High Energy Emission from Compact Objects

Emma de Oña Wilhelmi
Ramon y Cajal Fellow
Institute of Space Sciences, IEEC-CSIC, Barcelona
Massive Star
Massive Star

Binary?

Compact companion?

no

Massive companion?

Colliding wind sys.

e.g. Eta Carina
Emma de Ona Wilhelmi, TeVPA2017

- Massive Star
  - Binary?
    - yes
    - no
      - Massive companion?
      - yes
        - Neutron star?
      - no
        - Colliding wind sys.
          - e.g. Eta Carina
Massive Star

Binary?

yes

no

Compact companion?

yes

Neutron star?

yes

WR or OB/disk?

yes

PWNe in binary

Colliding wind sys.

e.g. Eta Carina

yes

Massive companion?

no

yes

e.g. PSR B1259-63

Compact companion?

yes

Massive companion?

no

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yes

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e.g. PSR B1259-63
Massive Star

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Colliding wind sys.

e.g. Eta Carina

Neutron star?

yes

WR or OB/disk?

yes

Low-mass X-ray?

yes

PWNe in binary

e.g. PSR B1259-63

Transitional ms-pulsar

e.g. XSS J2270-4859

yes

no
Massive Star

Binary?

Compact companion?

Neutron star?

Colliding wind sys.

e.g. Eta Carina

Massive companion?

WR or OB/disk?

WD?

Low-mass X-ray?

Novae

e.g. V407 Cyg

PWNe in binary

Transitional ms-pulsar

e.g. PSR B1259-63

e.g. XSS 12270-4859

Novae

Transitional ms-pulsar
Massive Star

Binary? yes

Compact companion? no

Massive companion?

Neutron star? yes

Colliding wind sys.

e.g. Eta Carina

no

yes

WR or OB/disk?

no

Low-mass X-ray? yes

WD? no

radio jets? no

Novae

e.g. V407 Cyg

yes

Transitional ms-pulsar

Microquasars

e.g. Cyg X-1

e.g. XSS 12270-485

e.g. PSR B1259-63

e.g. V407 Cyg

PWNe in binary
Massive Star

Binary? yes

No HE expected until...

Compact companion? no

Neutron star? yes

Colliding wind sys.

e.g. Eta Carina

Massive companion?

yes

Microquasars

e.g. Cyg X-1

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Novae

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e.g. XSS 12270-485

PWNe in binary

Low-mass X-ray? yes

WR or OB/disk?

no

WD?

no

yes

Novae

e.g. V407 Cyg

Microquasars

e.g. Cyg X-1

no

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Massive companion?

yes

Colliding wind sys.

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Neutron star?

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e.g. XSS 12270-485

yes

PWNe in binary

WR or OB/disk? yes

Novae

e.g. V407 Cyg

Supernova

Supernova

No HE expected until...
Massive Star

Compact companion? no →

Neutron star? yes →

Colliding wind sys. e.g. Eta Carina

Massive companion? no →

Neutron star remains? yes →

Supernova

No HE expected until...

Binary? yes →

WR or OB/disk? yes →

PWNe in binary

e.g. PSR B1259-63

e.g. XSS 12270-485

Low-mass X-ray? yes →

Transitional ms-pulsar

e.g. XSS 12270-485

WD? no →

radio jets? yes →

Microquasars e.g. Cyg X-1

e.g. Cyg X-1

Novae
e.g. V407 Cyg

no →

Pulsar
Massive Star

Binary?

yes ->

Compact companion?

no ->

Neutron star?

yes ->

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PWNe in binary

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Novae

Microquasars

e.g. PSR B1259-63

e.g. XSS 12270-485

e.g. V407 Cyg

e.g. Cyg X-1

e.g. Crab

Colliding wind sys.

e.g. Eta Carina

WD?

radio jets?

no ->

SNR Shell

Pulsar

yes ->

Neutron star remains?

no ->

Supernova

Novae

yes ->

e.g. V407 Cyg

no ->

PSR B1259-63

e.g. XSS 12270-485

no

No HE expected until...
Massive Star

Binary? yes

Massive companion? yes

Colliding wind sys. e.g. Eta Carina

No HE expected until...

Supernova

Neutron star remains? yes

Neutron star?

WD? no

radio jets? no

Microquasars e.g. Cyg X-1

Novae e.g. V407 Cyg

Low-mass X-ray? yes

Transitional ms-pulsar e.g. XSS 12270-485

Compact companion? no

WR or OB/disk? yes

PWNe in binary e.g. PSR B1259-63

Young? yes

SNR Shell

Pulsar e.g. Crab

Composite SNR
Massive Star

Compact companion?

