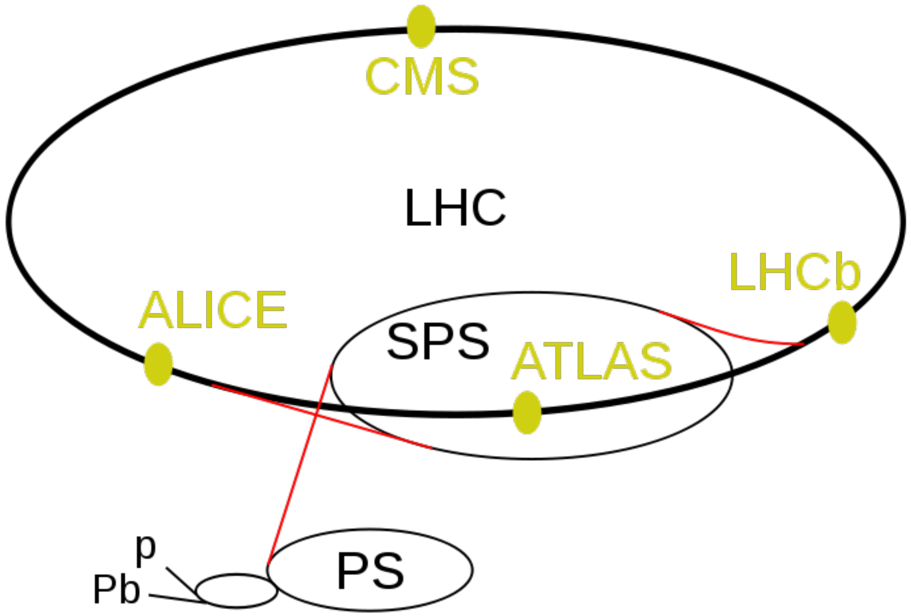
Characteristic energy loss time

$$t_{synch} = \frac{E}{dE/dt} \approx \frac{m^4}{e^4 B^2 E} \approx$$

$$10^{-9} \left[\frac{m}{m_e}\right]^4 \left[\frac{B}{10^5\ \mathrm{G}}\right]^{-2} \left[\frac{E}{10^{13}\,\mathrm{eV}}\right]^{-1} \mathrm{s}$$

Characteristic energy of synchrotron photons

$$E_{synch} \approx \frac{eBE^2}{m^3} \approx 10^{11} \left[\frac{m}{m_e}\right]^{-3} \left[\frac{B}{10^5\mathrm{G}}\right] \left[\frac{E}{10^{13}\mathrm{eV}}\right]^2 \mathrm{eV}$$



LHC proton beam is a source of UV/X-ray radiation with synchrotron luminosity (N~10^{14} particles in the beam)

$$P_{tot} \approx P_{synch} N \approx 10^{11} \left[\frac{B}{10^5\mathrm{G}}\right]^2 \left[\frac{E}{10^{13}\mathrm{eV}}\right]^2 \mathrm{erg/s}$$

If LHC-like accelerator would operate in space, it would be identifiable via a characteristic synchrotron spectral feature in the UV / X-ray band…

or in the γ-ray band….

Electromagnetic emission from particle accelerators

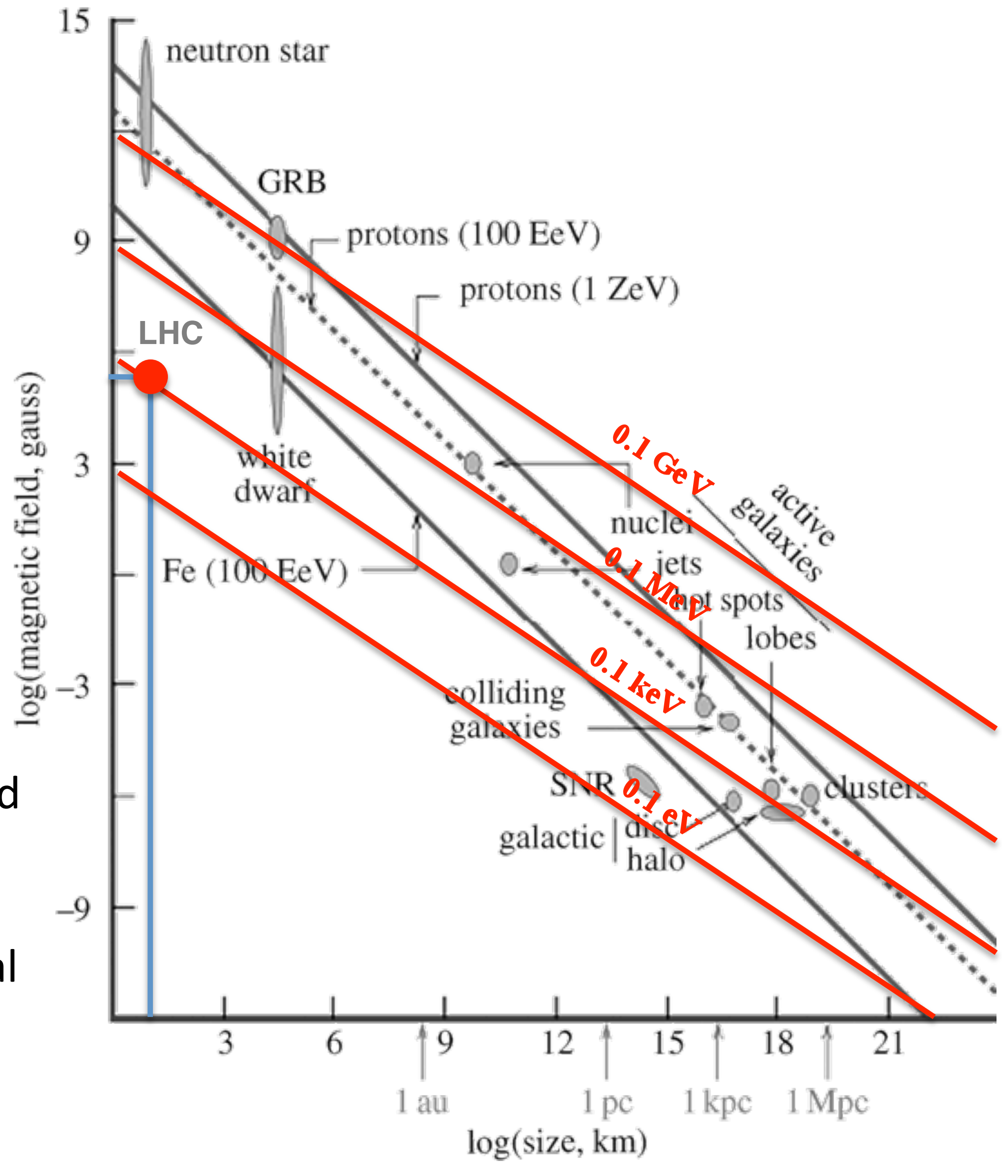
Particle acceleration is accompanied by electromagnetic emission with broad energy distribution.

CR sources could be identified via characteristic γ-ray emission signatures.

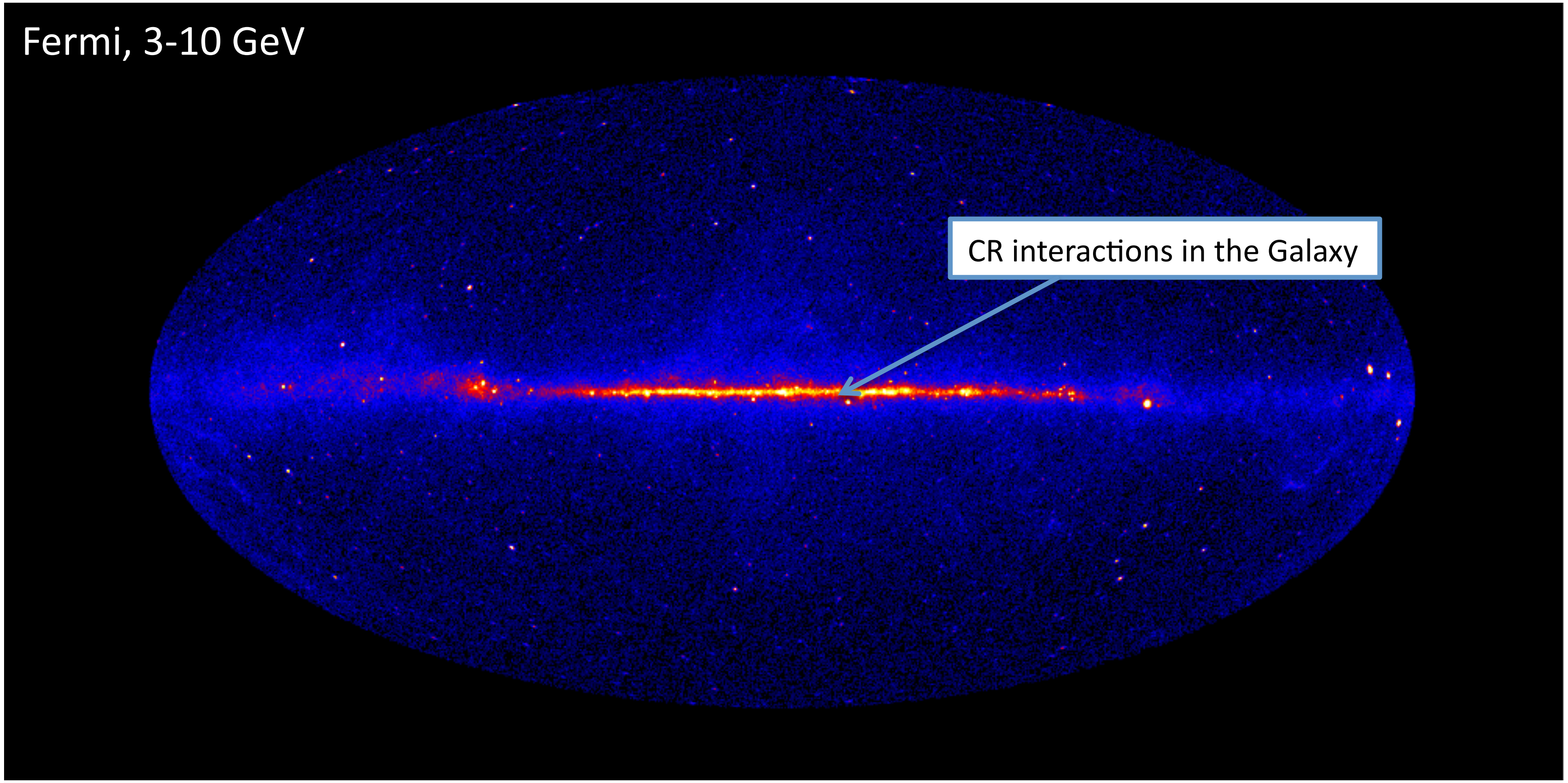
Energy spectra and CR luminosity of the sources could be derived from the measured electromagnetic spectra.

More generally, interactions of accelerated particles with magnetic and radiation fields and with matter at the acceleration site, lead to production of secondary particles. CR acceleration sites might be identifiable via characteristic emission signatures in "neutral messengers":

- photons
- neutrinos
- neutrons (?)



Gamma-ray emission from CR sources



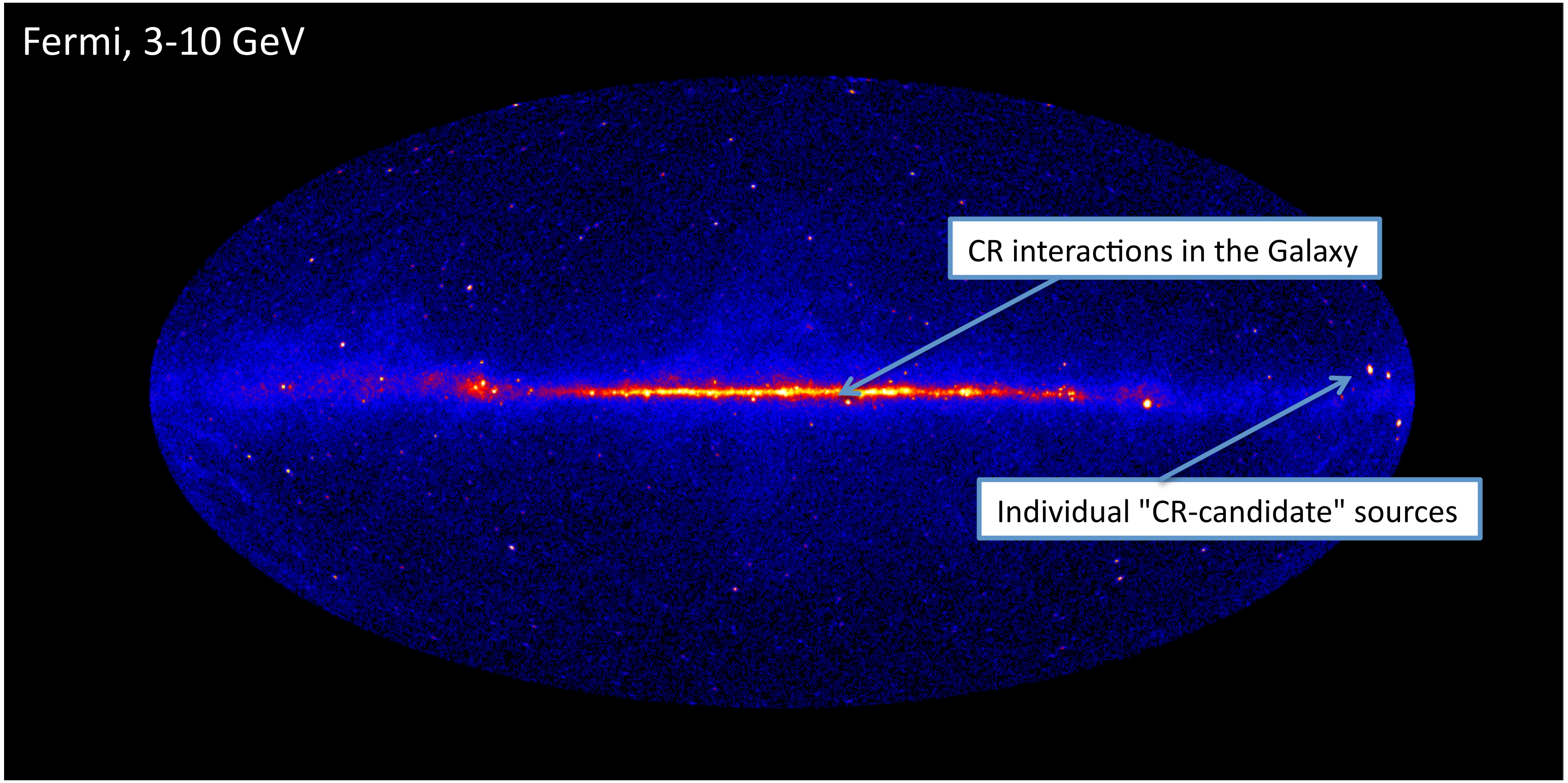
CRs are trapped by the Galactic magnetic field for ~10^7 yr.

