North-West University
South Africa

Astronomical Observatory
Ivan Franko University of Lviv
Ukraine

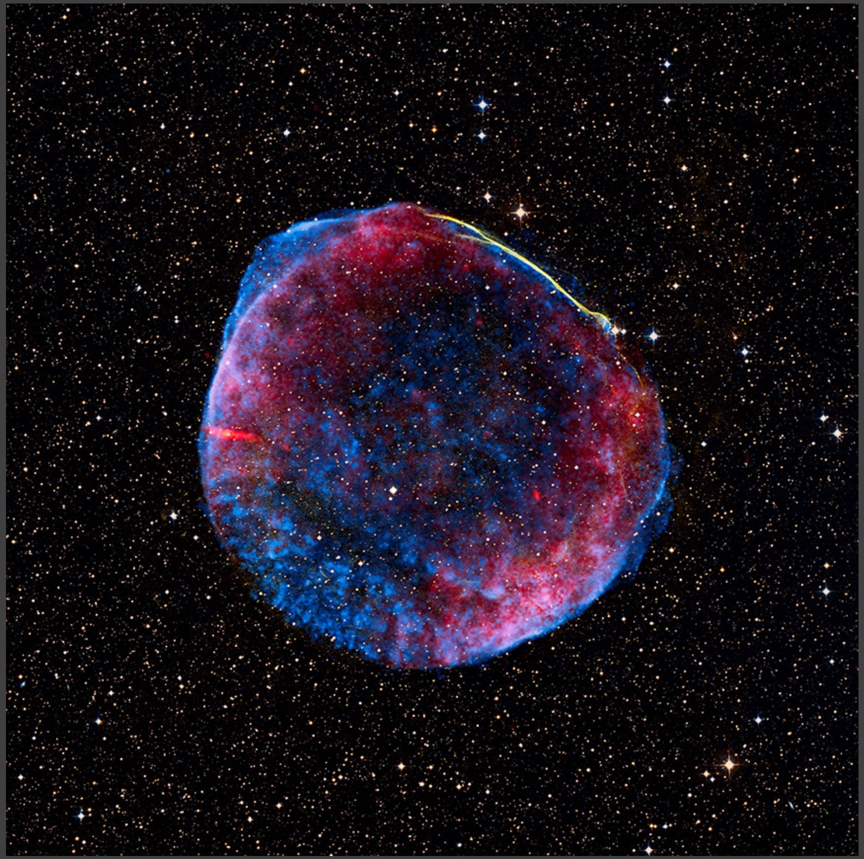
X-ray – gamma-ray synergies
Galactic sources

IURII SUSHCH

NWU (SOUTH AFRICA)/LVIV UNIVERSITY (UKRAINE)

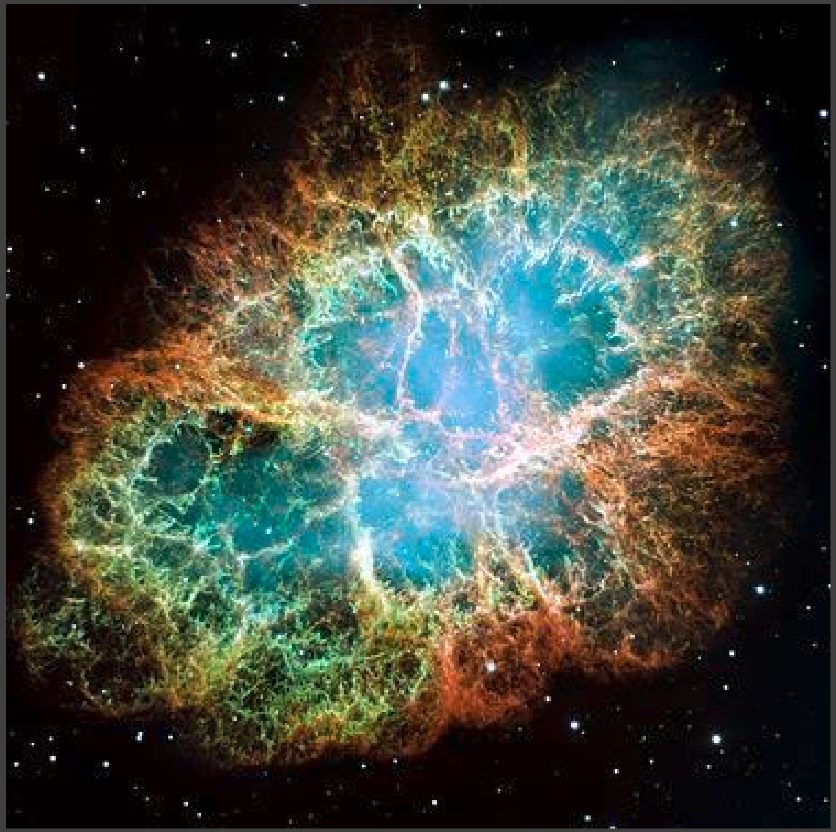
Sources that I will focus on...

- Supernova remnants



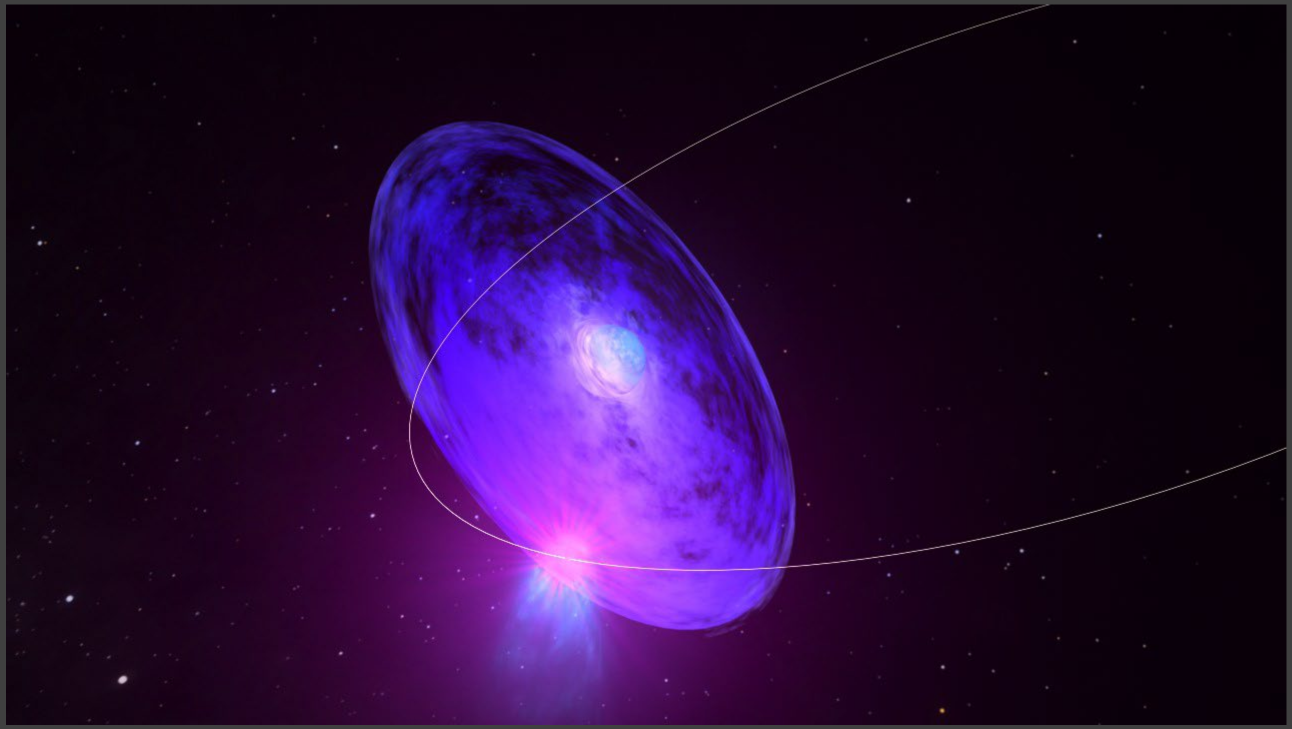
Sources that I will focus on...

- Supernova remnants
- Pulsar wind nebulae
- Gamma-ray binaries



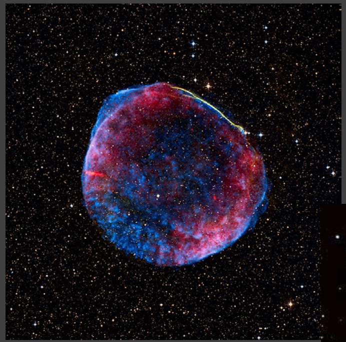
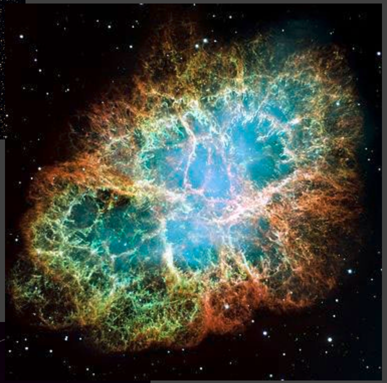
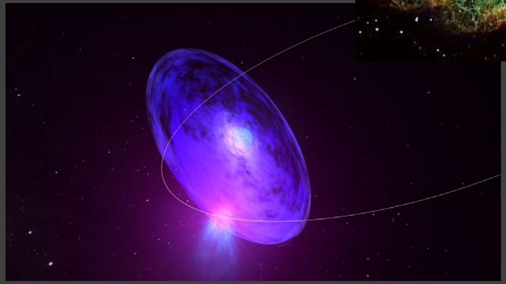
Sources that I will focus on...

- Supernova remnants
- Pulsar wind nebulae
- Gamma-ray binaries



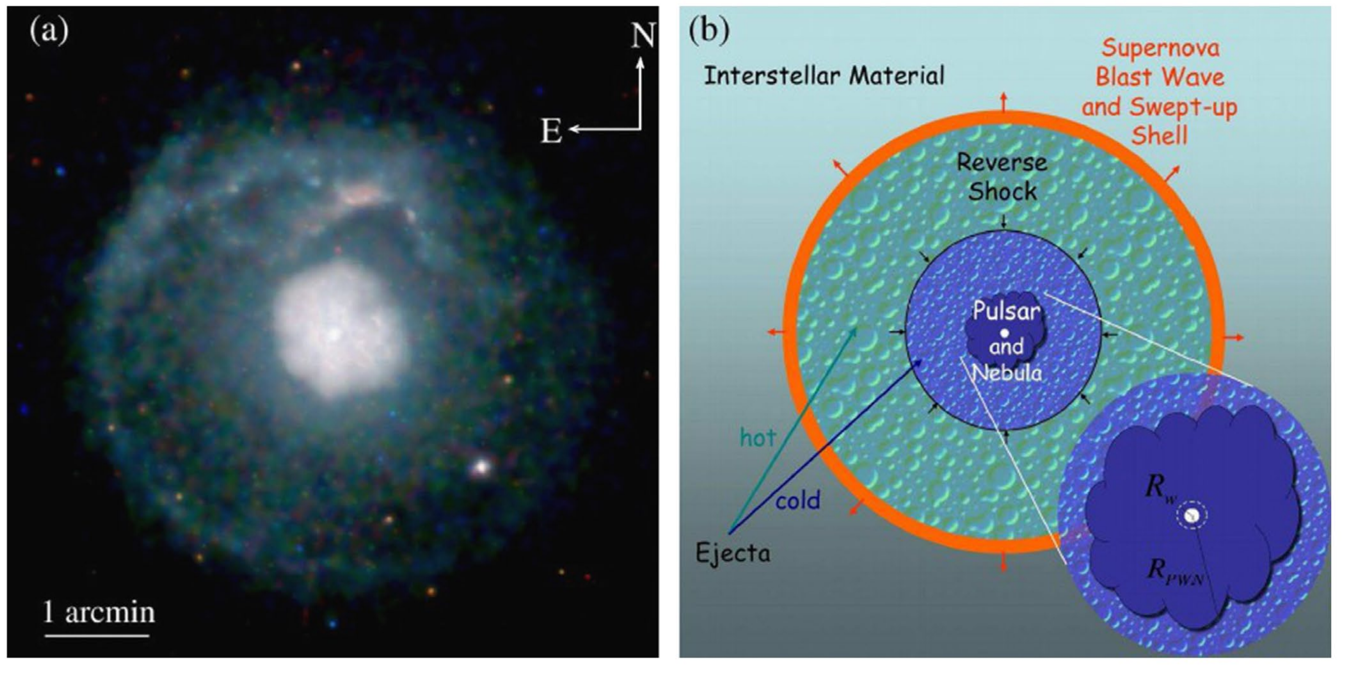
Sources that I will focus on…

- Supernova remnants
- Pulsar wind nebulae
- Gamma-ray binaries

Supernova remnants (SNRs)

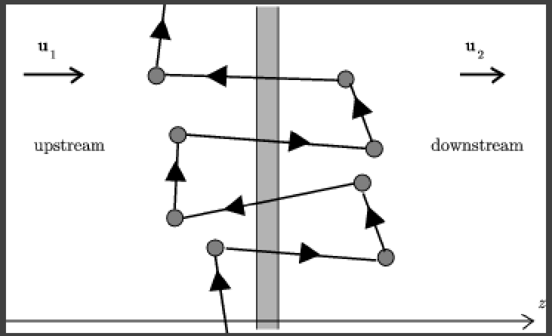
- Result of a powerful explosion ($\sim 10^{51}$ erg)
- Core-collapse of a massive star or thermonuclear disruption of white dwarfs
- Ejected material expands supersonically driving a strong shock
- Particles can be accelerated at the shock through the diffusive shock acceleration (DSA)



SNR G21.5–0.9:
Chandra X-ray image and cartoon illustrating the structure of a text-book core-collapse SNR

Supernova remnants (SNRs)

- Result of a powerful explosion ($\sim 10^{51}$ erg)
- Core-collapse of a massive star or thermonuclear disruption of white dwarfs
- Ejected material expands supersonically driving a strong shock
- Particles can be accelerated at the shock through the diffusive shock acceleration (DSA)

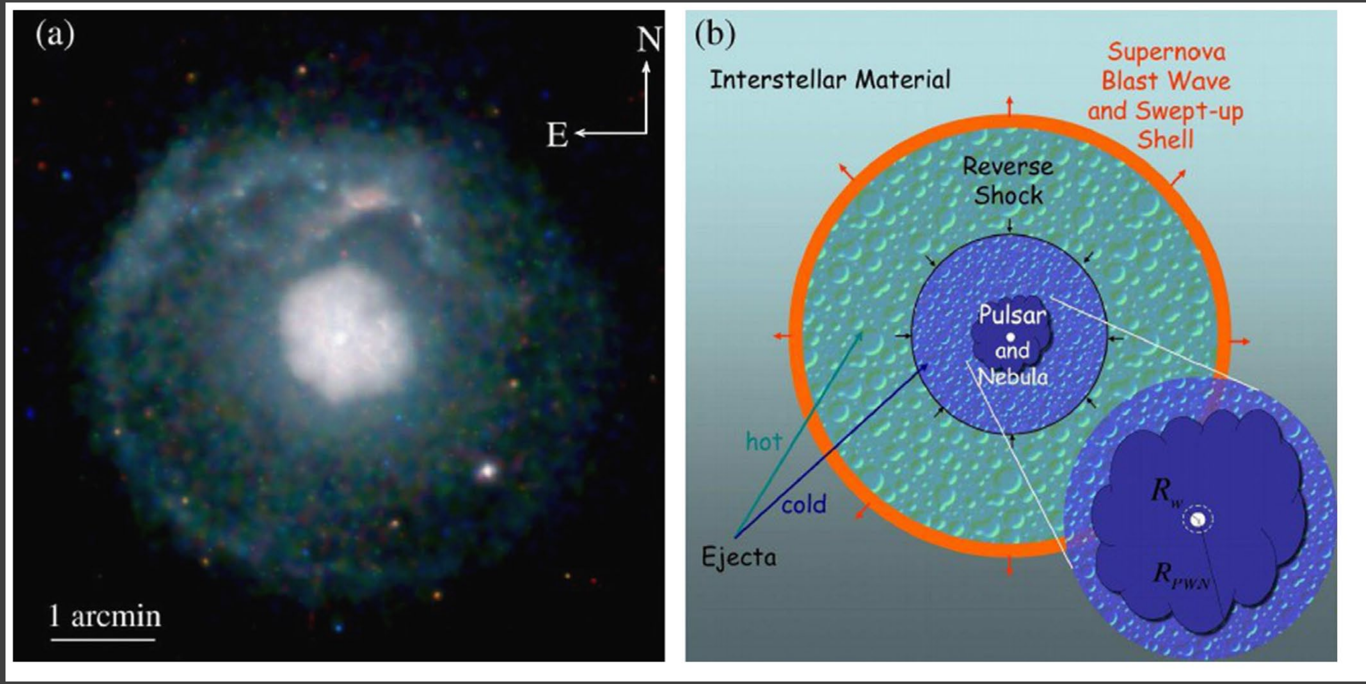


$N(E) \sim E^{-\alpha}$; $\alpha = \frac{r+2}{r-1}$

$r = \frac{u_1}{u_2} = 4$ - shock compression ratio

$N(E) \sim E^{-2}$

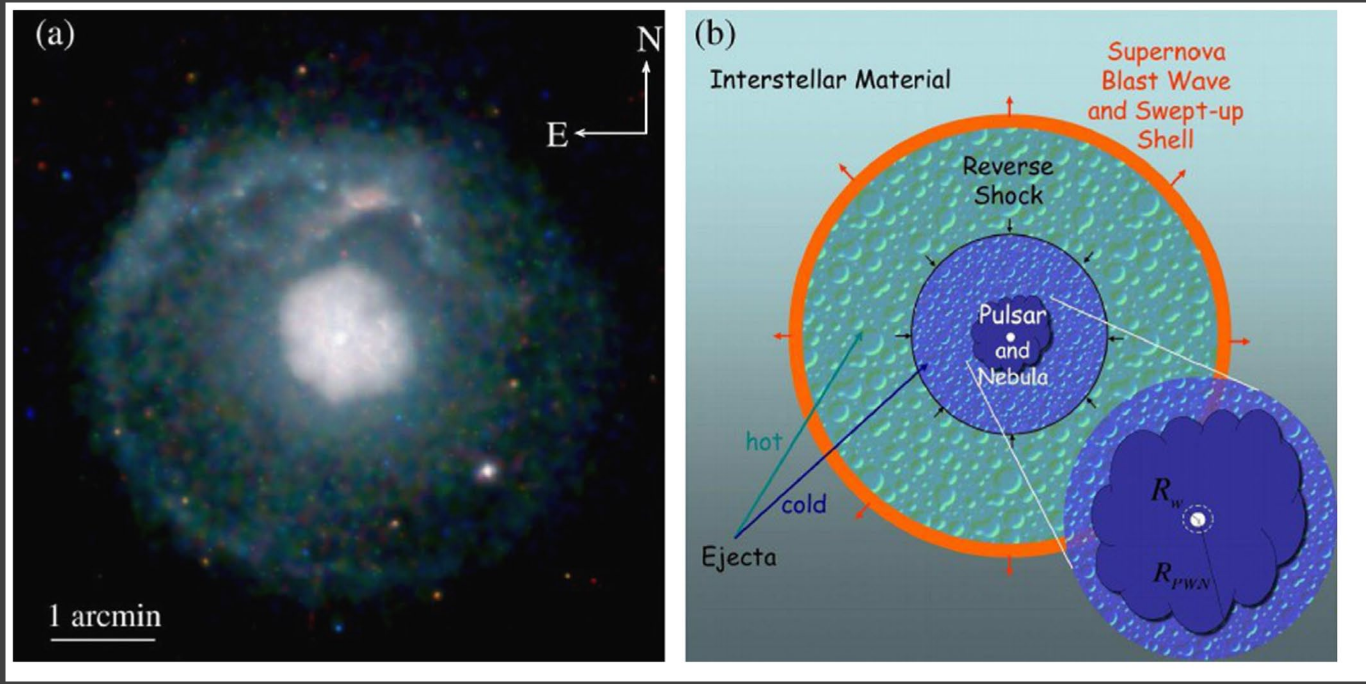
(e.g. Drury 1983, Malkov & Drury 2001, Reynolds 2008)



SNR G21.5–0.9:
Chandra X-ray image and cartoon illustrating the structure of a text-book core-collapse SNR

Pulsar wind nebulae (PWNe)

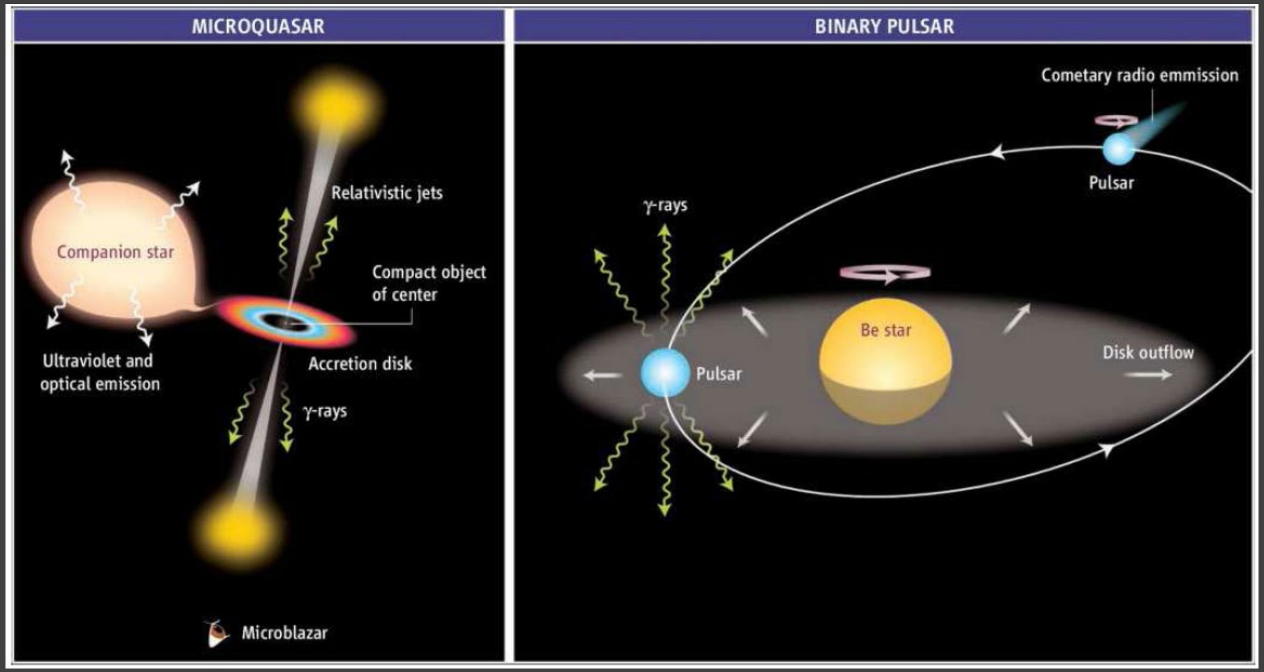
- Inner core collapses into the neutron star (or pulsar)
- Small, heavy, highly magnetized, fast rotators
- Generate a pulsar wind consisting of electrons/positrons
- Pulsar wind shapes a nebula around the pulsar
- The termination shock is formed between the blown-up nebula and freshly coming pulsar wind
- At this termination shock particles can be farther accelerated to a 'usual' power-law spectrum

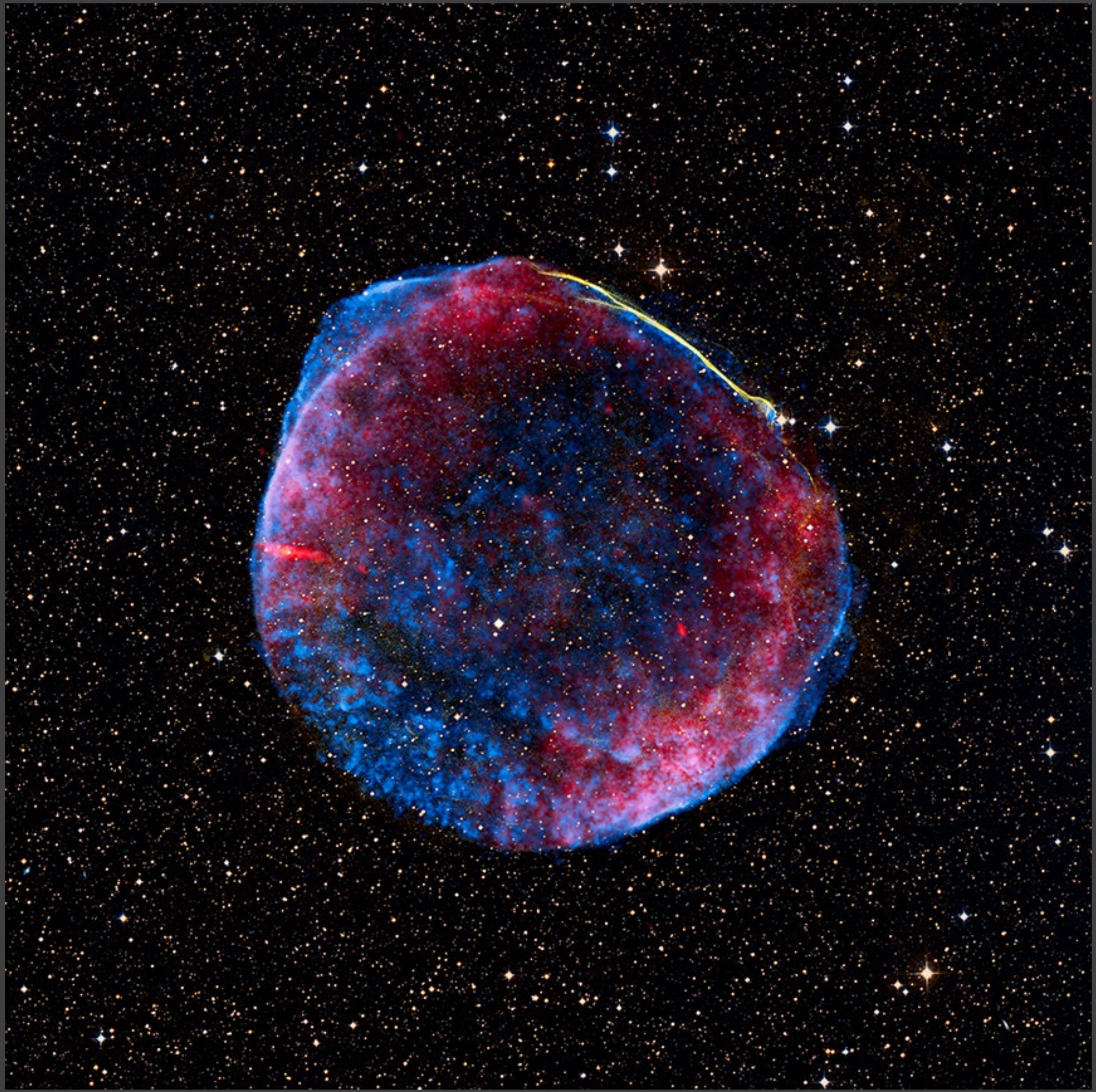


SNR G21.5–0.9:
Chandra X-ray image and cartoon illustrating the structure of a text-book core-collapse SNR

