Very High Energy Galactic Sources

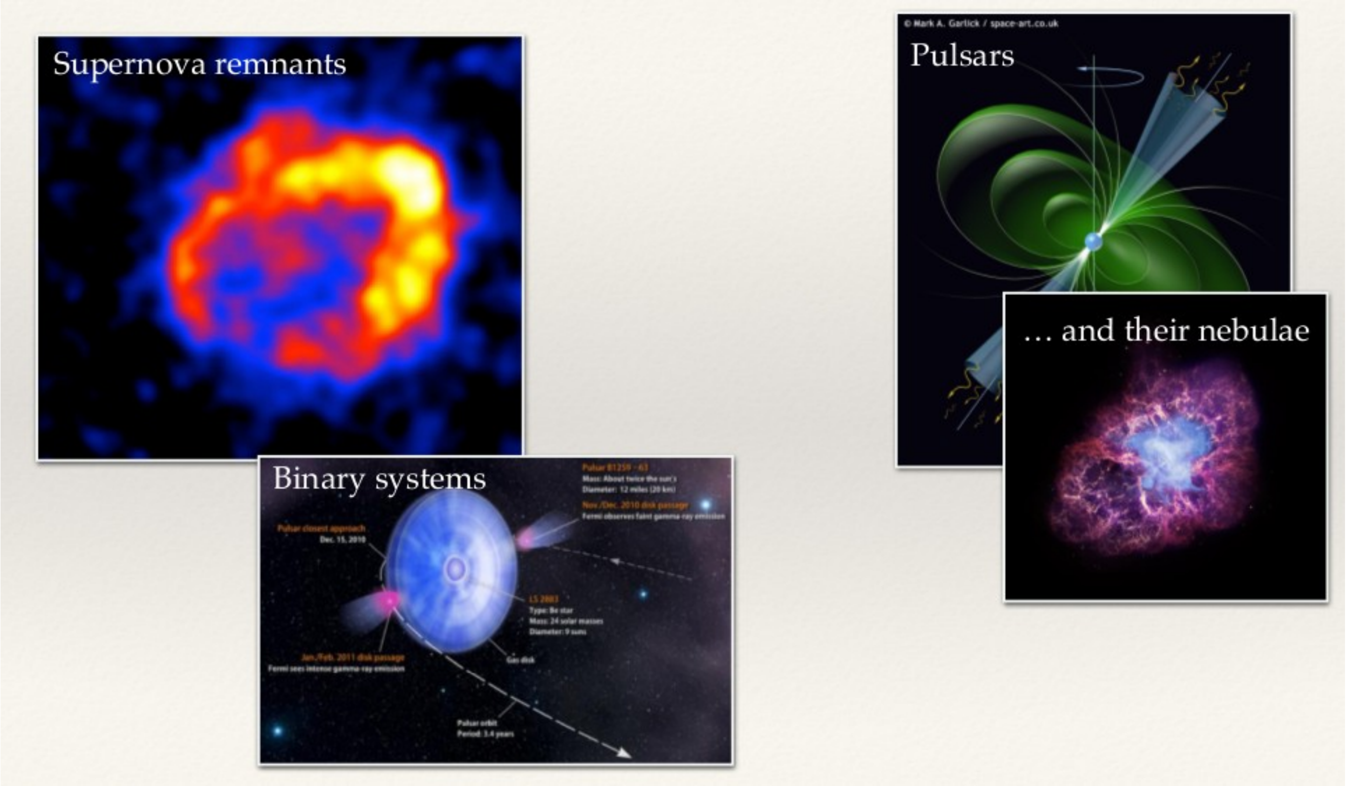
Luca Zampieri
INAF-Astronomical Observatory of Padova

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

Outline

The Galactic population of Very High Energy (VHE) localized sources:

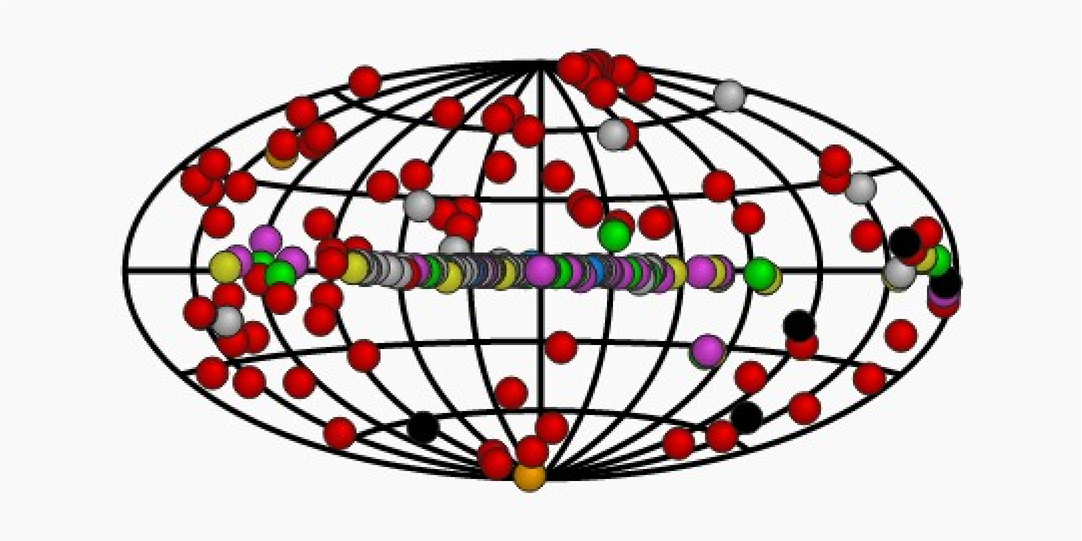
- Pulsars
- Pulsar Wind Nebulae (PWNe)
- Supernova Remnants (SNRs)
- Binary systems



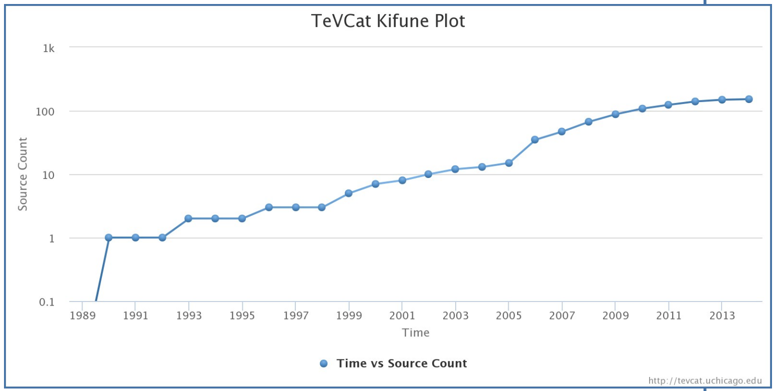
Credits

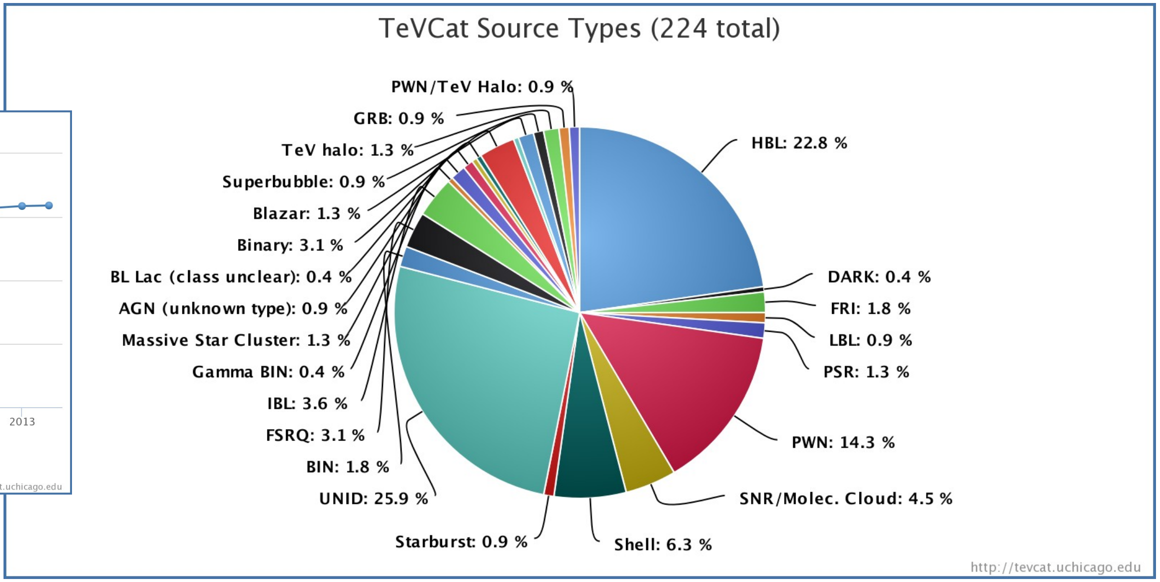
Material in this presentation is taken in part from:

- De Angelis & Mallamaci (2018, The European Physical Journal Plus, 133, 324)
- Funk (2015, CTA Summer School, Sexten)
- Holder (2019, CTA Symposium, Bologna)
- Rieger et al. (2013, Frontiers of Physics, 8, 714)

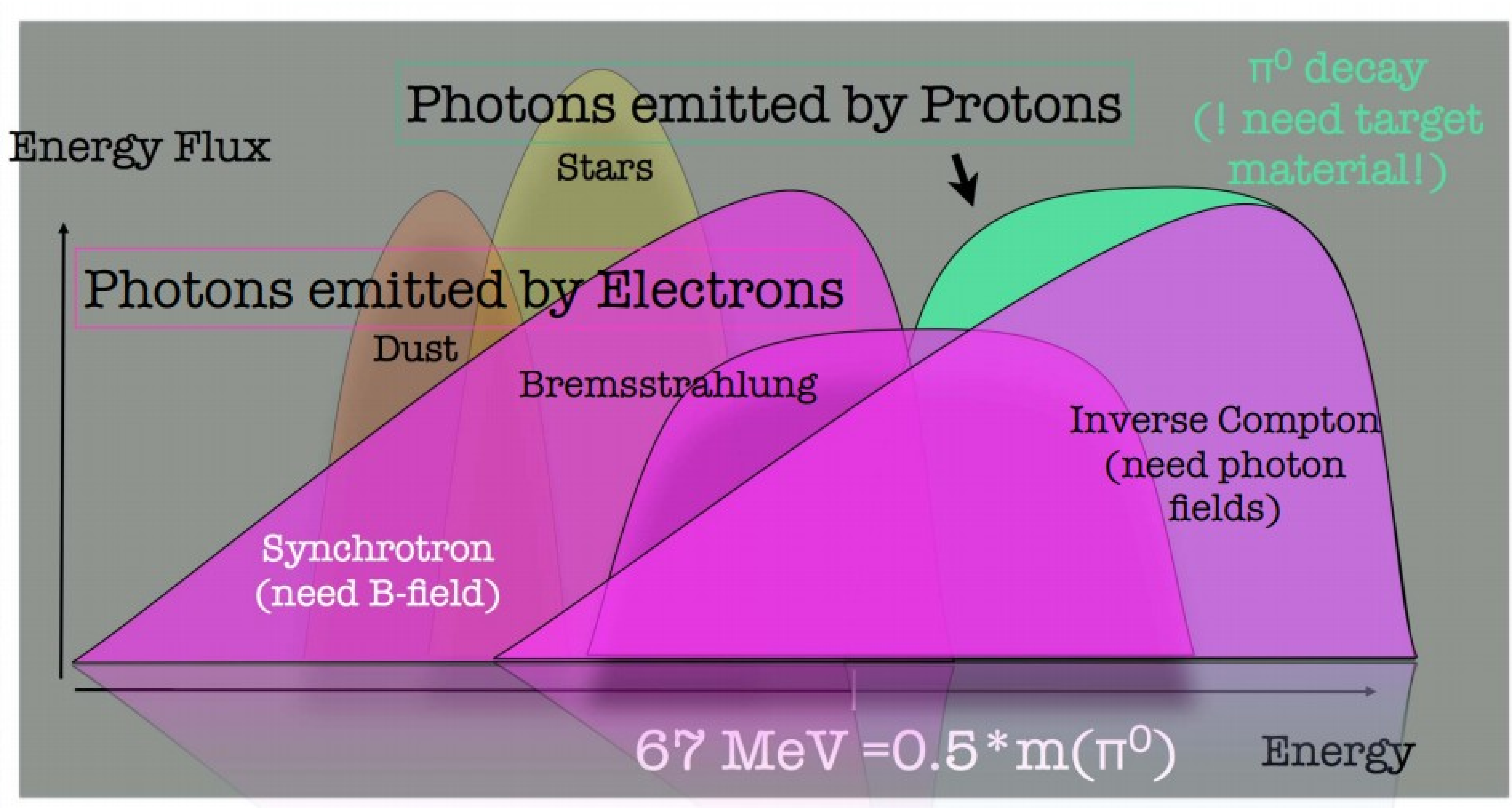


- GRB, AGN (unknown type), TeV halo
- PWN, PWN/TeV Halo, BIN
- HBL, IBL, FSRQ, FRI, Blazar, BL Lac (class unclear), LBL
- Shell, SNR/Molec. Cloud, Composite SNI
- Starburst, Superbubble
- UNID, TeV halo, DARK
- Binary, PSR, Gamma BIN
- Massive Star Cluster, Globular Cluster