During this time they propagate through the Interstellar Medium (ISM), n_{ISM}~$1\ \mathrm{cm}^{-3}$.

$$t_{CR-ISM} = (\sigma_{pp} n_{ISM})^{-1} \sim 10^8 \left[\frac{n_{ISM}}{1\ \mathrm{cm}^{-3}}\right]^{-1} \mathrm{yr}$$

CR particles loose some 10% of their energy on γ-ray emission, before leaving the Galaxy.

Gamma-ray emission from CR sources



CRs start their diffusion through the Galaxy at (unknown) CR sources.

γ-ray emission at the energies above $1\ \mathrm{GeV}$ from an astronomical object is a signature of on-going particle acceleration process in the source and, possibly, of CR production.

γ-ray observations in the energy band $\mathrm{E{>}1GeV}$ are of crucial importance for the problem of the origin of CRs.

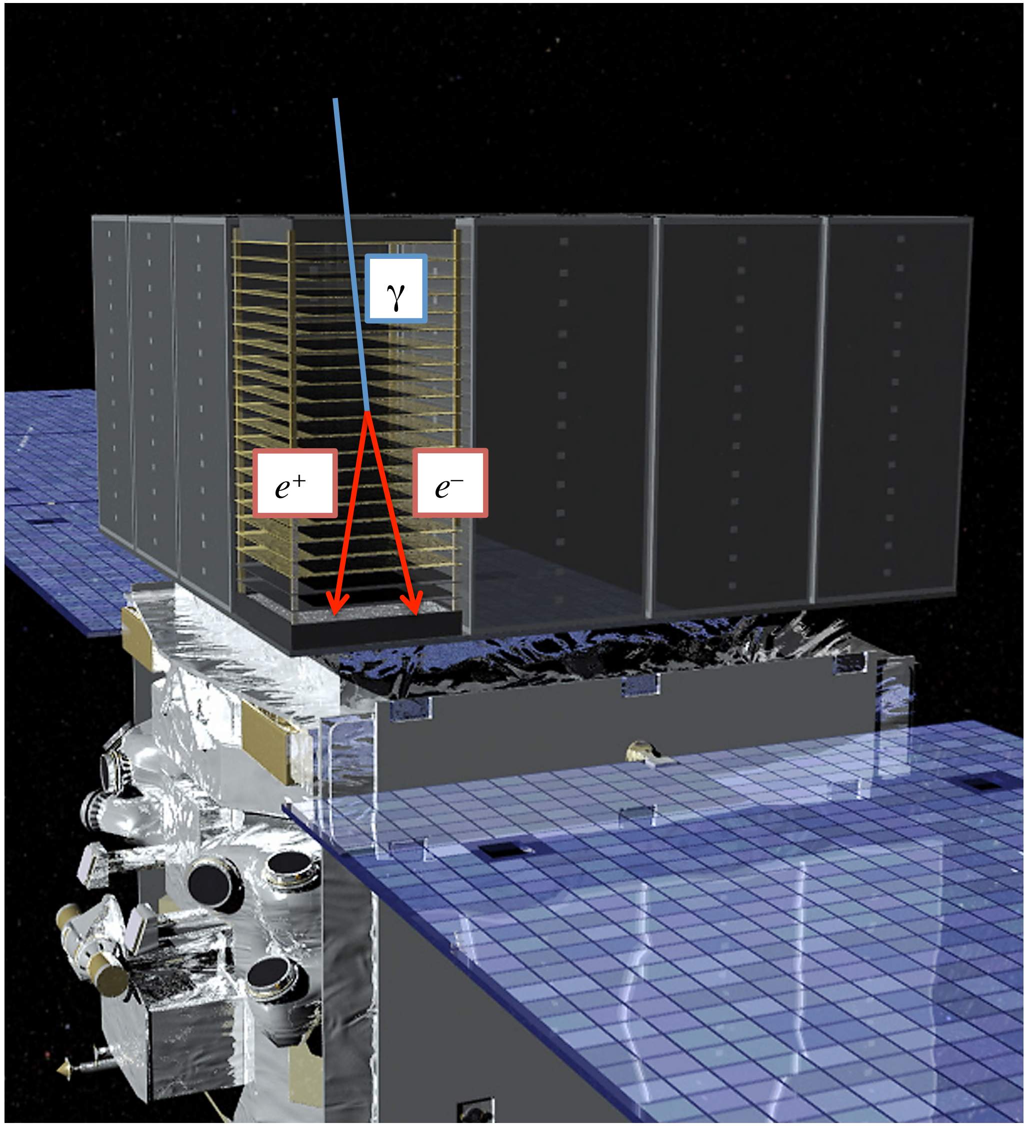
High-energy gamma-ray astronomy

Low-energy gamma-rays: 0.1-10 MeV

High-energy gamma-rays: 0.1-10 GeV

Fermi

Very-high-energy gamma-rays:
0.1-10 TeV



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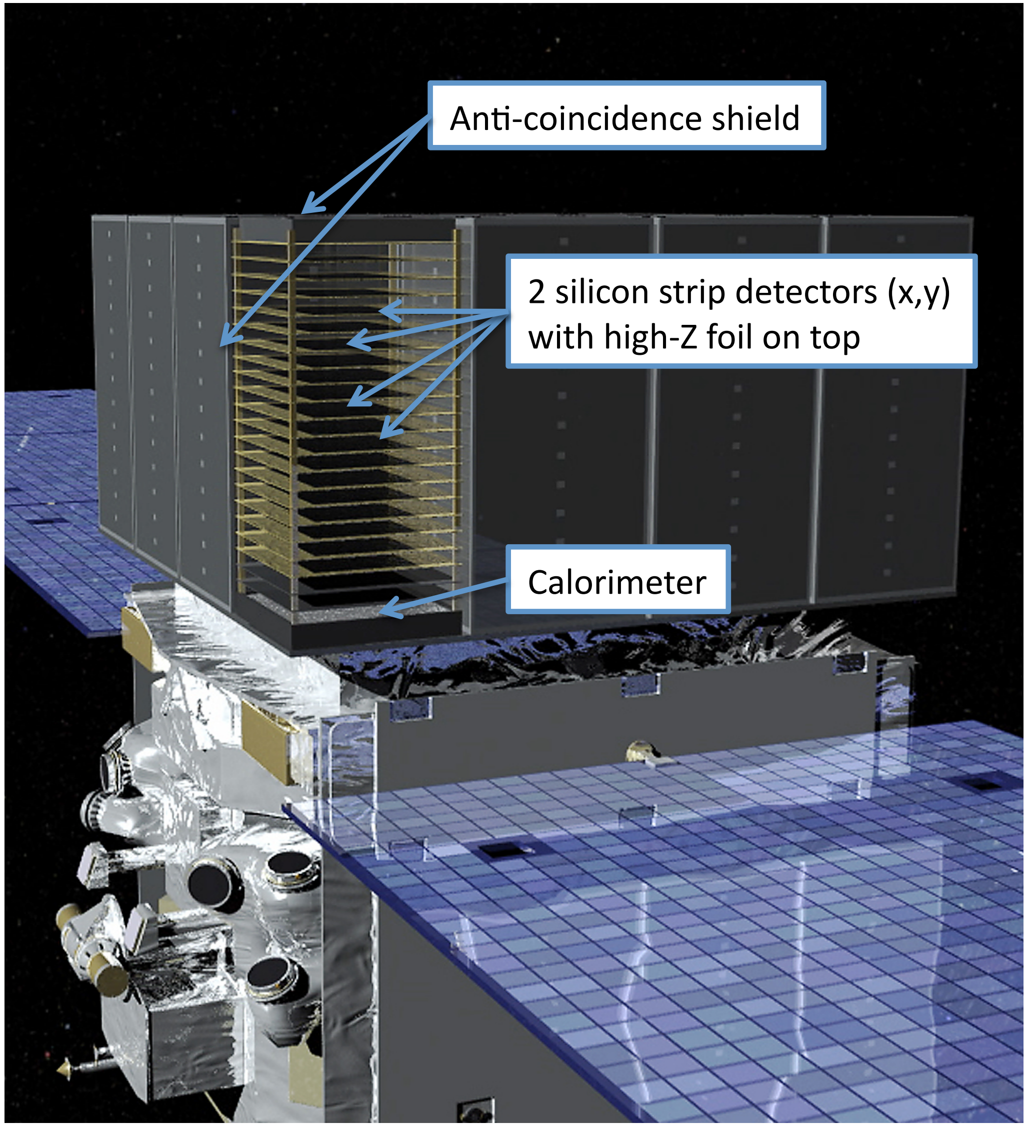
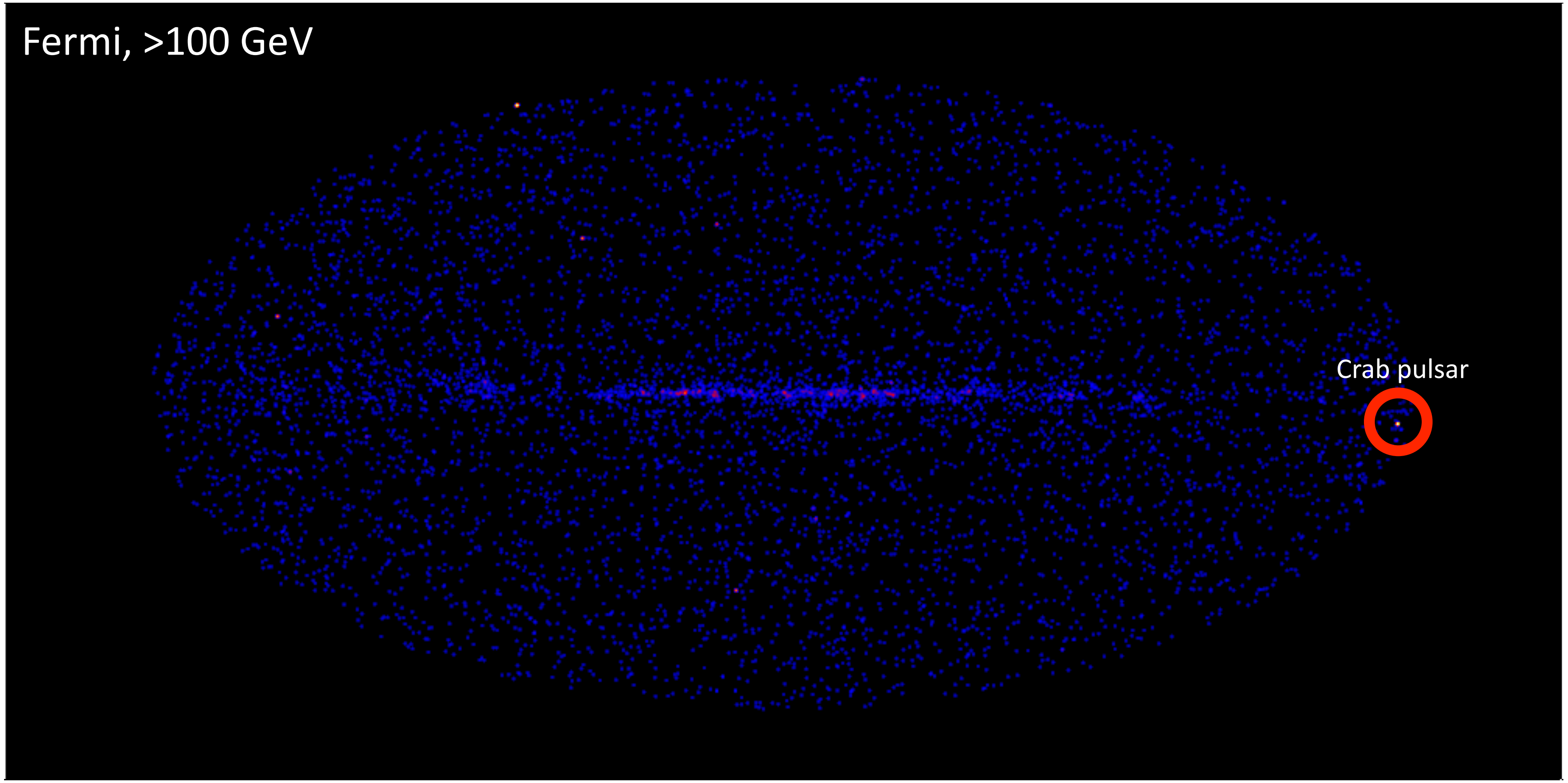


Fermi sky



Crab

Brightest steady γ-ray source on the sky at the energies above 10 GeV.

Source spectrum extends up to E>100 GeV without a signature of a high-energy cut-off.