Gamma-ray binaries

- Binaries which non-thermal emission peaks above 1 MeV (10 objects known so far)
- Massive star + compact source (pulsar or BH)
- Only for 3 we know for sure that the CS is a pulsar
- Particles are accelerated either at the termination shock of colliding pulsar and stellar winds or in accretion-powered jet subsequently producing gamma-ray emission
- Plerionic (pulsar as a CS) binaries are basically PWNe which are changing dynamically on very short time scales.
- Massive stars often feature a circumstellar disc which complicates things





SUPERNOVA REMNANTS

Non-thermal emission

- Radio – X-ray
  - Synchrotron

    e + B → e + γ
- VHE emission
  - Leptonic:

    inverse Compton scattering

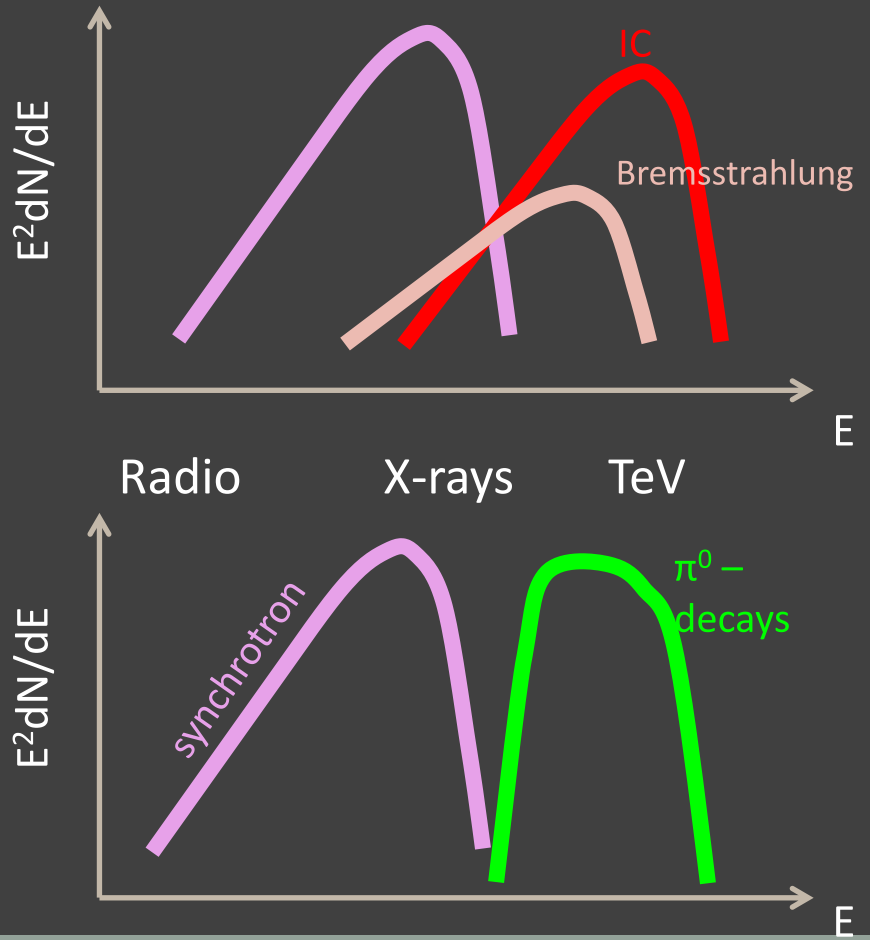
    e + γ → e + γ

    Bremsstrahlung

    e + Coulomb field → e + γ
  - Hadronic:

    π^0 – decays

    pp → π0 → γ + γ



Non-thermal emission

- Radio – X-ray
  - Synchrotron

    $e + B \rightarrow e + \gamma$
- VHE emission
  - Leptonic:

    inverse Compton scattering

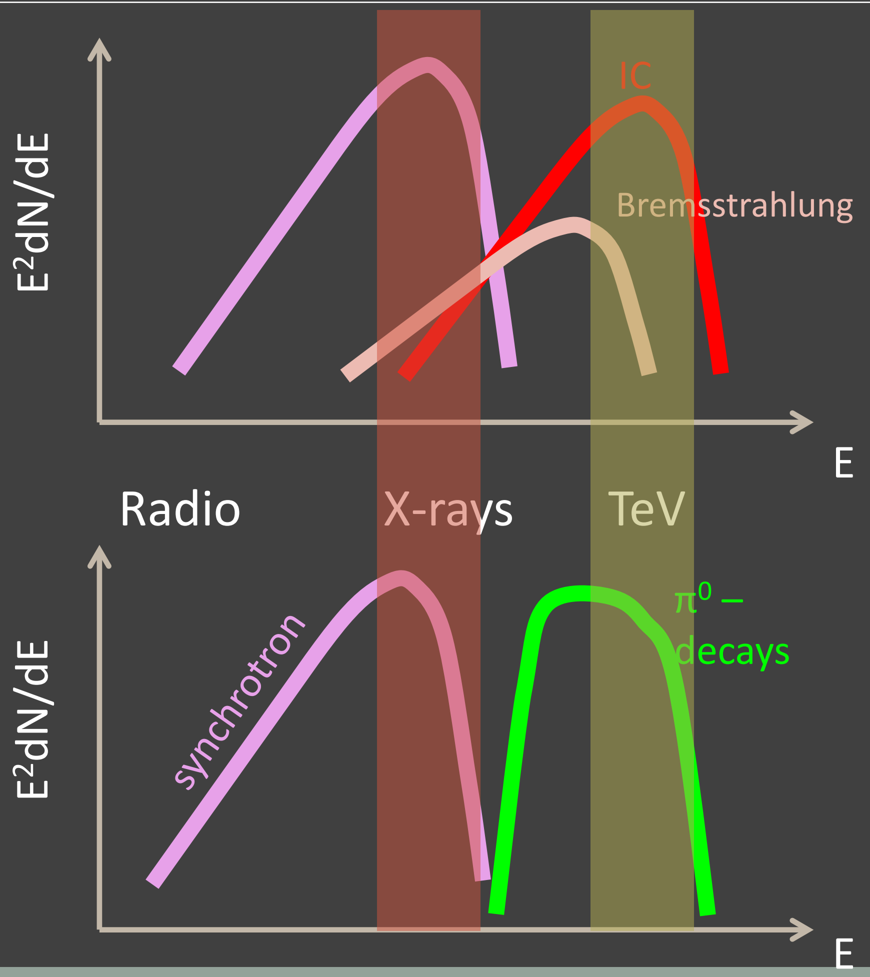
    $e + \gamma \rightarrow e + \gamma$

    Bremsstrahlung

    e + Coulomb field $\rightarrow e + \gamma$
  - Hadronic:

    π^0 – decays

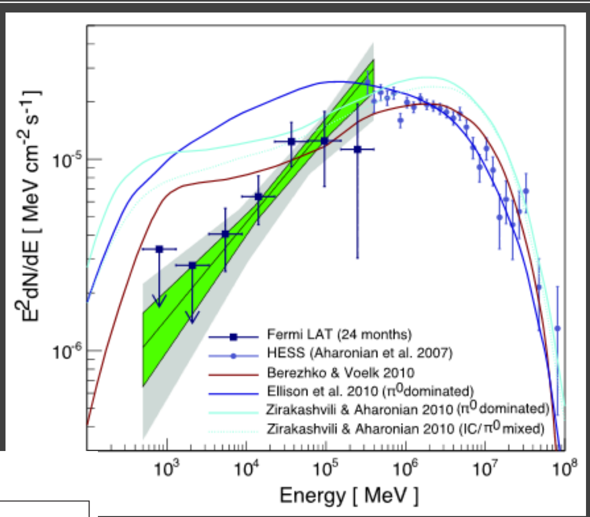
    $pp \rightarrow \pi 0 \rightarrow \gamma + \gamma$

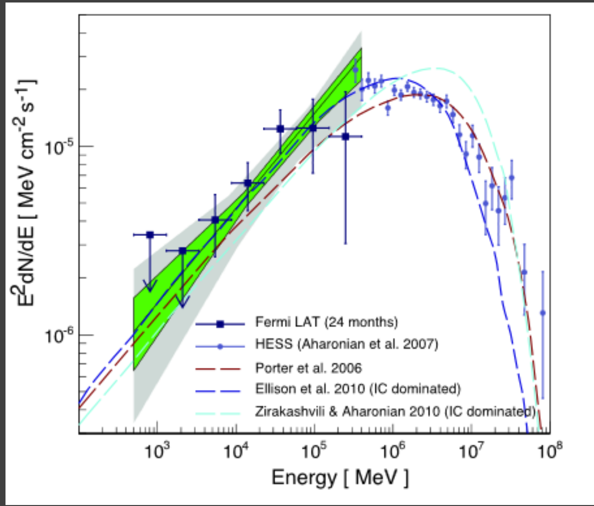


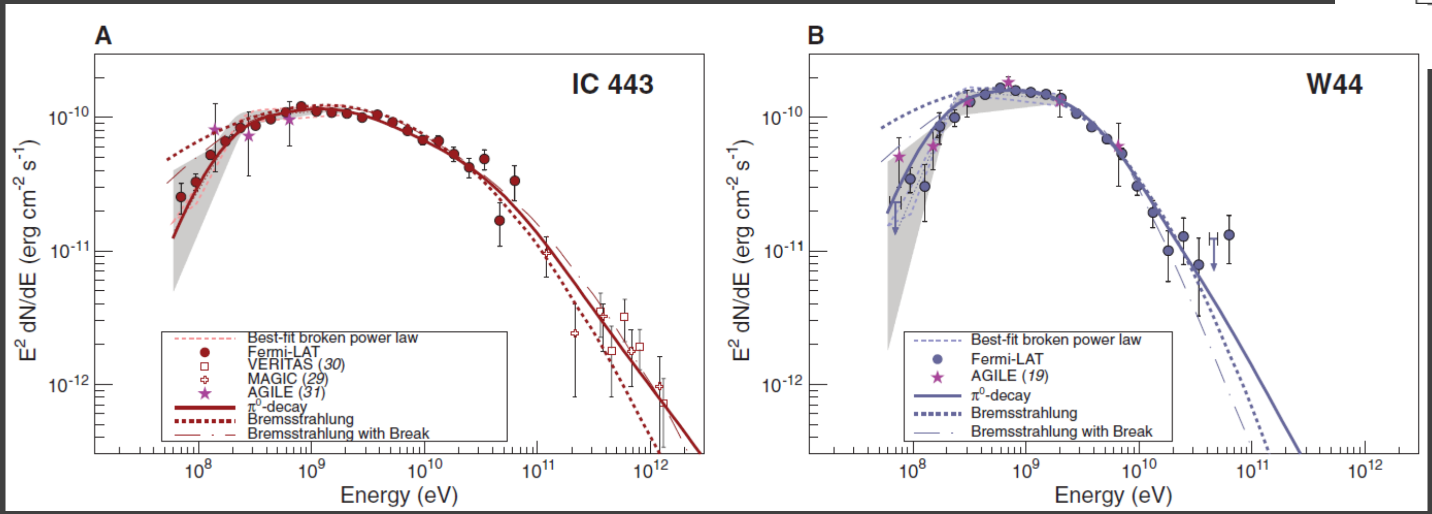
Gamma-ray spectrum: hadronic or leptonic?

leptonic

RX J1713.7-3946 *(Abdo et al. 2011)*



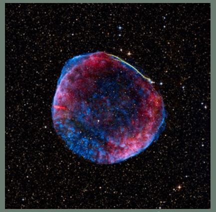




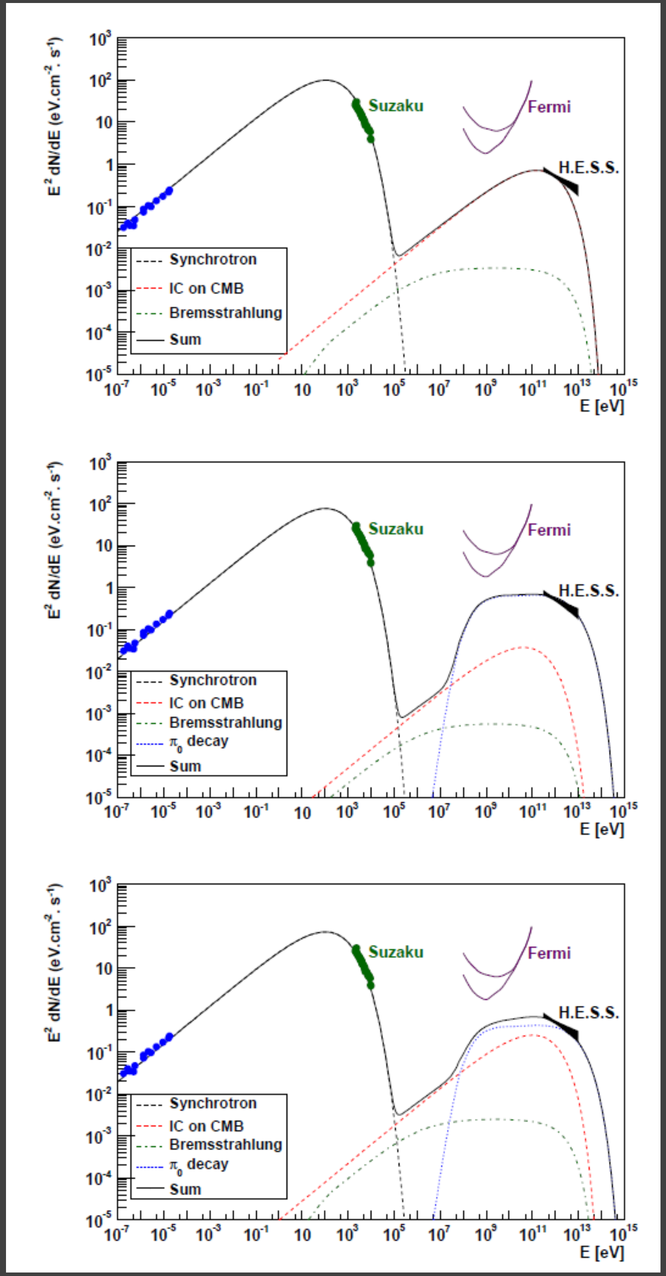
hadronic

Ackermann et al. 2013

Gamma-ray spectrum: hadronic or leptonic?

SN 1006 
(before it was detected by Fermi-LAT)

- Can be fit with both scenarios
- GeV energies needed to constrain the spectrum
- Different spectral slopes for X-rays an TeV is not necessarily a sign of different underlining particles – could be simply different part of the electron spectrum in the cut-off region



Ackermann et al. 2013

Non-thermal emission

- Radio – X-ray
  - Synchrotron

    $e + B \rightarrow e + \gamma$
- VHE emission
  - Leptonic:

    inverse Compton scattering

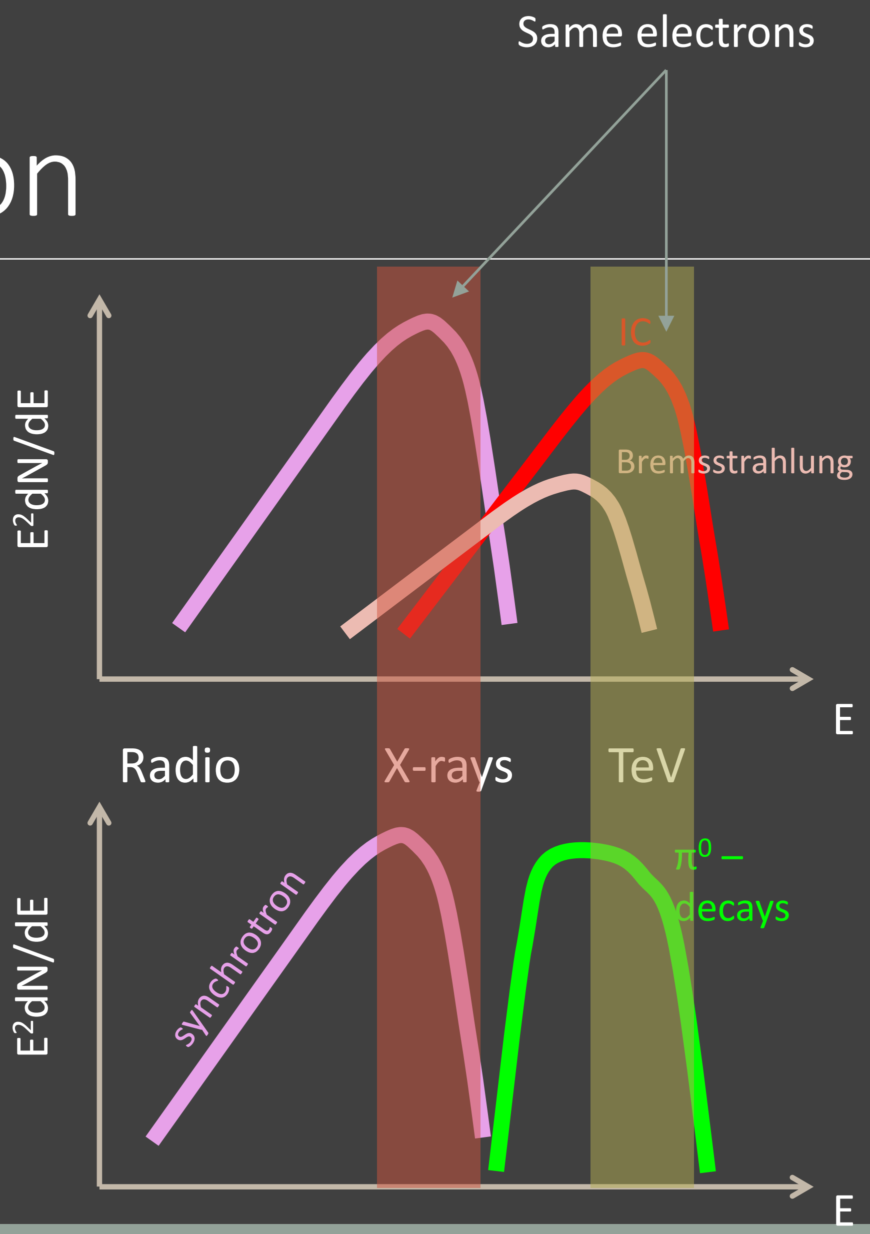
    $e + \gamma \rightarrow e + \gamma$

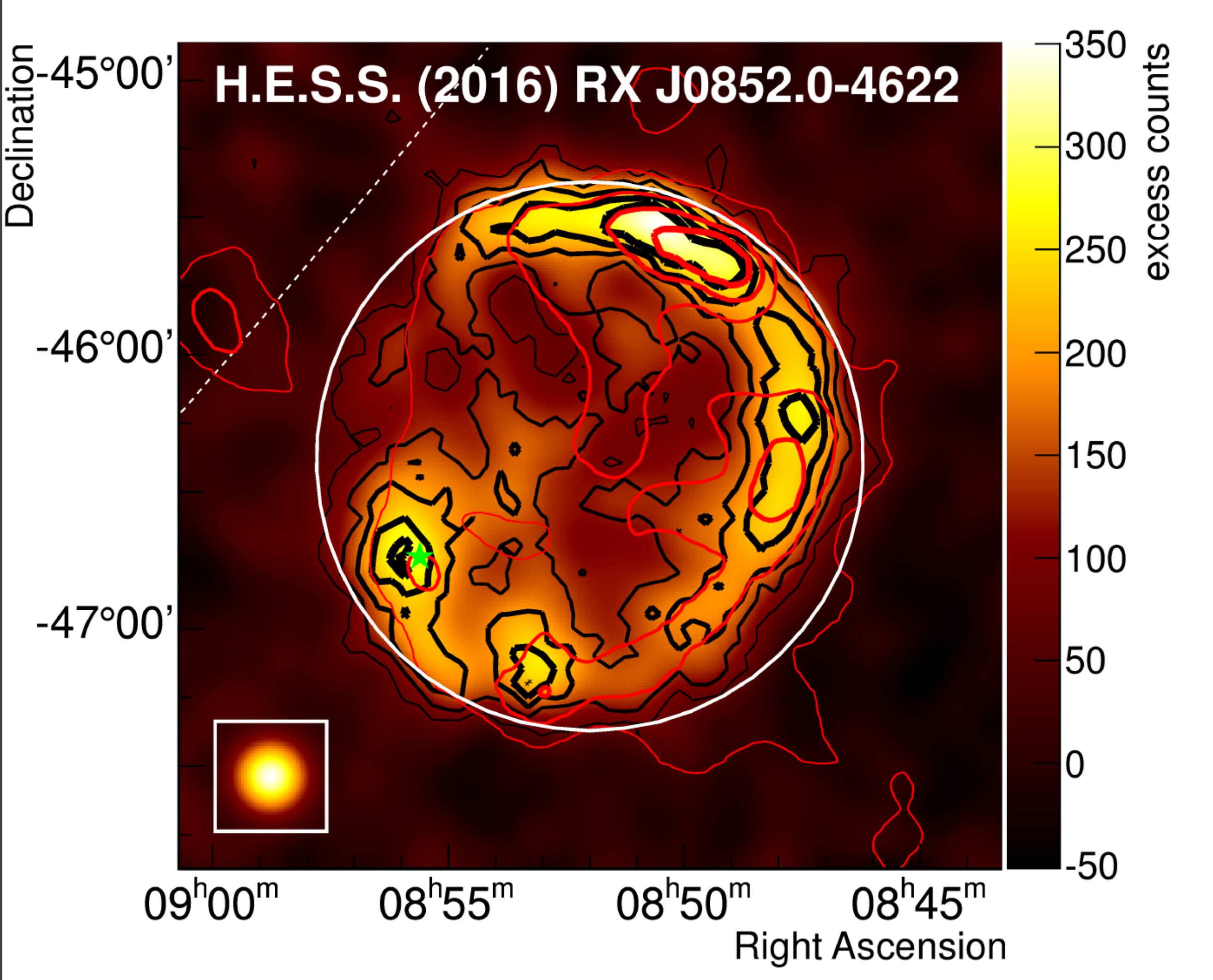
    Bremsstrahlung

    e + Coulomb field $\rightarrow e + \gamma$
  - Hadronic:

    π^0 – decays

    $pp \rightarrow \pi 0 \rightarrow \gamma + \gamma$





H.E.S.S. Collaboration 2018

X-ray/TeV Correlation

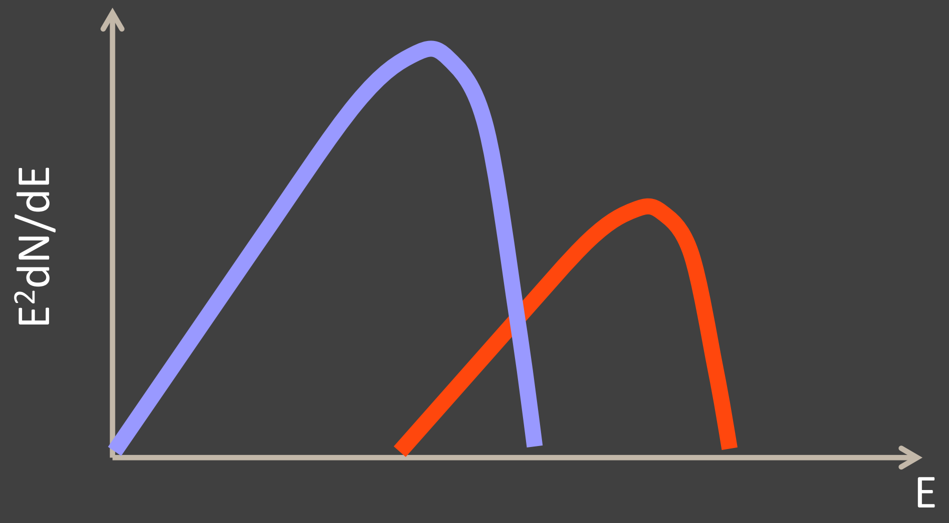
Vela Jr. SNR – nice example

Gamma-ray/X-ray as a probe of magnetic field

Higher B-Field,

lower electron density

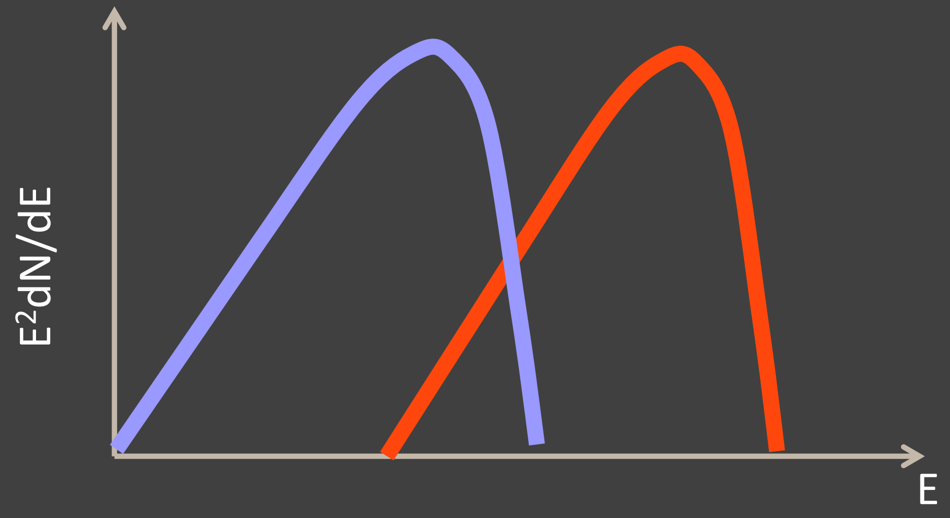
→ lower IC



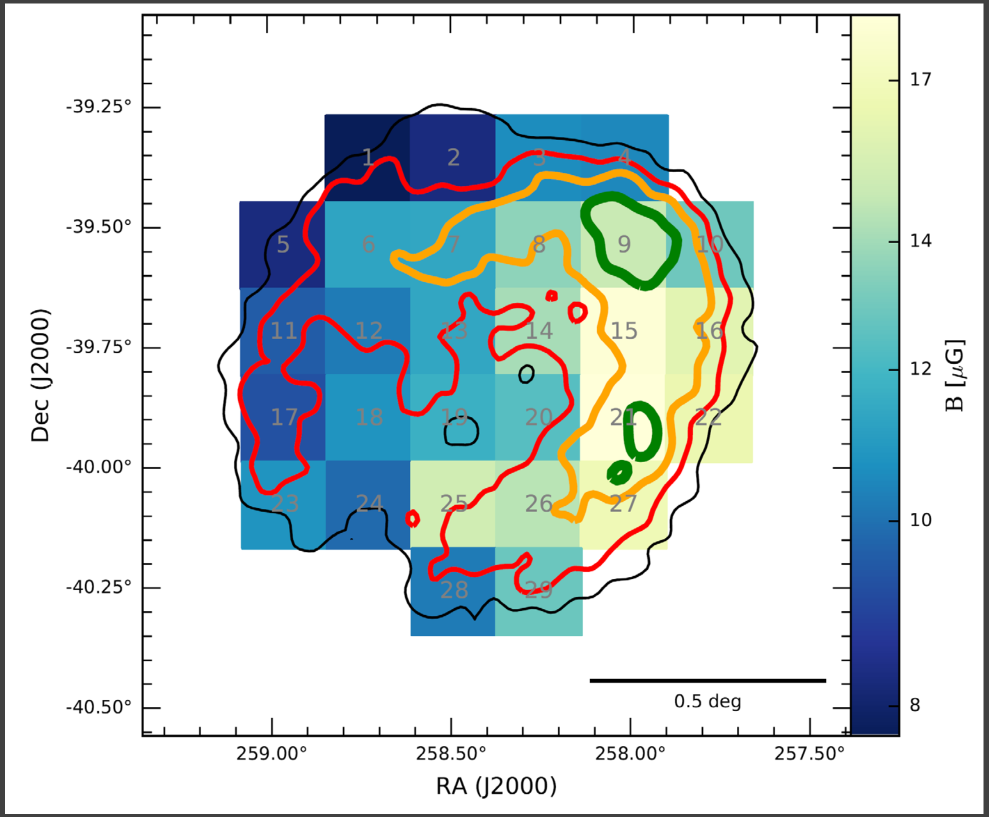
Lower B-Field,

higher electron density

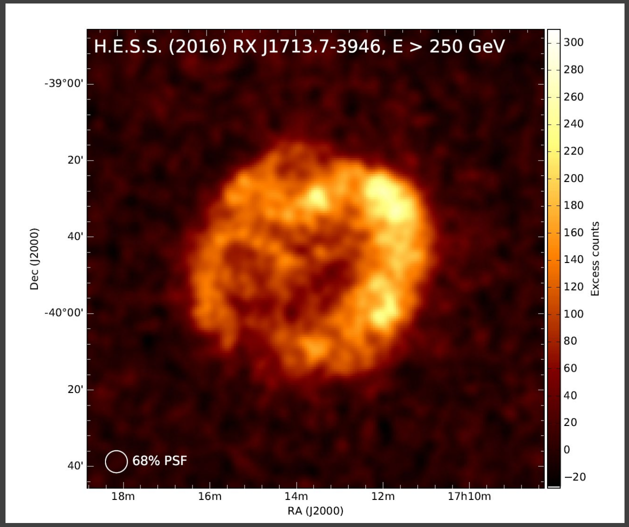
→ higher IC



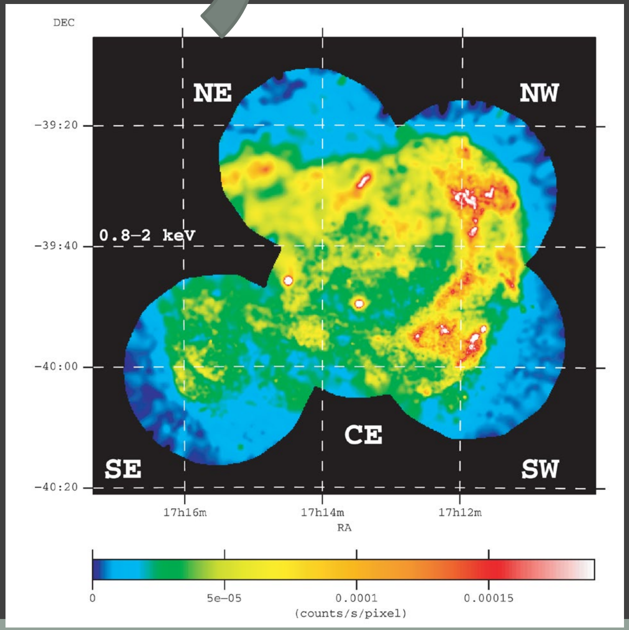
Probing magnetic field



Magnetic field map
H.E.S.S. collaboration, 2016

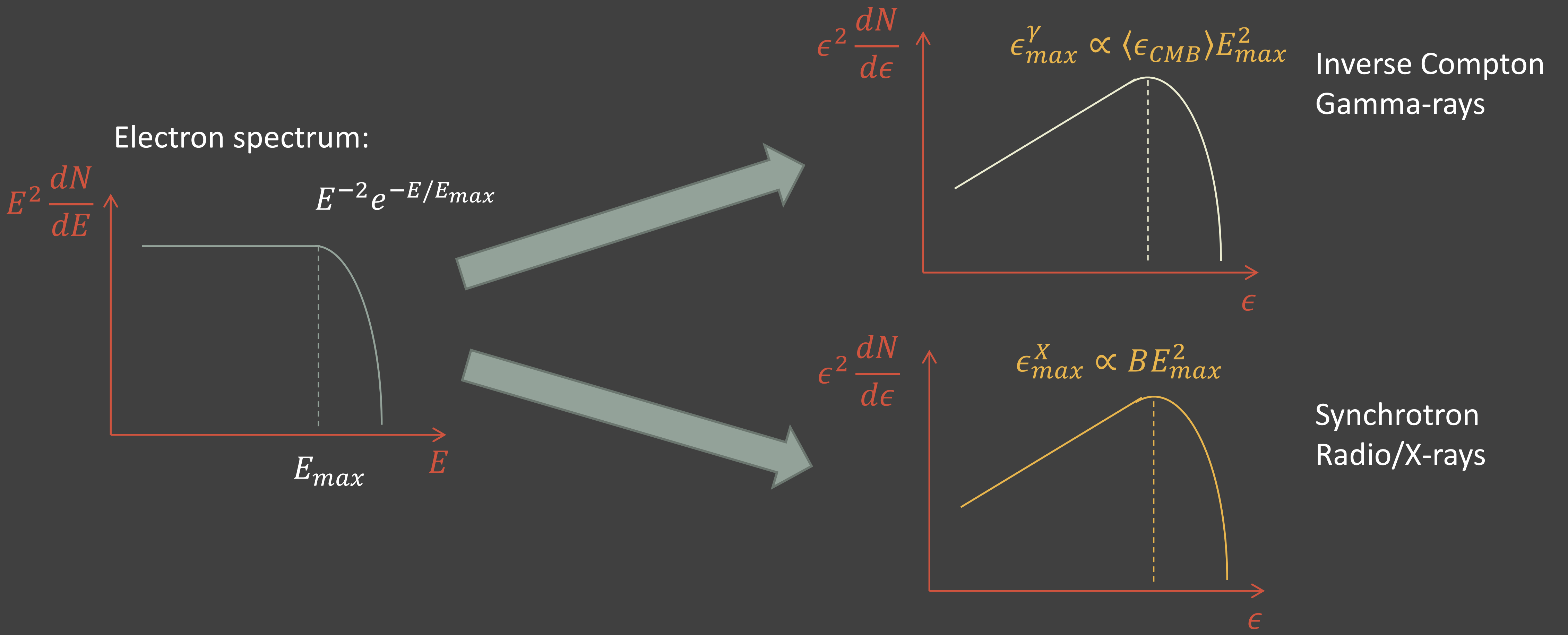


H.E.S.S. map
H.E.S.S. collaboration, 2016

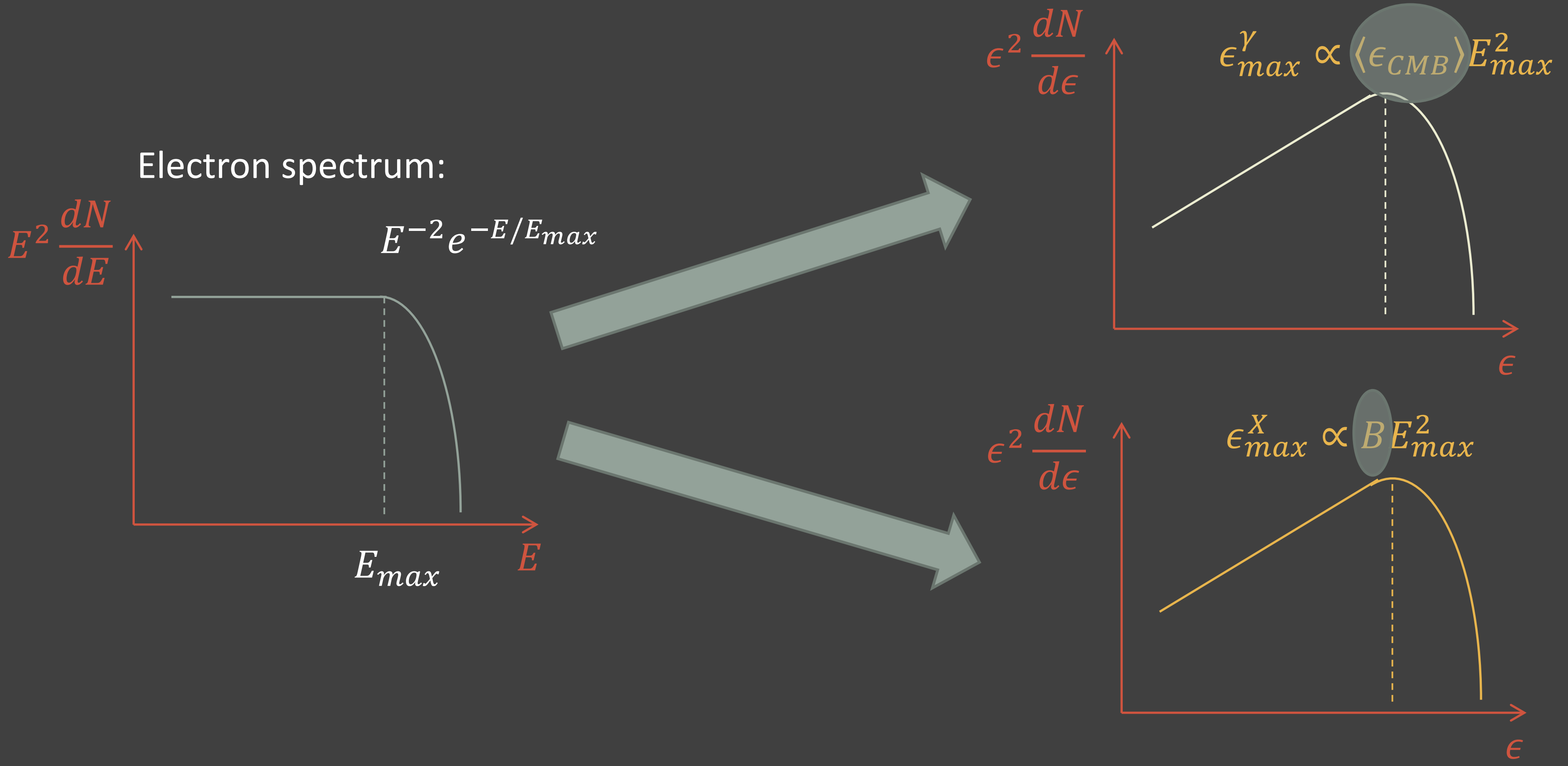


XMM-Newton map
G. Cassam-Chenaï, et al. 2004

Maximum energy



Maximum energy



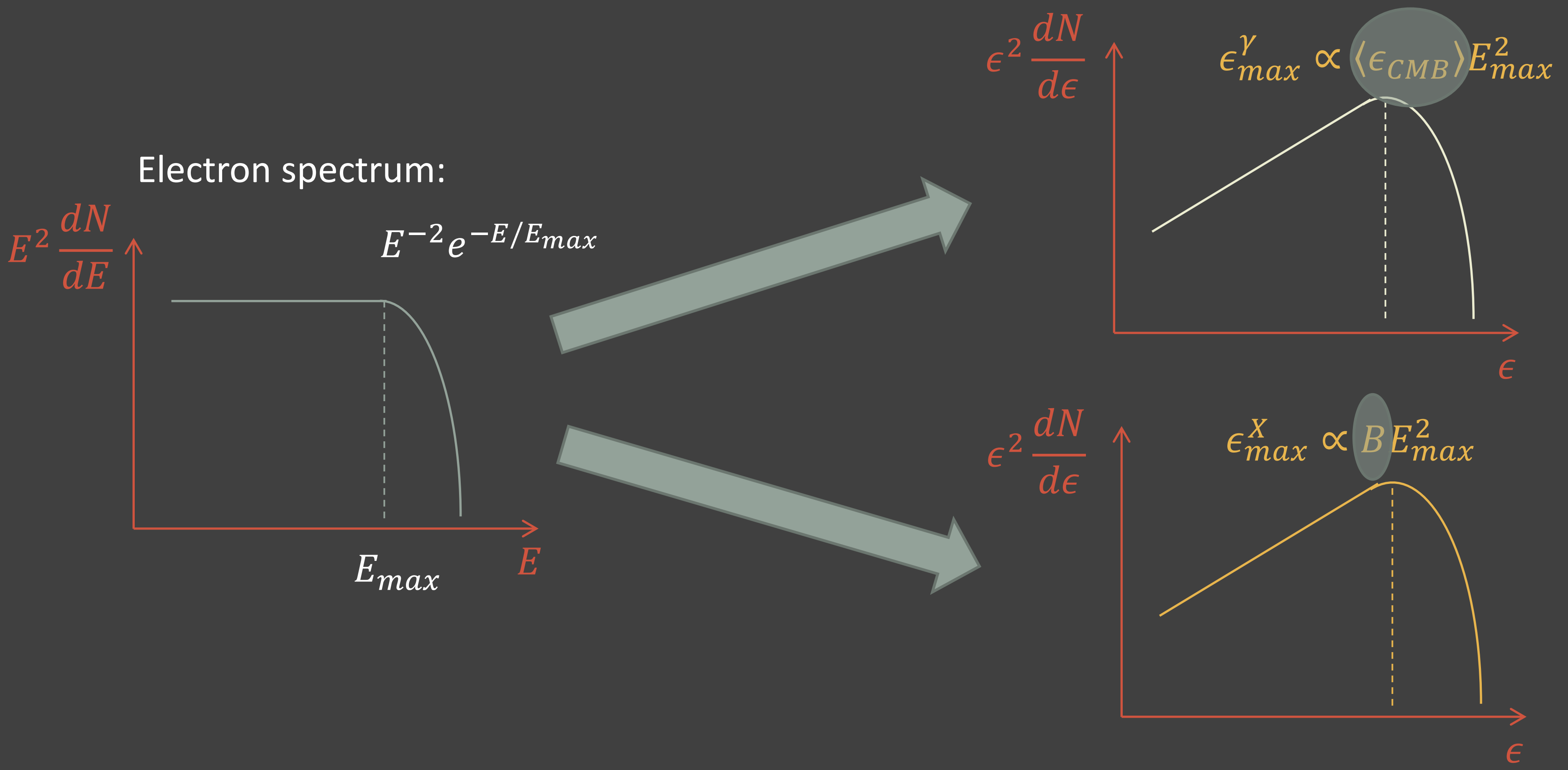
Inverse Compton
Gamma-rays

Synchrotron
Radio/X-rays

Maximum energy

Here we usually have to deal with CMB which average energy we know very well

Electron spectrum:

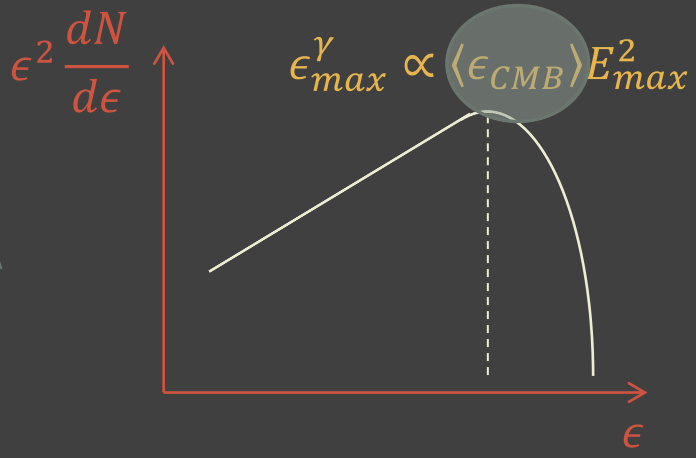


Inverse Compton Gamma-rays

Synchrotron Radio/X-rays

Maximum energy

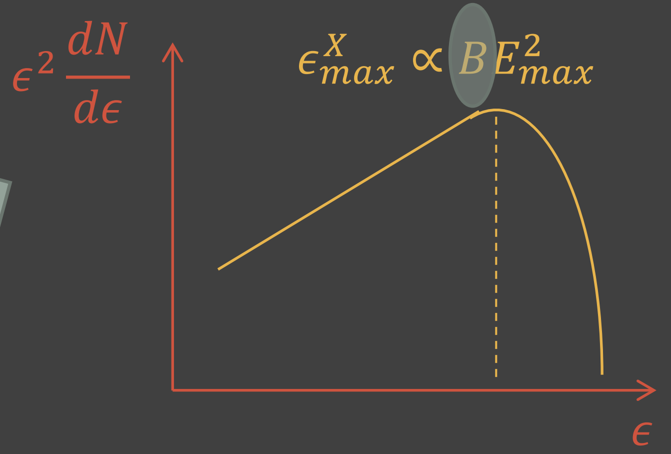
Here we usually have to deal with CMB which average energy we know very well



Inverse Compton
Gamma-rays

Constraint on the magnetic field

$$B = 9 \times 10^4 \frac{\epsilon_{max}^{X}}{\epsilon_{max}^{\gamma}} \ \mathrm{G}$$



Synchrotron
Radio/X-rays

Cooling dominated

- if the electron maximum energy is limited by synchrotron cooling ($t_{cool} = t_{acc} < age$) the X-ray cut-off energy loses dependence on magnetic field:

acceleration efficiency

$$E_{max} \propto B^{-1/2} \eta^{-1/2} v_{sh}$$

shock velocity

Cooling dominated

- if the electron maximum energy is limited by synchrotron cooling ($t_{cool} = t_{acc} < age$) the X-ray cut-off energy loses dependence on magnetic field:

acceleration efficiency

$$E_{max} \propto B^{-1/2} \eta^{-1/2} v_{sh}$$

shock velocity

$$\epsilon_{max}^{X} \propto B E_{max}^{2} \propto v_{sh}^{2} \eta^{-1}$$

We lose dependence on B and the X-ray cut-off energy serves a direct measure of the shock velocity to acceleration efficiency ratio

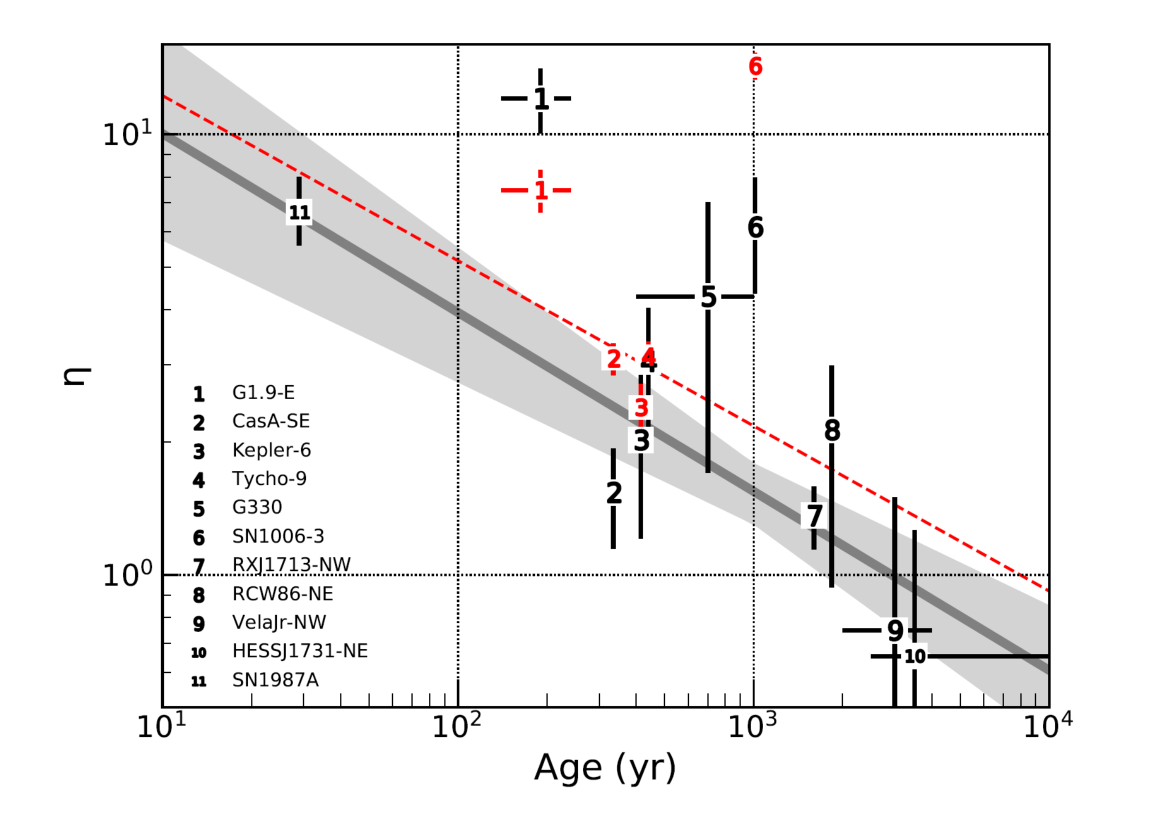
Evolution of acceleration efficiency

Diffusion coefficient

$$D \sim \frac{\eta E}{B}, \eta \geq 1$$

Determines how well particles are confined, i.e. how efficient they can be accelerated

η – acceleration efficiency



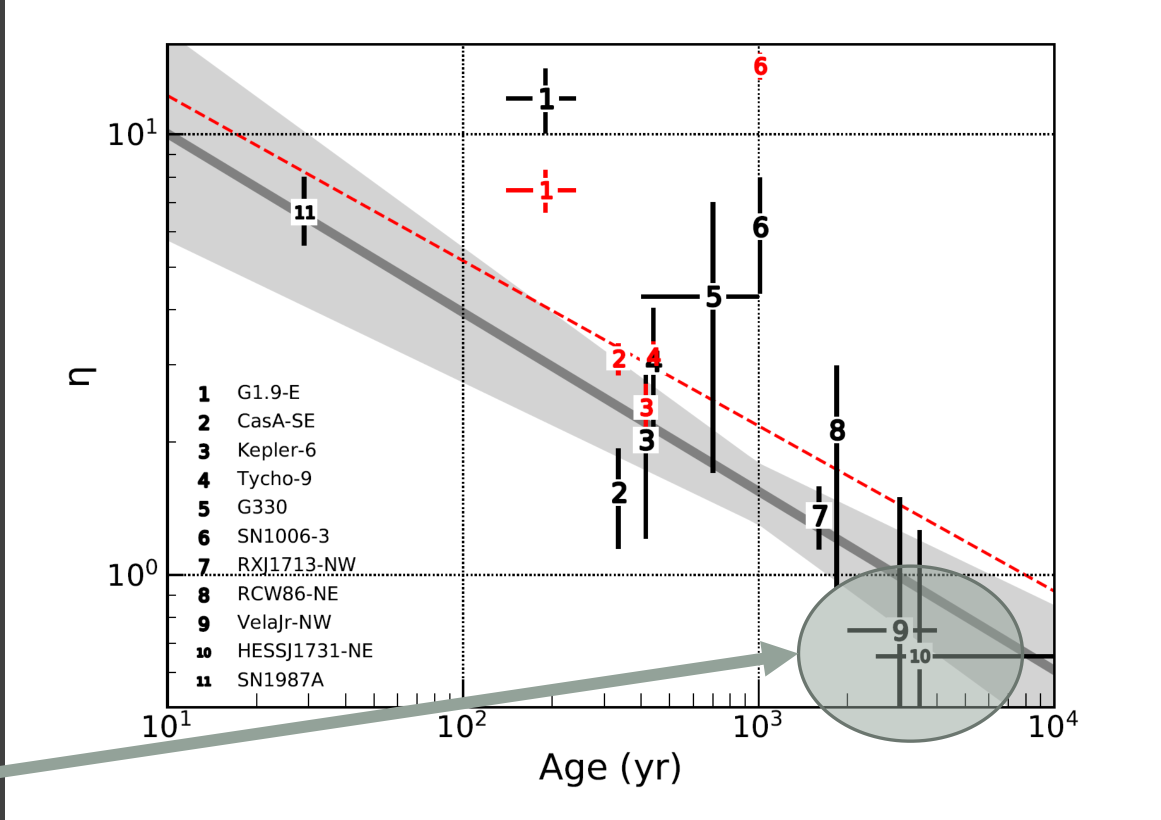
Evolution of acceleration efficiency

Diffusion coefficient

$$D \sim \frac{\eta E}{B}, \eta \geq 1$$

Determines how well particles are confined, i.e. how efficient they can be accelerated