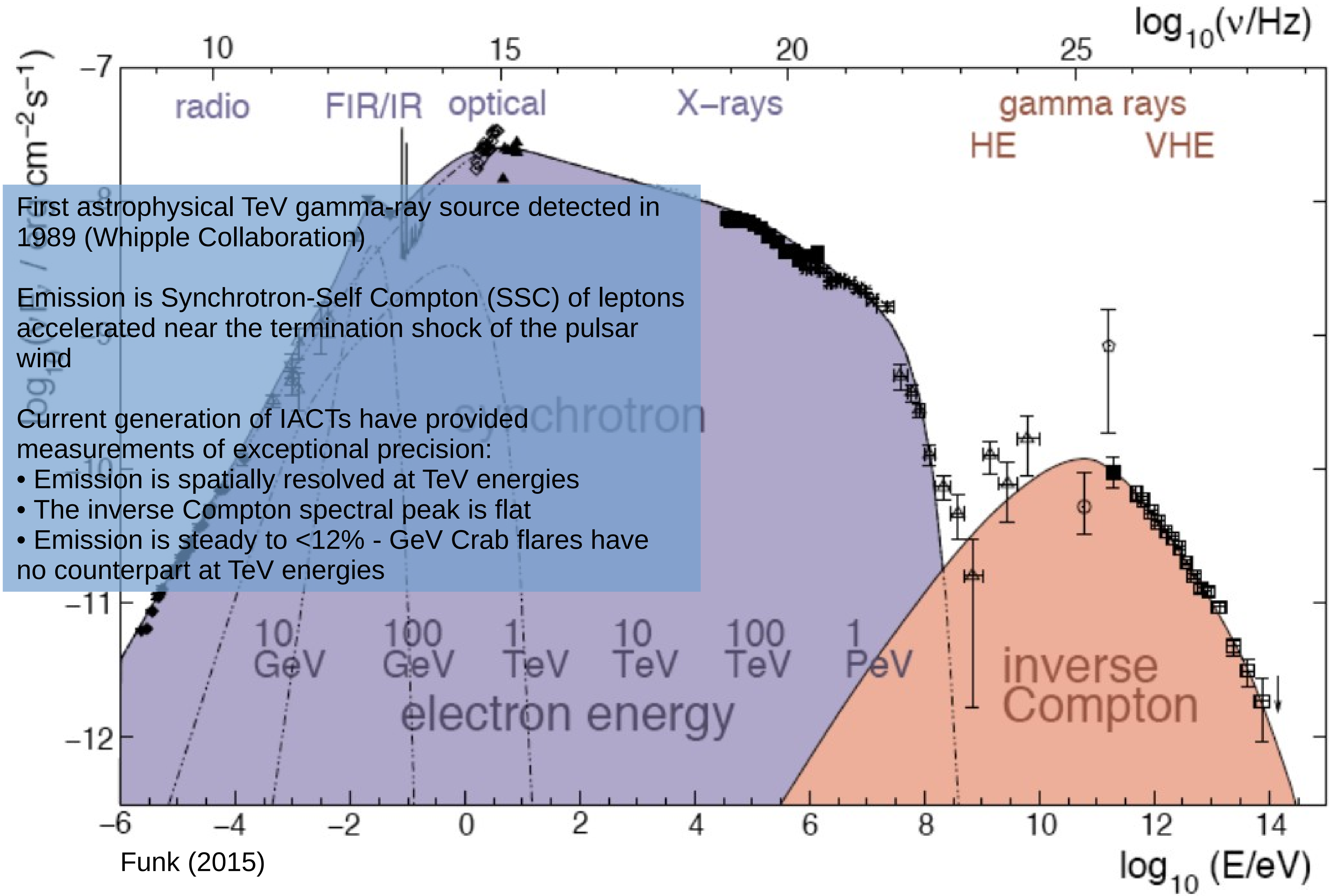


What type of emission are we seeing?



Funk (2015)

Crab Nebula: electron accelerator



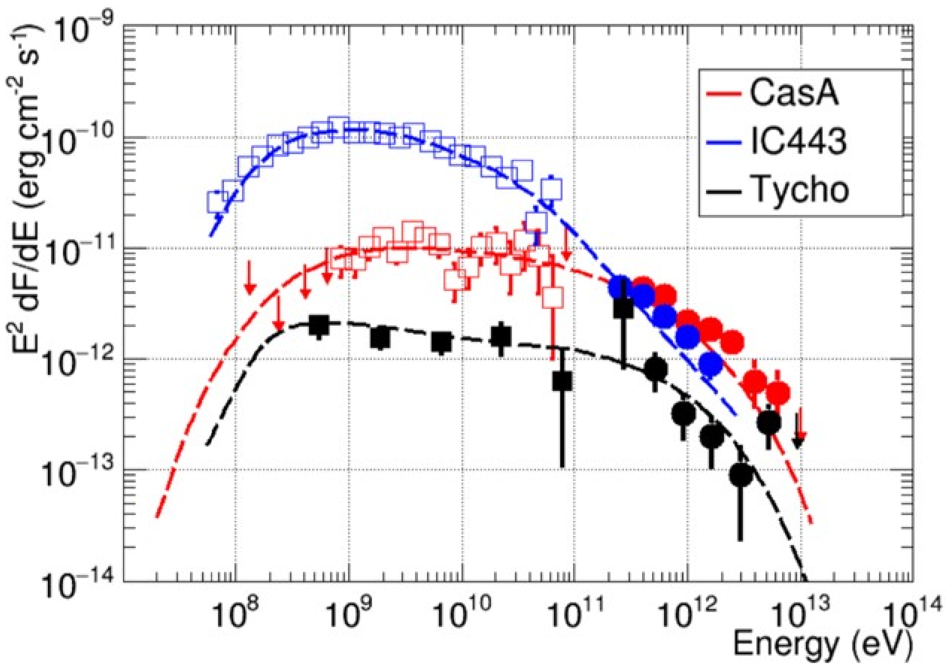
First astrophysical TeV gamma-ray source detected in 1989 (Whipple Collaboration)

Emission is Synchrotron-Self Compton (SSC) of leptons accelerated near the termination shock of the pulsar wind

Current generation of IACTs have provided measurements of exceptional precision:

- Emission is spatially resolved at TeV energies
- The inverse Compton spectral peak is flat
- Emission is steady to <12% - GeV Crab flares have no counterpart at TeV energies

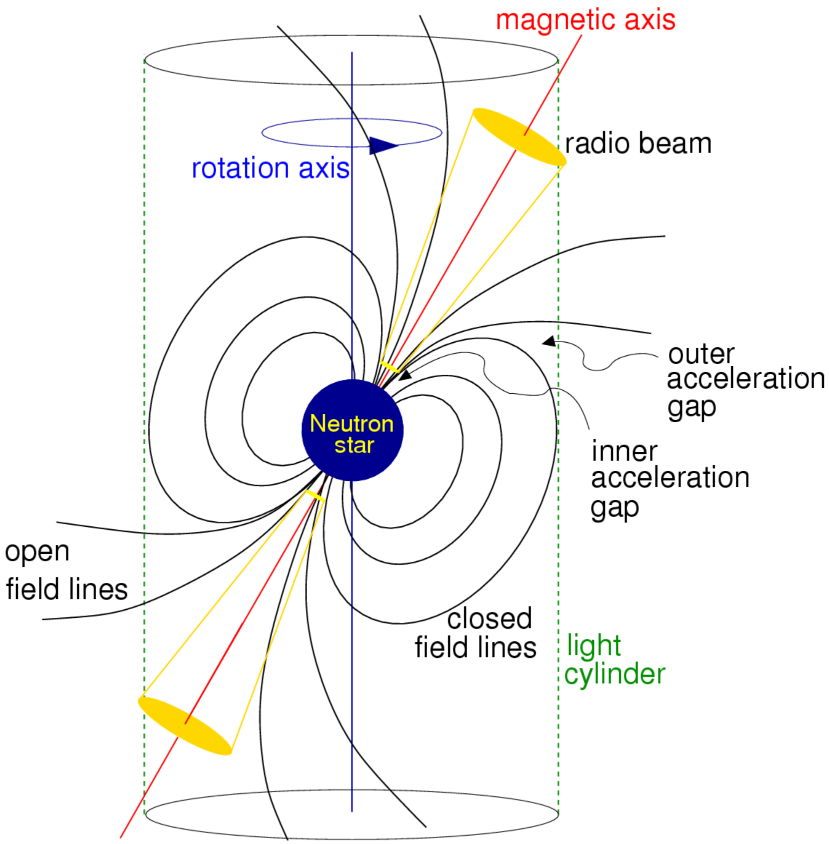
Funk (2015)



A univocal proof of the origin of CRs in SNRs would be the detection of γ-ray emission at extremely high energies, the so-called **PeVatron** (1 PeV=1.0e15 eV)

In SNR shocks with relatively low acceleration rates, synchrotron losses typically prevent the acceleration of electrons to energies beyond 100 TeV, and IC emission is suppressed because it occurs in the Klein-Nishina regime

Detecting gamma-rays up to 100 TeV would unambiguously establish a hadronic origin of the radiation



Pulsars - Rapidly rotating magnetized neutron stars born from the collapse of massive stars

Rotational period: 1 ms – 10s
Inferred magnetic field: 1.0e8 – 1.0e14 G
Mass: 1.4 Msun
Surface temperature: 1.0e6 K

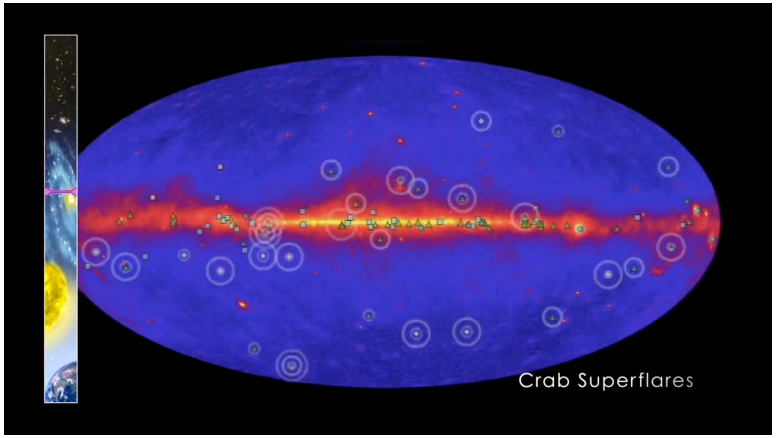
Unique laboratories for studying:

- nuclear matter equation of state
- relativistic electrodynamics
- intense gravitational fields
- particle acceleration
- interaction with their pulsar wind nebulae

They emit radiation in a beam that sweeps along our line of sight at every rotation