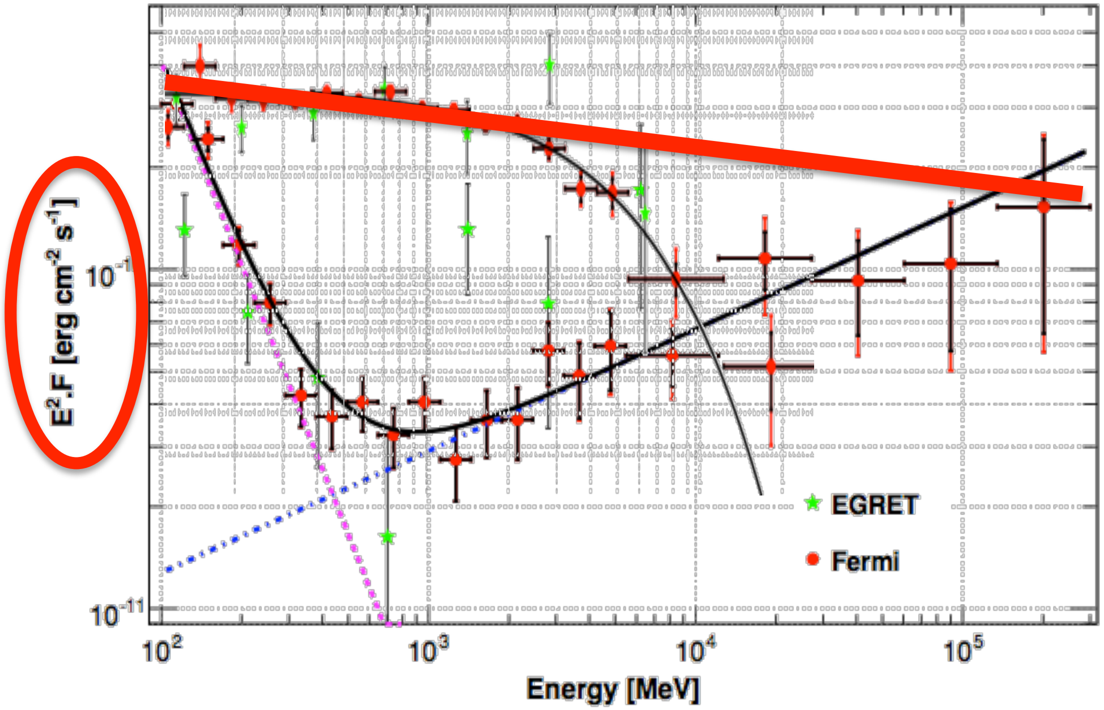
Crab is operating as an accelerator of particles with energies E>100 GeV.

Is this one of the sources responsible for the observed CR flux?

Does it accelerate protons and/or atomic nuclei?

If yes, do these protons/nuclei escape from the acceleration site to contribute to the "sea" of Galactic CRs?

Or it an electron (positron) acceleration site? If yes, do these electrons contribute to the observed CR electron flux?



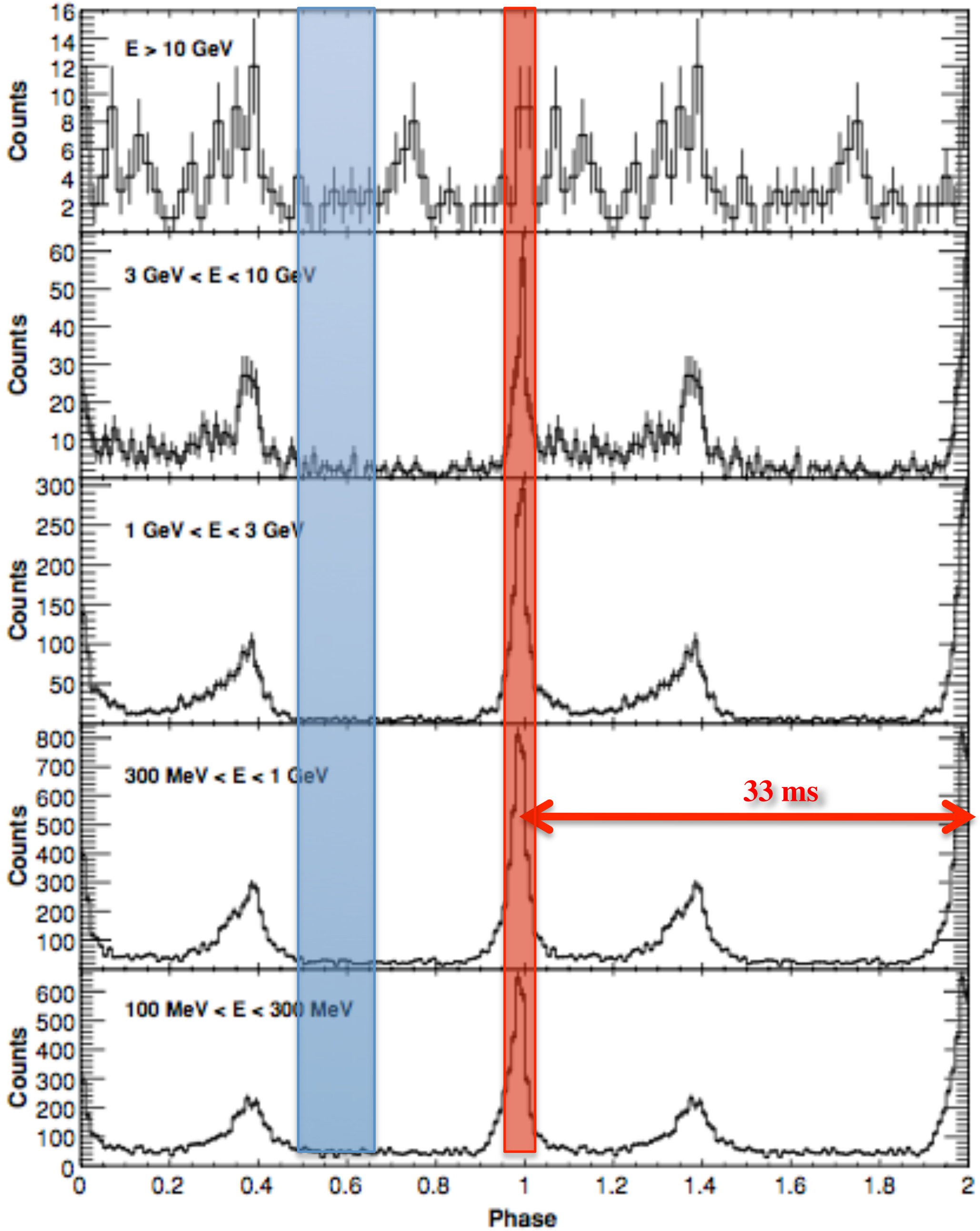
Crab pulsar

Gamma-ray emission from the source is modulated with a period P=33 ms

What is the nature of this periodic modulation?

a) rotation of the source?
b) oscillations of the source size?

The period and the pattern of modulation are extremely stable. The period increases at a rate $dP/dt \approx 4\times10^{-13}$ s/s.



Crab pulsar

Gamma-ray emission from the source is modulated with a period P=33 ms

The nature of this periodic modulation is source rotation.

The period and the pattern of modulation are extremely stable. The period increases at a rate $dP/dt \approx 4\times10^{-13}$ s/s.

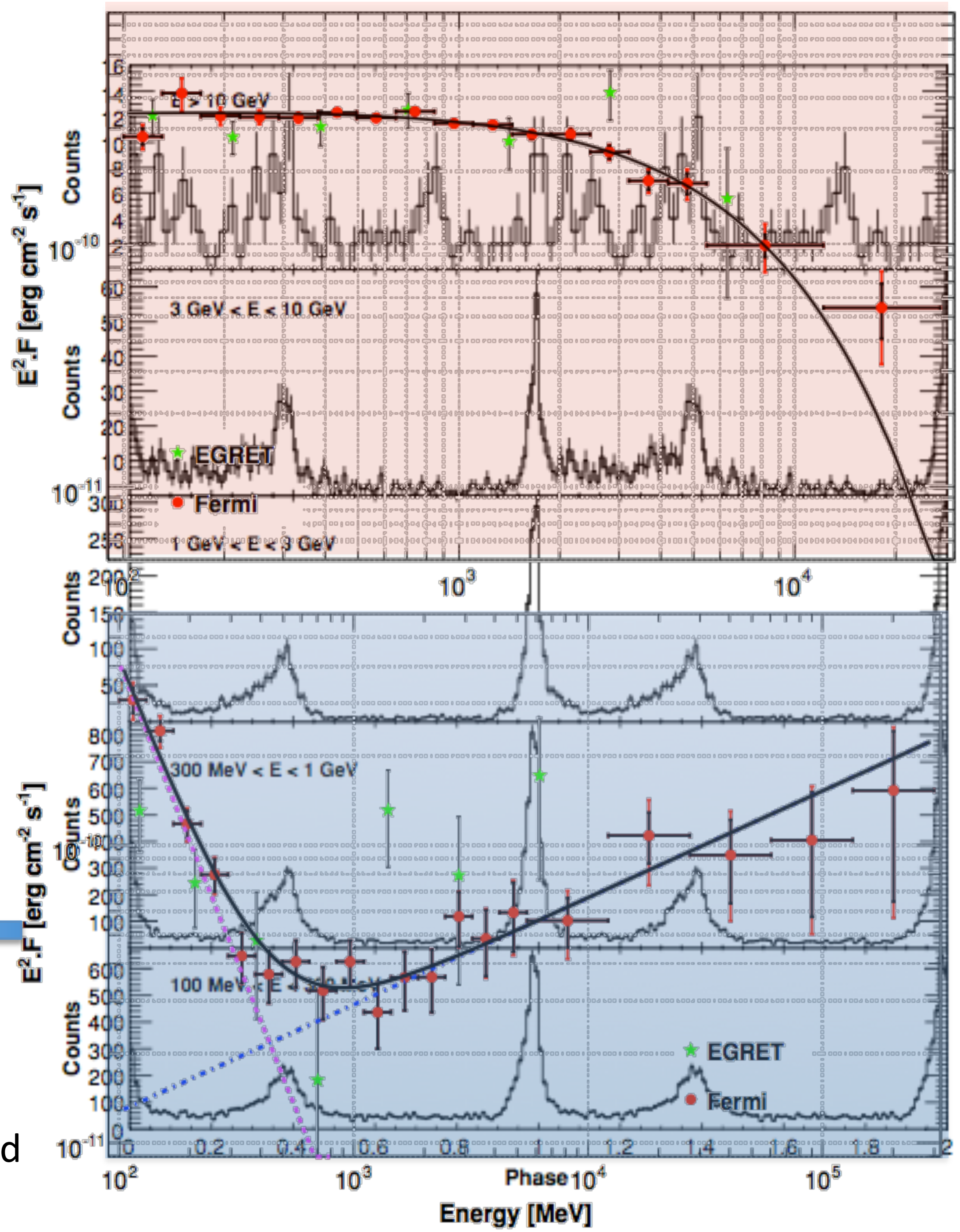
Spectrum strongly changes between "on pulse" and "off pulse" states

$$F = \frac{dN_{\gamma}}{dE} \sim E^{-\Gamma};$$

Energy flux

$$\int E \frac{dN_{\gamma}}{dE} dE = \int \left[E^2 F\right] d(\log E)$$

Source with a "hard" spectrum: $F \sim E^{-\Gamma}$ with $\Gamma<2$: much more power is emitted above 100 GeV, than at ~1 GeV.



Crab pulsar

What physical conditions / processes lead to particle acceleration?

What particles are accelerated (protons, nuclei, electrons)?

To what energies?

Could this the type of sources be responsible for the observed cosmic rays in our Galaxy?

Astropartilce

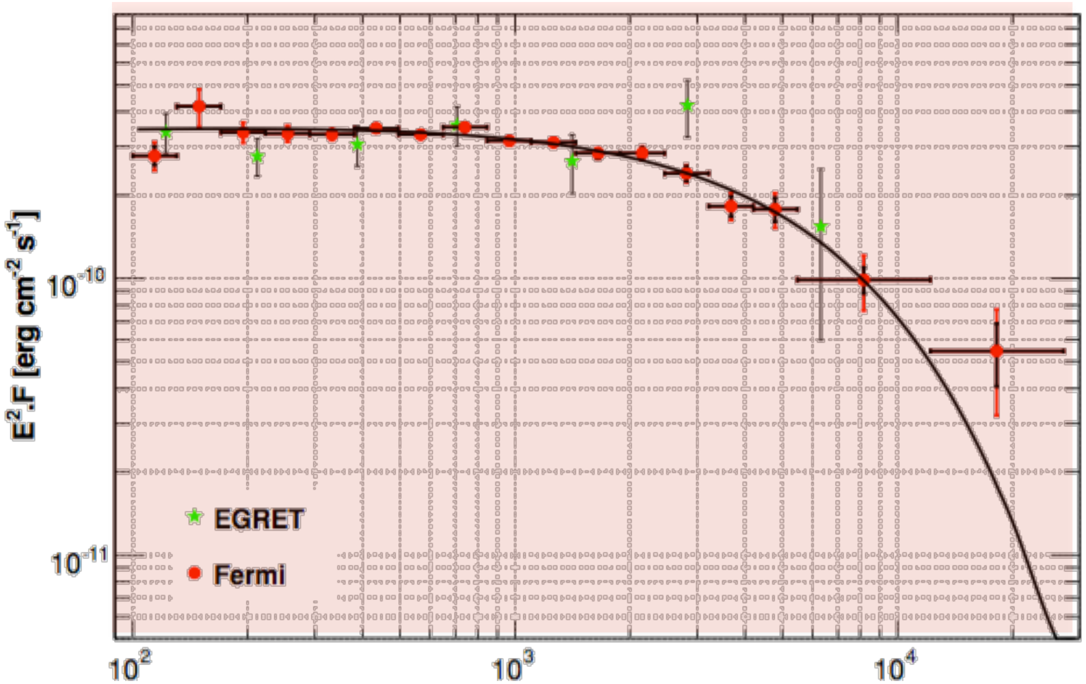
Astronomy

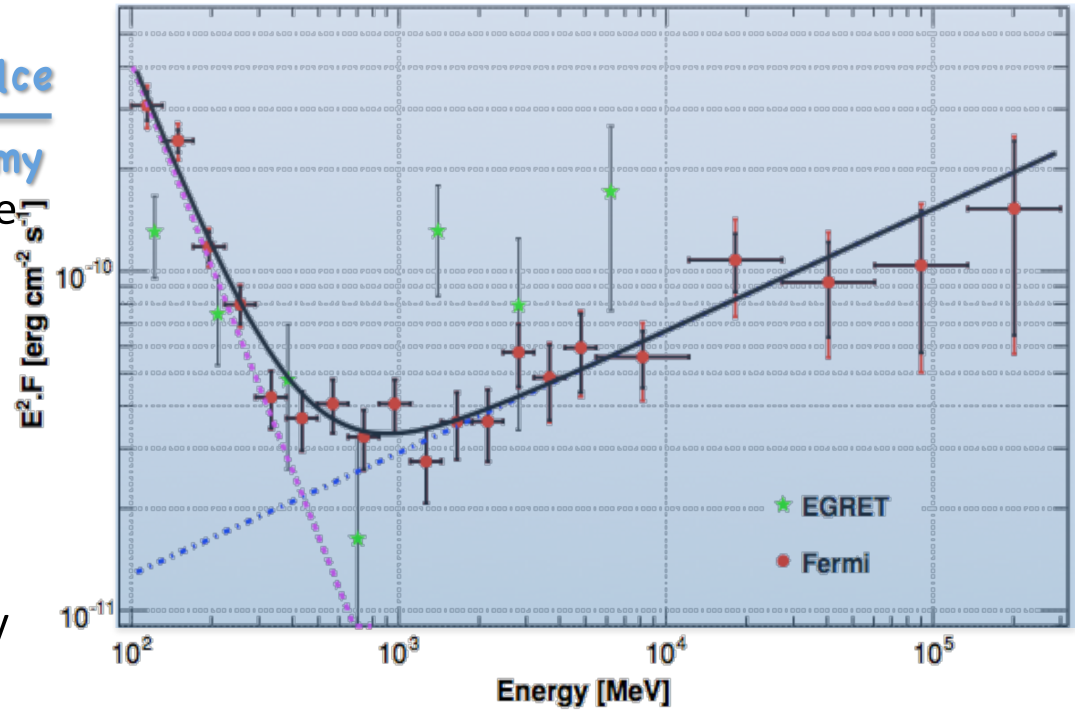
What kind of astronomical objects are pulsars?