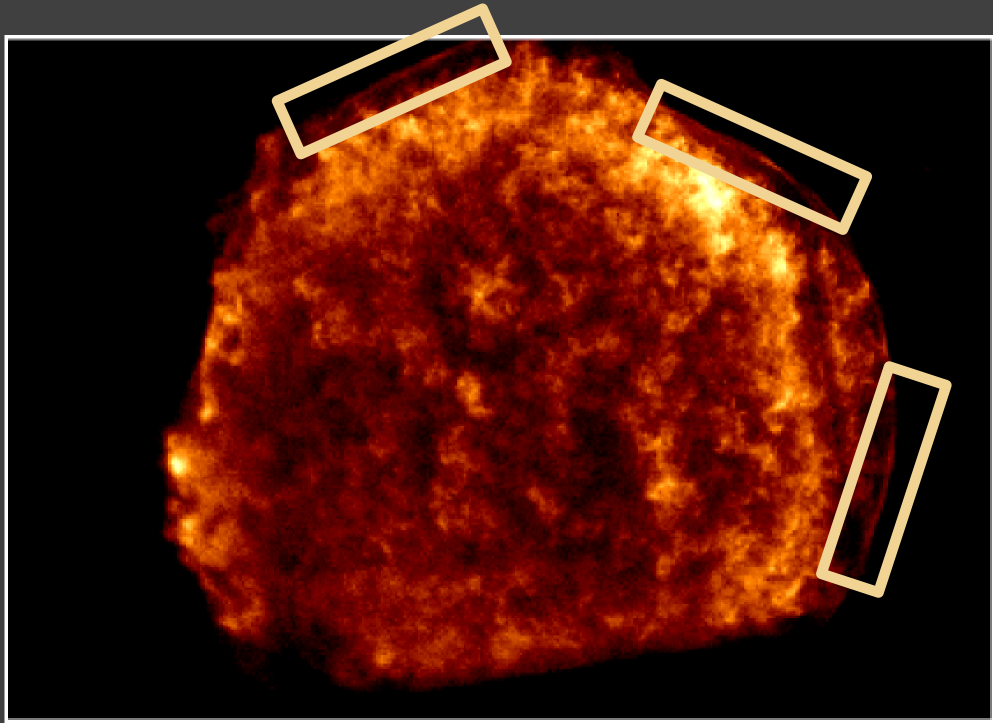
η – acceleration efficiency



Below 1! Synchrotron cooling not dominating

X-ray filaments

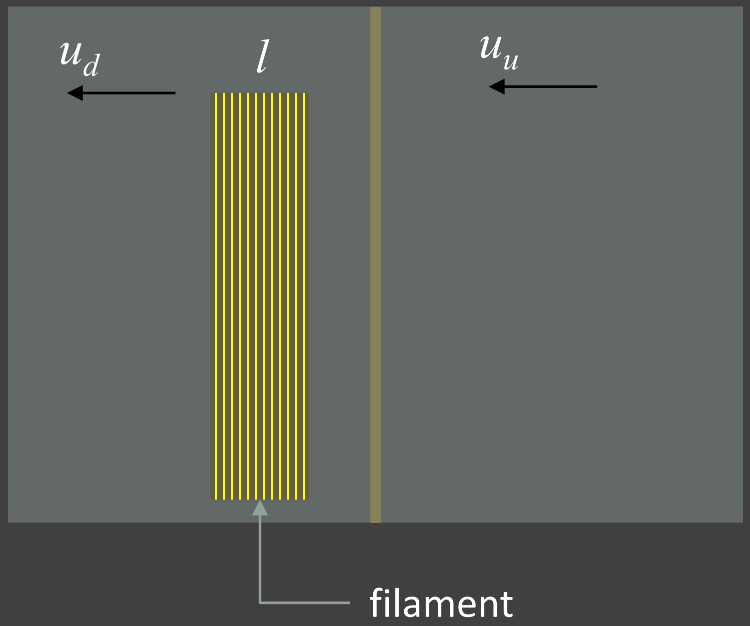
- X-ray filaments suggest a considerable amplification of magnetic field to hundreds of μG in case they are due to fast synchrotron cooling



Tycho SNR

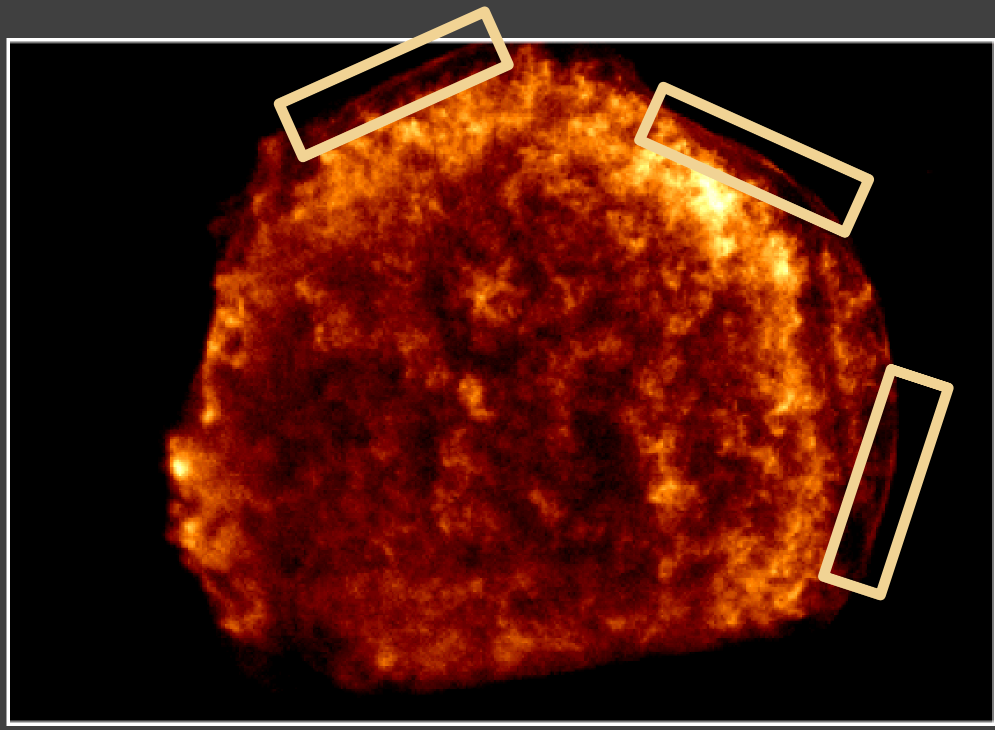
X-ray filaments

- X-ray filaments suggest a considerable amplification of magnetic field to hundreds of μG in case they are due to fast synchrotron cooling



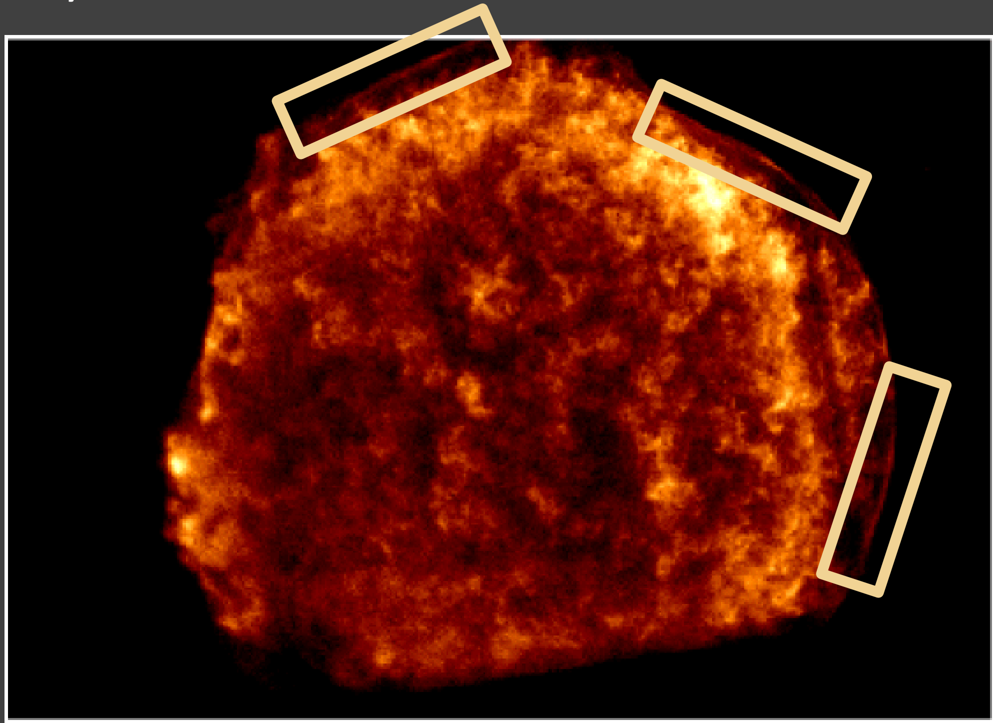
In time that electrons advect downstream from the shock they lose their energy severely due to high magnetic field and can't emit X-rays anymore

Tycho SNR



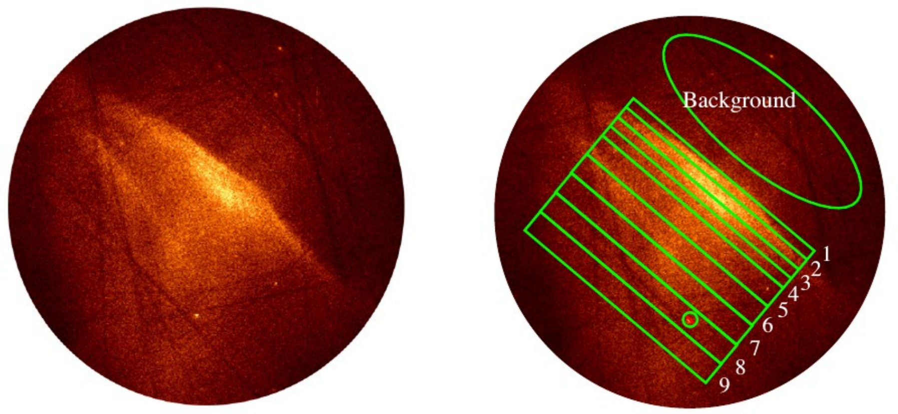
X-ray filaments

- X-ray filaments suggest a considerable amplification of magnetic field to hundreds of µG in case they are due to fast synchrotron cooling
- A strong argument in favor of hadronic origin of the gamma-ray emission
- Amplified magnetic field results in a faster DSA

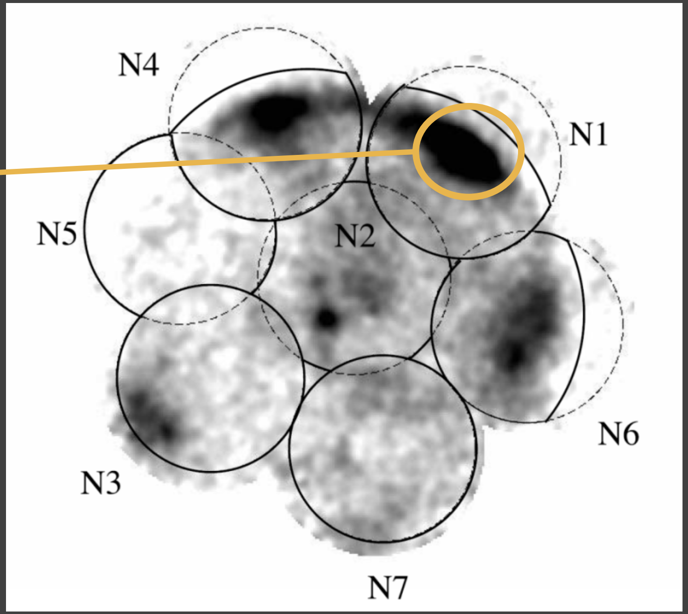


Tycho SNR

X-ray filaments



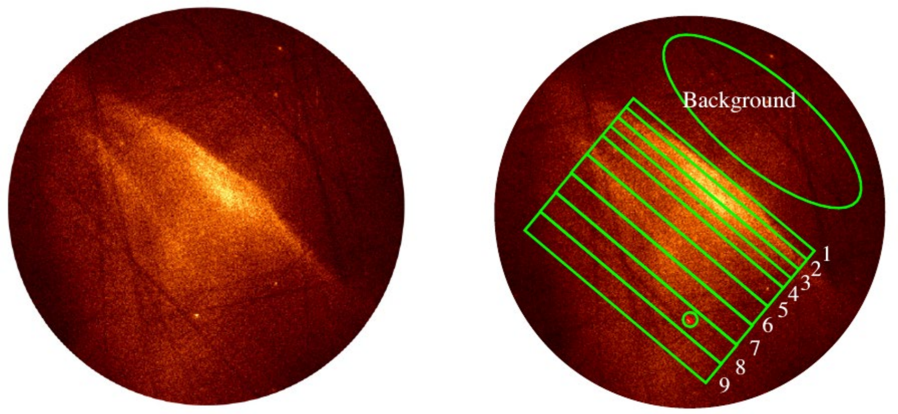
Kishishita et al. 2013



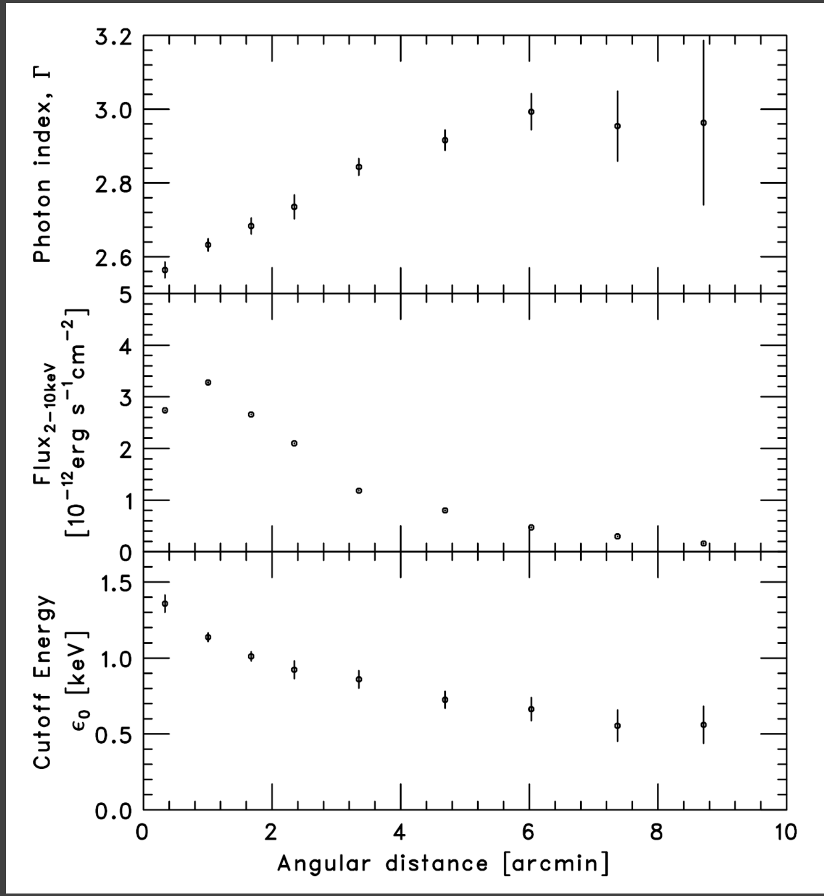
ASCA image, Aharonian et al 2007

Spatially resolved study of the X-ray spectrum for the Vela Jr. SNR

X-ray filaments

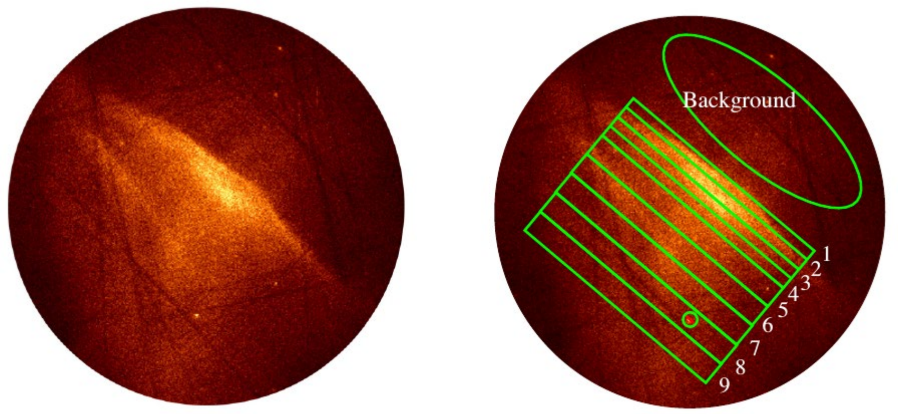


Kishishita et al. 2013

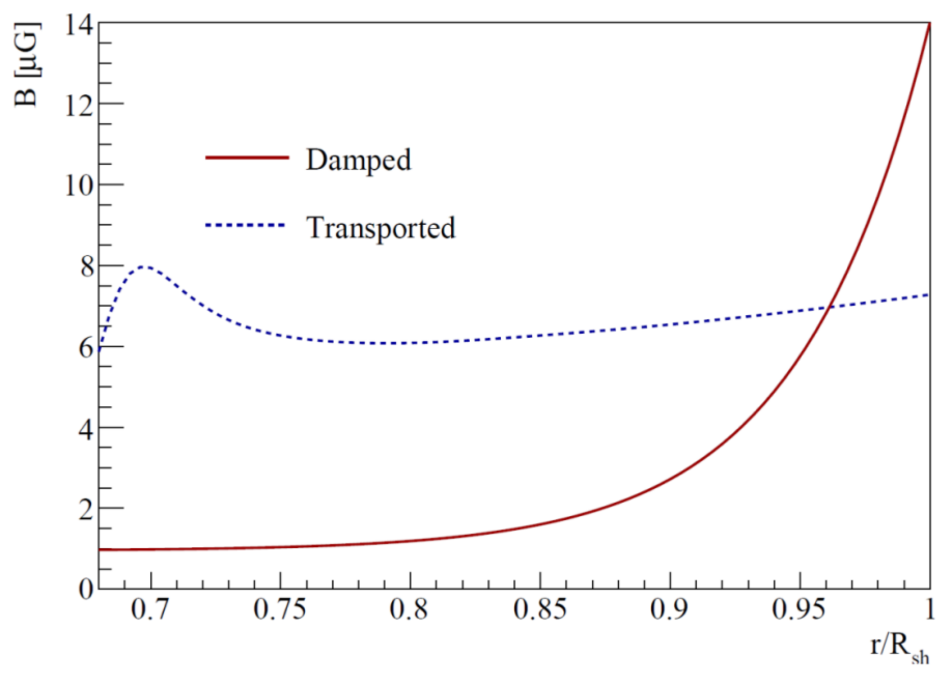


Spatially resolved study of the X-ray spectrum for the Vela Jr. SNR

Magnetic damping



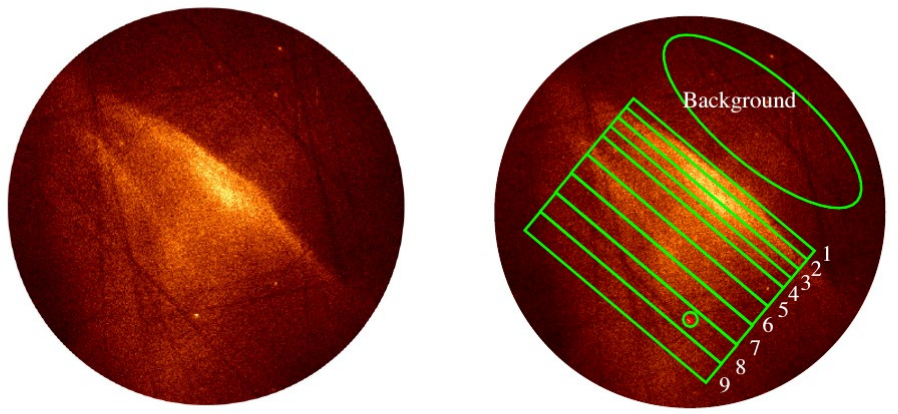
Kishishita et al. 2013



Sushch et al. 2018

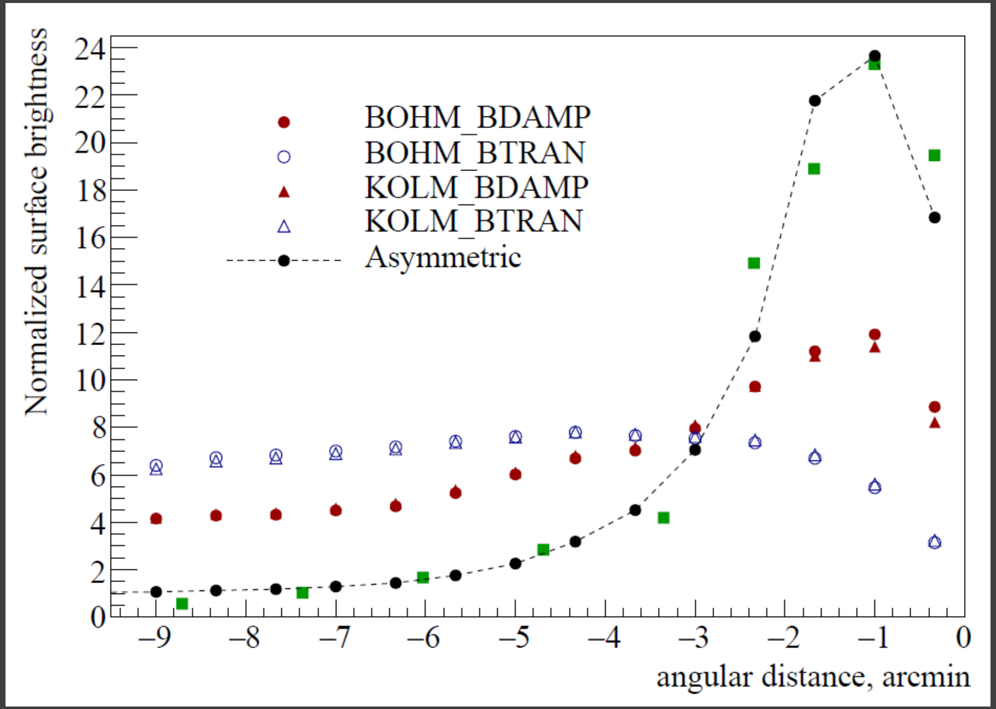
Damping of the turbulent magnetic field downstream → magnetic field is strong only in the small region close to the shock.

Magnetic damping



Kishishita et al. 2013

Damping of the turbulent magnetic field downstream → magnetic field is strong only in the small region close to the shock.



Sushch et al. 2018

Thermal X-rays

as a probe for *hadronic* gamma-rays

- Thermal X-ray emission is an indication of hot pasma with high density

Thermal X-rays

as a probe for *hadronic* gamma-rays

- Thermal X-ray emission is an indication of hot pasma with high density
- No thermal X-rays sets an upper limit on the ambient medium density at a level of ≤ 0.1 cm^{-3}
  an argument for leptonic scenario for gamma-rays

Thermal X-rays

as a probe for *hadronic* gamma-rays

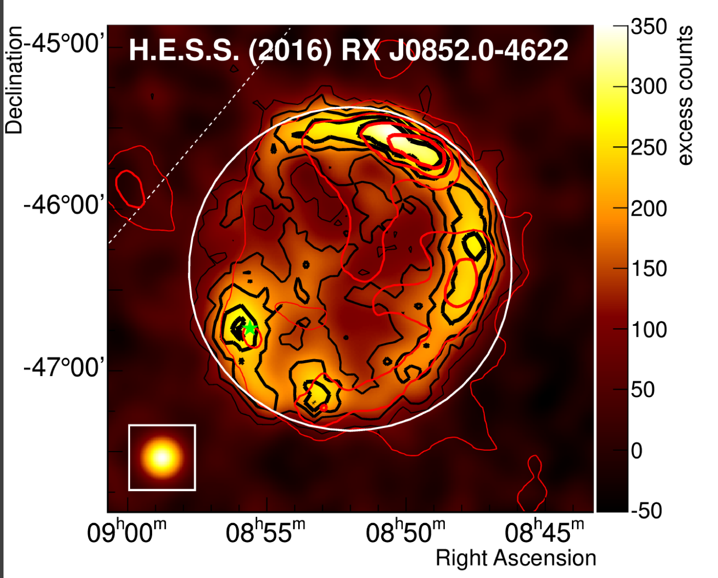
- Thermal X-ray emission is an indication of hot pasma with high density
- No thermal X-rays sets an upper limit on the ambient medium density at a level of $\lesssim 0.1\ cm^{-3}$
  an argument for leptonic scenario for gamma-rays

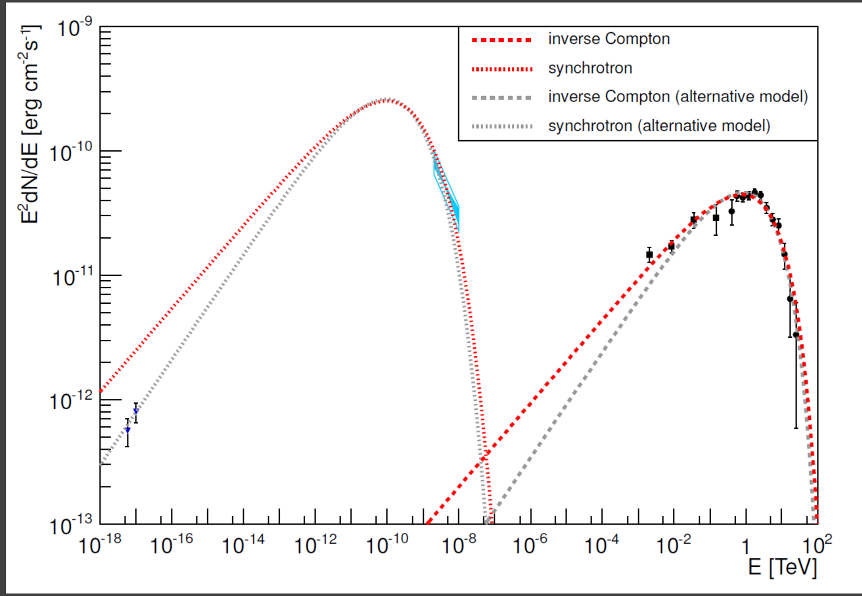
Vela Jr.