Neutron star?

WR or OB/disk?

SNR Shell

Low-mass X-ray?

Novae

Microquasars

Transitional ms-pulsar

Radio jets?

Supernova

No HE expected until...

Neutron star remains?

Pulsar

Young?

Relic PWNe

Binary?

Massive companion?

Colliding wind sys.

e.g. Eta Carina

Novae

e.g. V407 Cyg

PSR

Composite SNR

e.g. Crab

e.g. HESS J1303

PSR B1259-63

e.g. XSS 12270-485

PSR
To radiate high-energy gamma-ray, particles (electrons and hadrons) have to be accelerated to TeV energies or more:

- huge gravitational, magnetic and electric fields
- very dense background radiation
- relativistic bulk motions (black hole jets and pulsar winds)
- shock waves (SNRs), highly excited (turbulent) media, etc...
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Synchrotron-Curvature

\[ e^\pm + B \rightarrow \gamma + e^{\pm}_{\text{lower E}} \]

**Pulsars, Binaries, uQuasars...**

Bremsstrahlung: \( e \ N(e) \rightarrow e' \ \gamma N(e) \quad E_{\gamma} \sim 1/2 \ E_{e} \)

Pair Production: \( \gamma N(e) \rightarrow e^+e^- \ N(e) \)

\( e^+e^- \) annihilations: \( e^+e^- \rightarrow \gamma \ \gamma \) (511 keV line)
To radiate high-energy gamma-ray, particles (electrons and hadrons) have to be accelerated to TeV energies or more:

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**Inverse Compton**

\[ e^{\pm}_{\text{HE}} + \gamma_{\text{LE}} \rightarrow e^{\pm}_{\text{lowerE}} + \gamma_{\text{LE}} \]

**Binaries, PWNe, Pulsars!**
To radiate high-energy gamma-ray, particles (electrons and hadrons) have to be accelerated to TeV energies or more:

- huge gravitational, magnetic and electric fields
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Bremsstrahlung

\[ e^\pm + N(e) \rightarrow e' + \gamma N(e) \]

Regions of high density:
Galactic Center, dense clouds

Emma de Ona Wilhelmi, TeVPA2017
To radiate high-energy gamma-ray, particles (electrons and hadrons) have to be accelerated to TeV energies or more:

- huge gravitational, magnetic and electric fields
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**Proton-Proton**

\[ p + p \rightarrow \pi^0 + X + \ldots + \pi^\pm \]

\[ \gamma + \gamma \rightarrow \nu_\mu + \nu_e + \ldots \]

**SNRs, Novae, Diffuse...**

see Helzen talk at TeV PA 2017
Outlook

- **Pulsars in the GeV/TeV regime**
  - Neutron Stars that behave like pulsars
- **Transitional Pulsars**
  - Neutron Stars that sometimes behave like pulsars, sometimes not
- **High-energy binaries**
  - Neutron Stars that do not behave like pulsars
- **Novae at high-energies**
  - The big cousins of Neutron Stars
- **Compact objects with jets**
  - The wild cousins of Neutron Stars
- **SNRs and PWNe**
  - The extended family
The Fermi-LAT Pulsar Legacy

Phase folding using radio (X-ray) timing solutions
Blind periodicity searches in Fermi data:
GW algorithms (Plesch+2012) + Einstein@home
Mostly radio-quiet (Clark+2017) + few MSP (Clark+2016)
Radio follow-up of Fermi unidentified sources

<table>
<thead>
<tr>
<th>Energy</th>
<th># of pulsars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>~2200</td>
</tr>
<tr>
<td>Fermi, &gt;100MeV</td>
<td>161</td>
</tr>
<tr>
<td>IACT, &gt;50GeV</td>
<td>2</td>
</tr>
</tbody>
</table>

Credit: I Grenier (cf. D Smith)
**YOUNG PULSARS**

Radio loud/quiet: not an intrinsic property, but a function of the viewing angle
Larger $\dot{E}$ than radio: probably selection effect

\[ F_\gamma \propto \dot{E}, \quad 10^{11} < B_{\text{NS}} < 10^{14} \text{ G}, \quad 23\% \text{ of known PSRs} \]

**MS PULSARS**

ms P spun up by accretion from a binary companion

\[ 10^8 < B_{\text{NS}} < 10^{11} \text{ G} \]

50% of the known MSP

Despite the difference in $B$ and $\dot{E}$, similar observables

Gamma-ray properties result from:
- acceleration
- radiation
- cascading

‘Gaps’ where particles are accelerated:
- polar cap
- outer gap
- slot gap
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Gamma-ray Pulsars

\[ L_\gamma \sim \dot{E}_{\text{rot}}^{1/2} \] vs \( L_\gamma \sim \dot{E}_{\text{rot}} \): efficient screening vs pulsars with \( V_0 < 10^{13} \) V.