What is the mechanism of periodic modulation of electromagnetic emission from these sources?

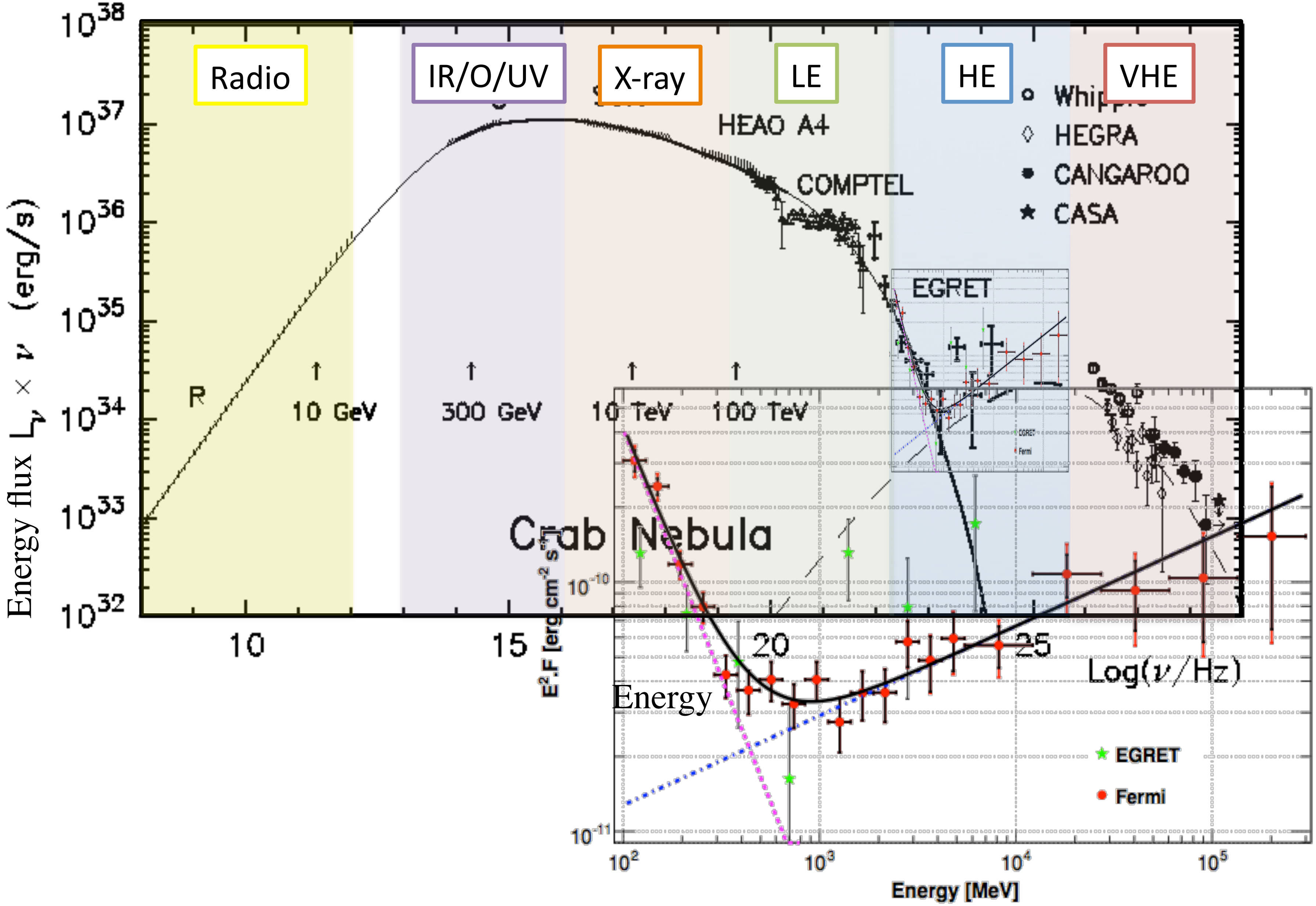
What powers the source activity?

What is the mechanism of gamma-ray emission?