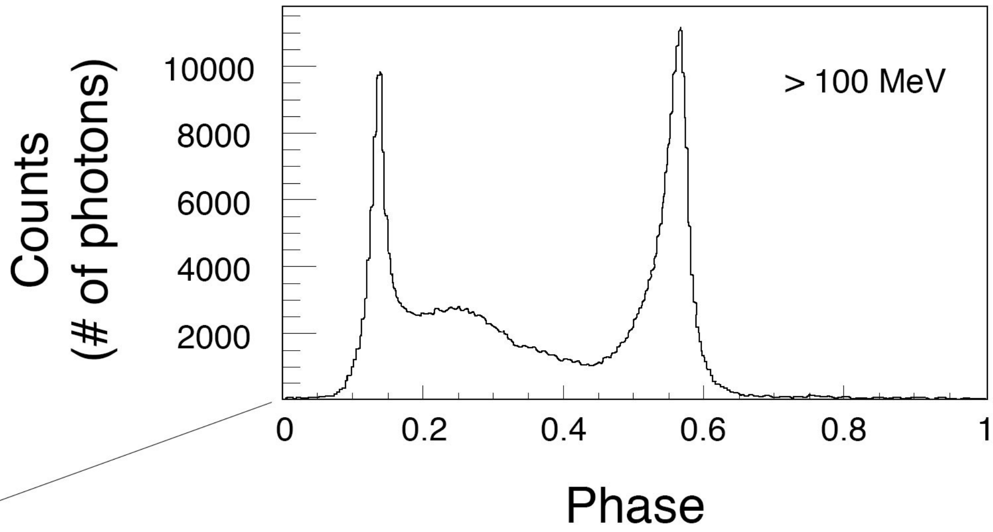
Gamma-ray pulsars

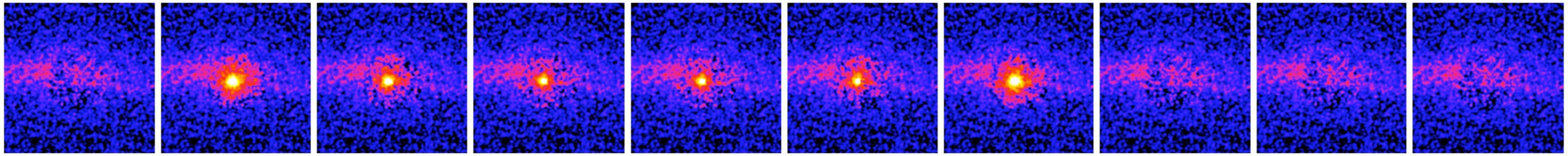
Most of the pulsar radiation (a few percent of their spin-down power) is emitted at high energies



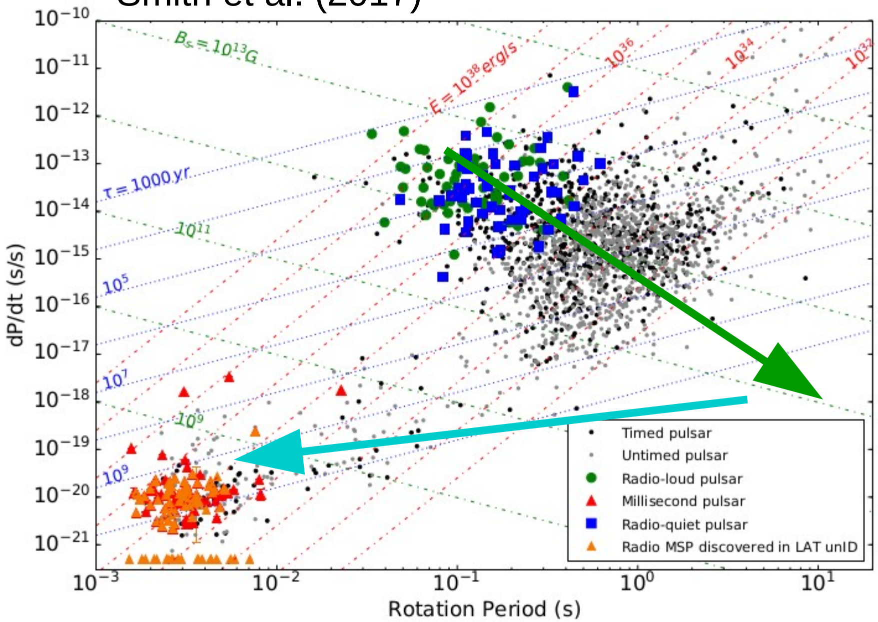
Number of gamma-ray pulsars identified with Fermi: > 215 (Smith et al. 2017)

A sizable fraction are millisecond pulsars in binary systems





Smith et al. (2017)



Radio ms pulsars are ~100 old pulsars with very short spin period and weak magnetic field, mostly in binaries

Why do they exist? Their magnetic field decayed and they should be rotating slowly (green line on the P-Pdot diagram)

Standard model --> They were '**recycled**' and spun up by deposition of angular momentum from accretion from a companion (cyan line)

Spectacular confirmation came from the discovery of **ms pulsars in accreting Low Mass X-ray Binaries** (Wijnands & van der Klis 1998)

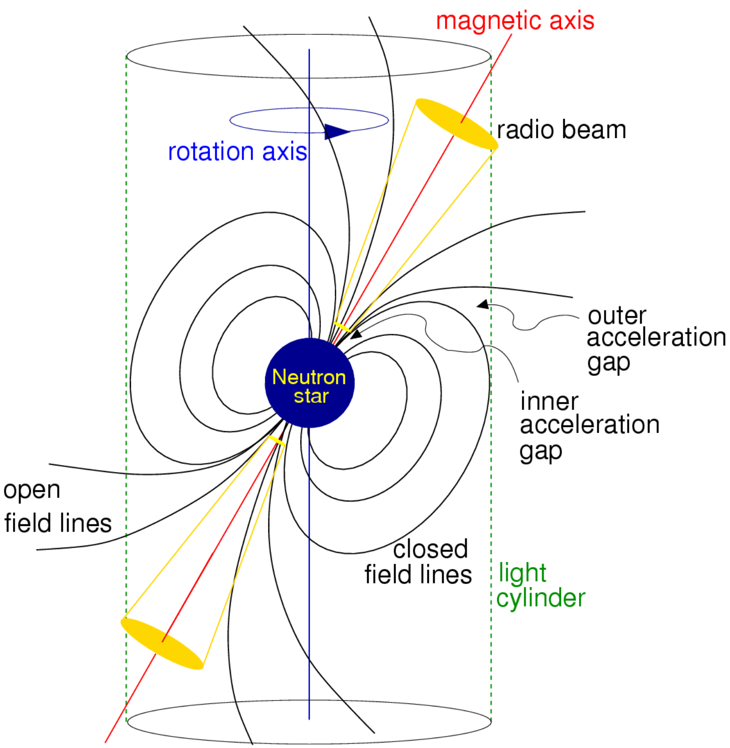
Only quite recently direct evidence that some of these systems can swing between a rotation-powered ms pulsar phase and an accretion phase was gathered (**transitional ms pulsars**; Papitto et al. 2013, Patruno et al. 2014, Stappers et al. 2014)

Origin of gamma-ray pulsed emission

Periodic gamma-ray radiation originates in regions of the magnetosphere, called **gaps**, where the electric field has a parallel component along the magnetic field lines

This electric field efficiently accelerates electrons and positrons to relativistic energies causing them to emit synchro-curvature radiation in the form of gamma-rays

Fermi-LAT light curves and spectra confirm this model and indicate that the gaps are located in the outer magnetosphere



Most spectra are best described by a power-law with an exponential cutoff of the form $E^{-\Gamma} \exp[-(E/E0)^b]$, with E0 = 1-10 GeV

Lack of a super-exponential cutoff (b > 1) beyond a few GeV effectively excludes the so-called polar cap, i.e. acceleration gaps close to the NS poles

Gamma-rays are severely suppressed by pair-production in the strong magnetic field close to the surface

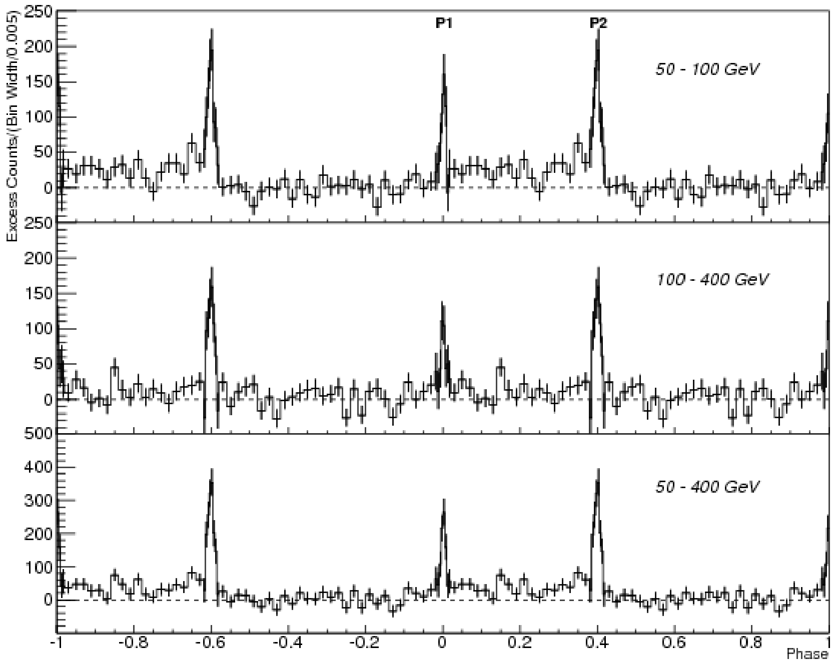
Models with exponential or sub-exponential cut-off (b<1) definitely favoured (slot gap and outer gap)

Only possibility after the detection of ~ 100 GeV pulsed emission from the Crab pulsar with MAGIC (Aliu et al. 2008)

The Crab pulsar in gamma-rays

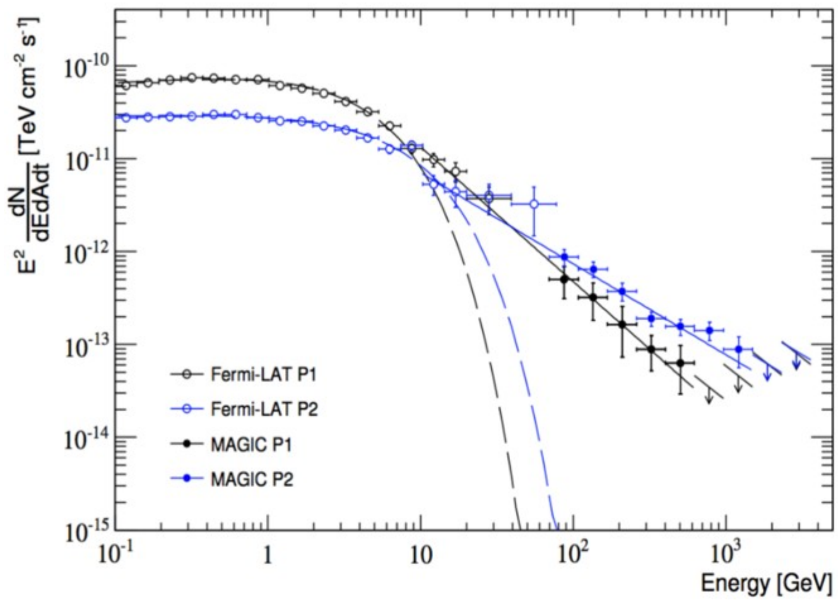
- Fermi-LAT measures a spectral break at 6 GeV
- Pulsed γ-ray emission above 100 GeV and up to 400 GeV was detected with VERITAS (Aliu et al. 2011) and MAGIC (Aleksic et al. 2012)
- Latest MAGIC results extend to 1 TeV (Ansoldi et al. 2016)
- H.E.S.S. has now detected the Vela pulsar up to 7 TeV (but no smooth connection from GeV to TeV). The Crab is not the only TeV pulsar

What is the pulsar emission mechanism at the highest energies? Absence of exponential cutoff makes curvature radiation unlikely. IC of magnetospheric emission from the pulsar wind (Aharonian et al. 2012)? What is the population(s)?