No thermal emission sets the upper limit on ambient density to $\sim 0.03\ cm^{-3}$

Good X-ray/TeV correlation

SED looks very leptonic





H.E.S.S. Collaboration 2018

Thermal X-rays

as a probe for *hadronic* gamma-rays

- Thermal X-ray emission is an indication of hot pasma with high density
- No thermal X-rays sets an upper limit on the ambient medium density at a level of ≤ 0.1 cm^{-3}
  an argument for leptonic scenario for gamma-rays
- Strong thermal X-ray component points to high density
  plausible significant contribution from hadronic interactions

Thermal X-rays

as a probe for *hadronic* gamma-rays

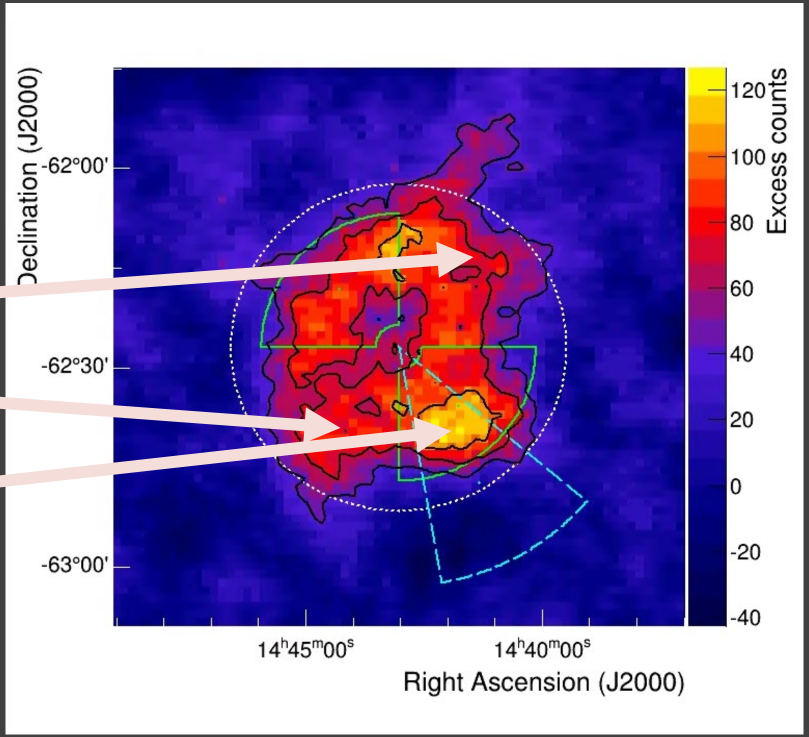
- Thermal X-ray emission is an indication of hot pasma with high density
- No thermal X-rays sets an upper limit on the ambient medium density at a level of $\lesssim 0.1$ cm^{-3}
  an argument for leptonic scenario for gamma-rays
- Strong thermal X-ray component points to high density
  plausible significant contribution from hadronic interactions

Thermal X-rays dominate

Significant thermal X-rays

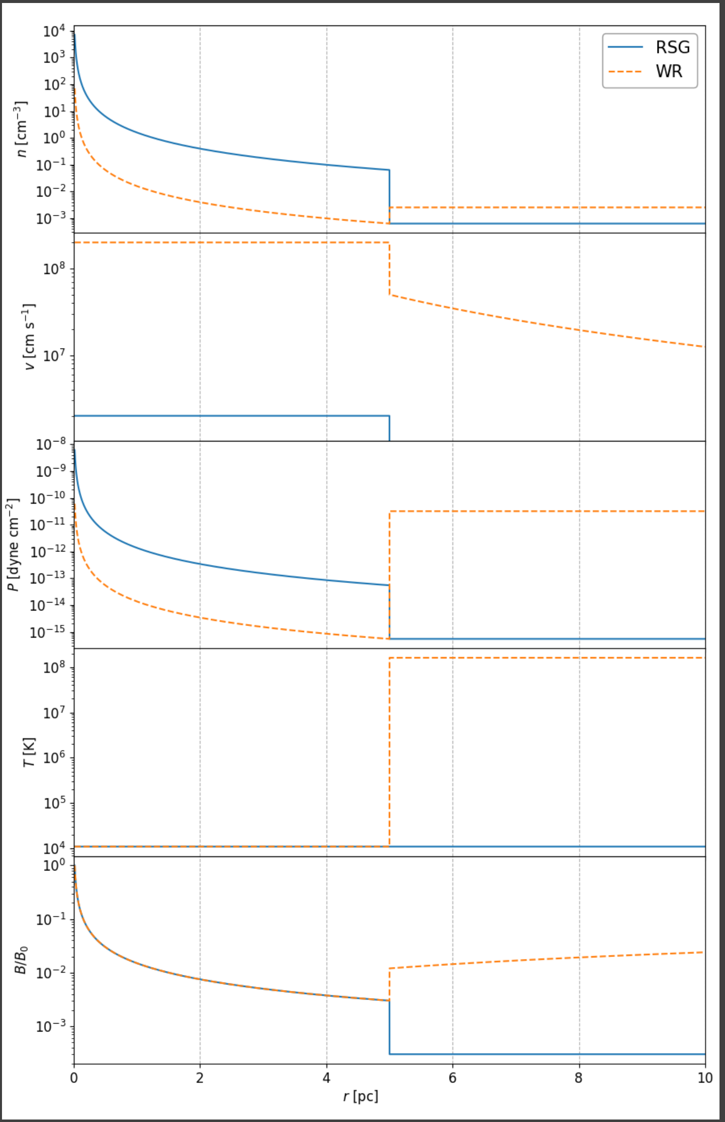
RCW 86
TeV image

H.E.S.S. Collaboration 2018



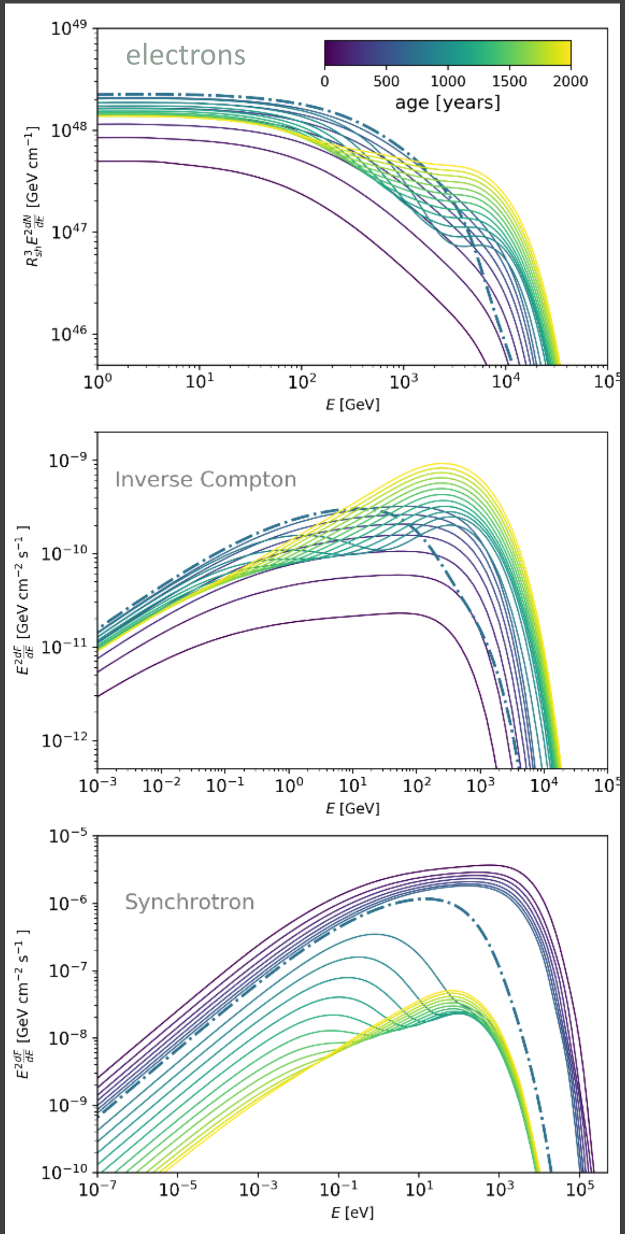
Is it all really that simple?

80 % of all SNRs are core-collapse and expand into the complex circumstellar medium created by stellar winds of their progenitor stars



Simplified MHD profiles describing the inner part of the stellar wind bubble for RSG and Wolf-Rayet cases

Sushch, et al. 2022



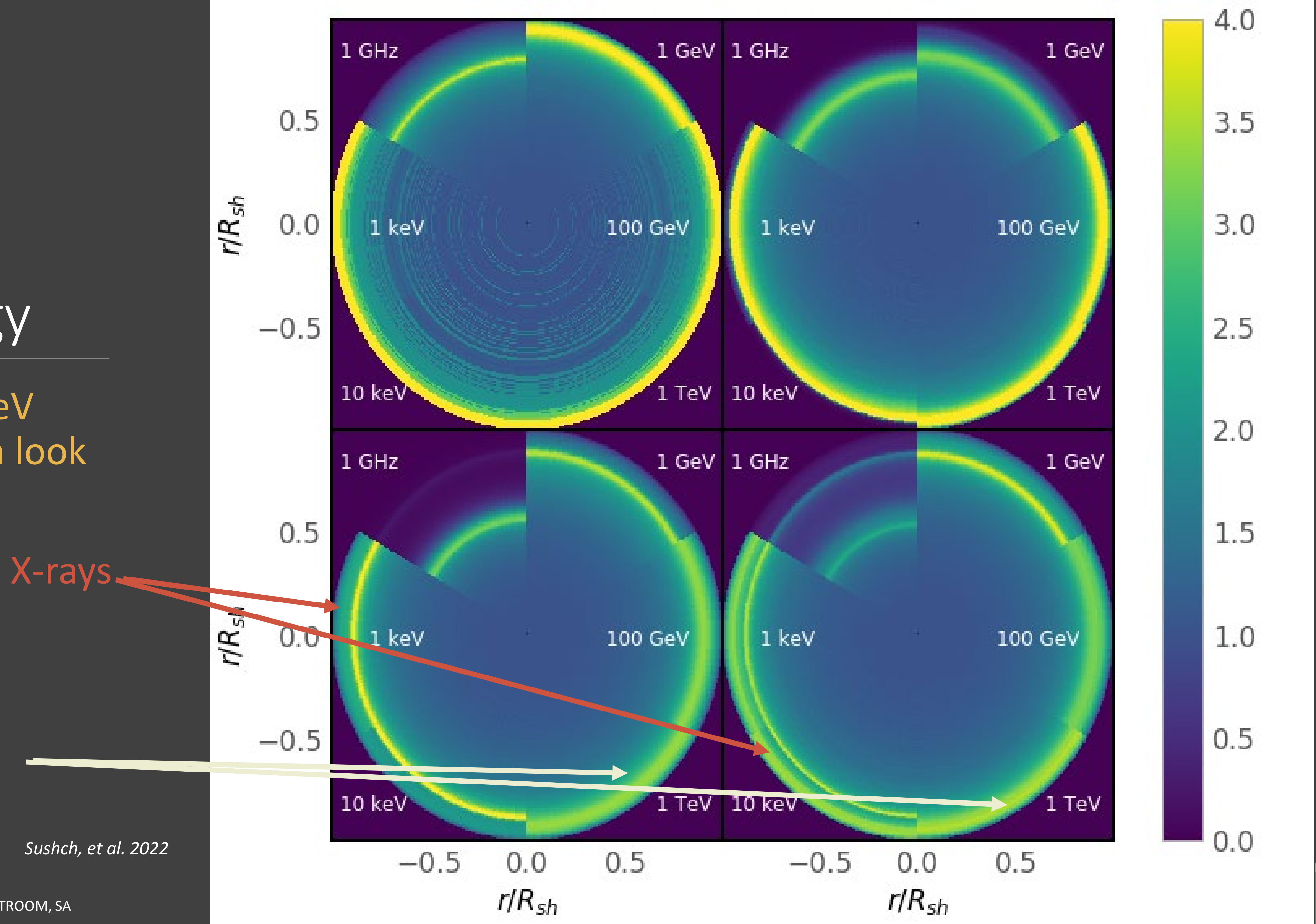
Sushch, et al. 2022

Spectra (RSG case)

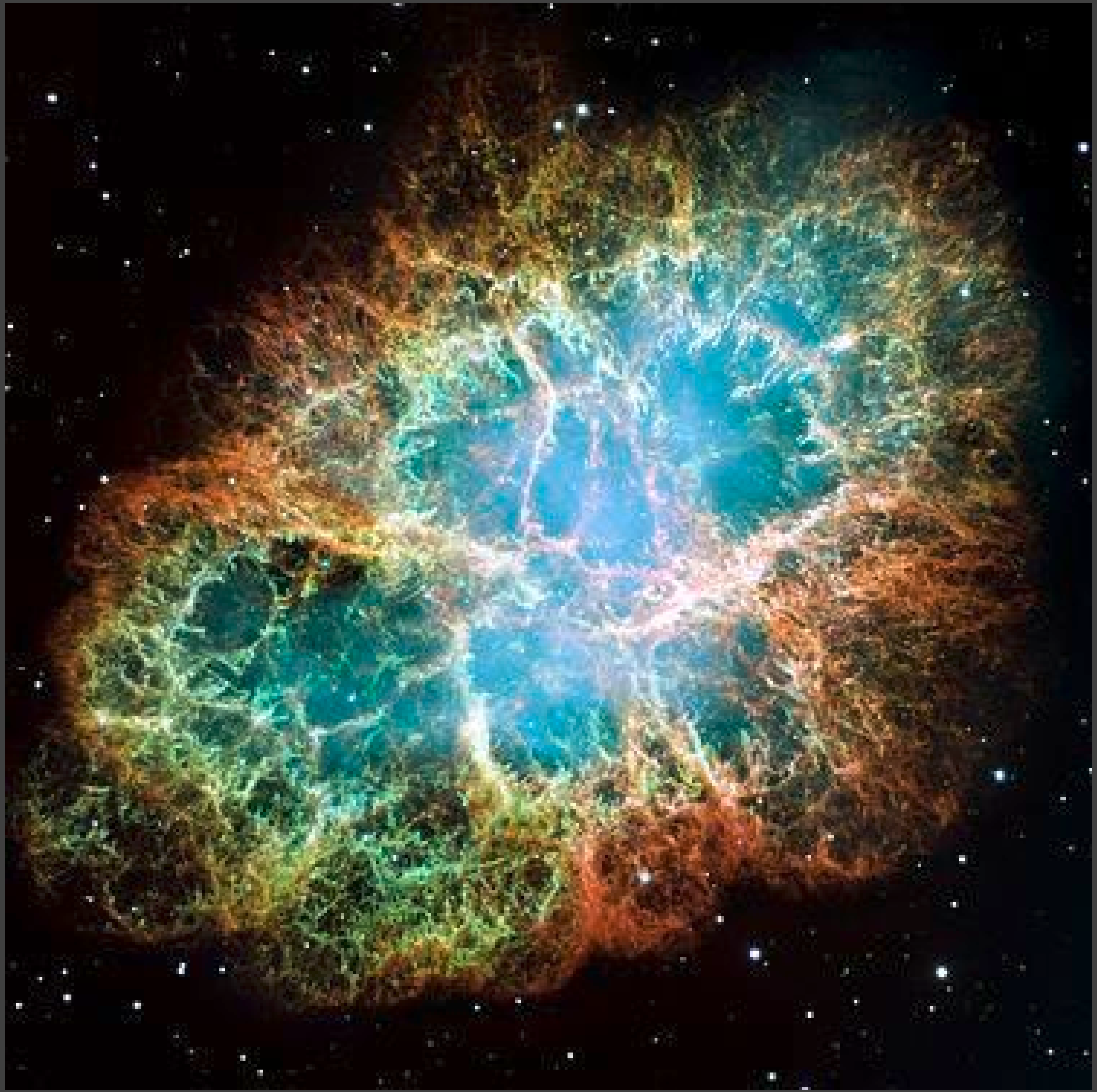
- Different populations of particles are created which are distinct in energy and location
- Strongly affects resulting emission spectra and not necessarily in the same way

Morphology

X-ray and and TeV morphology can look different

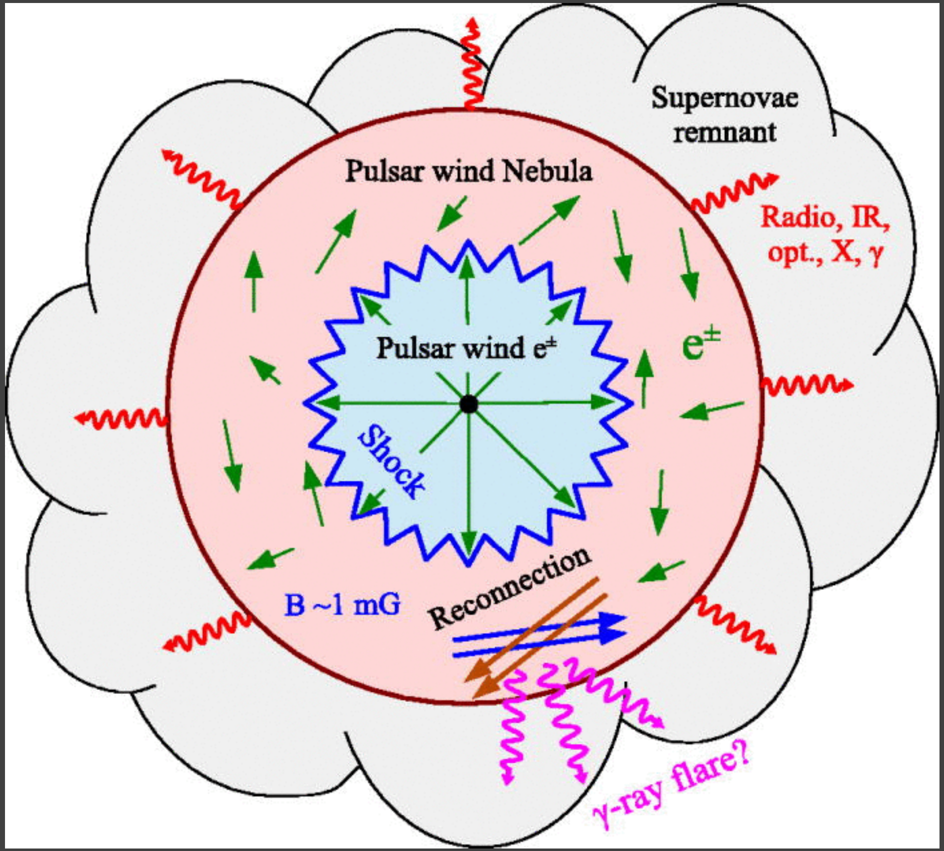


Sushch, et al. 2022



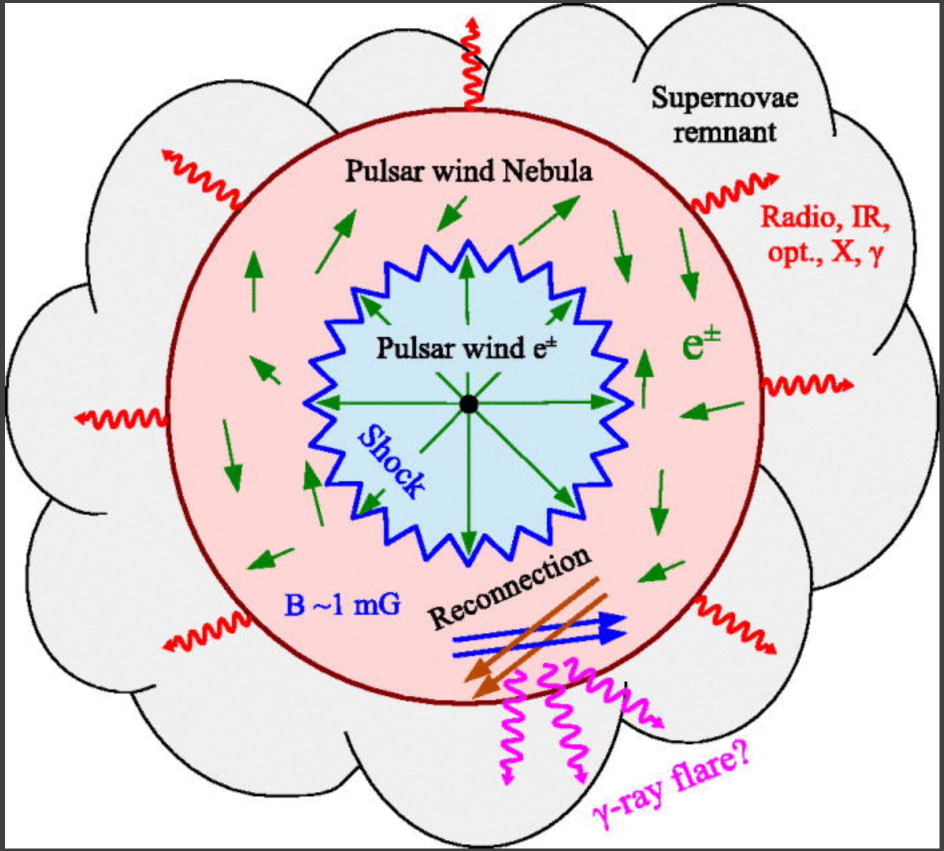
PULSAR WIND NEBULAE

PWNe. Morphology



- Pulsar keeps providing electrons and positrons in a form of wind
- Particles get further accelerated at the termination shock fill up the nebula
- In an ideal world should be nice and symmetric

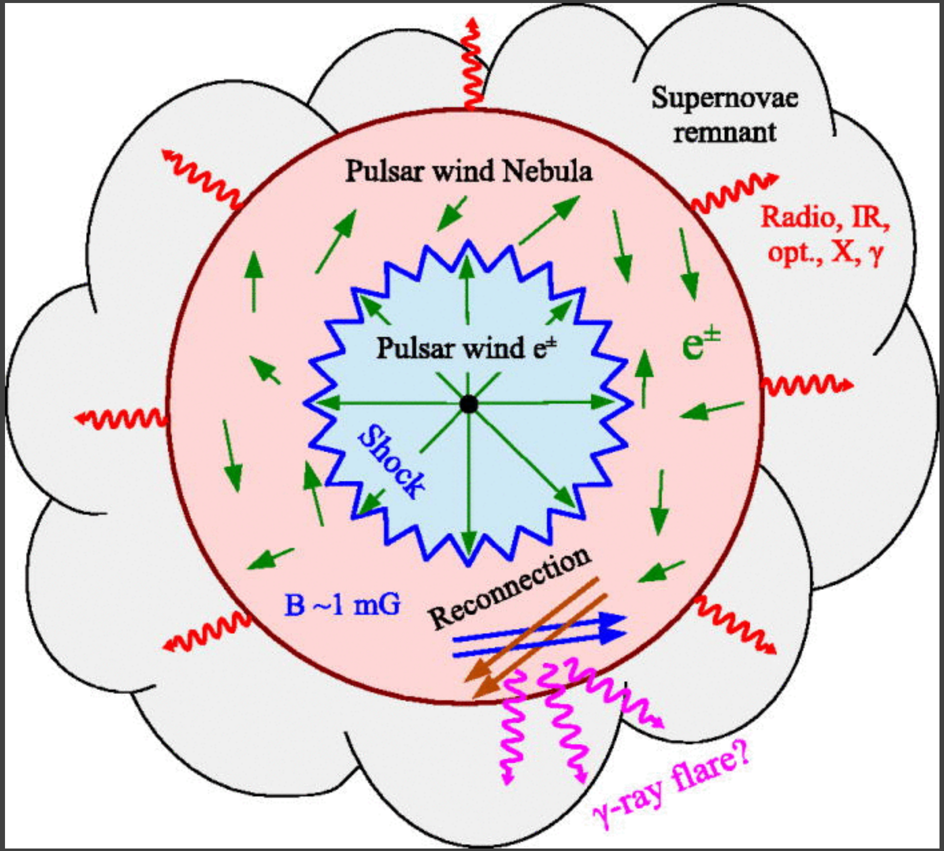
PWNe. Morphology



- Pulsar keeps providing electrons and positrons in a form of wind
- Particles get further accelerated at the termination shock fill up the nebula
- In an ideal world should be nice and symmetric

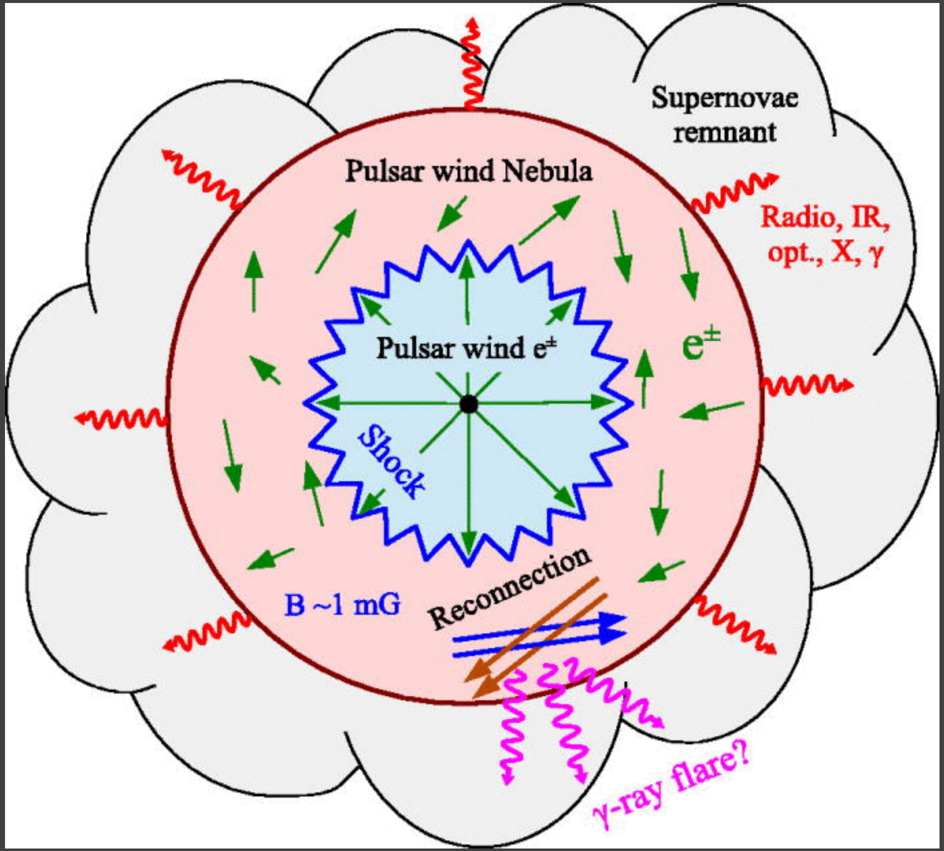
Crab Nebula

PWNe. Morphology



- Pulsar keeps providing electrons and positrons in a form of wind
- Particles get further accelerated at the termination shock fill up the nebula
- In an ideal world should be nice and symmetric
- Electrons will lose energy through synchrotron cooling as they diffuse away into the nebula