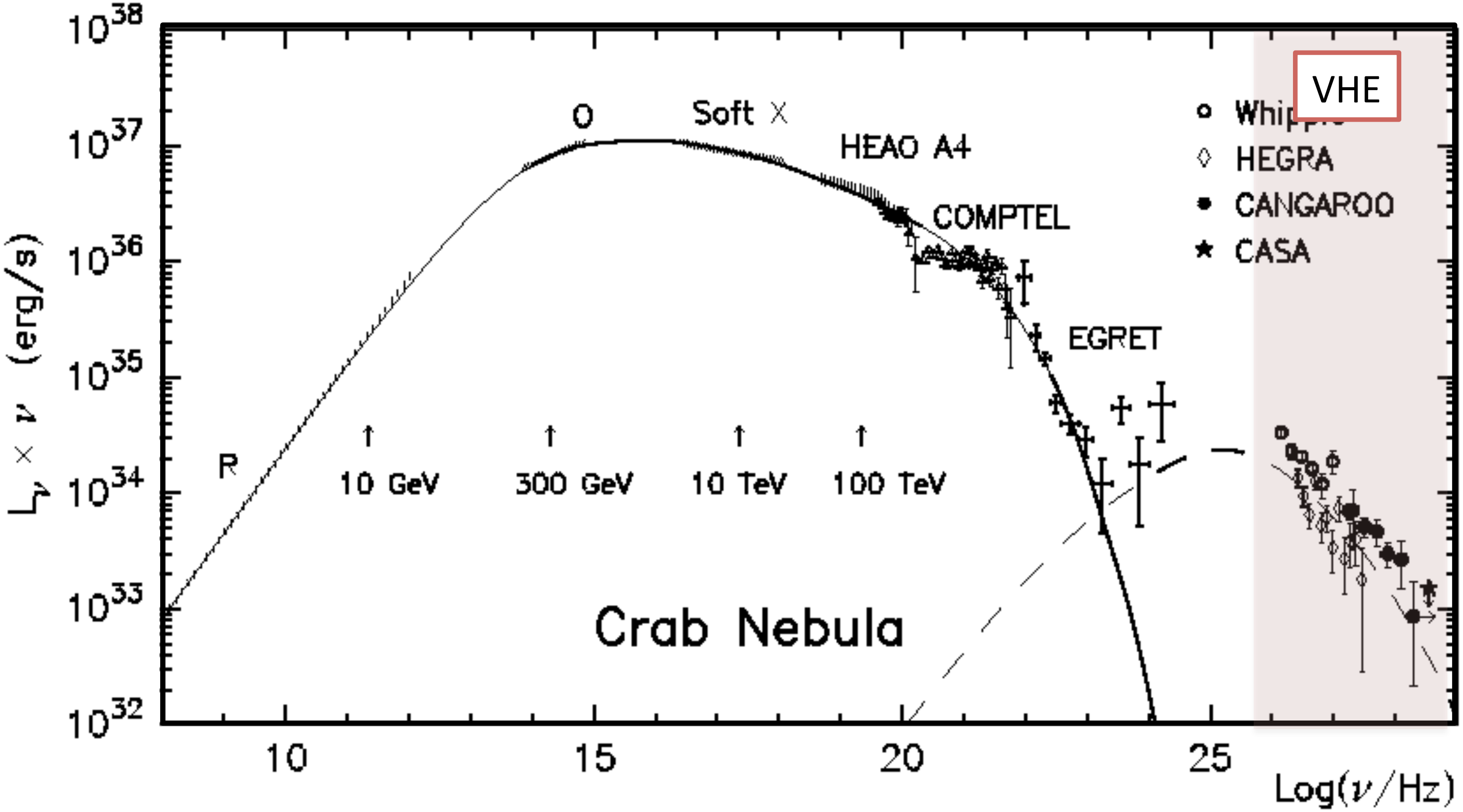




Multi-wavelength approach



Multi-wavelength approach



Very-high-energy gamma-ray astronomy

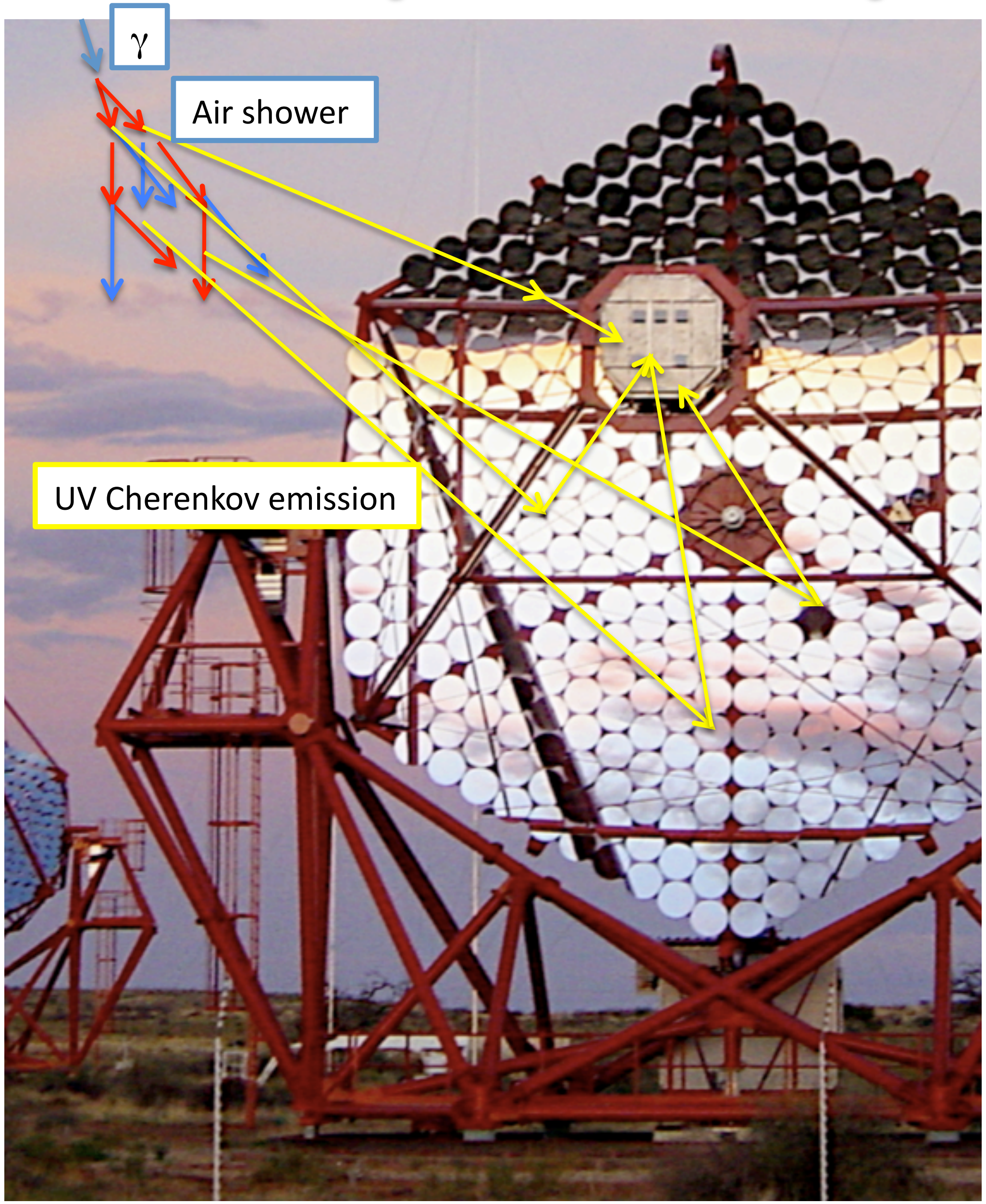
Low-energy gamma-rays: 0.1-10 MeV

High-energy gamma-rays: 0.1-10 GeV

Fermi

Very-high-energy gamma-rays:
0.1-10 TeV

HESS
Veritas
MAGIC



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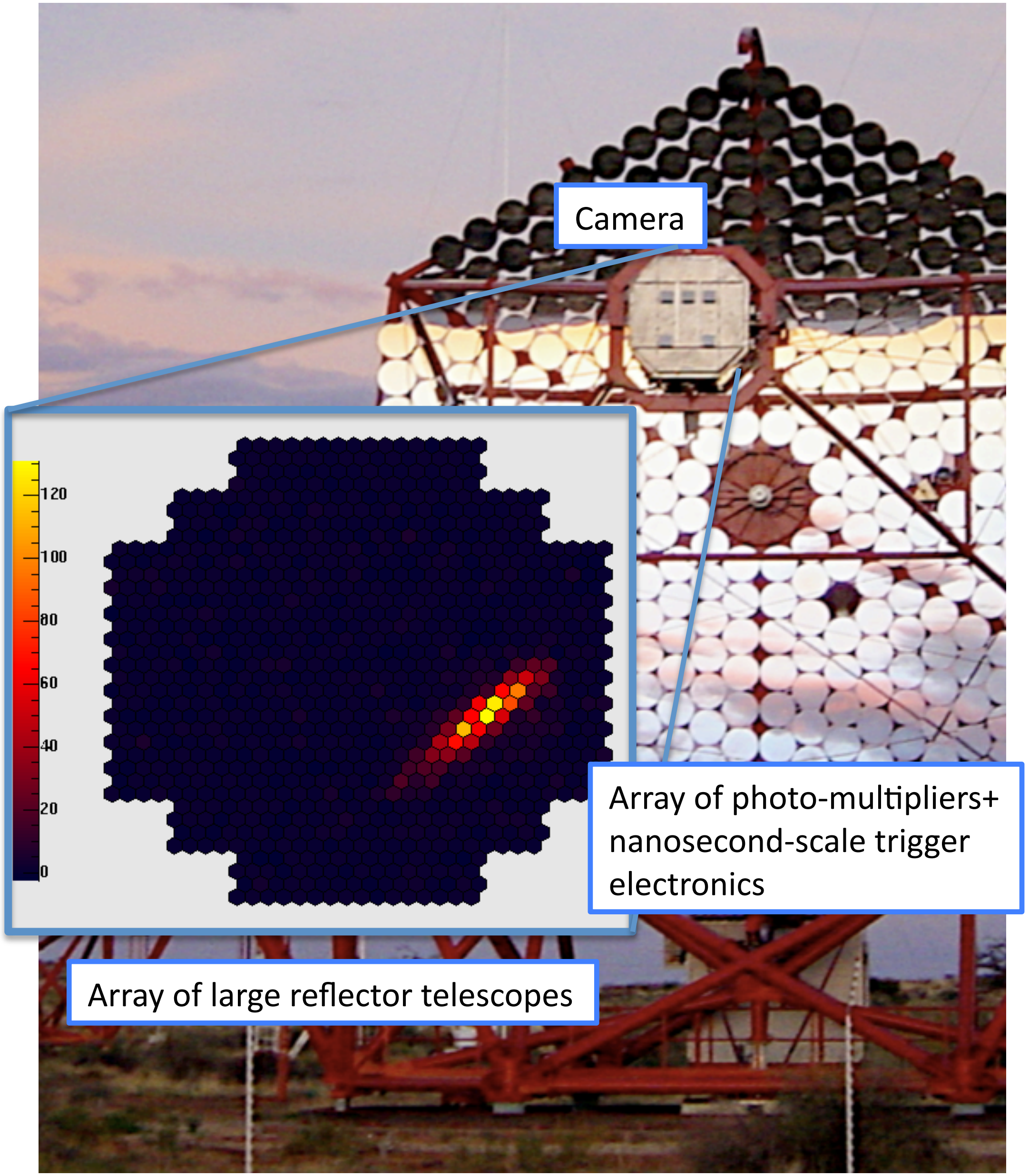
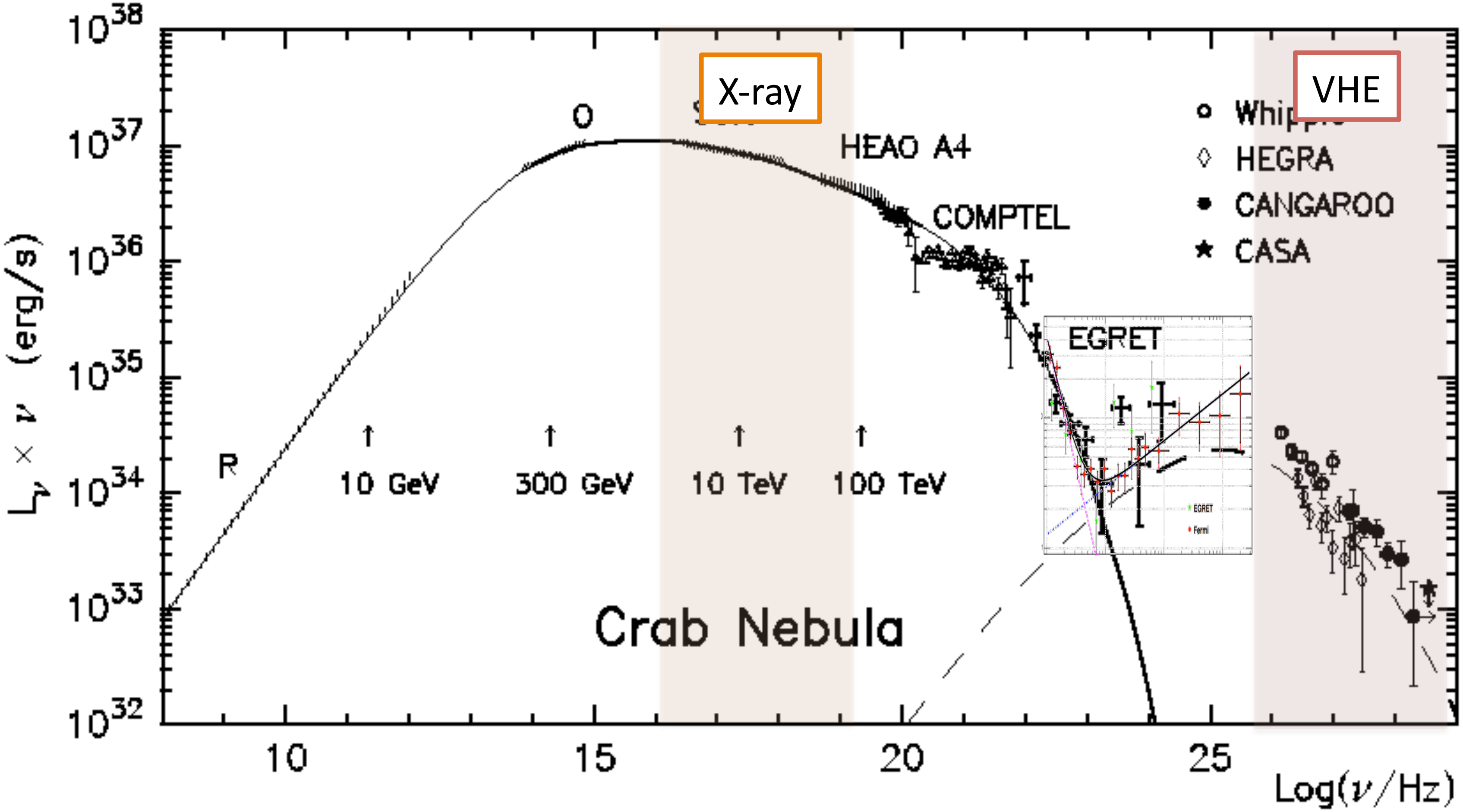


Multi-wavelength approach



Gamma astronomy

Low-energy gamma-rays: 0.1-10 MeV

High-energy gamma-rays: 0.1-10 GeV

Fermi

Very-high-energy gamma-rays:
0.1-10 TeV

HESS
Veritas
MAGIC

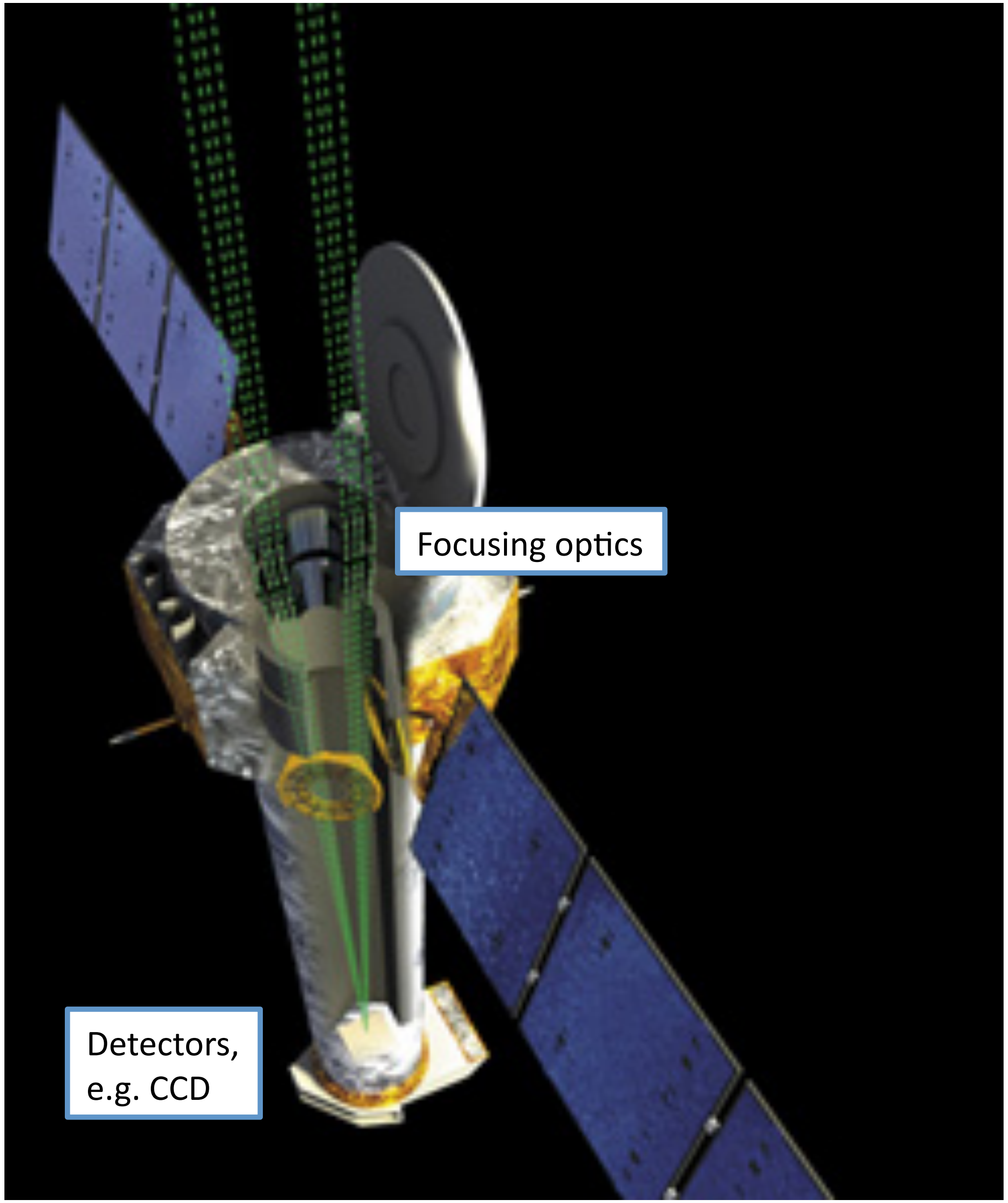
X-ray astronomy

Soft X-rays: 0.1-10 keV

Chandra
XMM-Newton

Hard X-rays: 10 - 100 keV

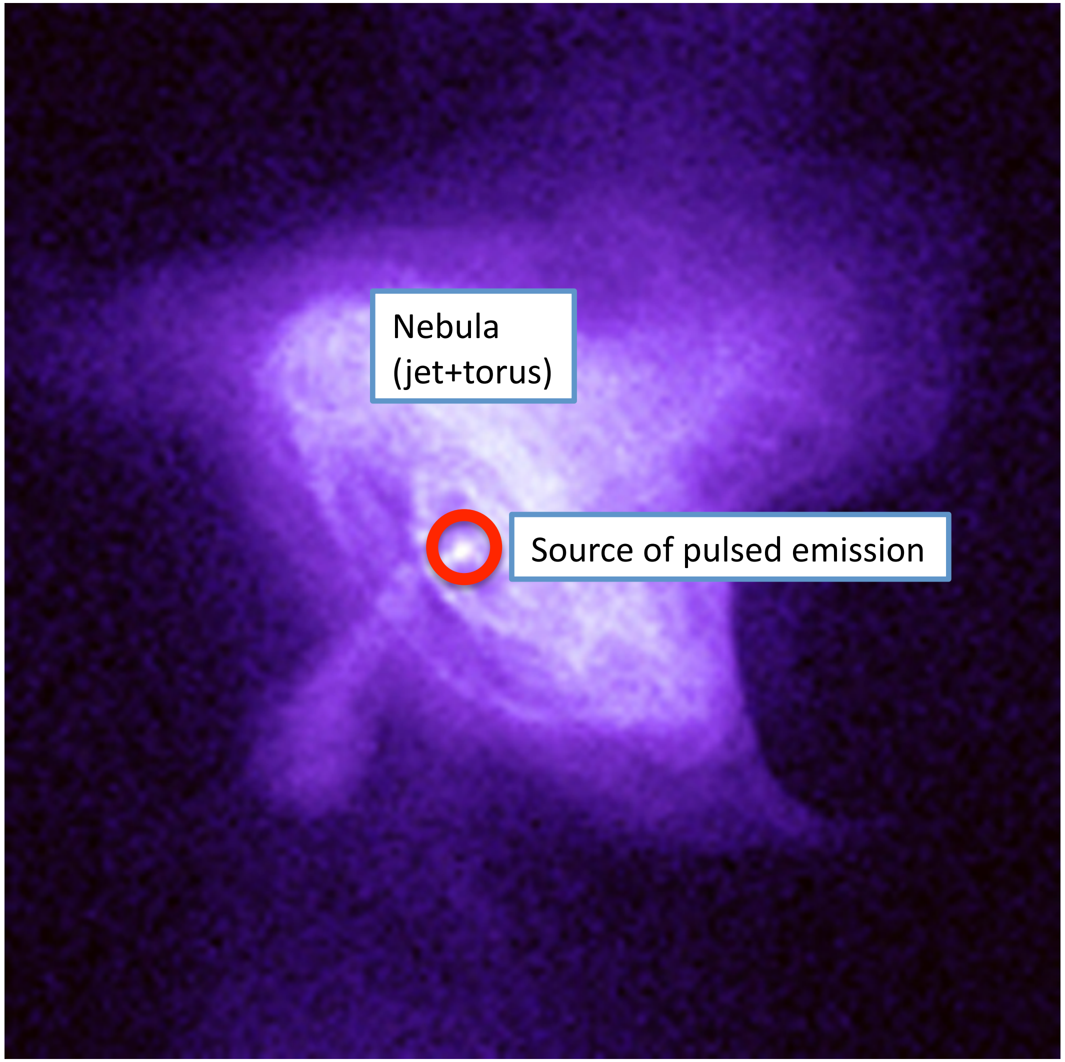
INTEGRAL
SWIFT
Suzaku



Crab in X-rays

X-ray telescopes resolve Crab into a point source of pulsed emission surrounded by an extended nebula.