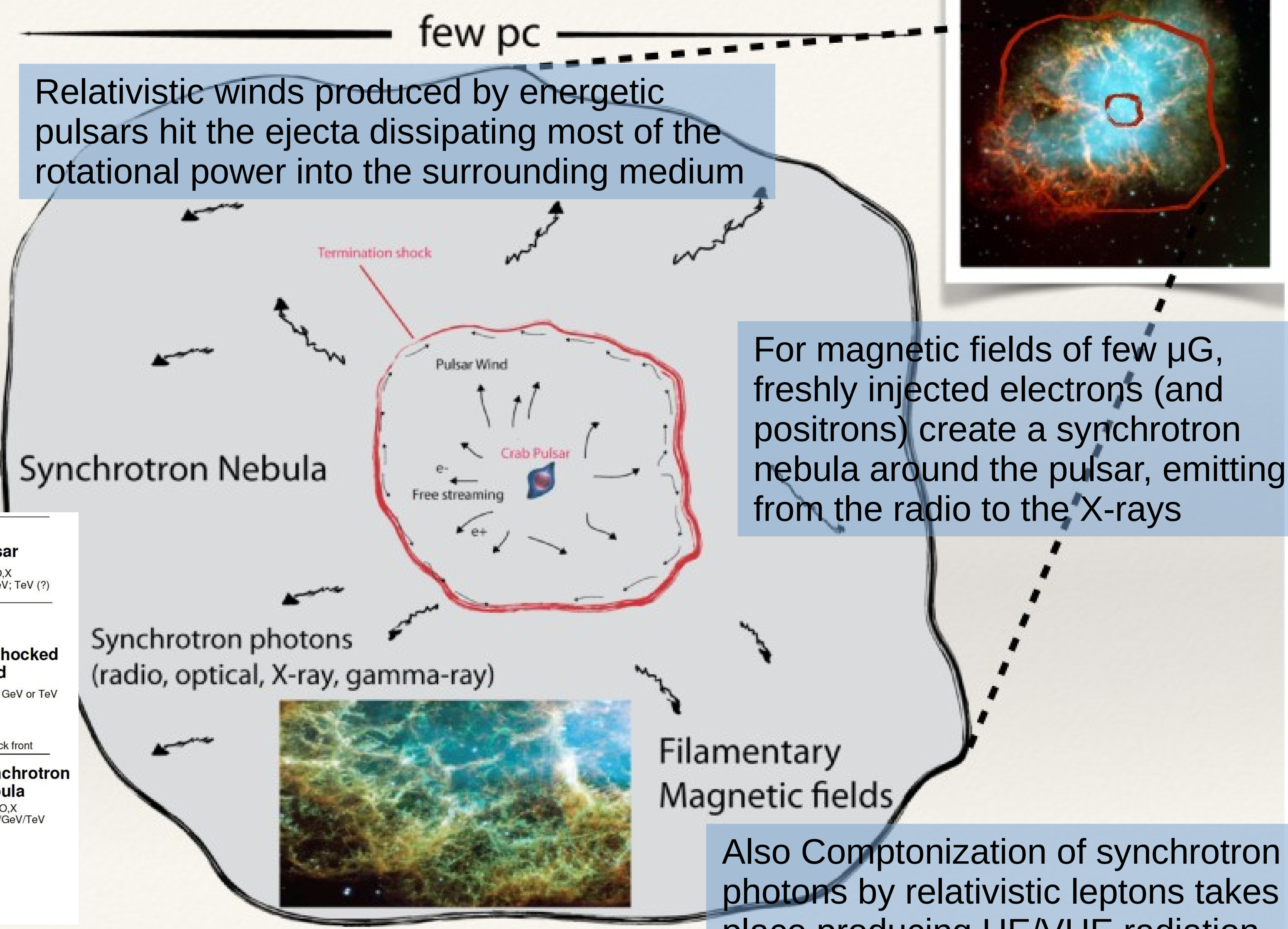
Aleksić et al (2012)

Ansoldi et al. (2016)



PWNe: ejecta energized by pulsars

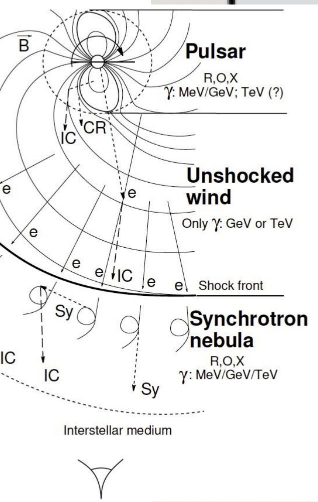
Funk (2015)



Relativistic winds produced by energetic pulsars hit the ejecta dissipating most of the rotational power into the surrounding medium

For magnetic fields of few μG, freshly injected electrons (and positrons) create a synchrotron nebula around the pulsar, emitting from the radio to the X-rays

Also Comptonization of synchrotron photons by relativistic leptons takes place producing HE/VHE radiation



Aharonian and Bogovalov (2003)

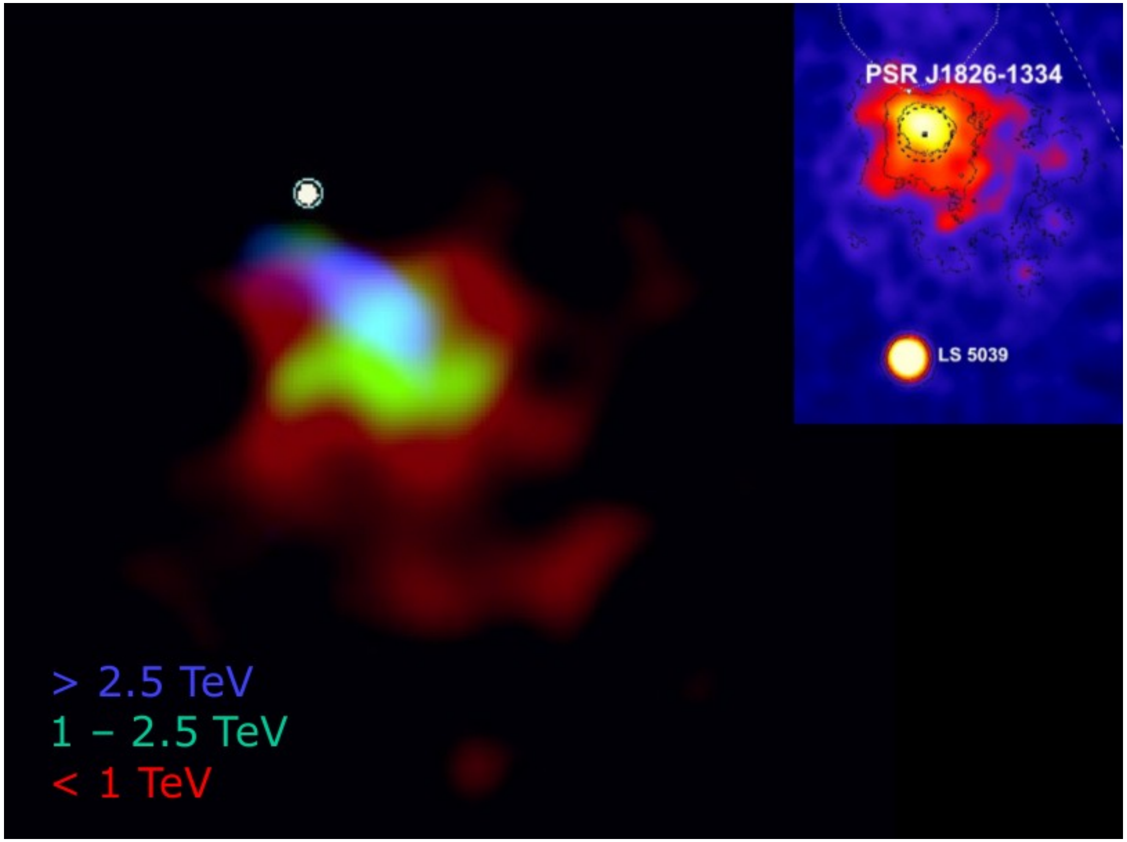
PWNe: Energy-dep. morphology

Identification of PWNe at TeV energies often thanks to (Rieger et al. 2013):

- radio/X-ray morphological correlations (e.g. Vela X)

- observations of an **energy-dependent morphology**, tracing the cooling mechanisms in the leptonic population (e.g. HESS J1825-137)

Softening of the spectral index measured in radial bins at increasing distance from the pulsar



- **Electrons suffer significant radiative losses as they propagate away**
- The inner high energy electrons radiate their energy through synchrotron emission faster: Psync = const E^2 B^2
- As they diffuse outwards, they stop emitting X-rays but their energy is still sufficient to emit via IC (also on CMB photons)

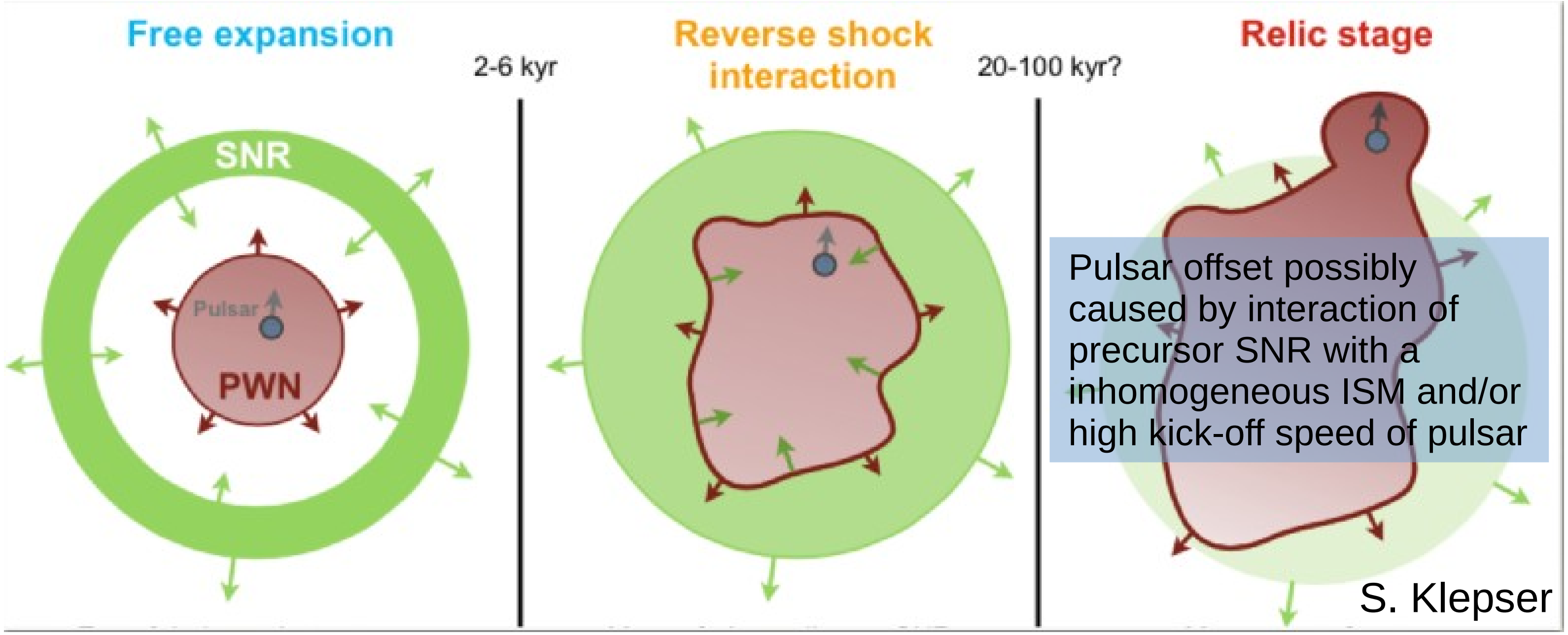
TeV more extended than X-ray emission region and energy dep. TeV morphology