PWNe. Morphology

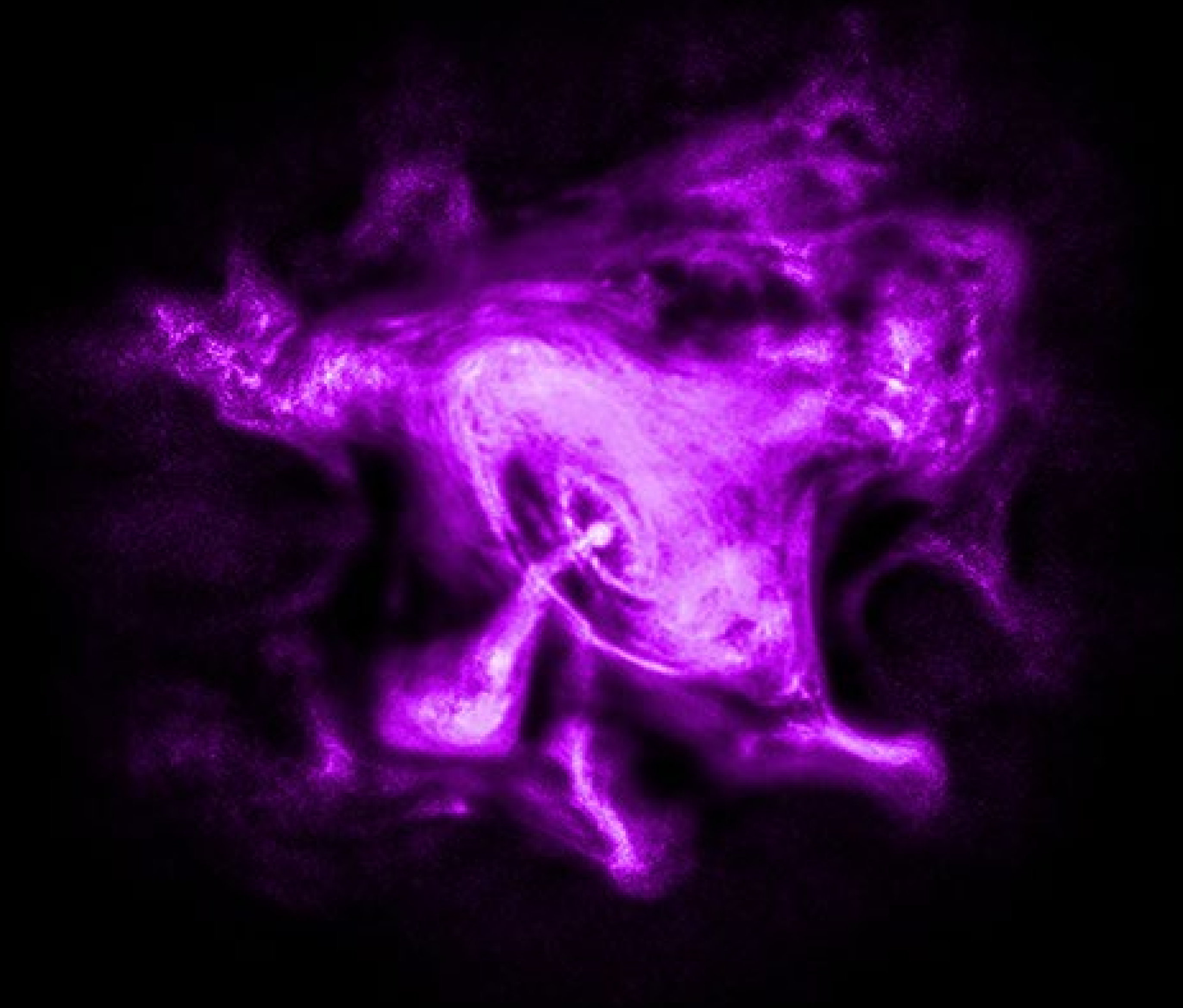


- Pulsar keeps providing electrons and positrons in a form of wind
- Particles get further accelerated at the termination shock fill up the nebula
- In an ideal world should be nice and symmetric
- Electrons will lose energy through synchrotron cooling as they diffuse away into the nebula
- We should see different things in radio and X-rays or in GeV and TeV

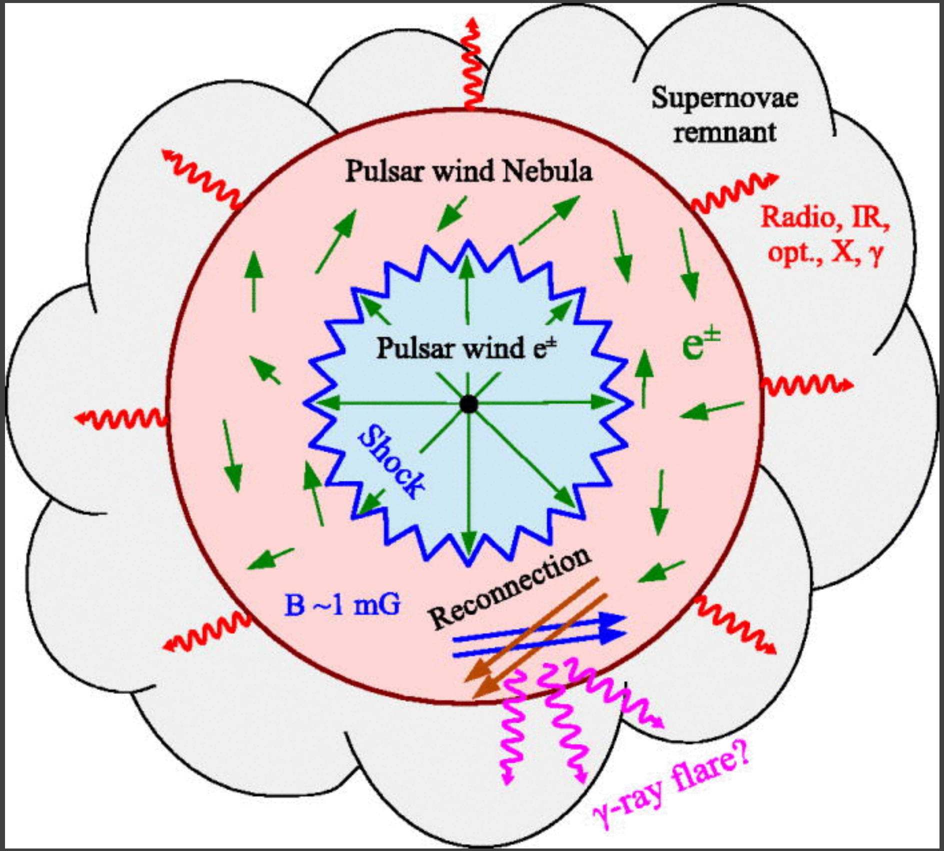

Composite image of the Crab Nebula
Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA/JPL/Caltech; Radio: NSF/NRAO/VLA; Ultraviolet: ESA/XMM-Newton

RADIO

X-RAY

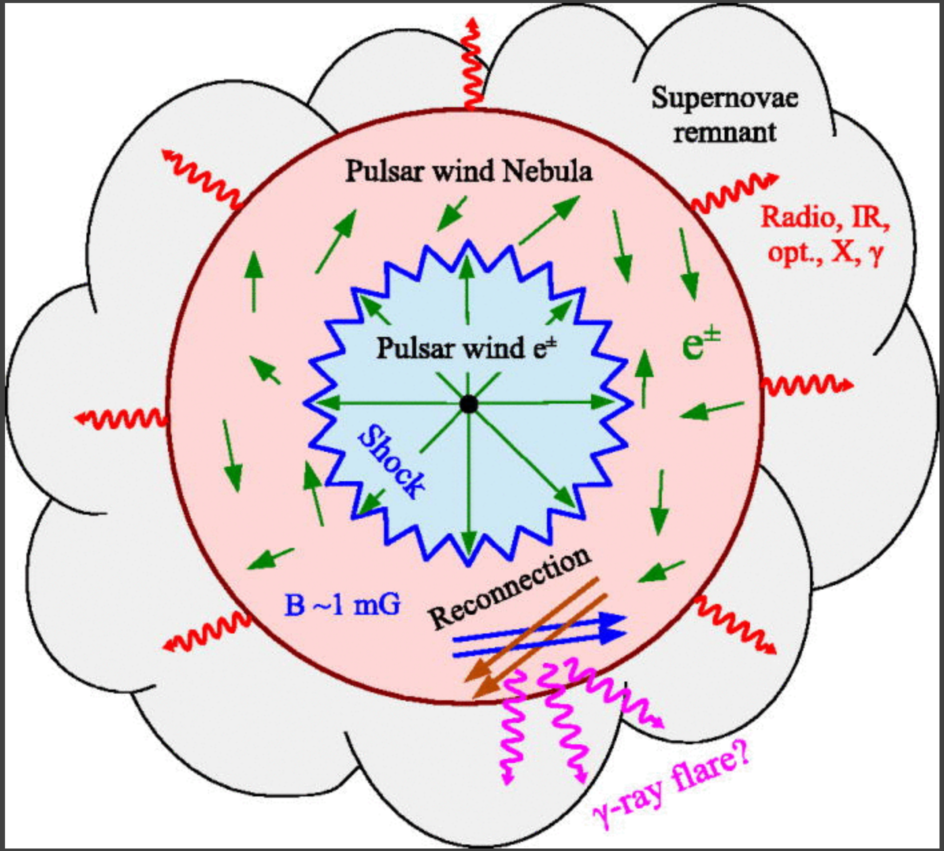


PWNe. Morphology



The world is not ideal!

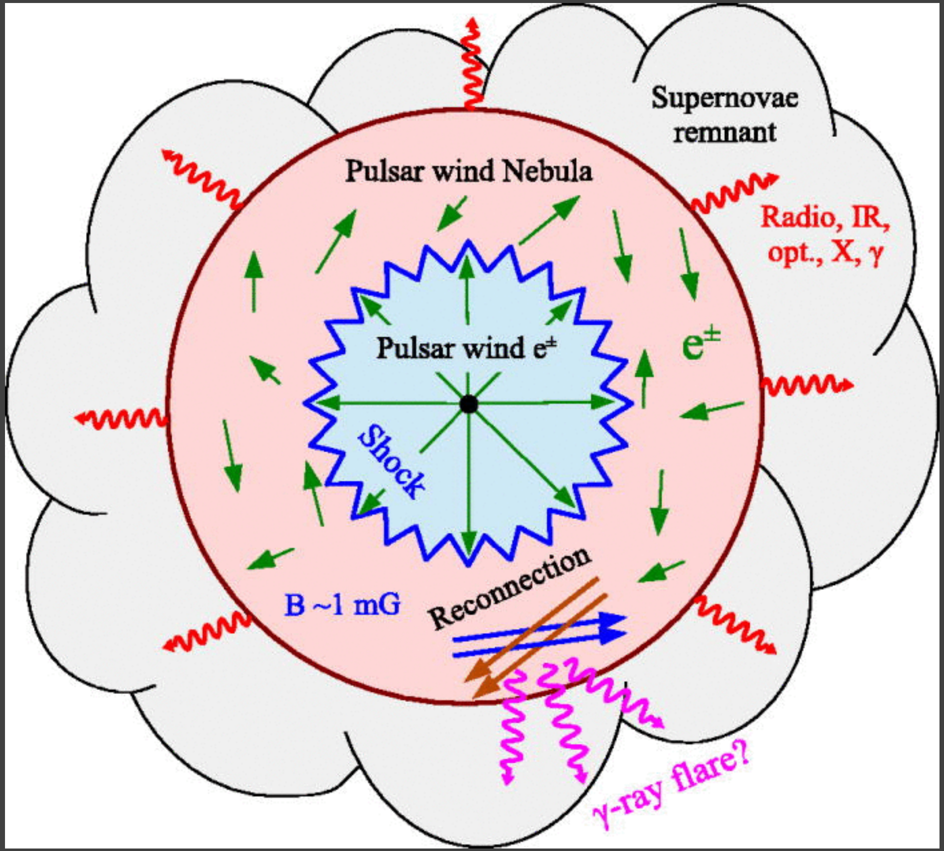
PWNe. Morphology



The world is not ideal!

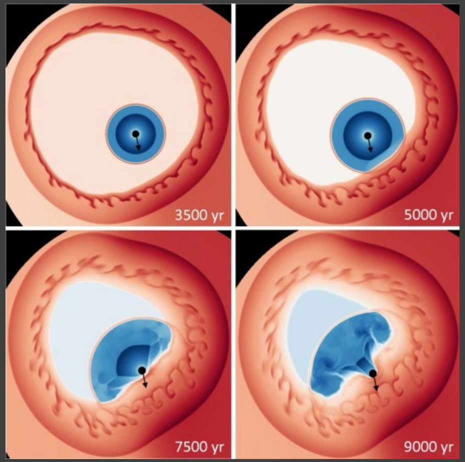
- Pulsar can move and quite fast

PWNe. Morphology

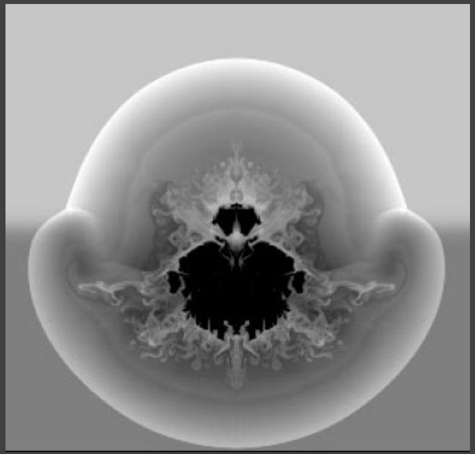


The world is not ideal!

- Pulsar can move and quite fast
- PWN can be crushed by the reverse shock of the SNR

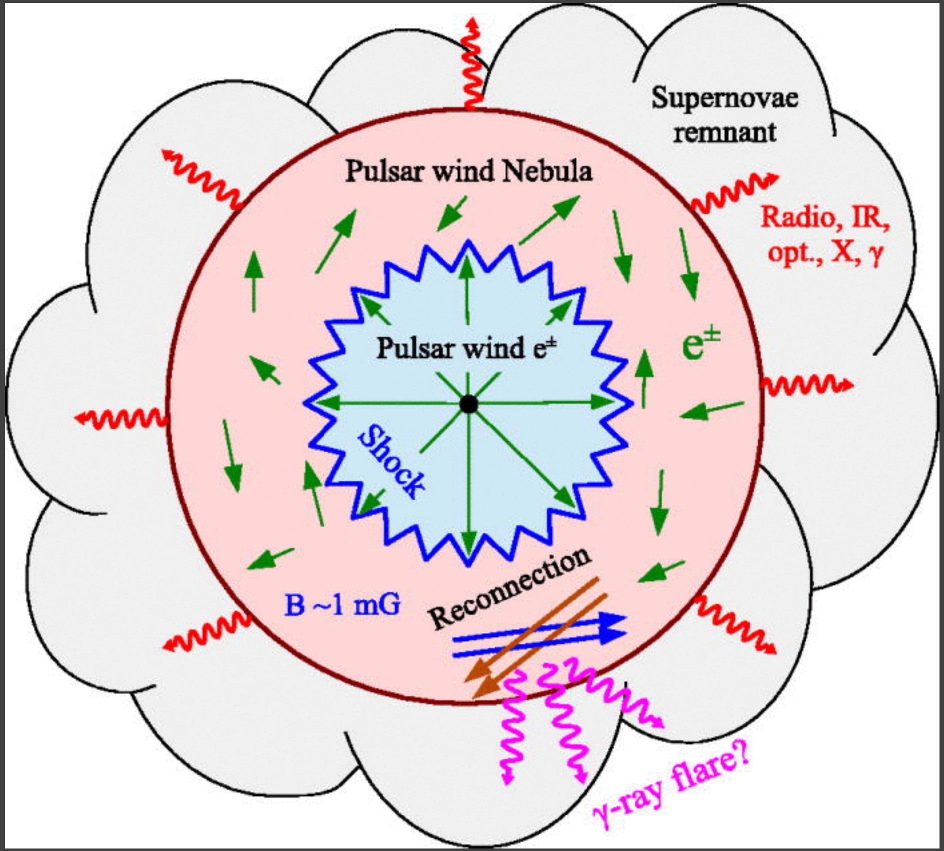


Pulsar in SNR MSH 15-56 (Temim et al. 2017)



Vela X (Blondin et al. 2001)

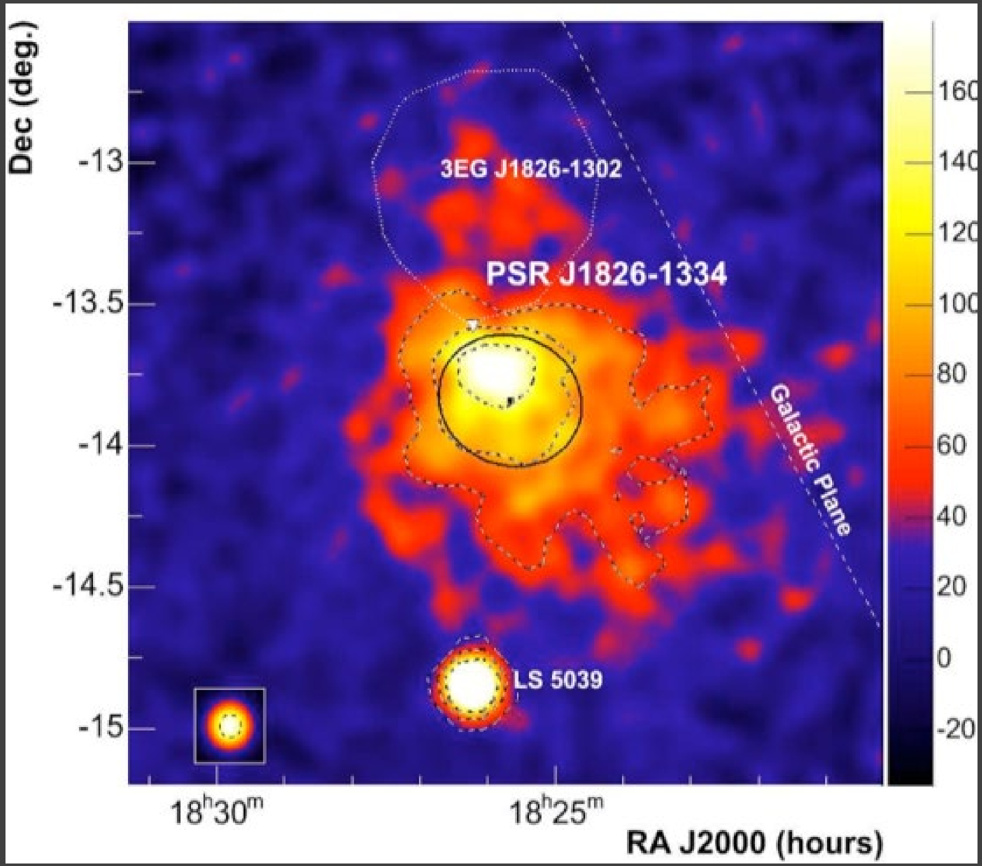
PWNe. Morphology



The world is not ideal!

- Pulsar can move and quite fast
- PWN can be crushed by the reverse shock of the SNR
- PWN can be completely destroyed as the pulsar leaves the SNR

PWNe. Morphology

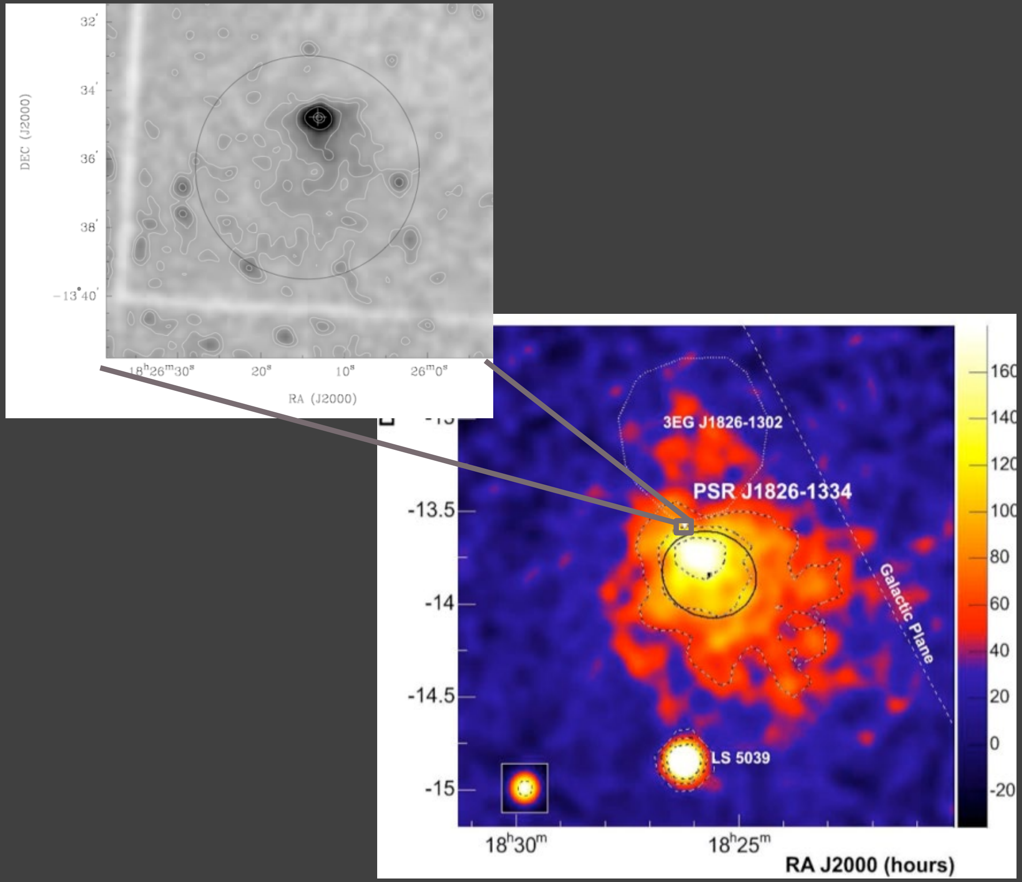


HESS J1825-137

- Very irregular shape
- Pulsar at the edge
- Peak emission not centred

TeV image of HESS J1825–137
Aharonian, et al. 2006

PWNe. Morphology

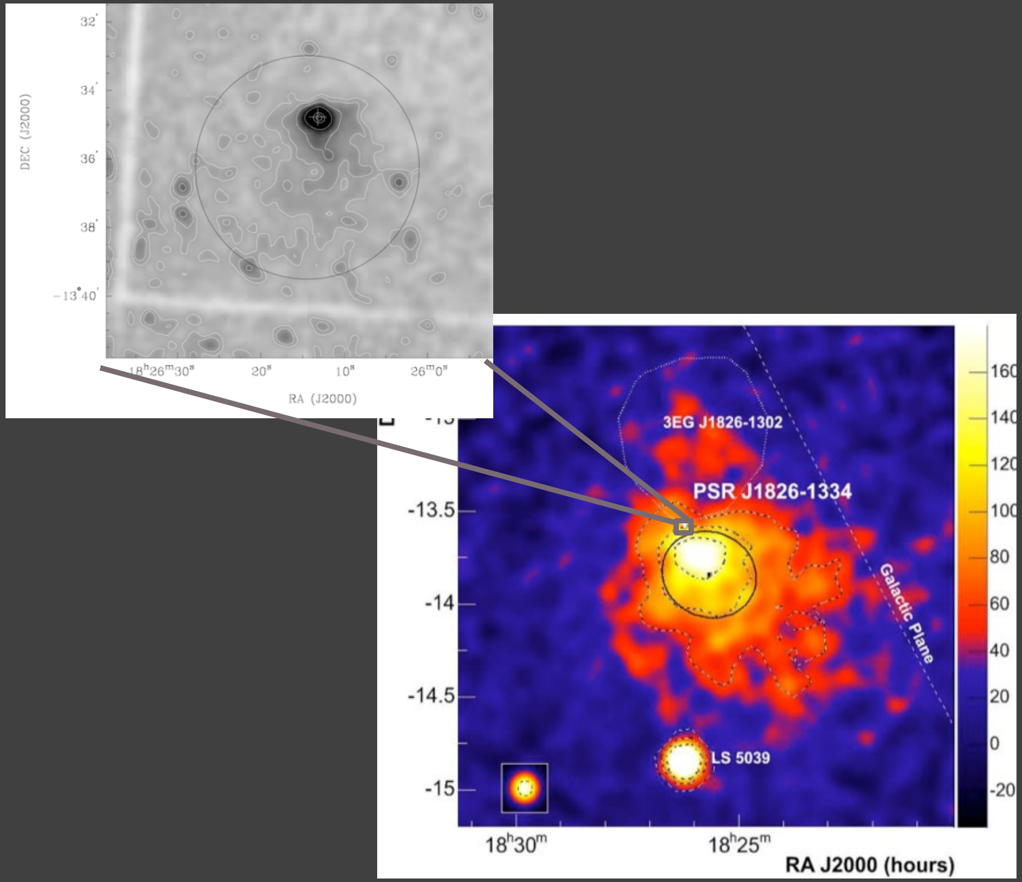


HESS J1825-137

- Very irregular shape
- Pulsar at the edge
- Peak emission not centred
- X-ray nebula is much much smaller

TeV image of HESS J1825–137
Aharonian, et al. 2006

PWNe. Morphology

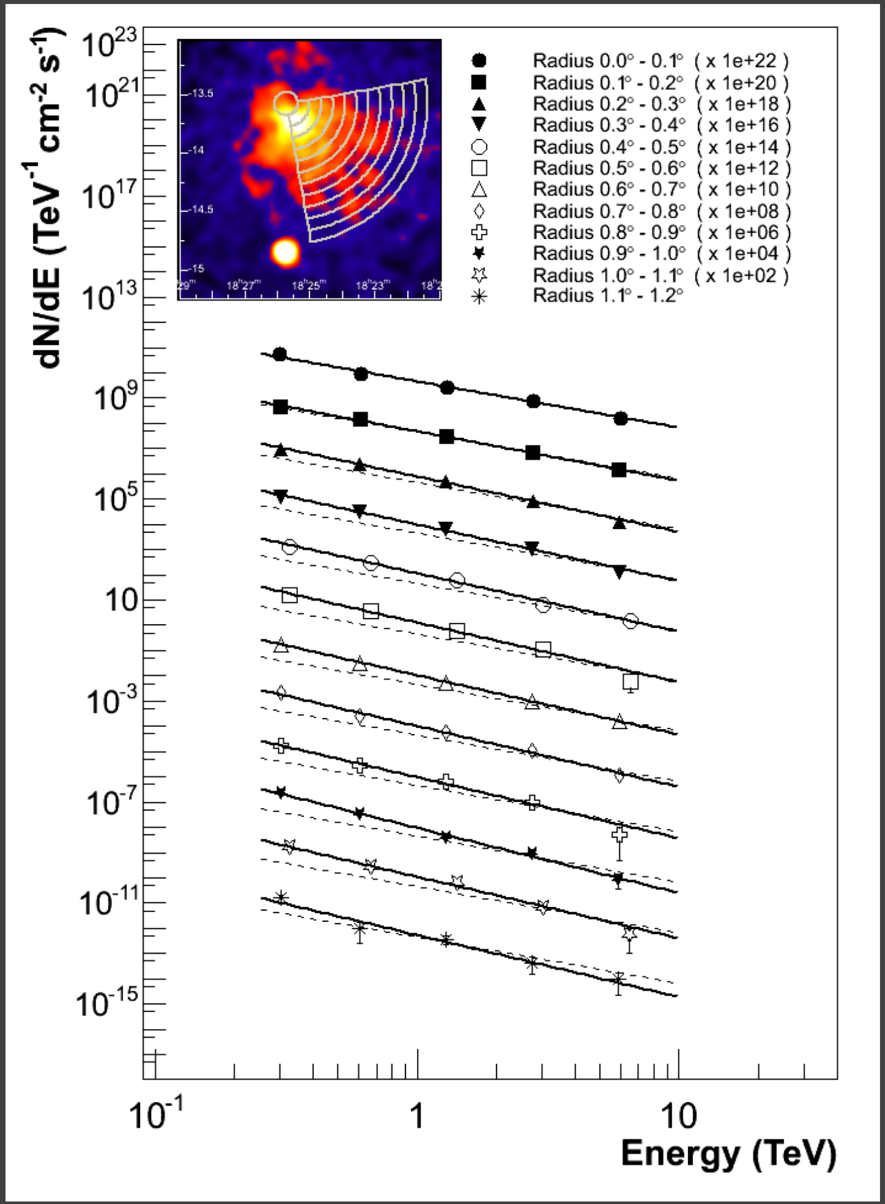


HESS J1825-137

- Very irregular shape
- Pulsar at the edge
- Peak emission not centred
- X-ray nebula is much much smaller

Most energetic electrons that produce X-rays are close to the pulsar

TeV image of HESS J1825–137
Aharonian, et al. 2006



Energy dependent morphology (H.E.S.S.)