Angular size of several arcsecond at the distance ~2kpc corresponds to $\sim 10^{17}$–10^{18} cm.



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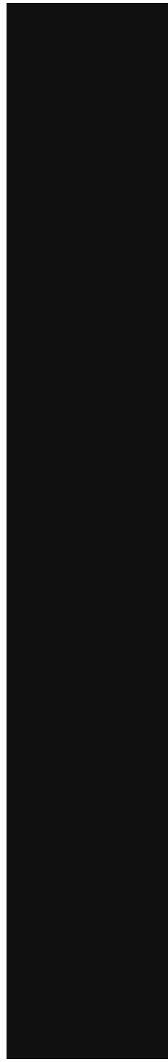


Crab in X-rays

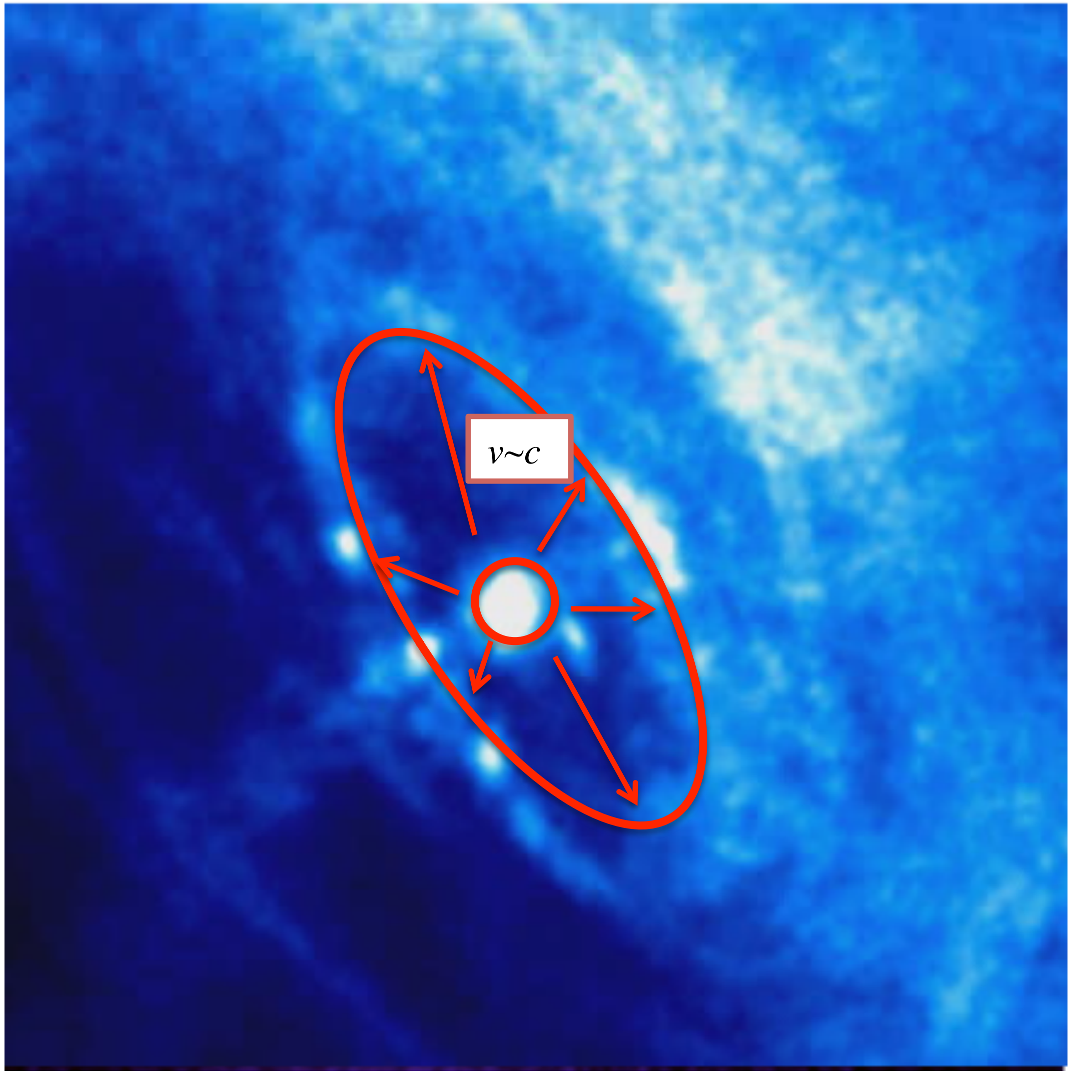
X-ray telescopes resolve Crab into a point source of pulsed emission surrounded by an extended nebula.

Angular size of several arcsecond at the distance ~2kpc corresponds to ~10^{17}–10^{18} cm.

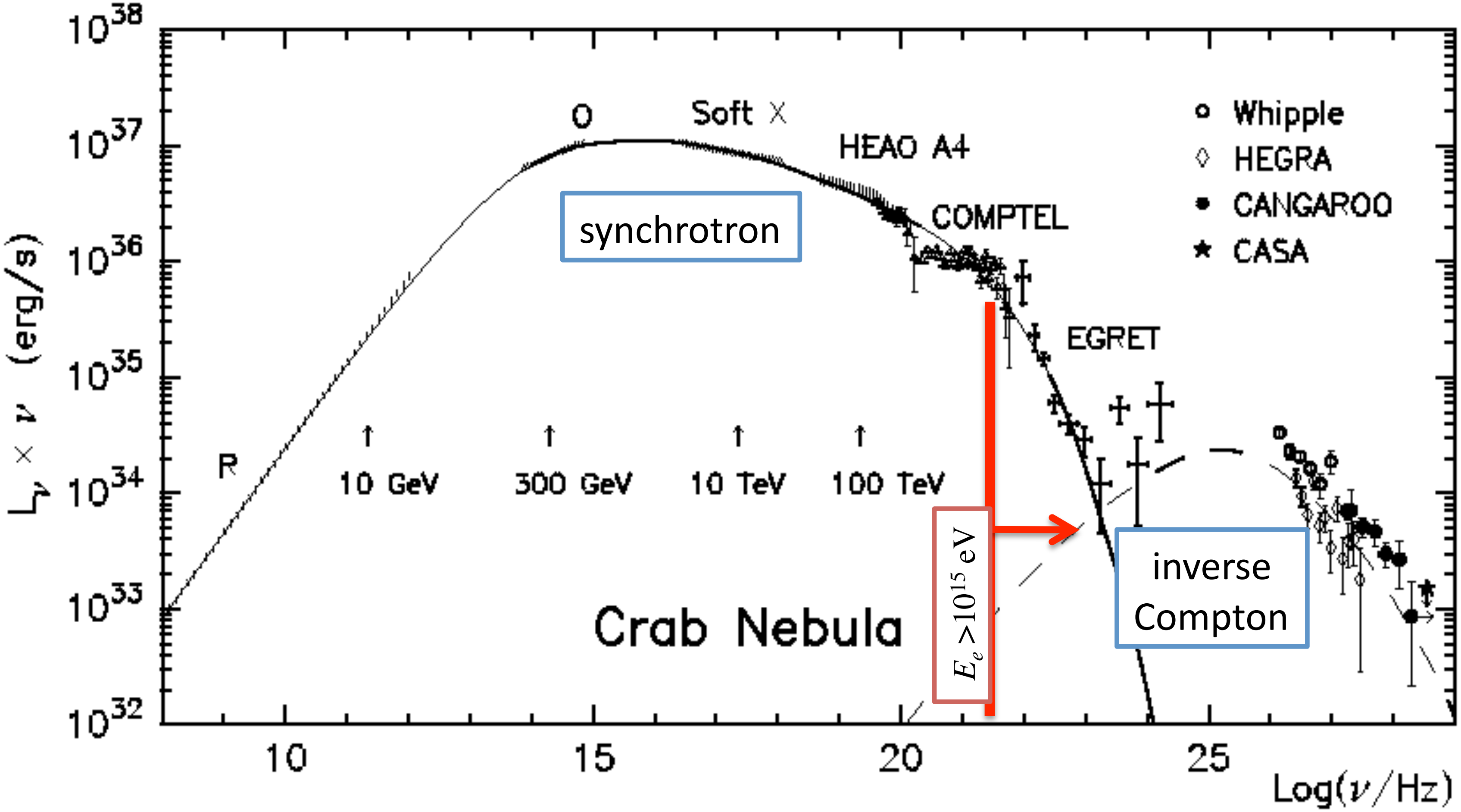
Nebula emission is variable on the time scale of several months (~3×10^{6} s)

$$t \sim \frac{R}{c} = \frac{10^{17}\,\mathrm{cm}}{3\times10^{10}\,\mathrm{s}} \sim 3\times10^{6}\,\mathrm{s}$$

Central source of pulsed emission generates relativistic outflow feeding the nebula



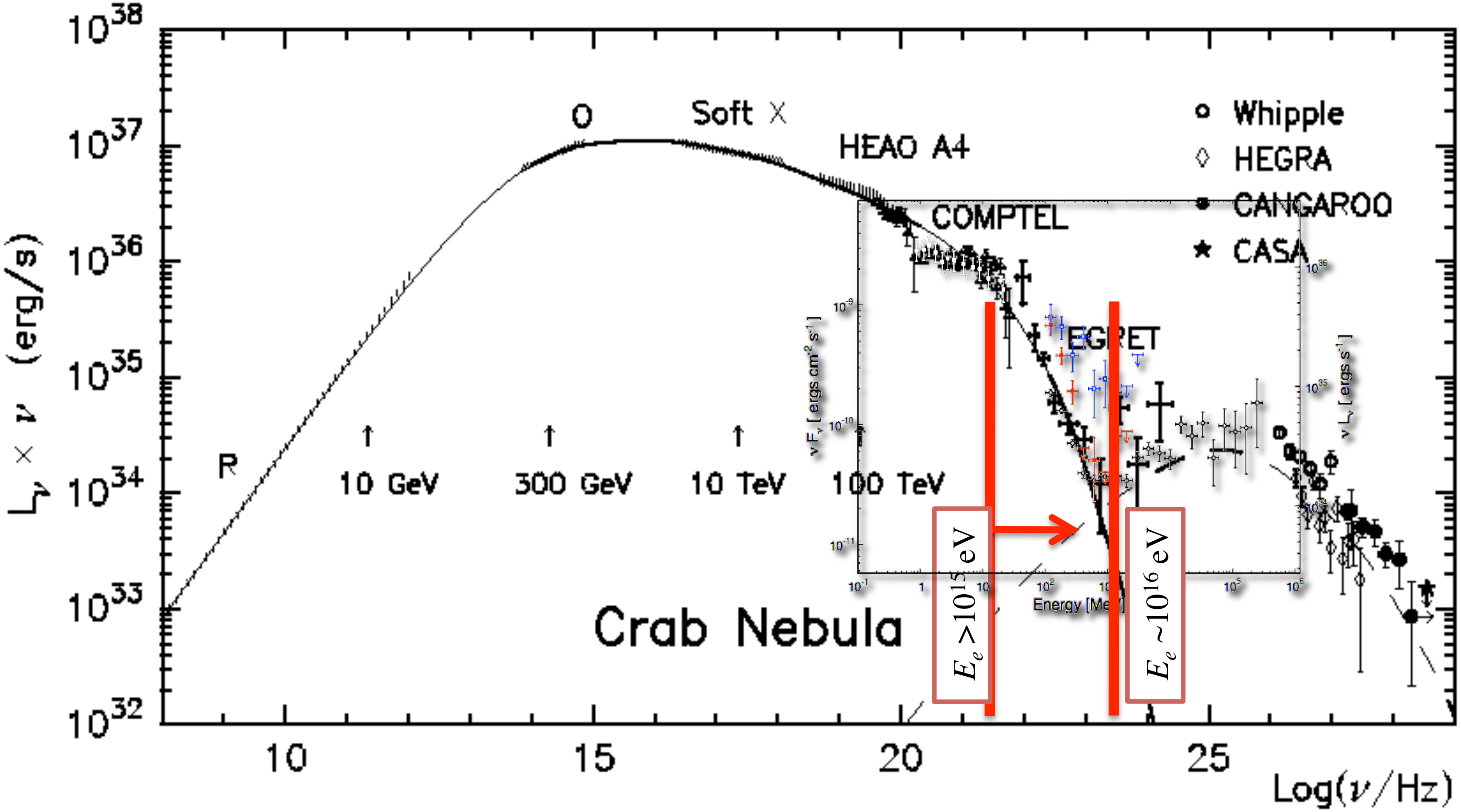
Crab as a Galactic PeVatron



Broad band electromagnetic emission could, in principle, be produced either by electrons/ positrons or by protons/nuclei filling the nebula.

Synchrotron emission from electrons is a reasonable hypothesis for the radio-to-GeV componennt of the spectrum. Inverse Compton emission from the same electrons is a plausible explanation for the 10 GeV – 100 TeV emission. Electron energies reach 10^{15} eV.

Crab as a Galactic PeVatron



Two γ-ray telescopes, Fermi and AGILE, have recently detected flares from Crab at the energies up to 1 GeV, on a time scale ~1 day.

$$E_{synch} \approx \frac{eBE_e^2}{m_e^3} \approx 0.5\left[\frac{B}{10^{-4}\,\mathrm{G}}\right]\left[\frac{E}{10^{16}\,\mathrm{eV}}\right]^2 \mathrm{GeV}$$

Crab as a Galactic PeVatron

Where do the PeV (10^{15} eV) electrons in the nebula come from?