Large scattering, however data point to free-free magnetosphere (pair production)

Young pulsars are more efficient when the slow down (\( V_0 = 6 \times 10^2 V(P/1s)^{-2}(B/10^8 T) \))

Old ms pulsars are the most efficient ones (>10%): large \( B_{\text{field}} \) in the outer regions of the compact MSP magnetosphere
**Gamma-ray Pulsars**

Spectral shape due to synchro-curvature of accelerated particles along acceleration gaps

Fine spectroscopic studies result in $b<1$ sub-exponential cutoffs: Caustics? 


Power-law extension to $E>\text{TeV}$: Inverse Compton emission from the wind? from the outer magnetosphere? see Talk by Rodriguez et al, MAGIC Col. TeVPA 2017

Several Models to explain the pulsed emission:

**Polar cap / Outer gap / slot gap**

**Stripped Wind**

-> they all result in pulsed radiation due to synchro-curvature radiation, but different shape

PIC & MHD simulations show a more complex picture.


The current sheet corrugates in oblique pulsars producing stripped winds


The high energy particles accelerated beyond the LC via reconnection

Pulsars in Binary Systems

- Transitional MSPs: Probing the recycling scenario

**Accretion powered state**
- Bright X-ray outburst ($\sim 10^{36}$ erg/s)
- X-ray pulsations

**An intermediate (propeller?) state**
- Sub-luminous accretion ($\sim 10^{34}$ erg/s)
- Brighter gamma-ray emission
- X-ray pulsations (10% level)

**Rotation powered state**
- Faint in X-rays ($\sim 10^{32}$ erg/s)
- Radio/gamma-ray pulsations
Variable Pulsars

Pulsars in Binary Systems
- Transitional MSPs: Probing the recycling scenario

Balance between gravity and field pressure
SSC of relativistic electrons accelerated during propeller state
Acceleration in the intra-shock?

* Torres et al, 2016
Variable Pulsars

- Pulsars in Binary Systems
  - Transitional MSPs: Probing the recycling scenario
  - High-energy Gamma-ray Binaries

Compact object + Massive Companion (OB/WR)
Point-like Sources at VHE, peaking at high-energies
Modulation of the VHE due to their interaction (5+1?)
Observed in radio, X-ray, HE and VHE
Difficult to reconcile all observations: geometry?
Not a unique behaviour: Ej. LS 5039 vs 1FGL J1018.6

<table>
<thead>
<tr>
<th></th>
<th>Flux (% Crab)</th>
<th>D (Kpc)</th>
<th>Flux variability (HE/VHE)</th>
<th>Periodic</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR B1259-63</td>
<td>0-10</td>
<td>1,5</td>
<td>yes/yes</td>
<td>yes (~3.4 years)</td>
<td>Aharonian+2005, Tam+2010, Mori+2011, Abdo+2011</td>
</tr>
<tr>
<td>HESS J0632+057</td>
<td>0-3</td>
<td>1,5</td>
<td>no/yes</td>
<td>yes (~300 days)</td>
<td>Li+2017, Malychev+2016, Maier+2015, Mori+2013, Veritas2013, Aharonian+2007</td>
</tr>
<tr>
<td>HESS J1832-093</td>
<td>0-1</td>
<td>4.4</td>
<td>-/no</td>
<td>—</td>
<td>Eger+2016, HESS Col. 2013, Mori+2017</td>
</tr>
</tbody>
</table>
Variable Pulsars

- **Pulsars in Binary Systems**
  - Transitional MSPs: Probing the recycling scenario
  - High-energy Gamma-ray Binaries
- **Isolated Pulsars**
  - Pulsars are not steady at lower energies (quakes, glitches,...)
  - First observed switch mode in a γ-ray pulsar: J2021+4026

- 20% flux drop
- Increase in spin down rate
- Change in the pulsar profile
- Decrease energy cutoff

Glitch!