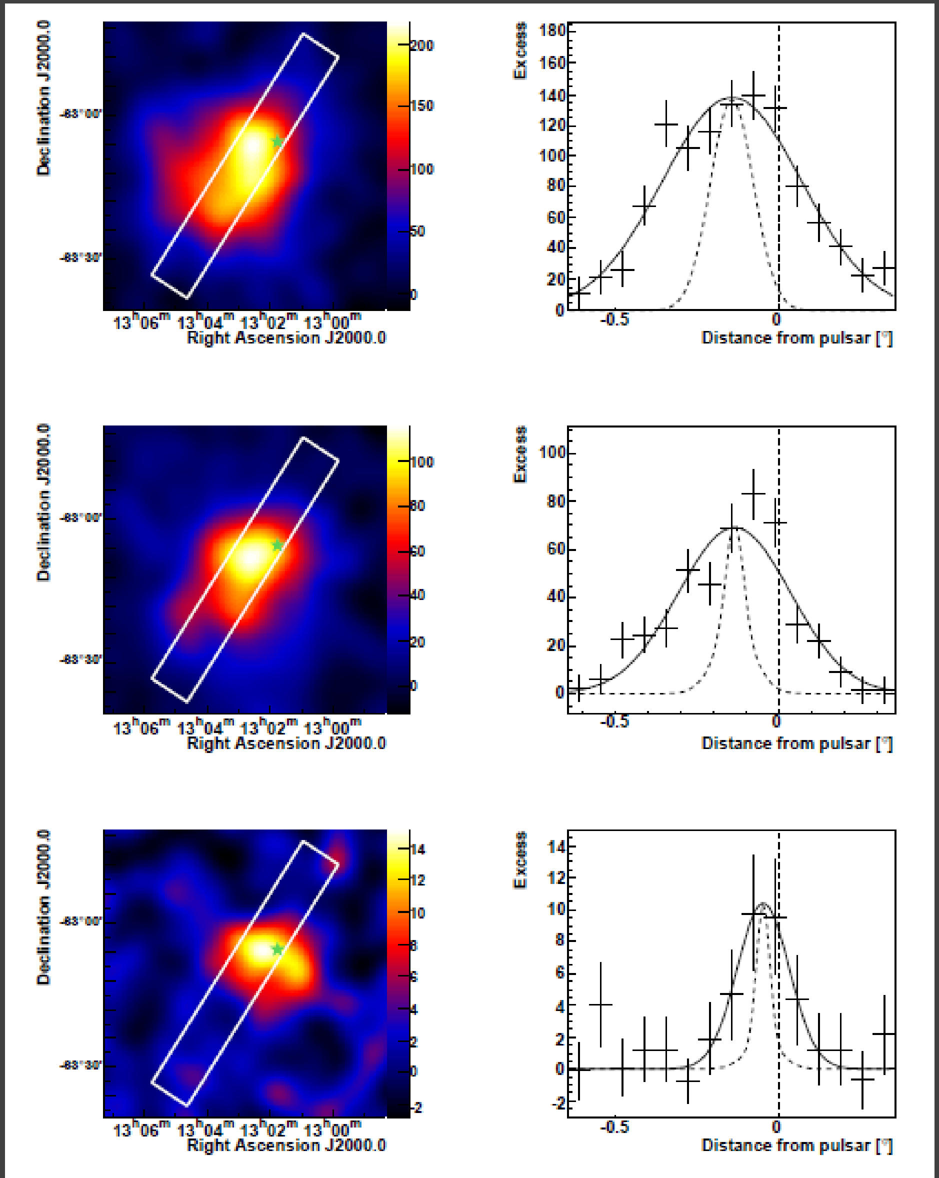
The gamma-ray spectrum softens with the distance from the pulsar meaning there are less high-energy photons and therefore less energetic electrons to produce them

Aharonian, et al. 2006

< 2 TeV

2-10 TeV

>10 TeV

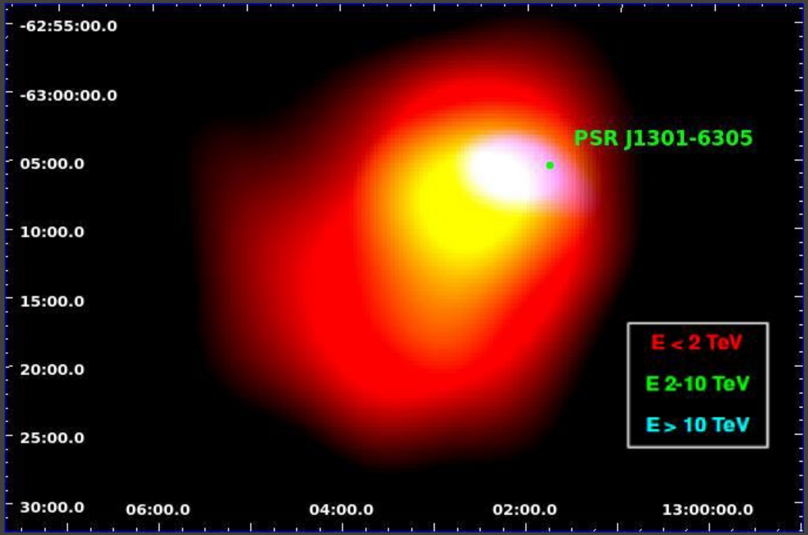


Energy dependent morphology (H.E.S.S.)

The case of HESS J1303-631

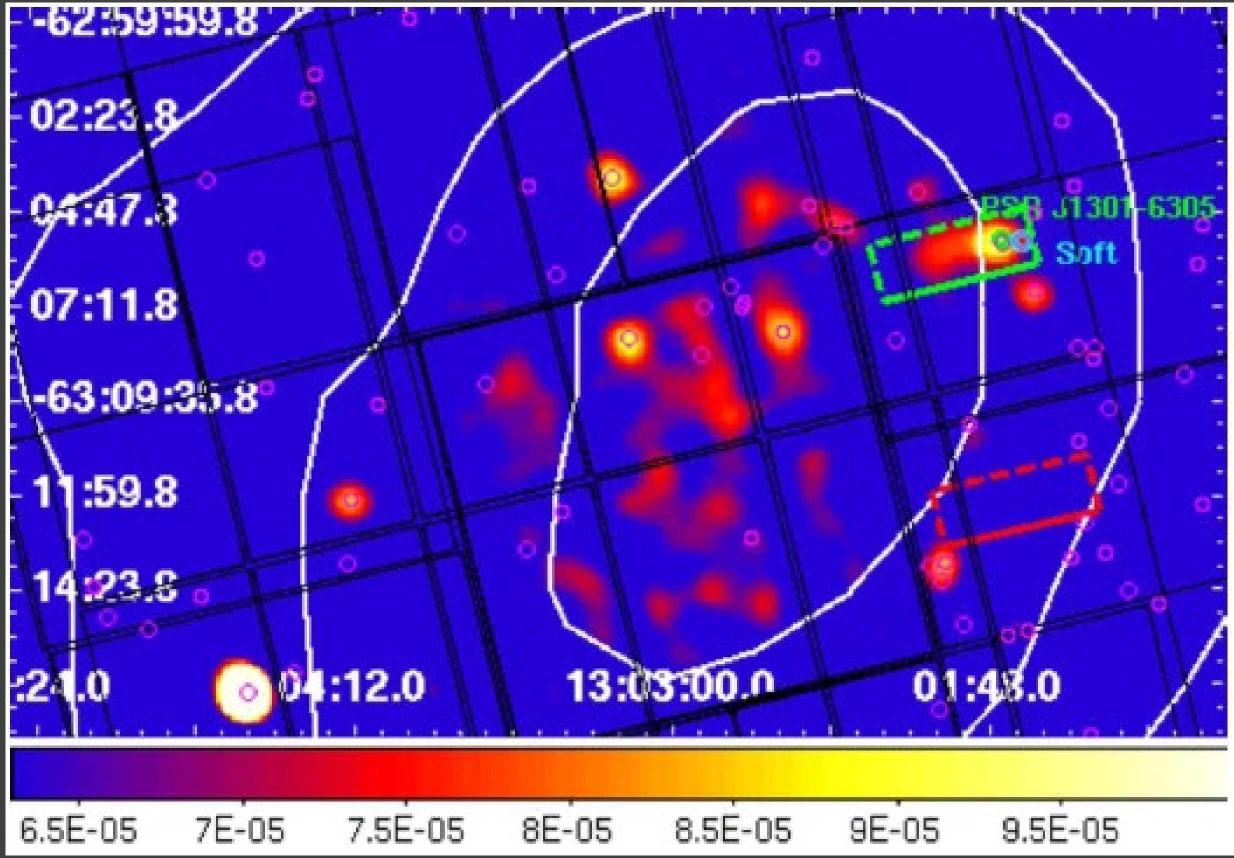
Maximum energy decreases as you move farther from the pulsar

HESS J1303-631
H.E.S.S. Collaboration 2012

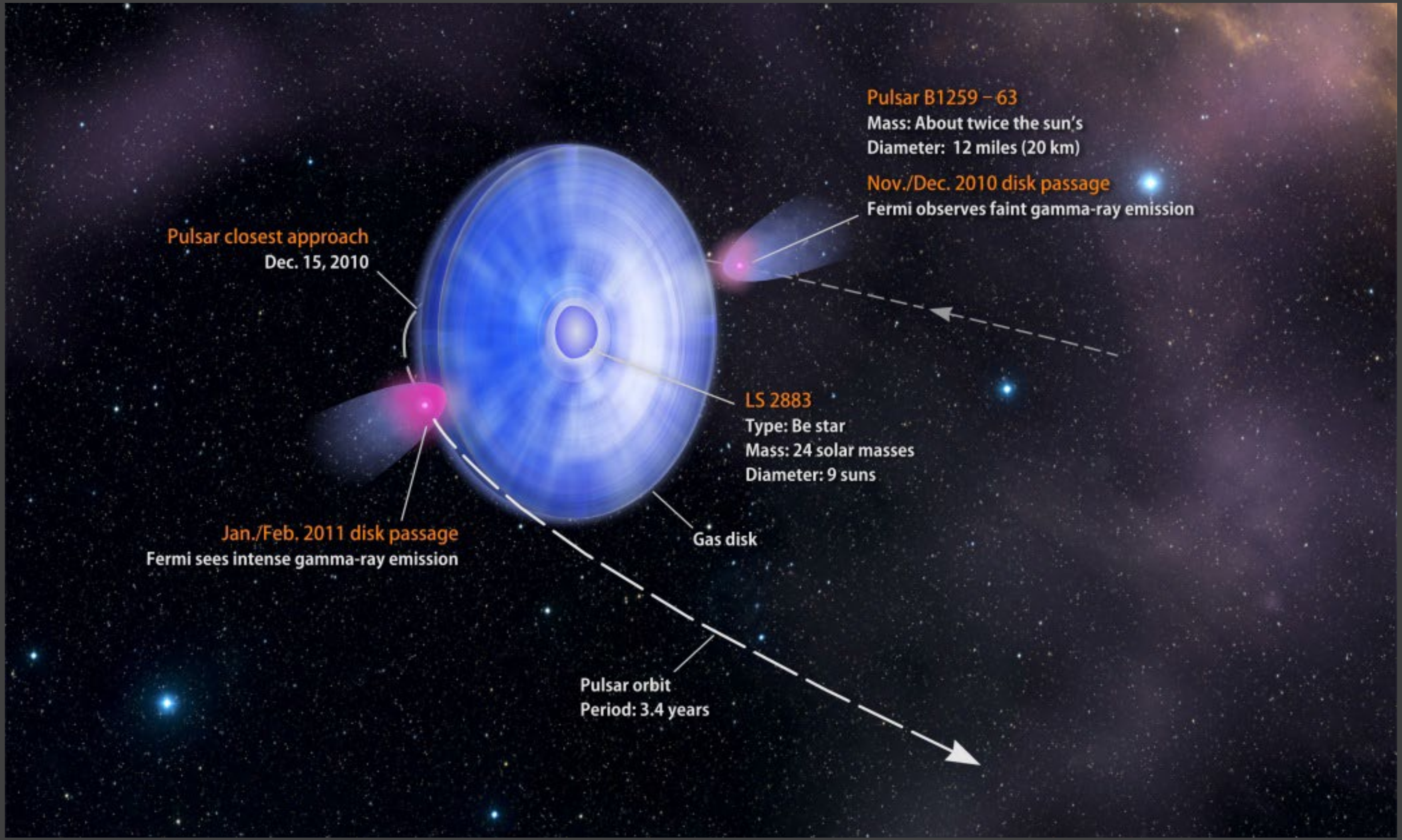


X-ray/TeV HESS J1303-631

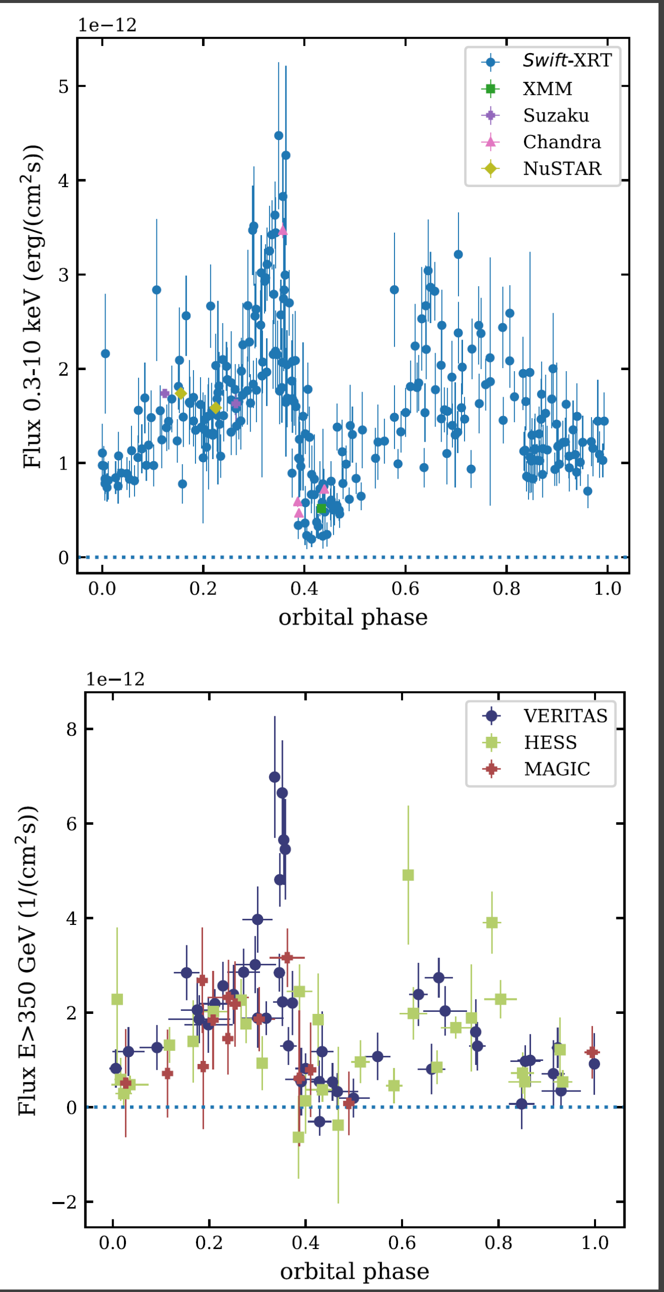
Much smaller X-ray PWN
with a tail that could indicate
pulsar's proper motion



XMM-Newton map with overlaid
H.E.S.S. contours
H.E.S.S. Collaboration 2012



GAMMA-RAY BINARIES

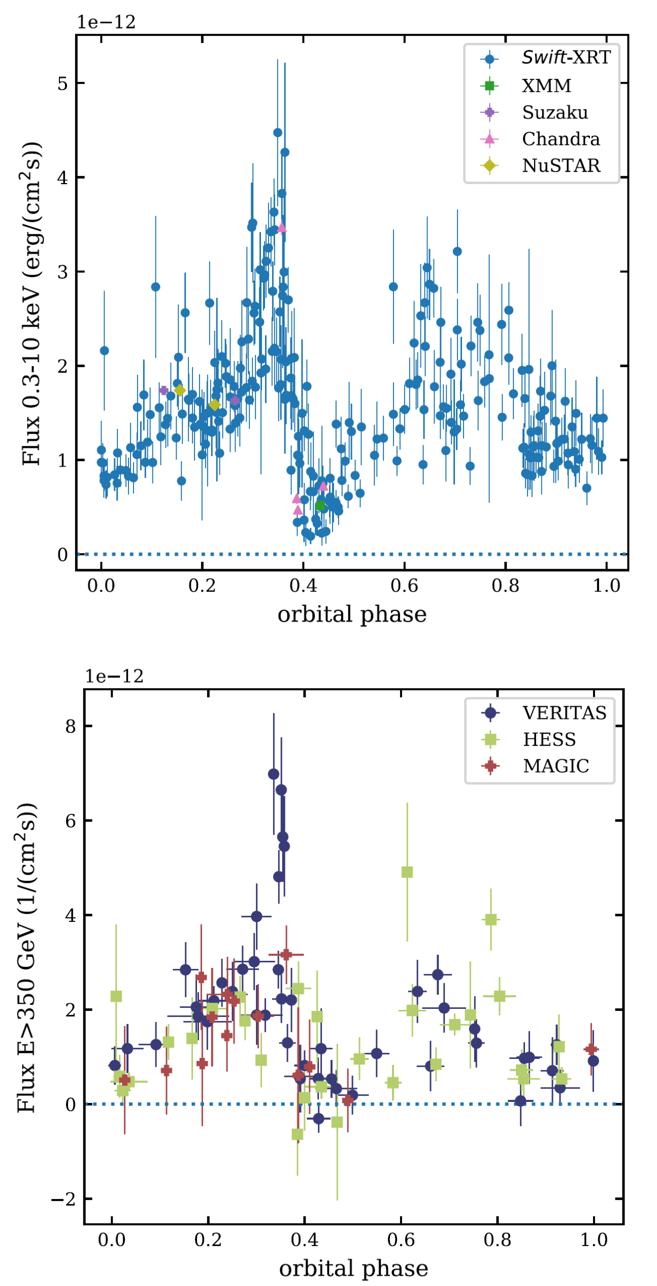


Light curves.
X-ray/TeV correlation

HESS J0632+057

- Very nice correlation of X-ray and TeV emission
  - Both are determined by the number of accelerated electrons rather than magnetic field and target photon field?
  - Conditions (magnetic field, target photon field) for radiation change in the same way for both synchrotron and inverse Compton?

Adams et al., 2021



Adams et al., 2021

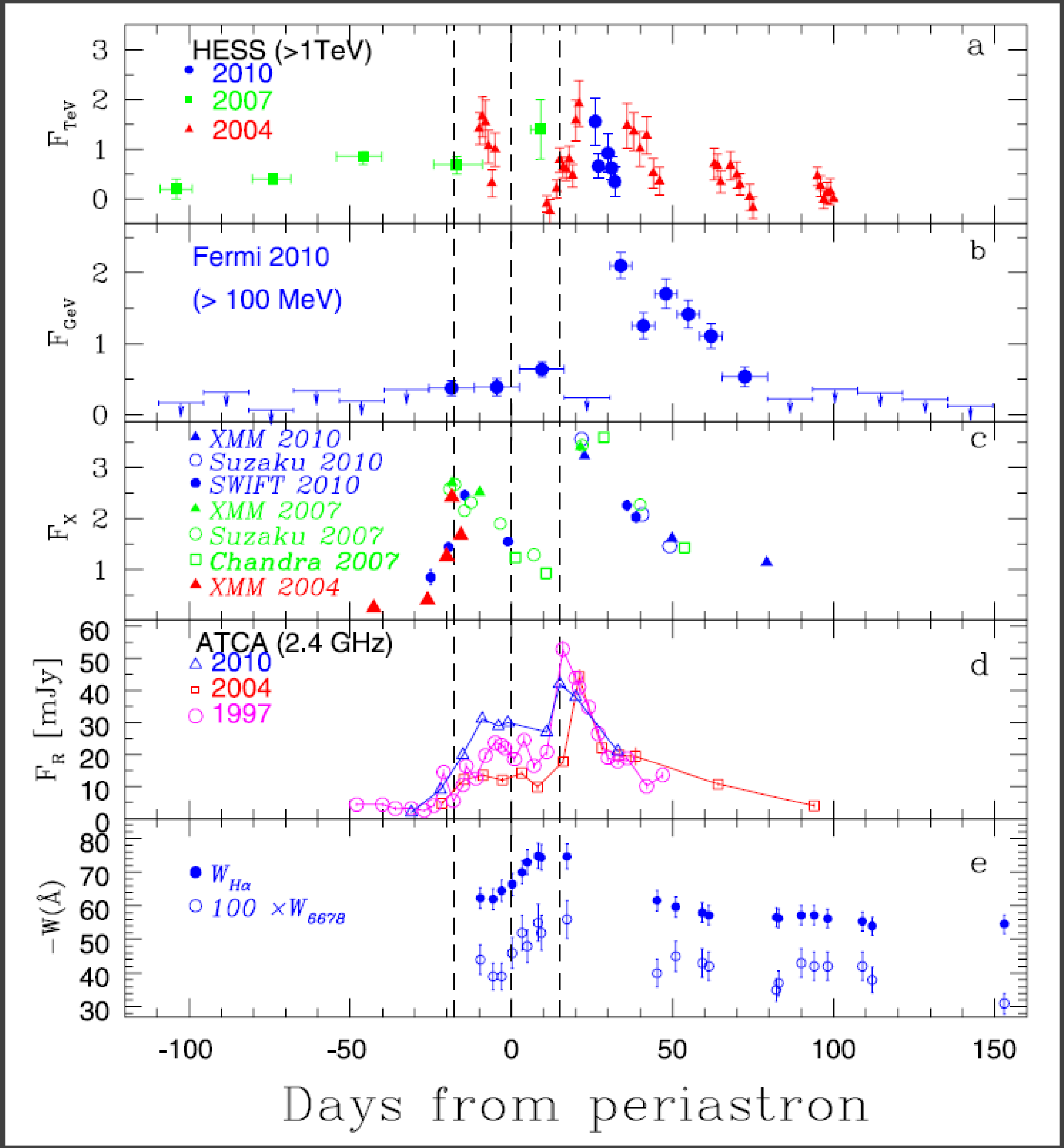
Light curves. X-ray/TeV correlation

HESS J0632+057

- Very nice correlation of X-ray and TeV emission
  - Both are determined by the number of accelerated electrons rather than magnetic field and target photon field?
  - Conditions (magnetic field, target photon field) for radiation change in the same way for both synchrotron and inverse Compton?