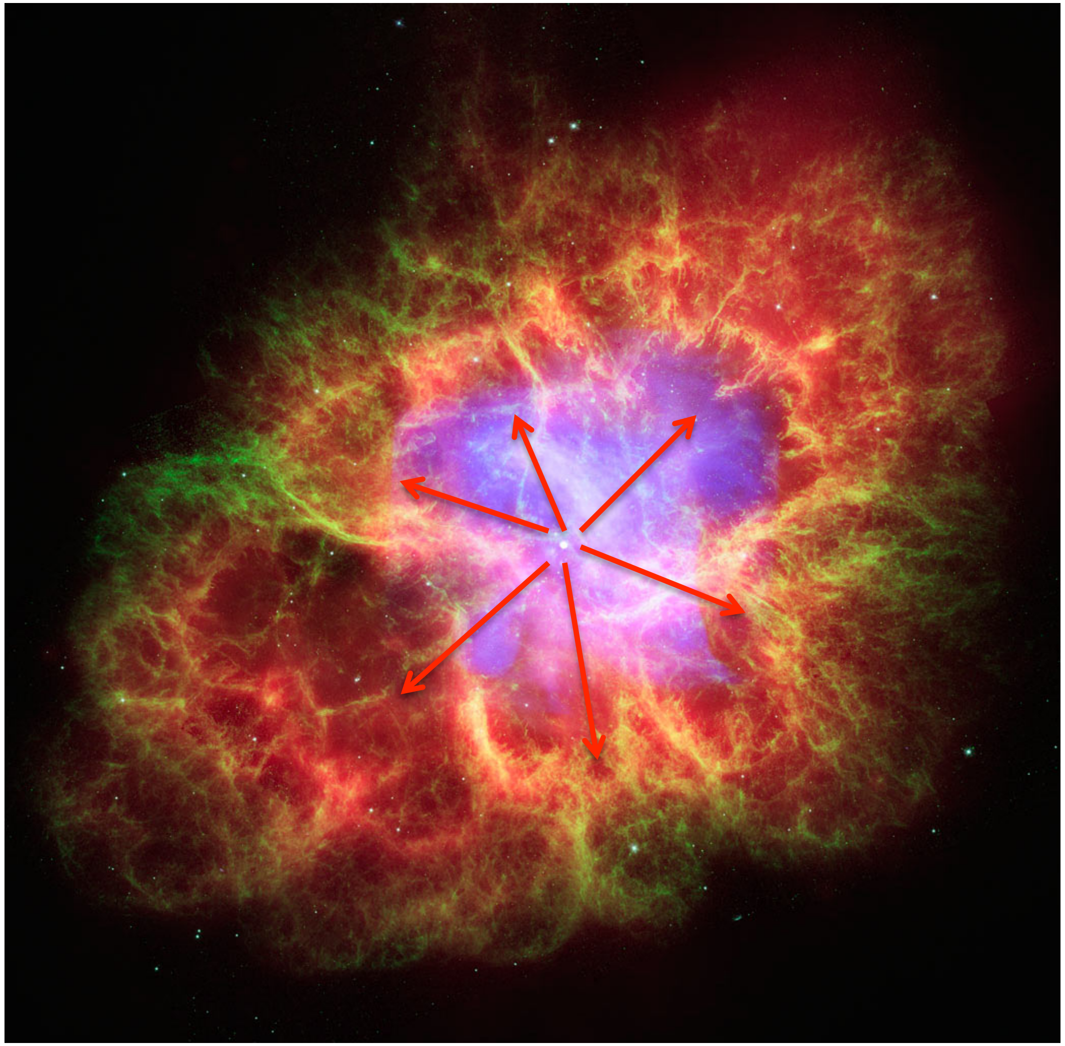
Or are they accelerated "in situ" in the nebula itself?

$$R < ct_{flare} \sim 10^{16}\left[\frac{t_{flare}}{3\text{ d}}\right]\text{cm}$$

What is the acceleration mechanism at work?

$$E_{\max} \le eBR \sim 3\times10^{14}\left[\frac{B}{10^{-4}\text{G}}\right]\left[\frac{R}{10^{16}\text{cm}}\right]\text{eV}$$

(equality for a linear accelerator with $|\vec{E}| \sim |\vec{B}|$). Magnetic field is known from the broad-band spectral properties.



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Crab as a Galactic PeVatron

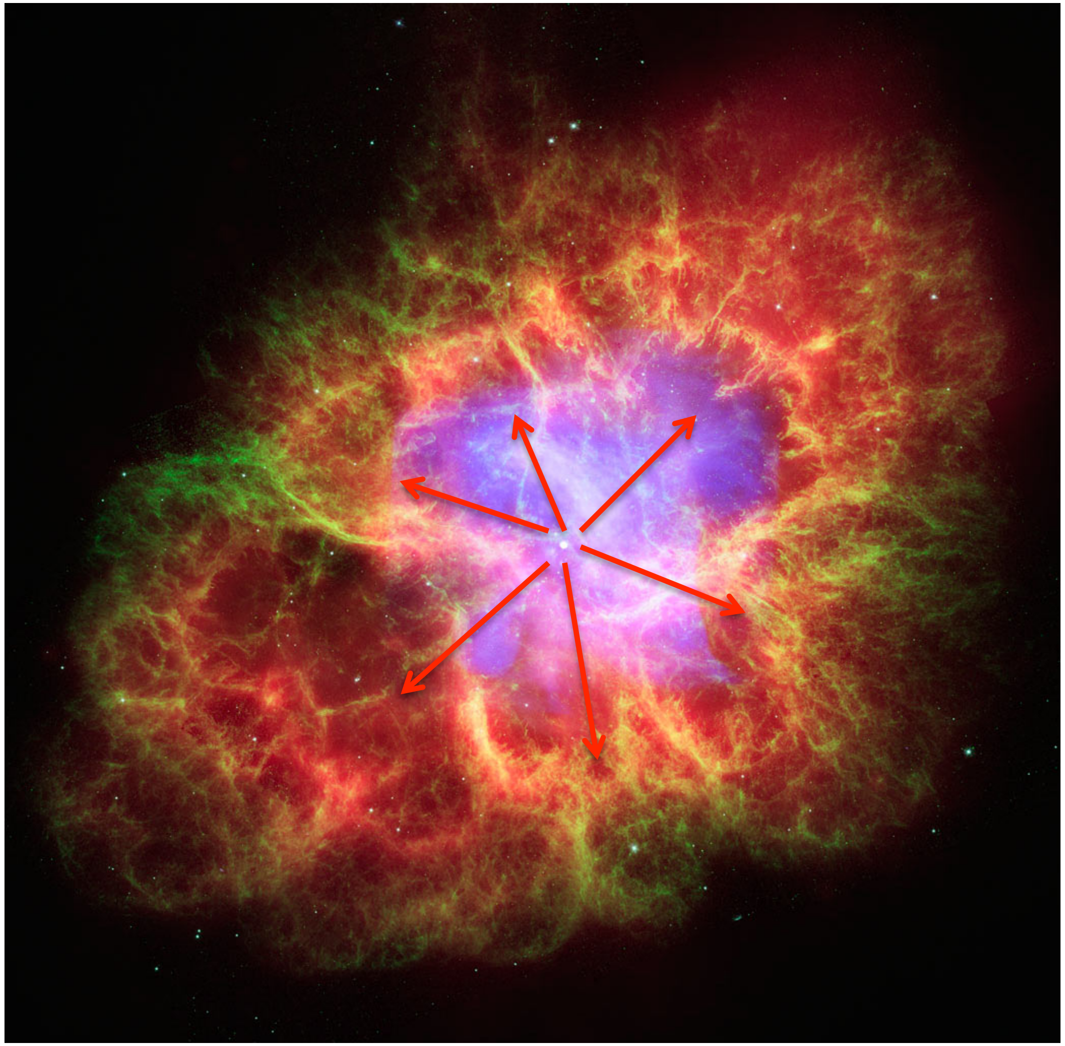
Where do the PeV (10^{15} eV) electrons in the nebula come from?

Are 1-10 PeV electrons injected directly from the relativistic wind from the compact source?

What is the nature of this compact source? What is the mechanism of particle acceleration?

What is the mechanism of generation of relativistic wind by the compact source?

What particles fill the wind (electrons + positrons or electrons + protons?)



Crab as a Galactic PeVatron

Contrary to electrons, protons do not loose their energy on synchrotron radiation in the nebula:

$$t_{synch} = \frac{E}{dE/dt} \approx \frac{m^4}{e^4 B^2 E} \approx$$

$$10^{13} \left[\frac{m}{m_p}\right]^4 \left[\frac{B}{10^{-4}\ \mathrm{G}}\right]^{-2} \left[\frac{E}{10^{15}\mathrm{eV}}\right]^{-1} \mathrm{yr}$$

The only way to infer the presence of high-energy protons is to look for the signatures of high-energy protons interacting with matter (low energy protons) and/or radiation fields.

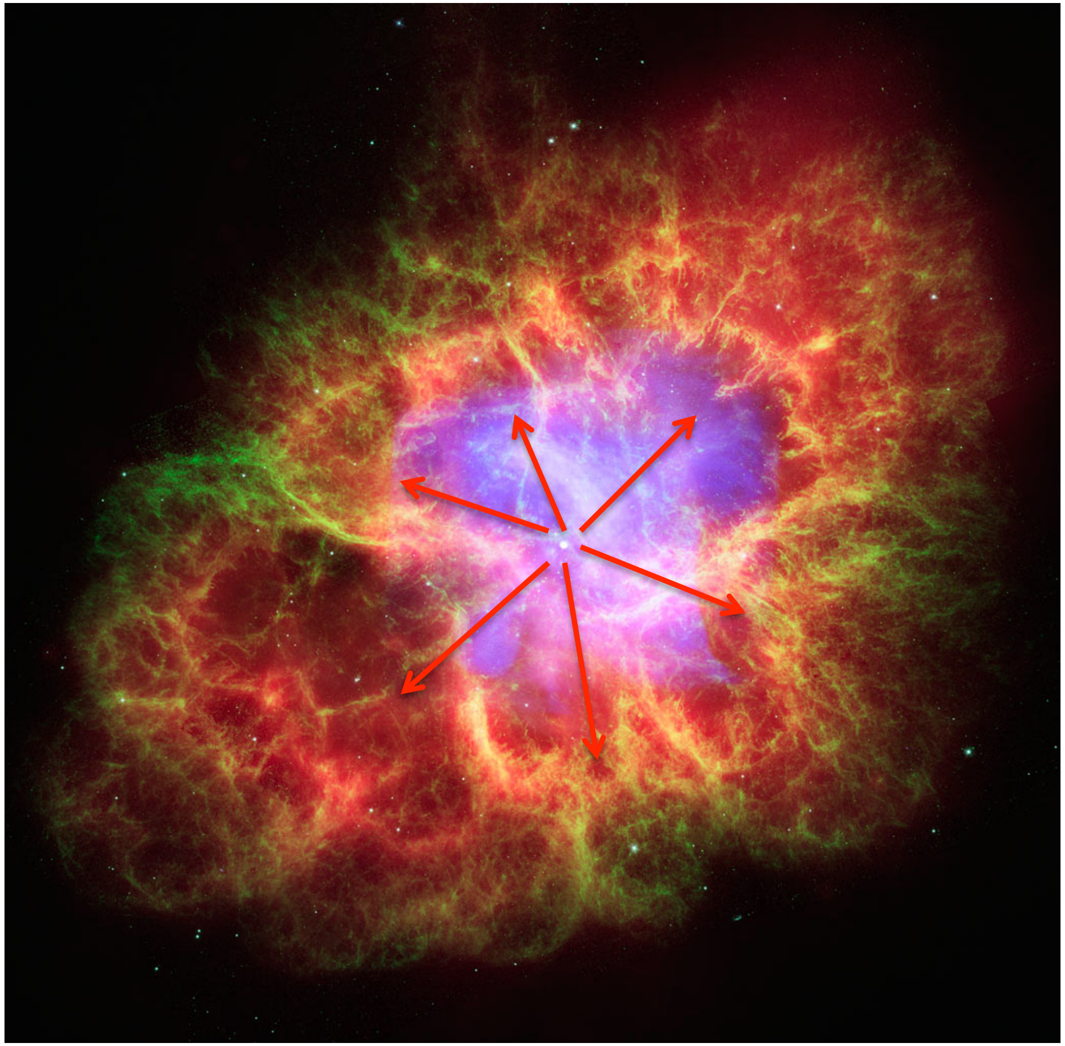
$$p + p \rightarrow p + p + \pi^0,\ \pi^0 \rightarrow 2\gamma$$

$$p + p \rightarrow p + n + \pi^+,\ \pi^+ \rightarrow \mu^+ + \nu_\mu,$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$n + p \rightarrow p + p + \pi^-,\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu,$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$