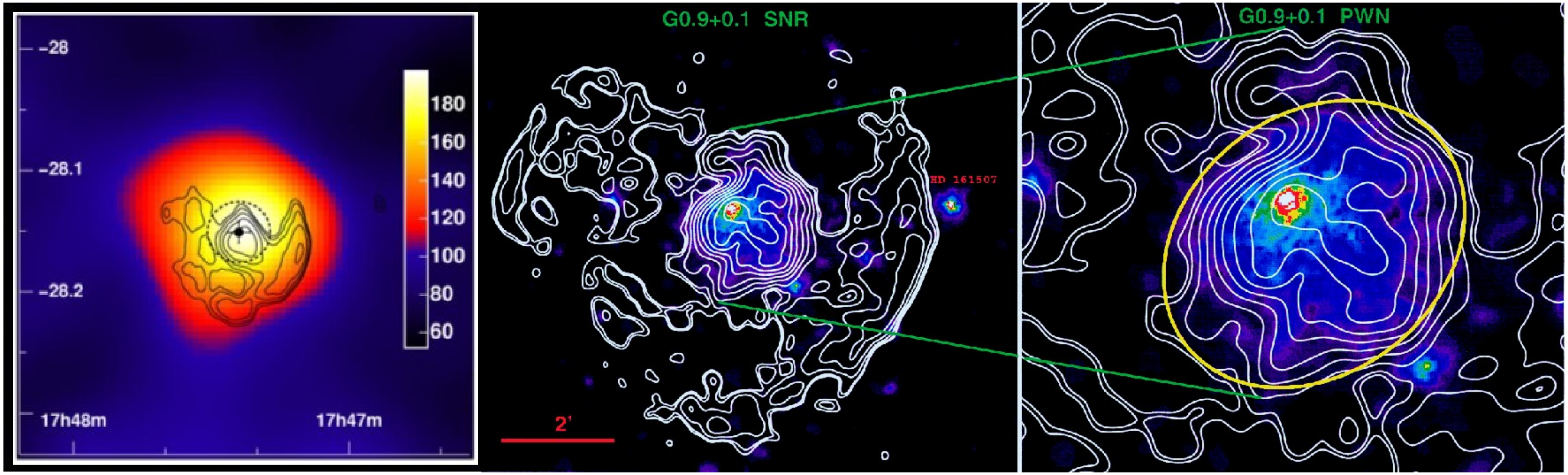
PWNe are the most effective Galactic sources of VHE gamma rays and constitute the largest Galactic TeV source population

The Galactic plane survey (GPS) performed with H.E.S.S. (Abdalla et al. 2018) started to reveal them

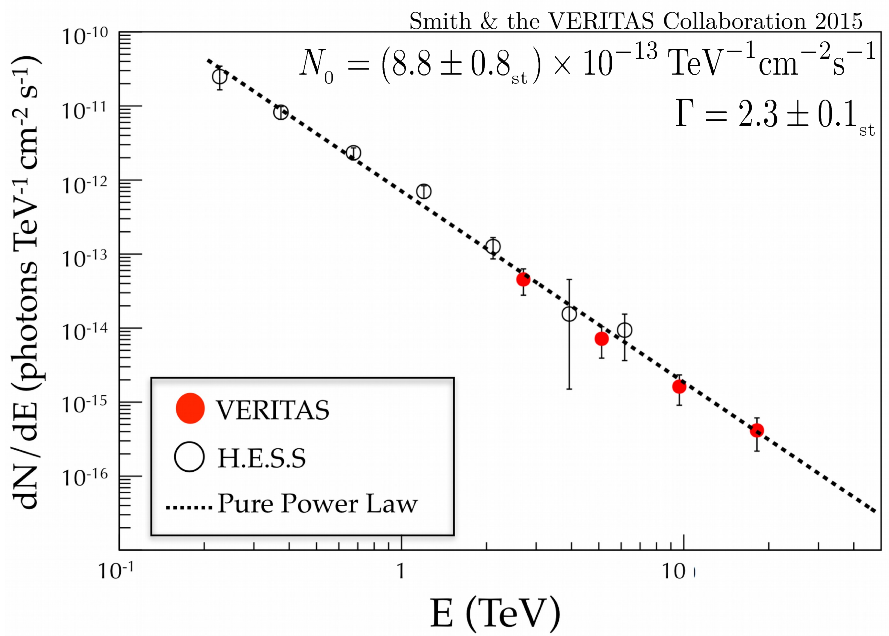
Two different groups:

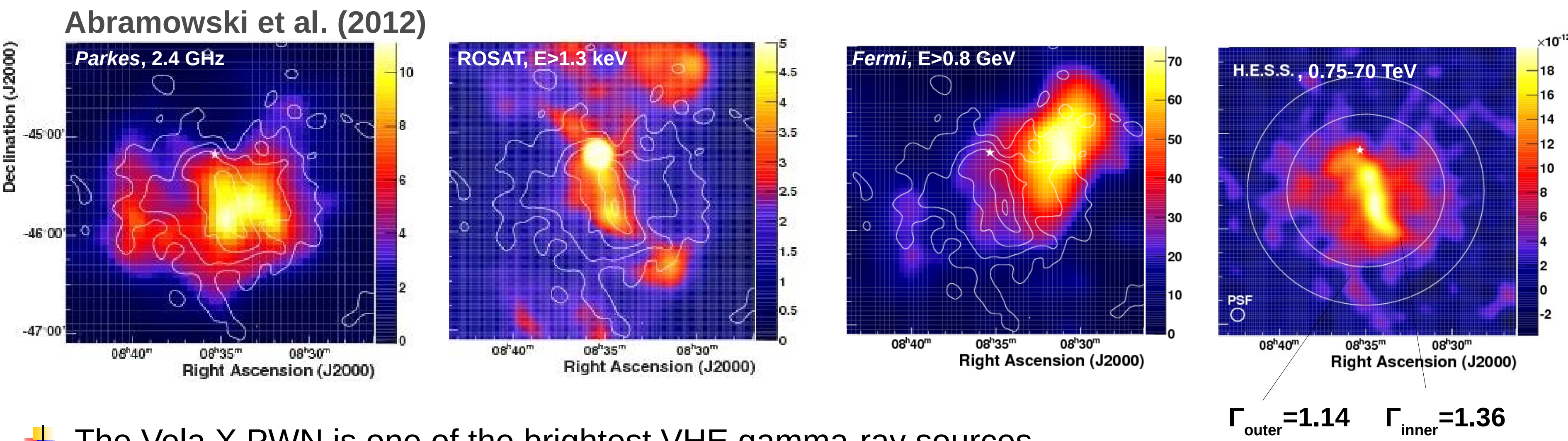
- Sources associated to young compact X-ray PWNe
- Evolved (extended and resolved) sources (the TeV emission seems to be due to a “relic” population of electrons)





- Composite SNR (~8'), bright core is the PWN (~2')
- Age < 5000 years
- Distance ~ 8,5 kpc
- Flux (>200 GeV) ~ 2% Crab flux
- Point-like source detected up to ~30 TeV



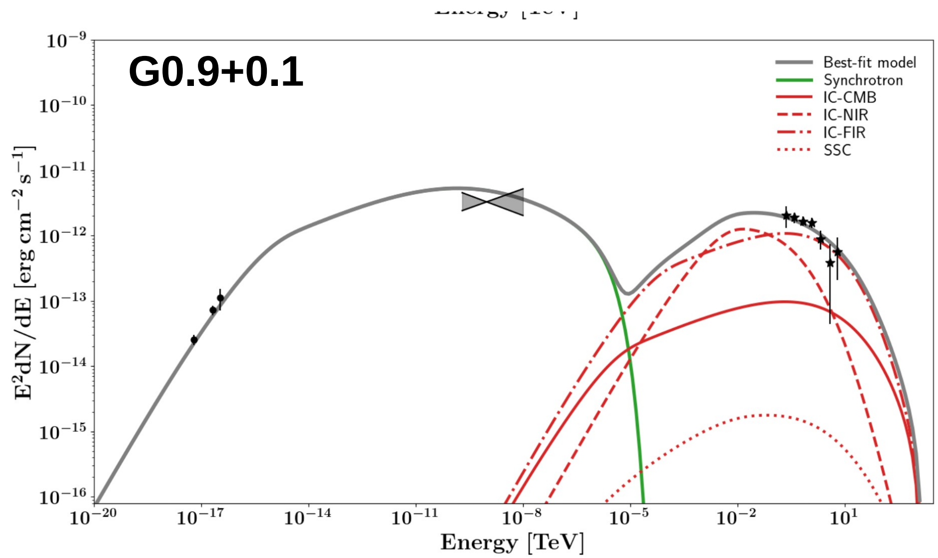


- The Vela X PWN is one of the brightest VHE gamma-ray sources
- It has a complex multi-component morphology:
  - Central cocoon (X-rays, TeV gamma-rays)
  - Extended “wings” (radio, GeV & TeV gamma-rays)
- A detailed spectral and morphological analysis of the VHE emission from the Vela PWN has been performed using H.E.S.S. data (Abramowski+2012):
  - Almost uniform γ-ray spectrum (inner and outer regions of the PWN described with PLEC models with different but consistent indexes within the errors)
  - Morphology modelled with the superposition of a radio (65% in flux) and X-ray (35% in flux) spatial map, assuming that VHE emission is produced by the same leptonic populations responsible for the X-ray cocoon emission and radio extended “wings”

Detailed calculation: Evolution of a young PWN in free expansion (1D) and calculation of its spectrum (Gelfand et al. 2009):

$$\frac{\partial N(E,t)}{\partial t} = Q(E,t) - \frac{\partial}{\partial E}[f(E,t)N(E,t)] - \frac{N(E,t)}{\tau_{esc}}$$

Advective equation in energy with a source term Q and an escape term N/tau, where tau is the escape time (the medium is finite)



Fiori et al. (2019)

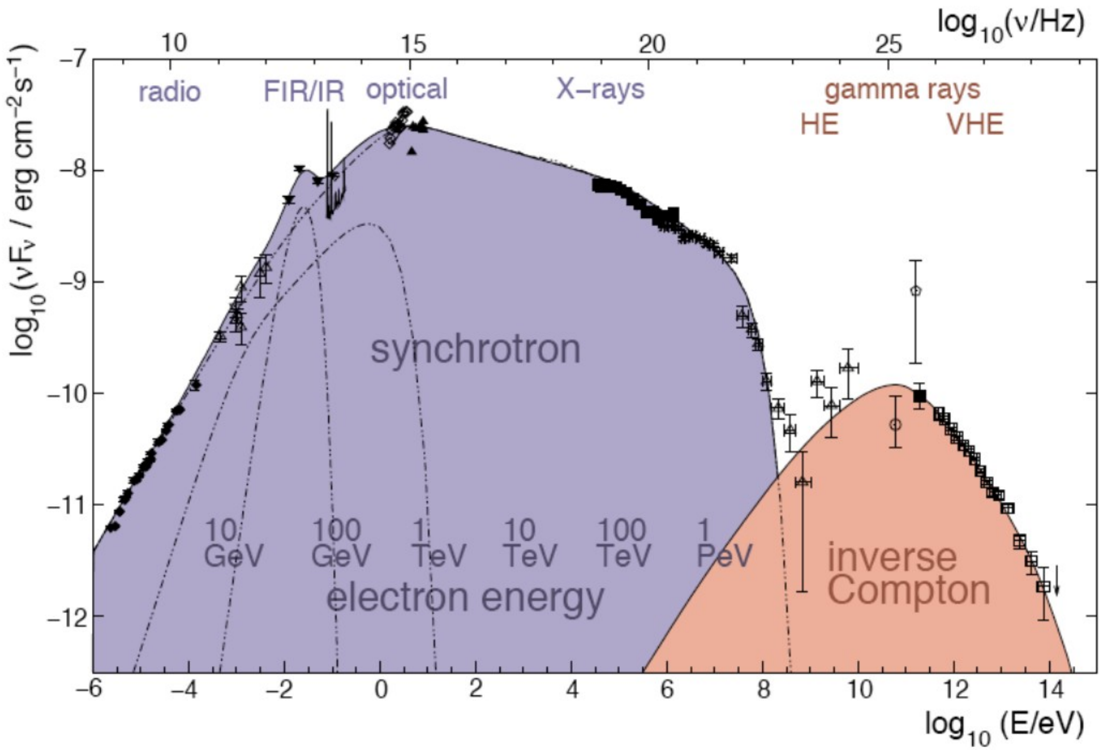
For IC on CMB: $L_{VHE}/L_X \sim 0.1\ (B/10\ \mu G)^{-2}$

In a PWN with a nebular magnetic field of about 10 μG or less, the IC gamma-ray production efficiency could be as large as 10%

- Age ~ 950 years
- Distance ~ 2 kpc
- Remnant of SN 1054

Fitting of the X-ray and TeV gamma-ray fluxes leads to a robust estimate of the average nebular magnetic field: <~ **100 μG**

- Inefficient in producing VHE gamma rays
- High spin-down power compensates



The Fermi-LAT data reveal a sharp transition from the synchrotron to the IC component at around 1 GeV

Measurements have almost approached 100 TeV. The IC component should extend to the maximum energy of the accelerated electrons, i.e., 1 PeV

Supernova Remnants at TeV energies

Supernova Remnants (SNRs) are relics (ejected envelope) of the explosion of massive (> 8 Msun) stars