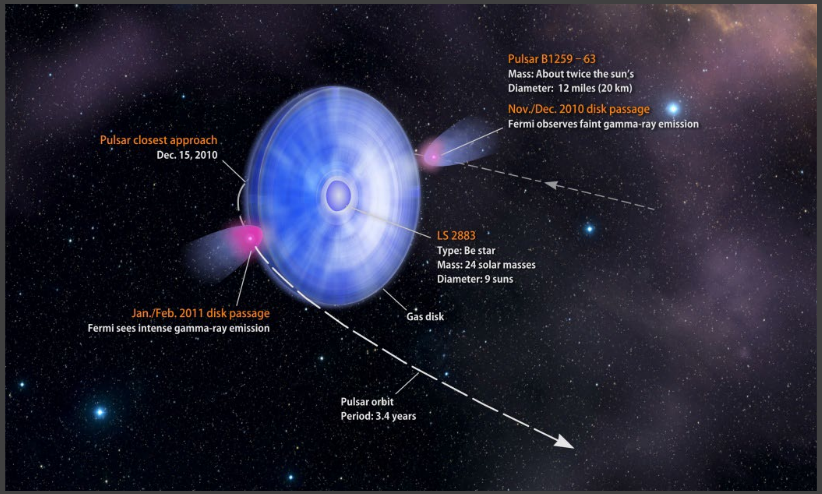
Not completely clear whether correlation should be expected or not, because conditions might change in a different way, e.g. due to the circumstellar disc

PSR B1259-63



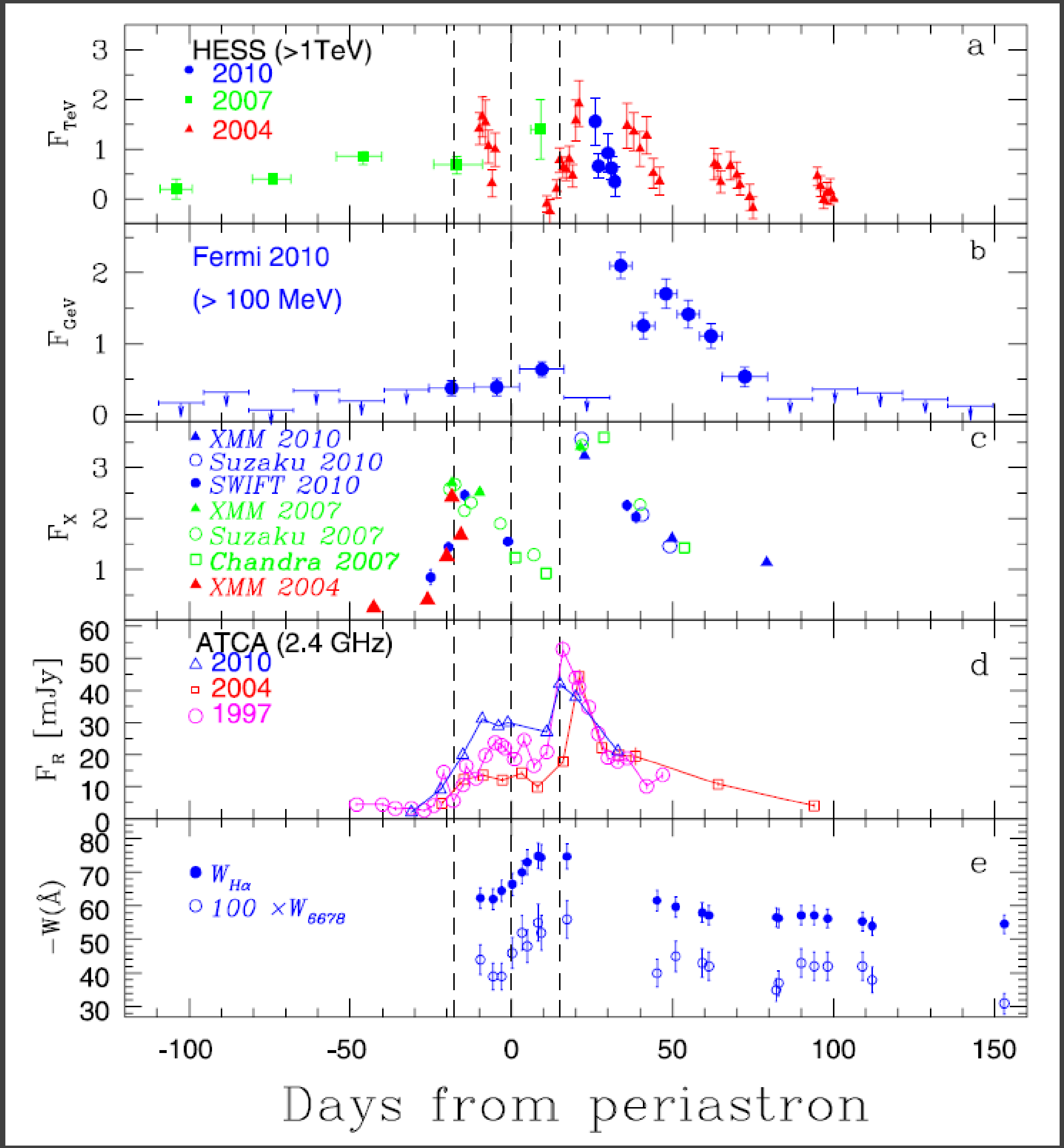
Chernyakova et al., 2014

- X-ray peaks coincide with disc crossings
  - Makes sense – magnetic field should be larger
- TeV peaks seem to correlate with X-rays
  - Not clear why, because maximum emission is naively expected where pulsar is the closest to the star

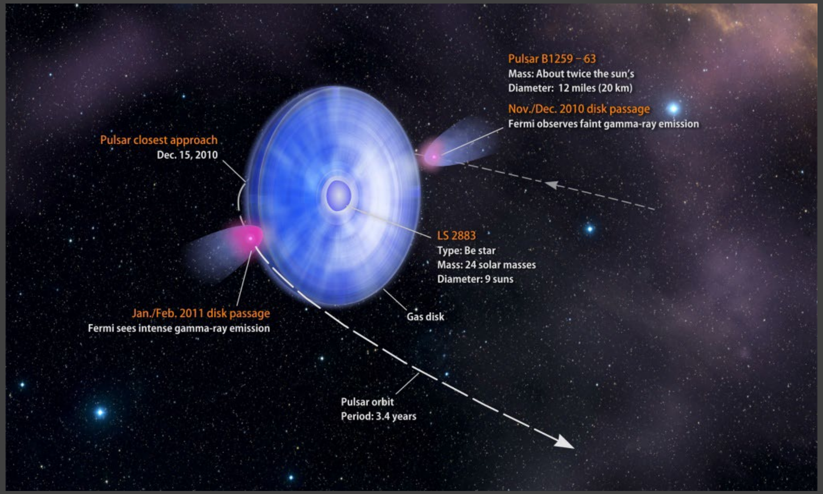


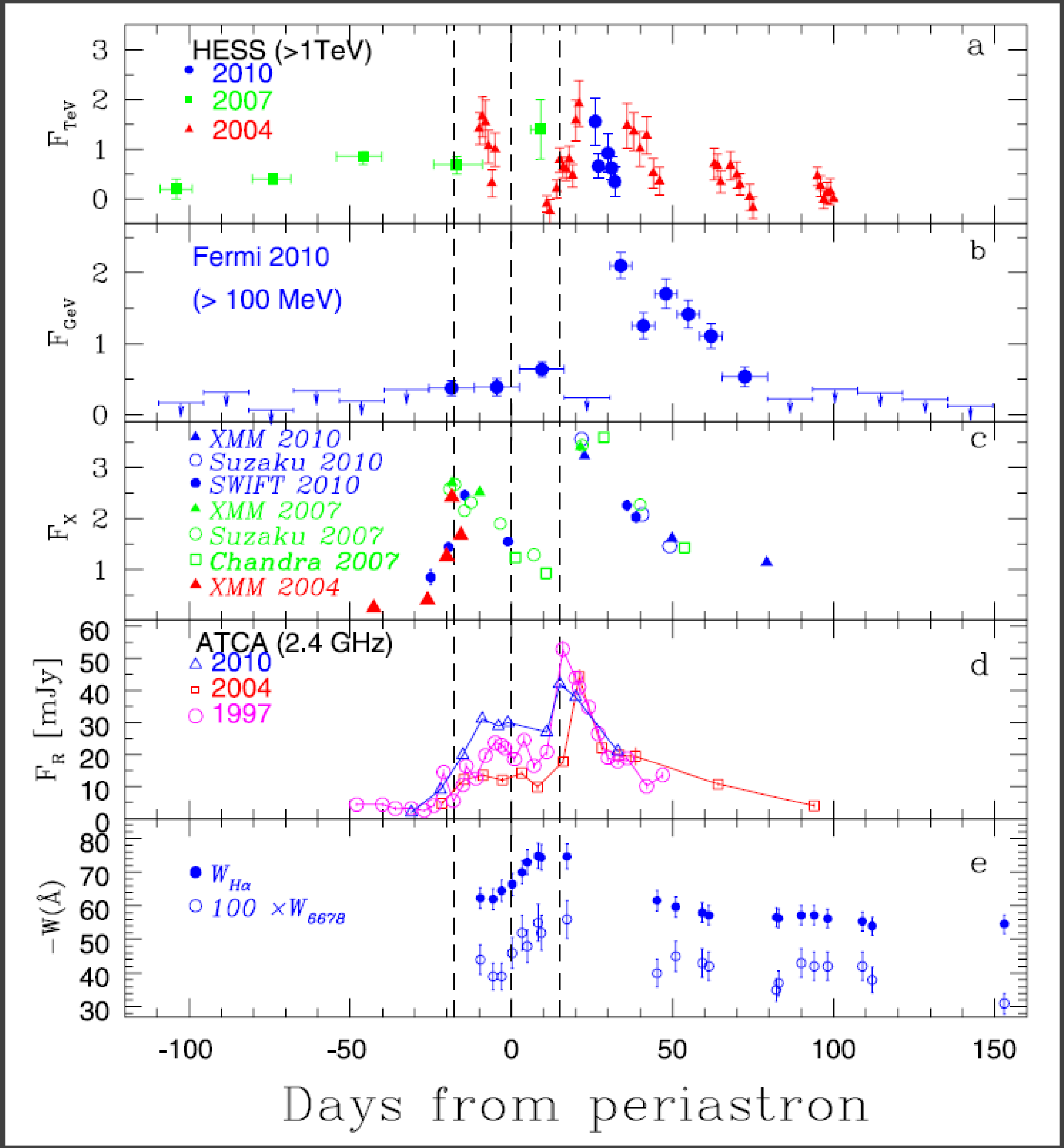
PSR B1259-63

Correlation is the coincidence?



Chernyakova et al., 2014



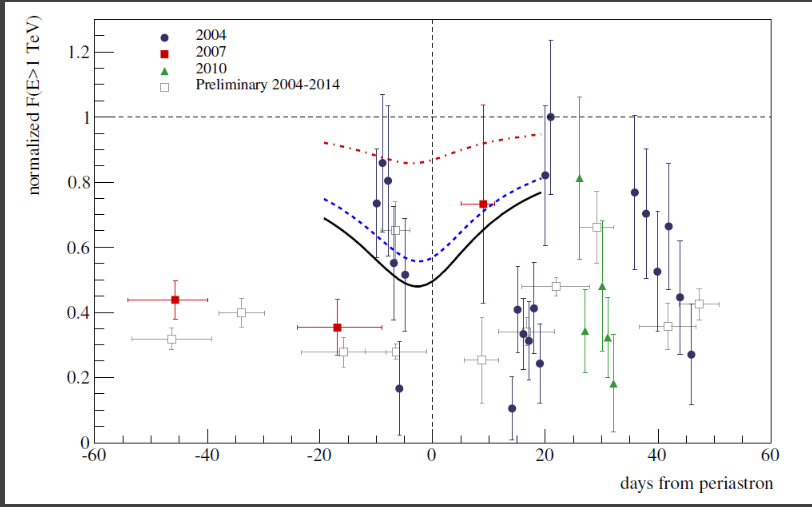


Chernyakova et al., 2014

PSR B1259-63

Correlation is the coincidence?

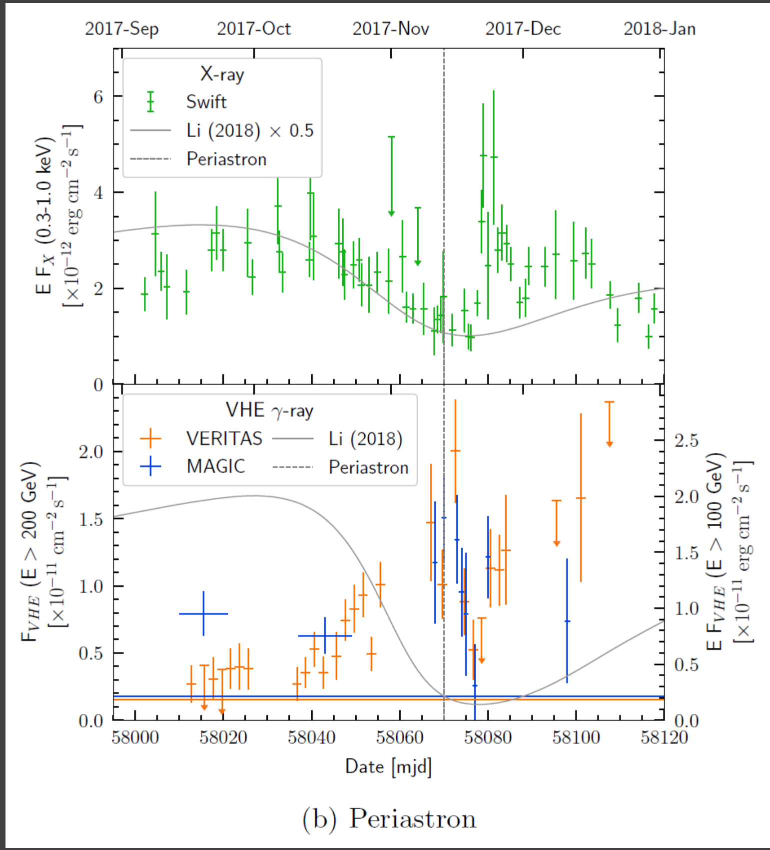
- Gamma-ray decrease at periastron due to gamma-gamma absorption
- X-rays increase at disc crossings due to the increase of the magnetic field



Sushch & van Soelen, 2017

PSR J2032 + 4127/MT91 213. No Correlation

- No correlation between X-rays and gamma-rays
  - Gamma-rays peak at periastron
  - X-rays have a dip at periastron

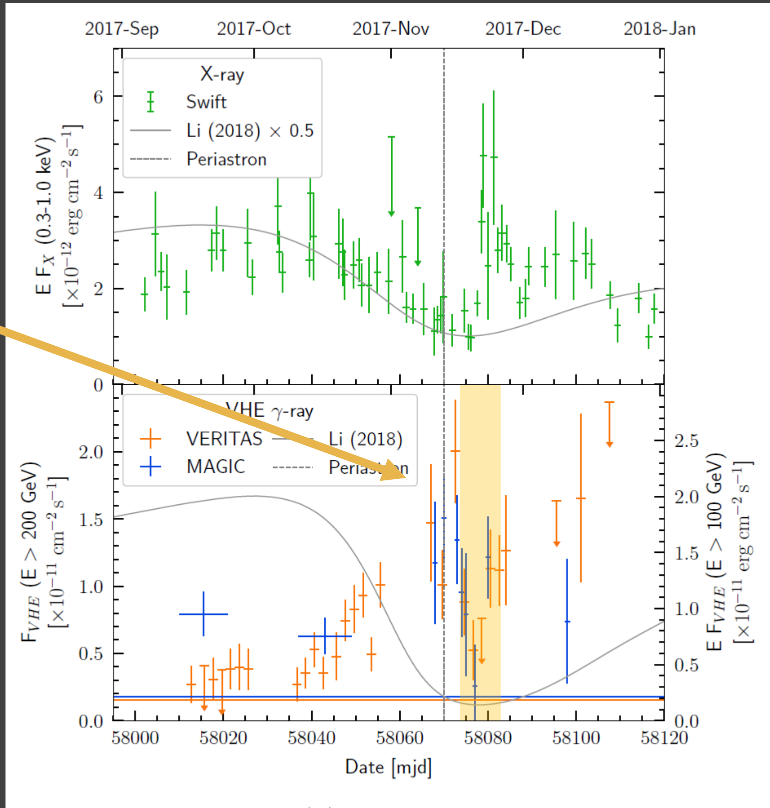


(b) Periastron

VERITAS & MAGIC, 2018

PSR J2032 + 4127/MT91 213. No Correlation

- No correlation between X-rays and gamma-rays
  - Gamma-rays peak at periastron
  - X-rays have a dip at periastron
- Gamma-gamma absorption seems to be strongest where gamma-rays dip
  - A bit uncertain because orbital solutions are quite uncertain



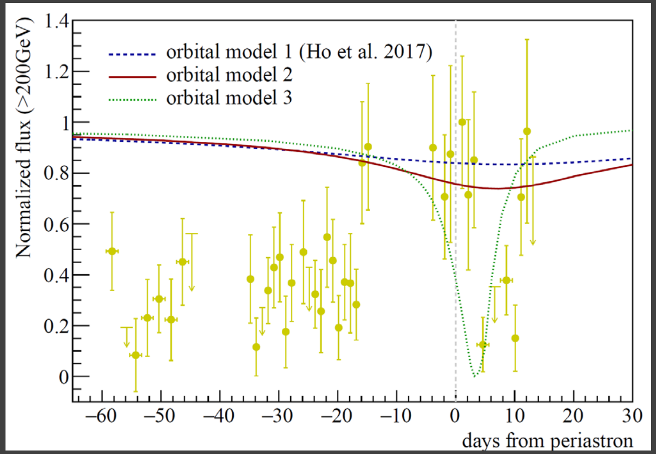
(b) Periastron

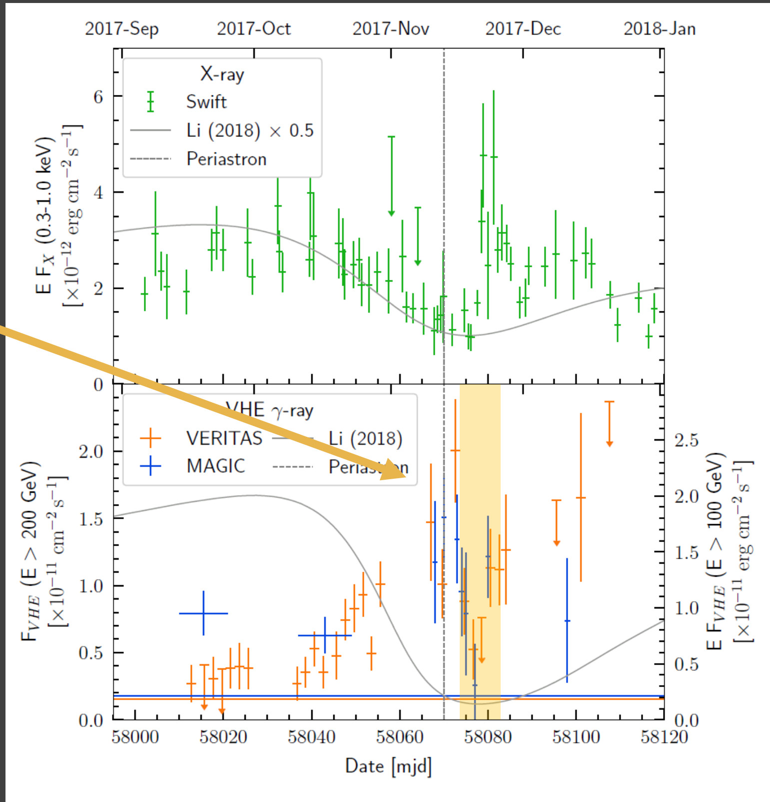
VERITAS & MAGIC, 2018

PSR J2032 + 4127/MT91 213. No Correlation

- No correlation between X-rays and gamma-rays
  - Gamma-rays peak at periastron
  - X-rays have a dip at periastron
- Gamma-gamma absorption seems to be strongest where gamma-rays dip
  - A bit uncertain because orbital solutions are quite uncertain

Sushch&van Soelen (in prep.)



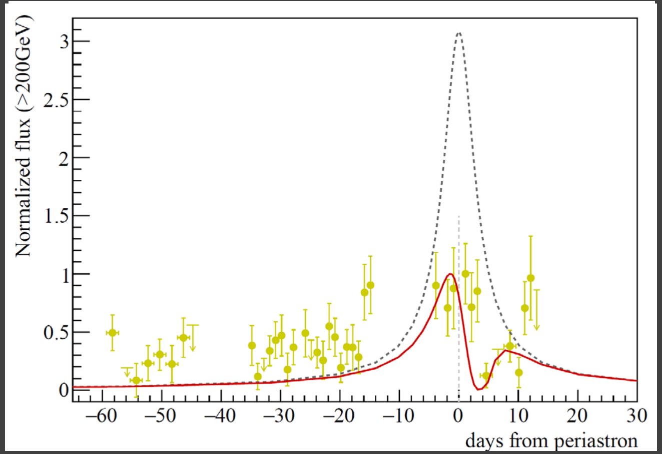


(b) Periastron

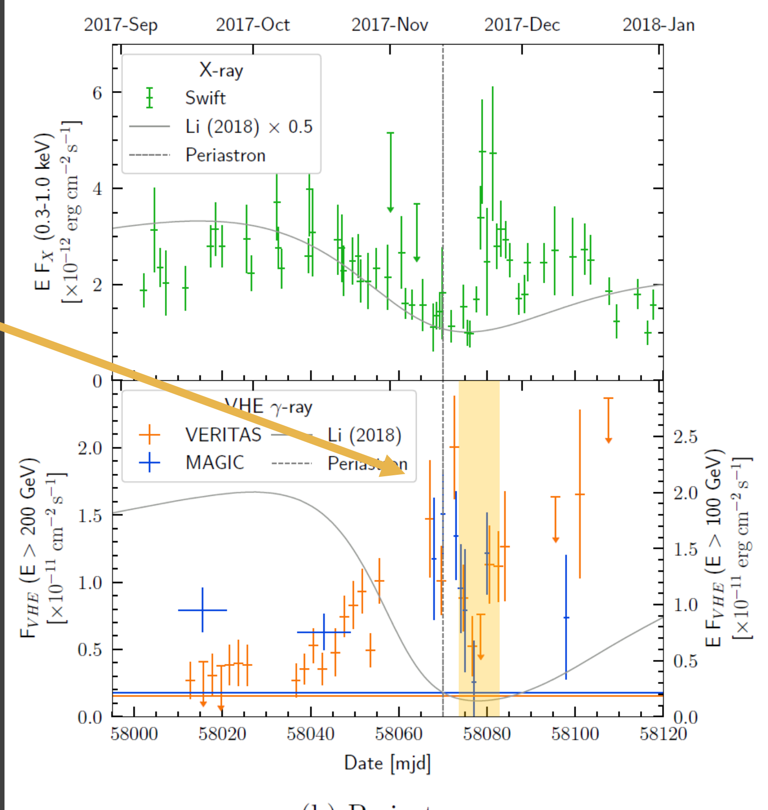
VERITAS & MAGIC, 2018

PSR J2032 + 4127/MT91 213. No Correlation

- No correlation between X-rays and gamma-rays
  - Gamma-rays peak at periastron
  - X-rays have a dip at periastron
- Gamma-gamma absorption seems to be strongest where gamma-rays dip
  - A bit uncertain because orbital solutions are quite uncertain



Sushch&van Soelen (in prep.)



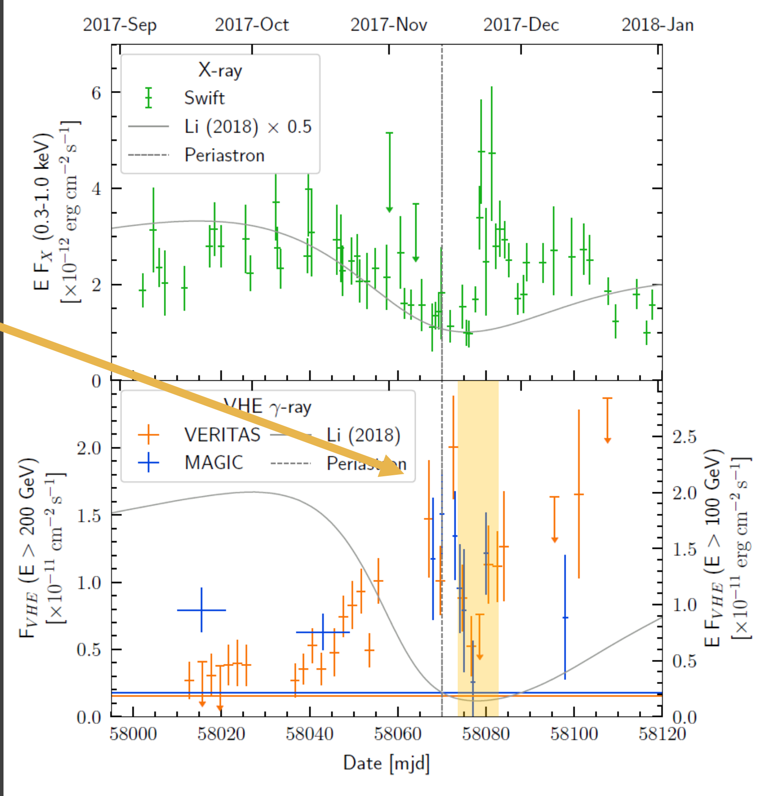
(b) Periastron

VERITAS & MAGIC, 2018

PSR J2032 + 4127/MT91 213. No Correlation

- No correlation between X-rays and gamma-rays
  - Gamma-rays peak at periastron
  - X-rays have a dip at periastron
- Gamma-gamma absorption seems to be strongest where gamma-rays dip
  - A bit uncertain because orbital solutions are quite uncertain

The orbital period is about 50 years – much longer than other sources, so maybe we just see it better resolved and can spot the difference?



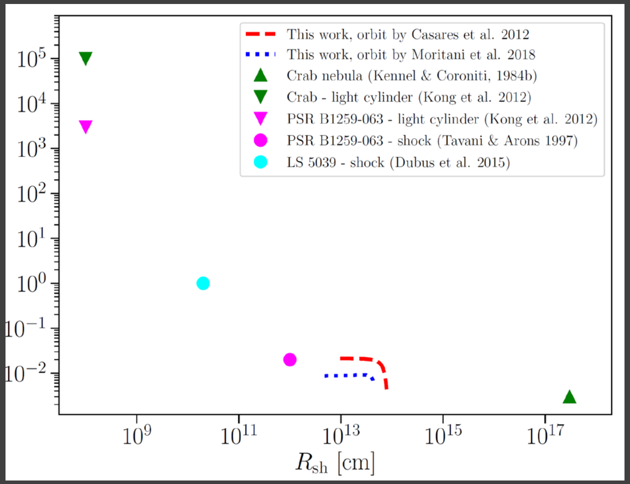
(b) Periastron

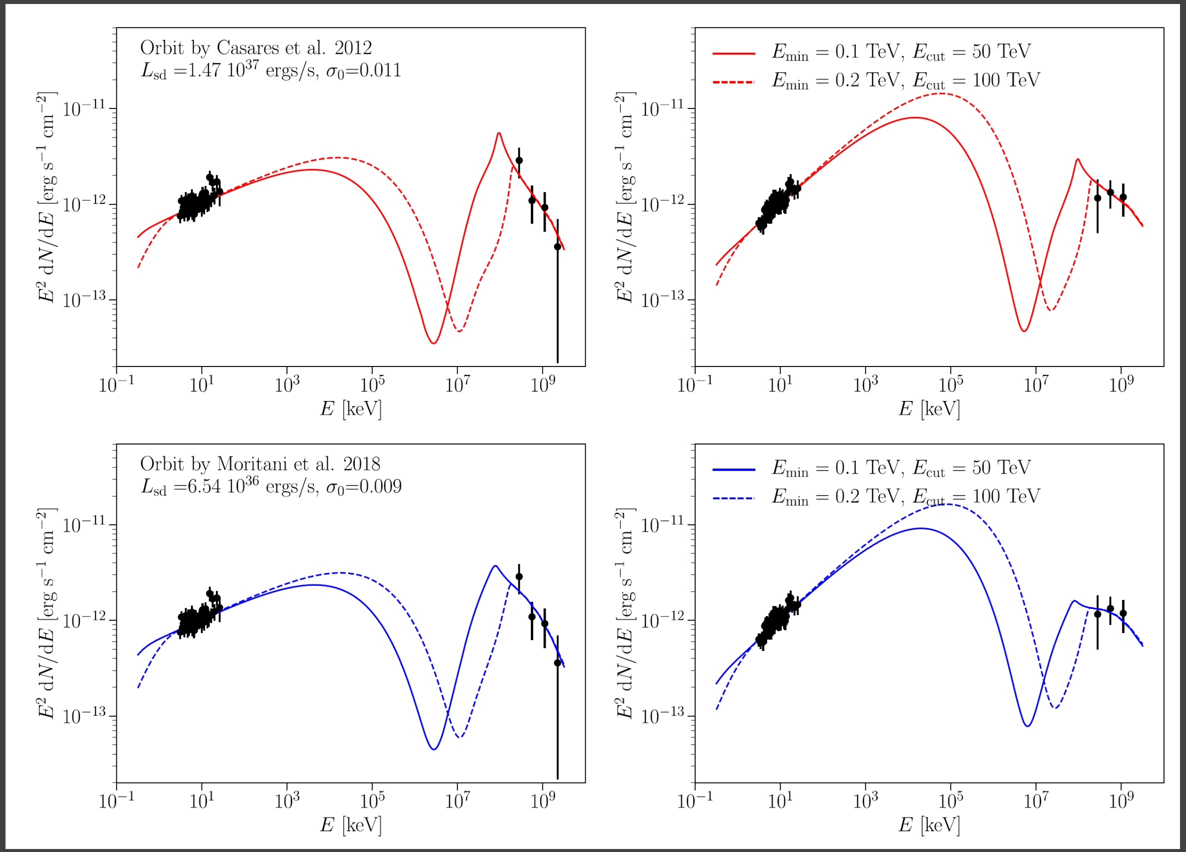
VERITAS & MAGIC, 2018

X-ray-TeV modelling

Simultaneous NuSTAR and VERITAS observations of HESS J0632+057

By a joint fit with a model one can probe such important parameters of the pulsar wind as magnetization





Summary

Combining X-ray and TeV is extremely useful, and we need to do it more and coordinate it better!