Gamma astronomy

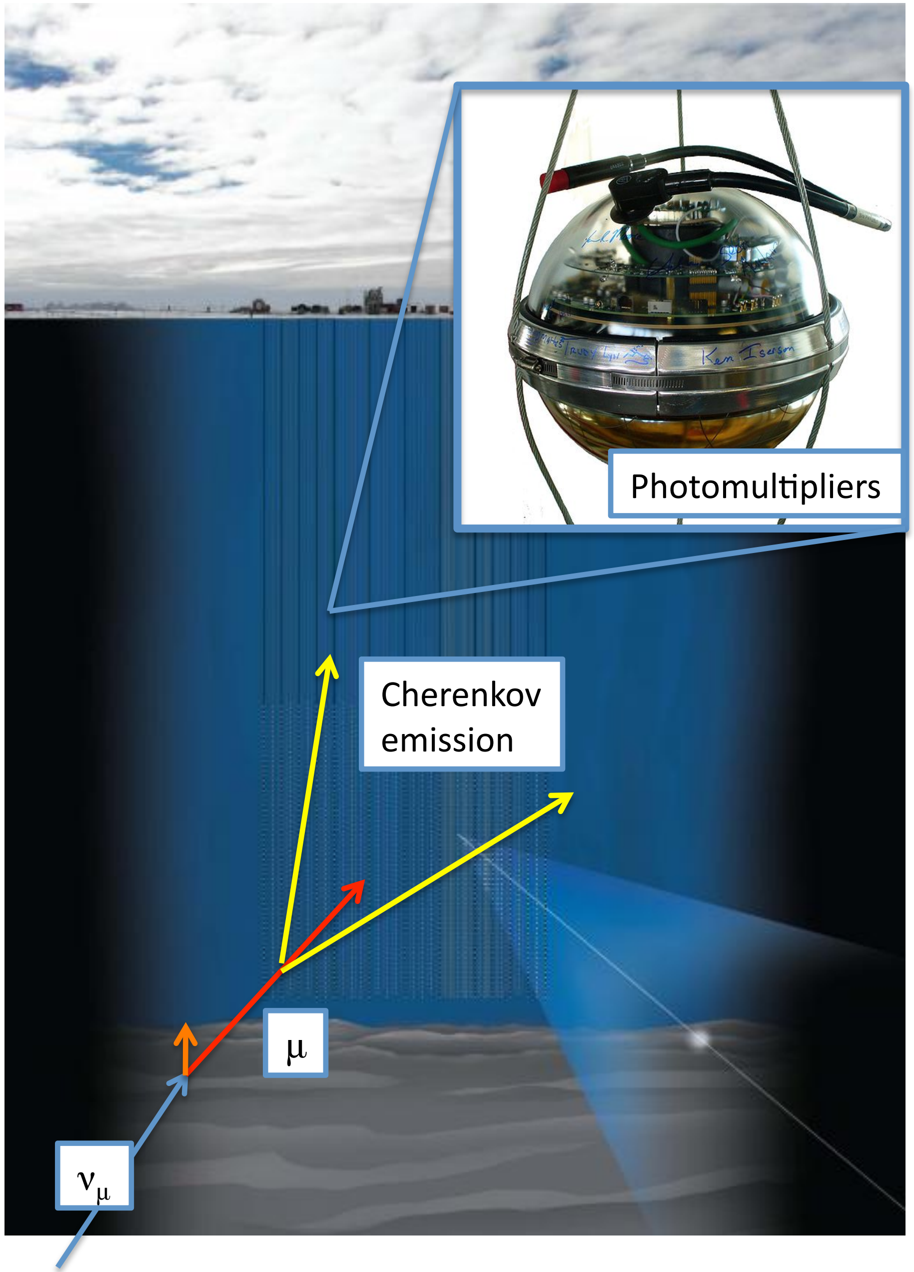
Fermi
HESS
Veritas
MAGIC

X-ray astronomy

Chandra
XMM-Newton
INTEGRAL
SWIFT
Suzaku

High-energy neutrino astronomy

IceCube
Antares



High-energy proton sources

$$p + p \to p + p + \pi^0,\ \pi^0 \to 2\gamma$$

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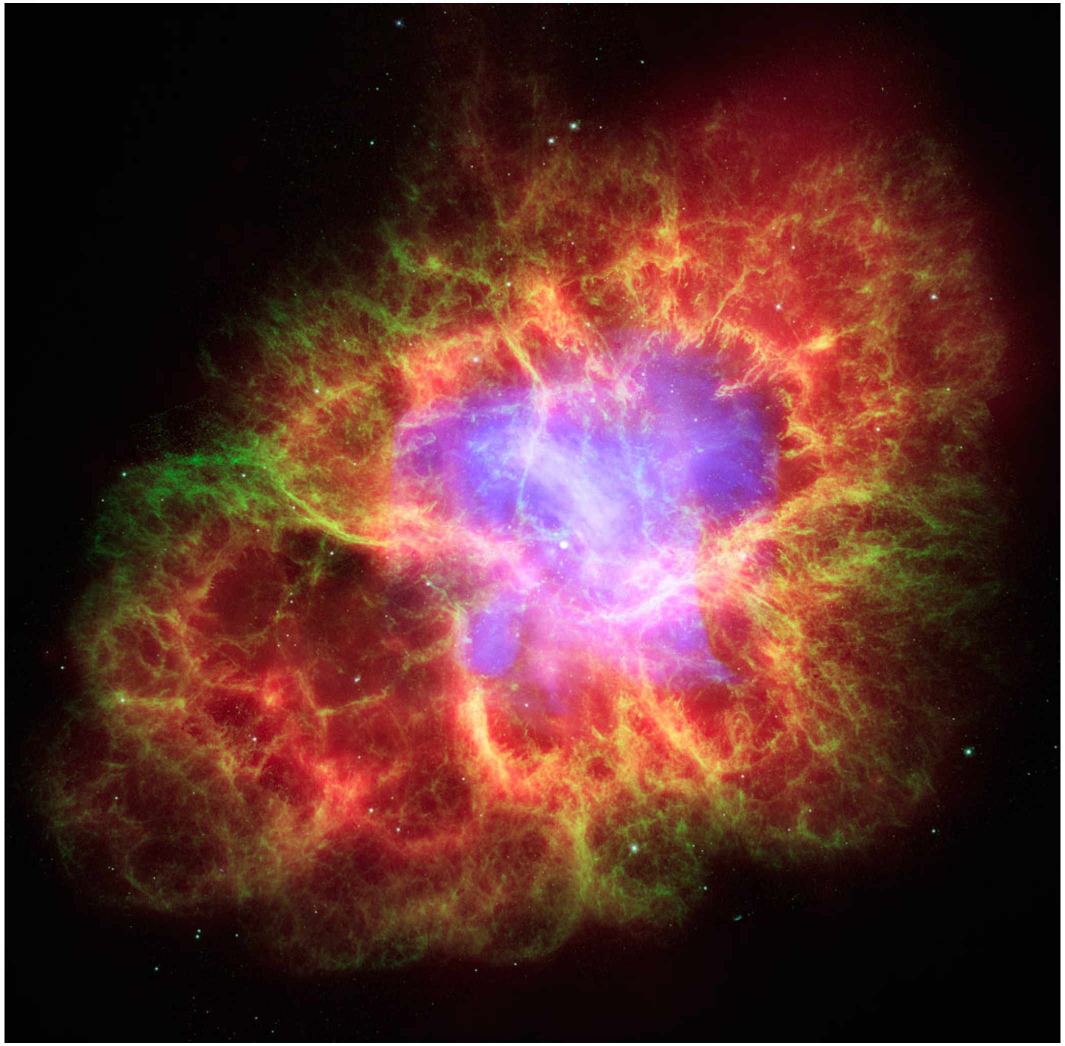

Proton-proton interaction cross section: σ_{pp}~10^{-26} cm^2. Proton-gamma interaction cross-section $\sigma_{p\gamma}$~10^{-28} cm^2.

Typical density of interstellar medium in the Galactic disk is n_{ISM}~1 cm^{-3}. Density of photons of Cosmic Microwave Background radiation is n_{CMB}≈400 cm^{-3}.

$$t_{pp} \sim \frac{1}{c\sigma_{pp} n_{ISM}} \approx 10^8 \mathrm{yr} \sim t_{p\gamma}$$

Age of the Crab pulsar is ~10^3 yr<<t_{pp}, $t_{p\gamma}$. Neutrino production is extemely inefficient process.

High-energy proton sources

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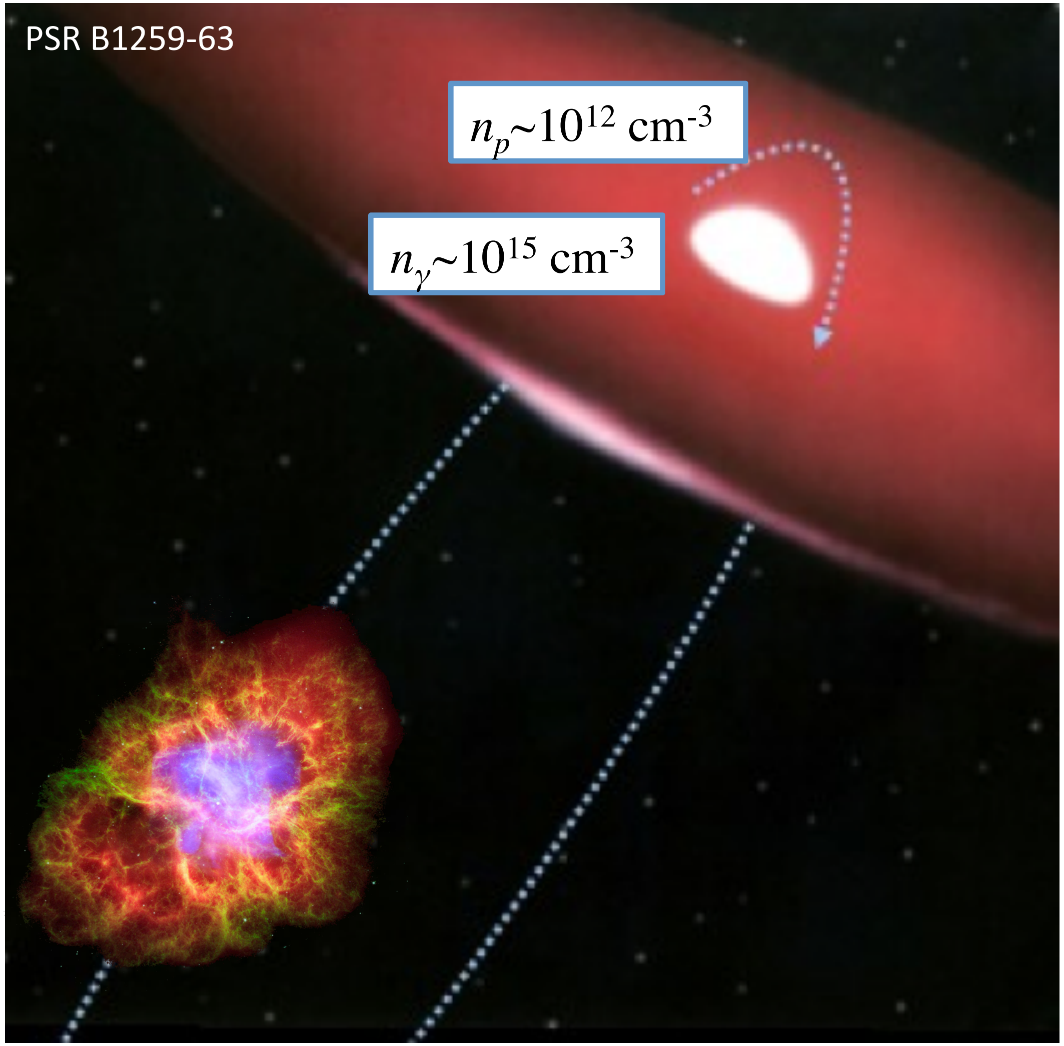


Proton-proton interaction cross section: $\sigma_{pp}\sim10^{-26}$ cm^2. Proton-gamma interaction cross-section $\sigma_{pp}\sim10^{-28}$ cm^2.

Typical density of interstellar medium in the Galactic disk is $n_{ISM}\sim1$ cm^{-3}. Density of photons of Cosmic Microwave Background radiation is $n_{CMB}\approx400$ cm^{-3}.

$$t_{pp} \sim \frac{1}{c\sigma_{pp} n_p} \approx 10^3\ \mathrm{s} \sim t_{p\gamma}$$

Neutrino production could be efficient in high-density proton sources

High-energy proton sources

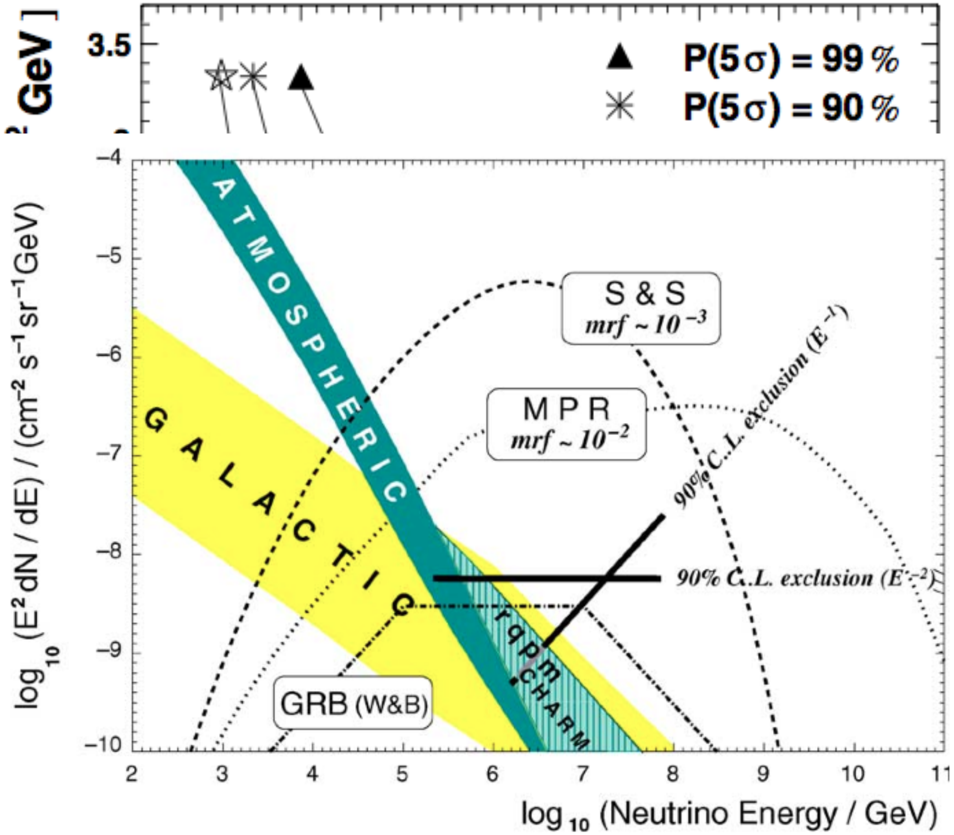
Construction of the IceCube detector at the South Pole was recently completed. Data taking is on-going.

IceCube would be able to detect neutrino sources which produce flux higher than ~10^{-11} erg/cm^{2}s in the 10-100 TeV band.

Sensitivity at lower energies is limited by

(a) low neutrino interaction cross-section
(b) high atmospheric neutrino background.

It is not clear if compact Galactic CR sources producing sufficiently 10-100 TeV neutrino high flux exist.



Ahrens et al., 2004, Astropart.Phys. 20,507

Summary

Particle acceleration in astrophysical sources is accompanied by electromagnetic and/or neutrino emission.

Identification of CR sources is possible only via study of this electromagnetic and/or neutrino emission.

Tools of high-energy and very-high-energy gamma-ray astronomy enable direct identification of astronomical sources working as particle accelerators.

Example of Crab: a source hosting a PeVatron accelerator (identified using the tools of "multi-wavelength" astronomy).

The tools of multi-wavelength astronomy might be complemented in the near future by very-high-energy neutrino astronomy tools.