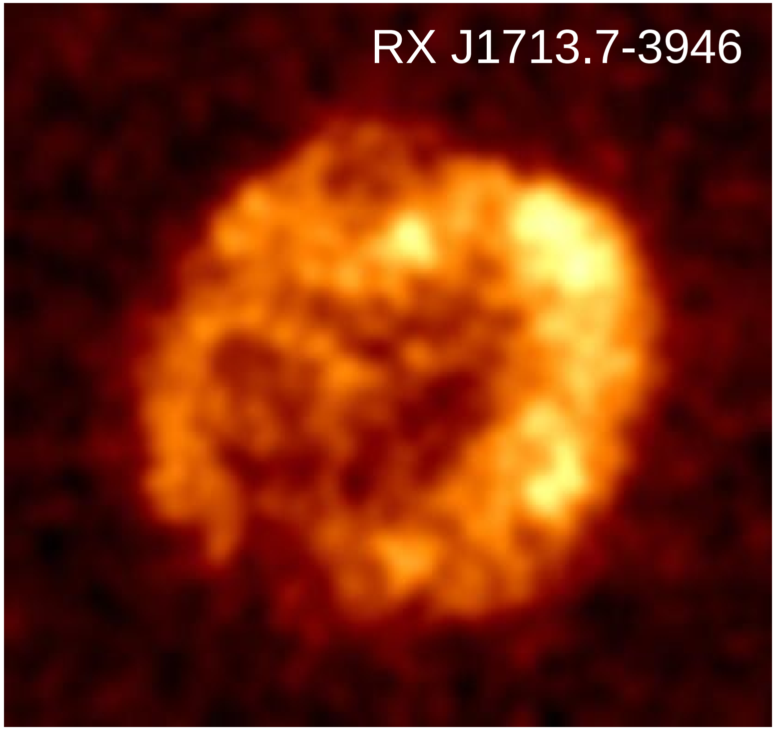
After core collapse and supernova (SN) explosion, the ejecta hit the surrounding medium and produce a shock wave that heats up and accelerates electrons and protons

Emission from the SNR consists of **thermal emission from the post shock-heated gas** and **non-thermal emission from shock-accelerated particles**

Acceleration occurs at shock fronts through **diffusive shock acceleration** (**DSA**; O'C Drury 1983, Blandford and Eichler 1983, Bell 2012)

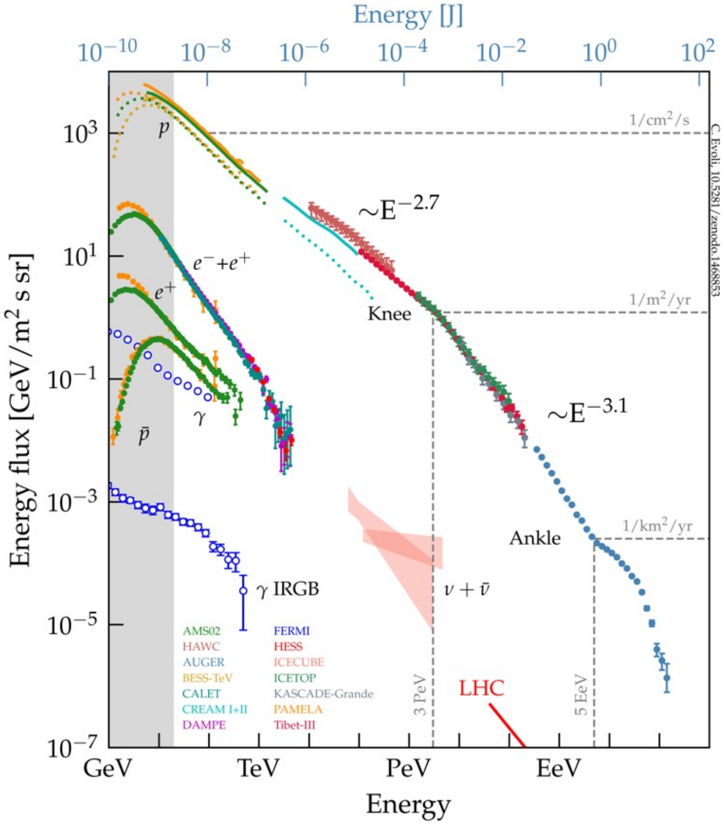
Accelerated particles reach relativistic energies and interact with ambient magnetic fields, with ambient photon fields, or with matter, **producing gamma-rays**

The production rate of relativistic particles reaches a maximum, **1.0e3-1.0e4 years after the supernova explosion**



SNRs and Cosmic Rays

https://zenodo.org/record/2360277#.XRJRNJ9fiCI



SNRs are promising candidates to supply the majority of Galactic Cosmic Rays (CRs)

CRs are highly energetic protons, nuclei and electrons which are measured from 1.0e9 eV up to 1.0e21 eV with an almost featureless continuous spectrum

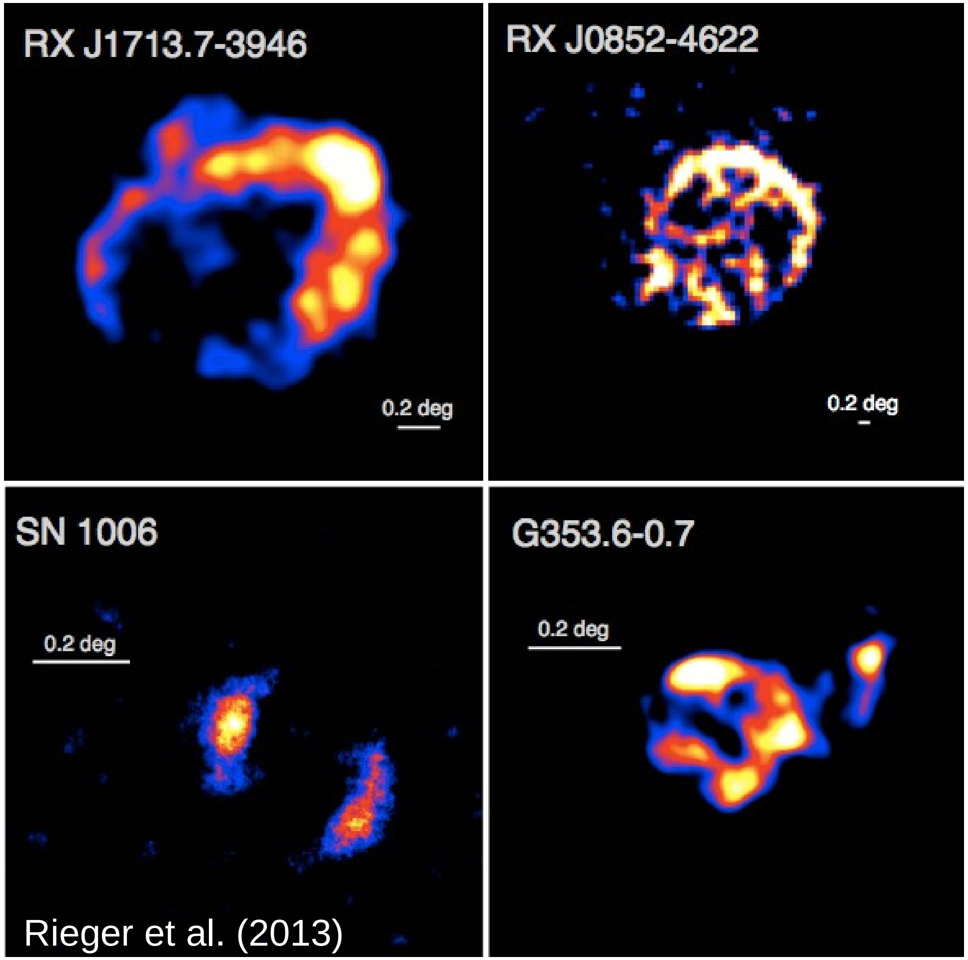
> The most prominent deviation from a pure power-law (with index of about −2.7) happens in the ”**knee**”, where the index changes to ∼ −3.1 at about 4 PeV (Kulikov and Kristiansen 1958), and the ”**ankle**”, a second steepening at about 5.0e17 eV

It is widely believed that CRs below the knee are accelerated inside our Galaxy and SNRs are thought to be the main contributor

CR energy production rate: W ≈ **(0.3 − 1)×1.0e41 erg/s**

- Easily explained if one assumes that **10% of the kinetic energy released in supernova explosions** (2.0e39 erg/s/kpc2) is used for accelerating CRs (e.g. Ginzburg and Syrovatskii 1964, Gaisser 1990, Berezinskii et al. 1990)
- Moreover, highly efficient conversion of kinetic energy of bulk motion to relativistic particles can be achieved through **DSA in the shocks created in SNRs**

Shell-type SNRs in the TeV domain

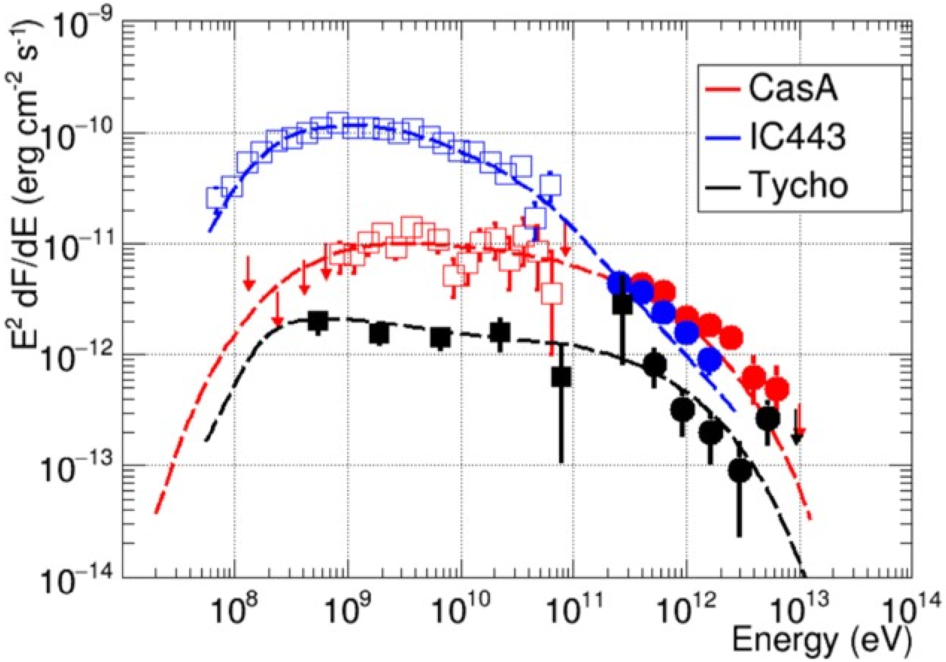


- A population of SNRs with shell-type TeV morphology is detected (e.g. Cas A, Tycho, SN 1006), which now includes a TeV-only detection (HESS J1912+101) (Holder 2019)
- Detected up to ∼3.5 kpc, with a typical size of **0.2-1 deg**
- γ-ray luminosities **(0.1−1)×1.0e33 erg/s**
- Future instrument like CTA should be able to detect SNRs up to 15 kpc, thus sampling the whole Galaxy (∼100 new SNRs could be discovered; Acero et al. 2012)

Good correlation of the TeV emission sites with the non-thermal emission detected in the X-rays

Shell-type SNRs in the TeV domain

What is the relative contributions of accelerated protons and electrons to the gamma-ray emission?



The ratio of gamma-rays produced by accelerated protons interacting with the surrounding gas, and by ultra-relativistic electrons up-scattering the 2.7K CMB radiation, is very sensitive to generally unknown parameters, in particular to the gas density and the magnetic field of the ambient medium (e.g. Yuan et al. 2012)

Discrimination between leptonic and hadronic particle populations is often difficult

Ratio of electron IC to proton π0-decay gamma-rays production rates at 1 TeV:

1.0e3 (We/Wp)(n/1 cm^{-3})$^{-1}$

where We and Wp are the total energies in 20 TeV electrons and protons

Even for a very small electron-to-proton ratio (at the stage of acceleration), e/p = 1.0e−3, **the contribution of the electron-IC component will dominate in the TeV domain**

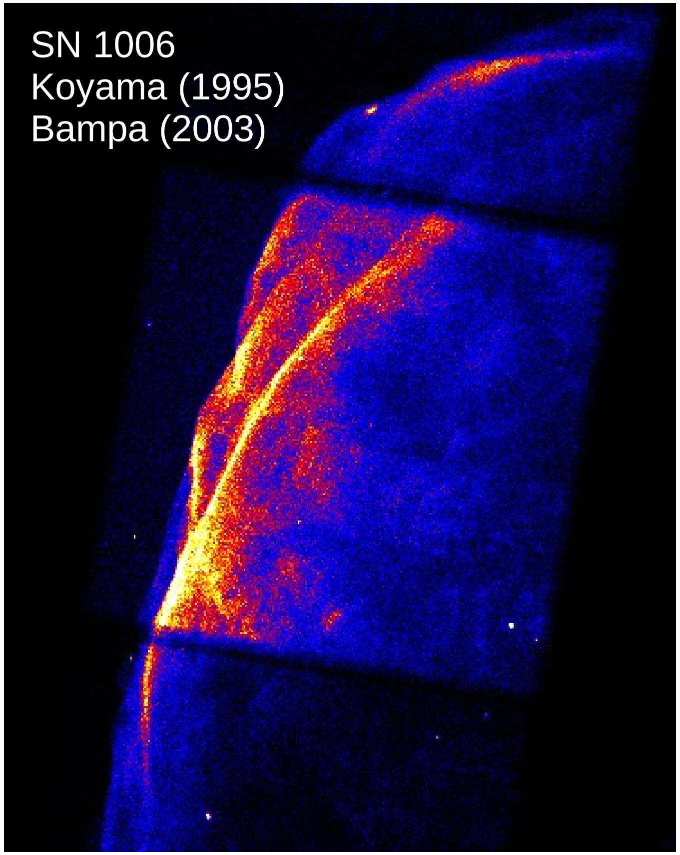
Could be different if proton-to-electron acceleration ratio exceeds ∼ 1.0e3, not excluded given the uncertainty associated to the injection problem in DSA (Malkov and O'C Drury 2001)

Ratio of electrons cooled via IC on CMB photons to those cooled via synchrotron radiation: $W_{CMB}/W_B \approx 0.1(B/10\mu G)^{-2}$

If the magnetic field in the shell significantly exceeds 10μG, then the accelerated electrons are cooled predominantly via synchrotron radiation (X-rays) and the π0-decay hadronic component will dominate in the TeV domain

Shell-type SNRs in the TeV domain

Only a small number of SNRs are detected at VHE - If TeV emission is observed, how can we identify the accelerated particles?



1) High B field in the filaments

Acceleration sites for both electrons and protons are expected to be located at the shock, in small filaments where the B field is amplified

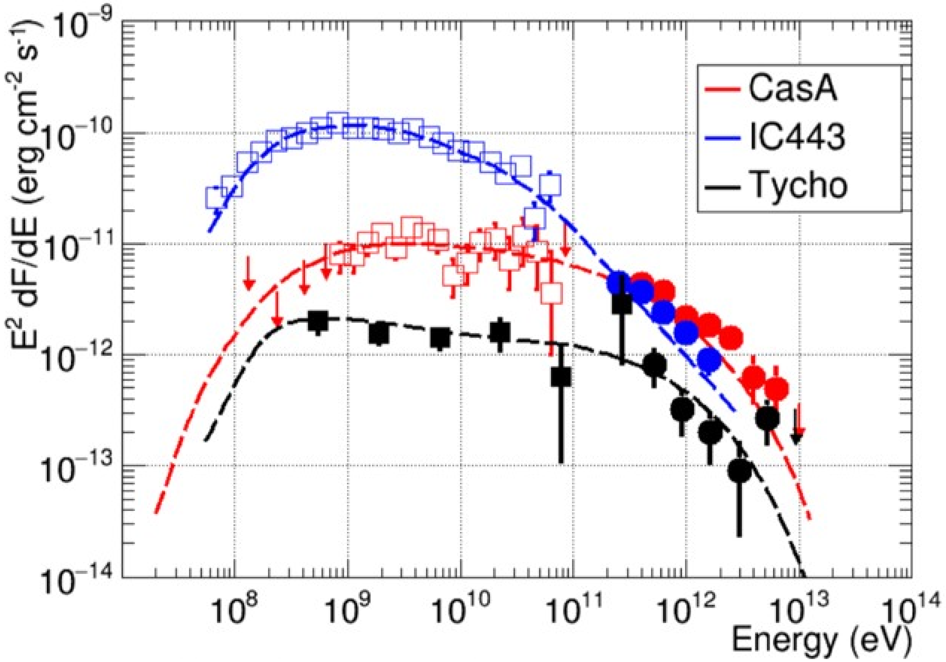
Accelerated electrons trace the filaments emitting significant non-thermal synchrotron X-ray radiation

In some cases (e.g. RX J1713.7-3946, Tycho, Cas A) magnetic fields estimated from multi-wavelength observations are **>0.1 mG** (Vink and Laming 2003, Uchiyama et al 2007)

This restricts the contribution of the IC component and **favours an hadronic origin of the TeV emission**

If IC and synchrotron components originate in different zones, these constraints are less robust, and more complex models implying multi-zone emission regions are needed

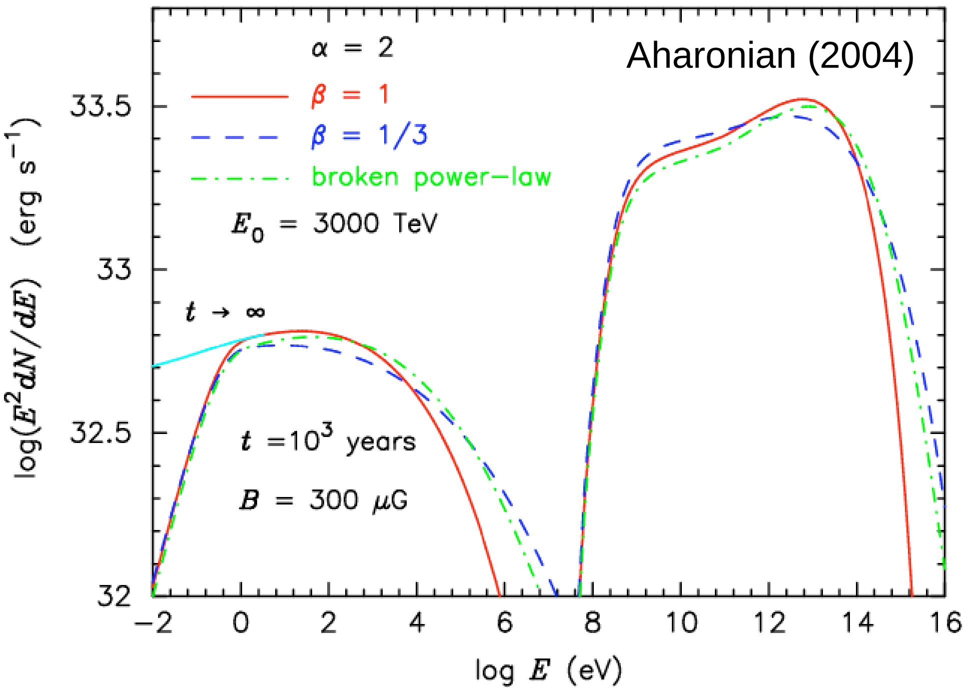
Future improvement of the angular resolution to a few arcmin should permit a detailed study of the TeV radial profile in comparison with the X-ray radiation profile



2) Hard TeV spectra

A **hard spectral index of ~2.0** (e.g. Tycho, Cas A) from the MeV-GeV range to ~1 TeV is consistent with a hadronic scenario (as predicted by the DSA theory; Atoyan et al. 2000, Volk et al. 2008, Atoyan and Dermer 2012)

Together with the high magnetic field amplification derived from synchrotron X-ray filaments, this **favours an hadronic scenario** in these SNRs



2) Hard TeV spectra

A univocal proof of the origin of CRs in SNRs would be the detection of γ-ray emission at extremely high energies, the so-called **PeVatron** (1 PeV=1.0e15 eV)

In SNR shocks with relatively low acceleration rates, synchrotron losses typically prevent the acceleration of electrons to energies beyond 100 TeV, and IC emission is suppressed because it occurs in the Klein-Nishina regime

A contribution of IC gamma-rays to the radiation above 10 TeV is expected to gradually fade out

Detecting gamma-rays up to 100 TeV would unambiguously establish a hadronic origin of the radiation

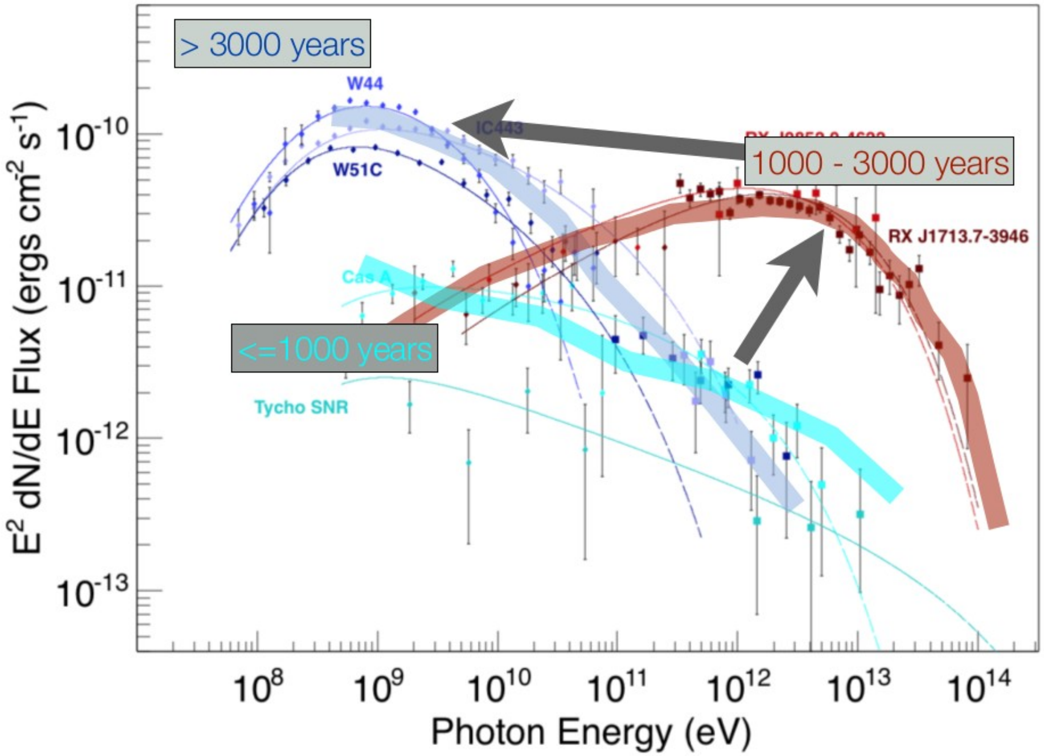
Shell-type SNRs in the TeV domain

3) Protons diffuse away and interact with nearby high-density environments (molecular clouds)

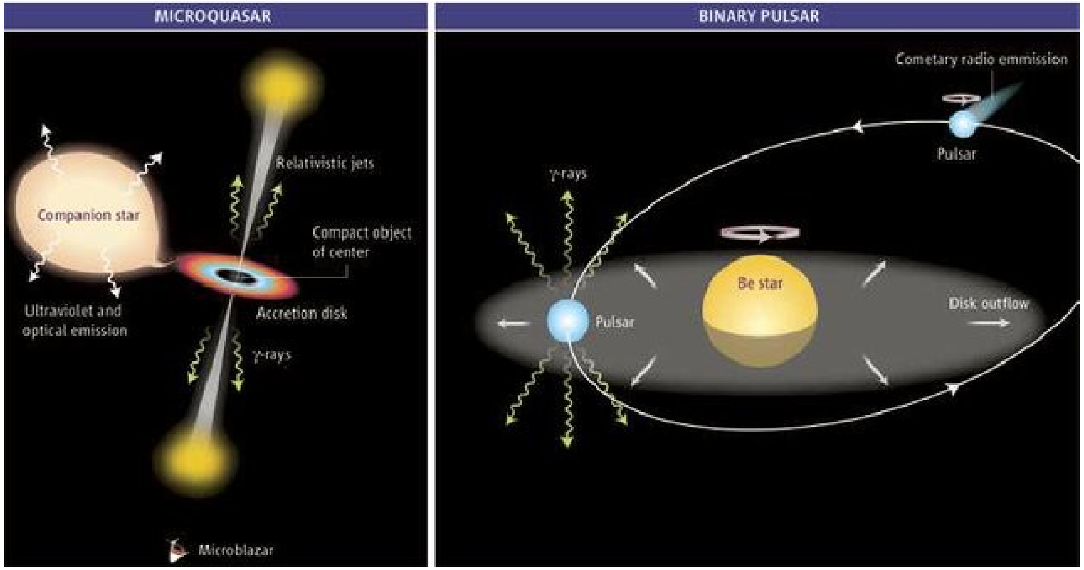
An example is SNR W28 (Aharonian et al. 2008), where a clear **correlation between the TeV emission and massive molecular clouds emitting in CO** has been observed

Another example of this type of scenario is IC 443 (Albert et al. 2007, Acciari et al. 2009, Tavani et al. 2010, Abdo et al. 2010), where the GeV and TeV emission appear shifted from each other

SNRs may only be able to accelerate CRs to PeV energies in the first ~ 1000 yr, while later the high-energy hadrons escape from the system



TeV binary systems



Mirabel (2006)

TeV emission arises from the interactions between a massive star and a compact object, a stellar black or a ms pulsar (e.g. Bednarek 2006, Dubus 2006, Khangulyan et al. 2008, Sierpowska-Bartosik and Torres 2008):

- in an accretion-powered jet (**microquasar scenario**)
- in the shock between a pulsar wind and a stellar wind (**wind-wind scenario**)

Variability implies a compact emission region which translates into a *VHE point-like source morphology* at a distance of 1 to 5 kpc

Maximum flux of ∼5−15% of the Crab Nebula flux and similar spectral indices (2.0 to 2.7)

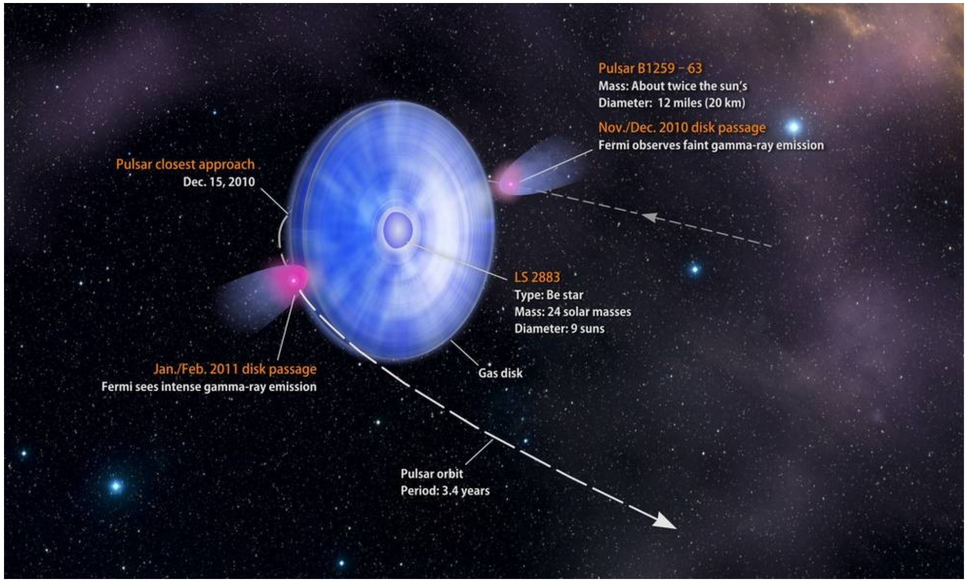
Four sources identified, plus other less certain sources (e.g. HESS J1018-589, Abramowski et al. 2012; Cyg X-1, Albert et al. 2007)

PSR B1259-63 (or LS 2833)

Consisting of **a 48 ms pulsar orbiting a massive Be star** and crossing its disk every 3.4 years, on a highly eccentric orbit

VHE emission occurs at the termination shock produced by the interaction of a **pulsar-wind with a stellar-wind**

Electrons are accelerated at the shock, producing HE and VHE gamma-rays by IC up-scattering of stellar UV photons (Dubus 2006, Dubus et al. 2010)



Credits: NASA's Goddard Space Flight Center/Francis Reddy

- Wind-wind interaction can result in the formation of an **extended cometary-shaped radio structure** rotating with the orbital period (Dubus 2006)

  Evidence for variable and **extended (AU-scale) radio emission has been found** (Moldon et al. 2011)

- The source exhibited a post-periastron **orphan flare at GeV energy** not observed in the TeV range (Abdo et al. 2011, Tam et al. 2011, Abramowski et al. 2013)

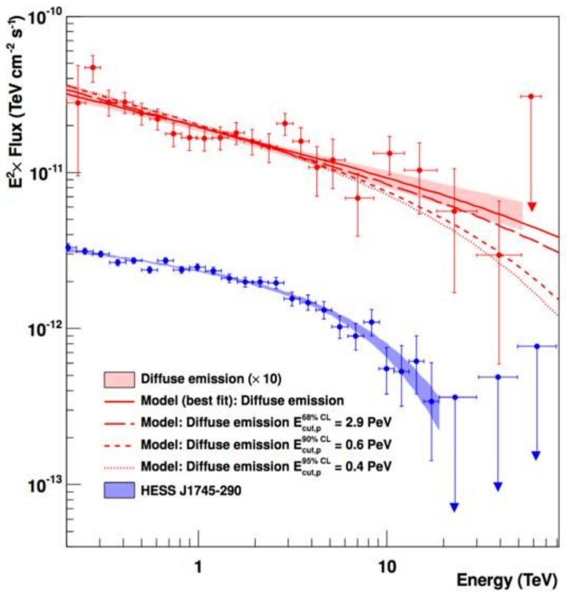
  Suggests that the **GeV and the TeV emission are produced by different mechanisms** (Abramowski et al. 2013)

The Galactic Center (GC) region

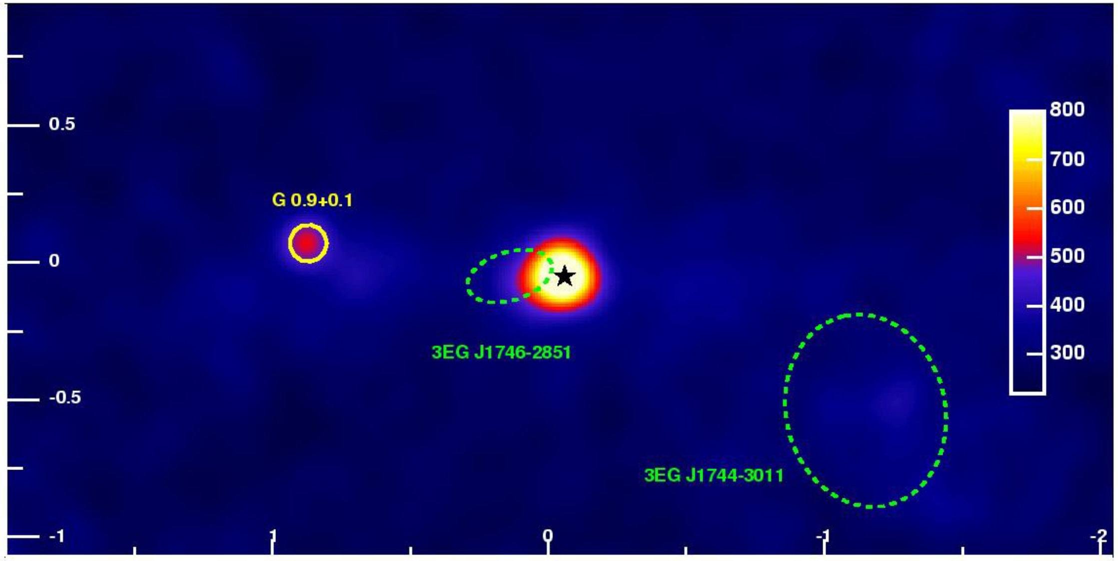
The GC harbours many remarkable objects

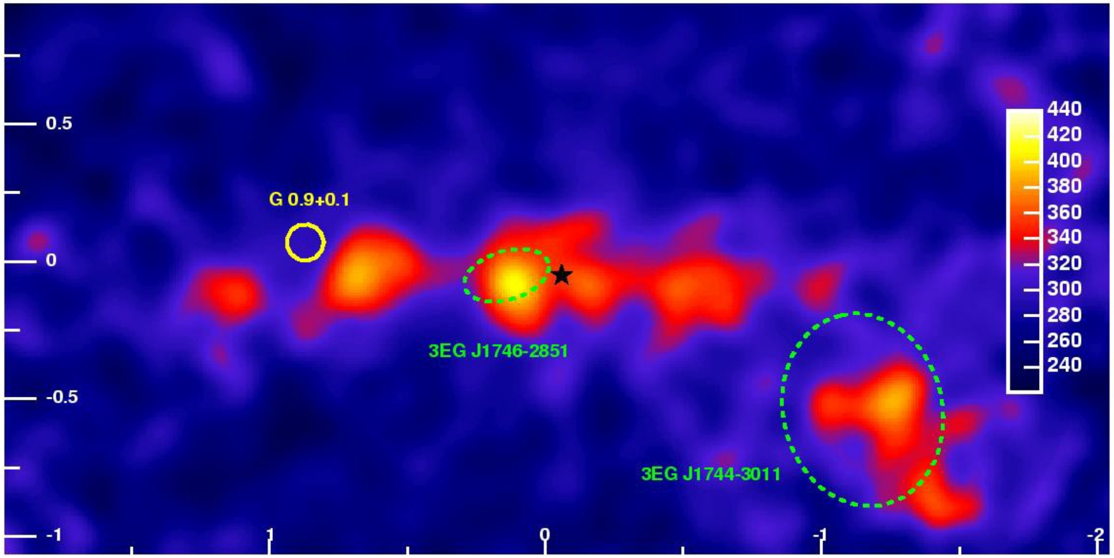
Bright, steady TeV source, spatially coincident with SgrA* with a broad-band spectrum that spans from 100 MeV to 30 TeV

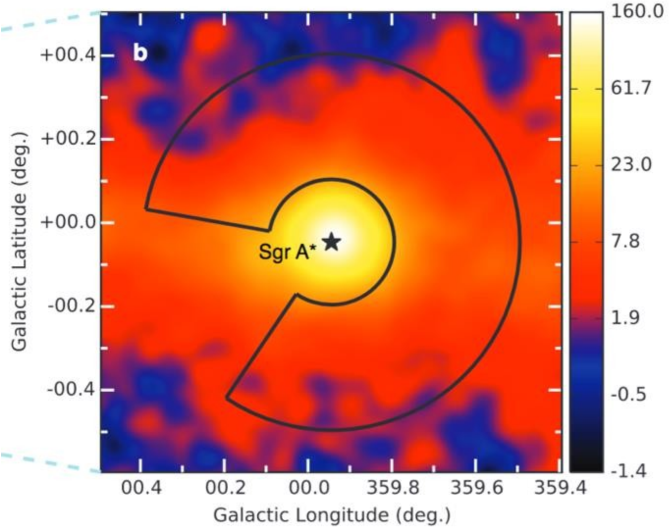
Diffuse emission along the plane, within a few degrees of the GC, with a spectrum extending to 40 TeV with no cutoff



Abramowski et al. (2016)







Abramowski et al. (2016)
H.E.S.S. Collaboration

Sgr A* is the potential source indirectly responsible for the gamma-ray signal through interactions of accelerated runaway particles later injected into the surrounding dense gas environment (Aharonian and Neronov 2005, Linden et al. 2012)

The GeV-TeV spectrum can be naturally explained by propagation effects of protons interacting with the dense gas within the central 10 pc region

The required total energy of protons currently trapped in the gamma-ray production region, Wp = Lγ tpp = 1.0e49 (n/1.0e-3 $cm^3)^{-1}$ erg is quite modest, given that the density in the circumnuclear ring could be as large as 1.0e5 cm^{-3}

This indicates **presence of PeV particles –- but not sufficient to explain Galactic CR flux**

Pulsars and their nebulae

- ❖ Pulsar geometry and particle population
- ❖ Temporal Evolution

SNRs

- ❖ Origin of cosmic rays up to the knee
- ❖ Leptonic versus hadronic component

Understanding particle acceleration, escape, and diffusion