✓ Glitch cause a re-arrangement of the B structure → $\alpha$ change (Ng+2016)
Variable Pulsars

- Pulsars in Binary Systems
  - Transitional MSPs: Probing the recycling scenario
  - High-energy Gamma-ray Binaries
- Isolated Pulsars
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The Crab... Nebula!
Short (~hours) burst happening at a rate of 2-3 per year
Pulsed emission does not show variation, PWN!
Compact region (<10^{-3} pc) with significant energy (∼10^{35-36} erg/s) → emission anisotropic → doppler/kinetic boosting?
Particle acceleration in magnetic reconnection? γ ∼ 10^{9}
No detected counterpart at lower energies
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Novae

<table>
<thead>
<tr>
<th>Nova</th>
<th>Distance</th>
<th>Duration</th>
<th>Fluence</th>
<th>Number of Photons</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kpc)</td>
<td>(days)</td>
<td>(photons cm$^{-2}$)</td>
<td>($10^{41}$)</td>
<td>($10^{42}$ erg)</td>
</tr>
<tr>
<td>V1324 Sco</td>
<td>4.5</td>
<td>17</td>
<td>0.72 ± 0.04</td>
<td>1.77 ± 0.40</td>
<td>1.27 ± 0.29</td>
</tr>
<tr>
<td>V959 Mon</td>
<td>3.6</td>
<td>22</td>
<td>0.79 ± 0.12</td>
<td>1.23 ± 0.39</td>
<td>0.67 ± 0.21</td>
</tr>
<tr>
<td>V339 Del</td>
<td>4.2</td>
<td>27</td>
<td>0.45 ± 0.07</td>
<td>0.96 ± 0.27</td>
<td>0.57 ± 0.16</td>
</tr>
<tr>
<td>V1369 Cen</td>
<td>2.5</td>
<td>39</td>
<td>0.71 ± 0.14</td>
<td>0.54 ± 0.24</td>
<td>0.30 ± 0.13</td>
</tr>
<tr>
<td>V5668 Sgr</td>
<td>2.0</td>
<td>55</td>
<td>0.52 ± 0.11</td>
<td>0.25 ± 0.14</td>
<td>0.12 ± 0.07</td>
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Cheung+2016

Cyg X-1

Cyg X-3

uQuasars

Main sequence

19 Mar – 29 Mar 2010

Nova Cygni 2010 (V407 Cyg)

Pulsars

Emma de Ona Wilhelmi, TeVPA2017
Pulsar Wind Nebulae

- Largest population of Galactic Gamma-ray Sources
- Extended - Mean size ~ 0.2
- Correlated with bright ($E_{dot} > 10^{35}$ erg/s) young ($\tau < 10^5$ yrs)
- The most efficient gamma-ray acceleration
- First VHE Unbiased Population Studies (HESS Col. 2017)

see also Gallant, Weinstein talks in TeVPA 2017

Emission due to off-scattering of CMB/IR/Synchrotron photons from relativistic electrons

http://tevcat.uchicago.edu/

1989-2004

Source Types

Donath et al (HESS Col.) 2017
Pulsar Wind Nebulae

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2005-2006 Source Types

Donath et al (HESS Col.) 2017
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2007-2010 Source Types

PWN

Donath et al (HESS Col.) 2017
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http://tevcat.uchicago.edu/

Emission due to off-scattering of CMB/IR/Synchrotron photons from relativistic electrons

1989-2017

Source Types

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Pulsar Wind Nebula

Evidence that the TeV luminosity of PWNe decays with time while they expand in (angular) size. Time-dependent modeling describes fairly well the general trends.
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**Pulsar Wind Nebula**

**HESS Col+2016**

**Preliminary**

**Blanch, dEOW, Fernandez 2017**
Excellent correlation with X-rays (large size compensates sometimes the relatively poor angular resolution $\sim 0.1^\circ$)

- Particle-dominated nebulae, away from equipartition
- High photon field density
- Pulsar offset from the center of the TeV emission: proper velocity or evolution of the SNR in an inhomogeneous medium

see also Slane talk in TeVPA 2017
Excellent correlation with X-rays (large size compensates sometimes the relatively poor angular resolution \(\sim 0.1^\circ\)).

- **Particle-dominated nebulae, away from equipartition**
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(HESS Collaboration)

(MSH 15-52)
PWNe: Test-bench for particle acceleration and propagation

In comparison with other sources of relativistic magnetised plasma, PWNe can be resolved in great detail.
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If all of them at the same distance:

CTA Simulations using ctools* 100h

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<td>MSH 15-520</td>
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<td>1.56</td>
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<tr>
<td>HESS J1825-137</td>
<td>0.8</td>
<td>54.5</td>
<td>3.9</td>
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Looking at the inner part of the nebula

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**Looking at the inner part of the nebula**

**CTA Simulations using ctools* 100h**

*http://cta.irap.omp.eu/ctools/index.html

Emma de Ona Wilhelmi, TeVPA2017
In comparison with other sources of relativistic magnetised plasma, PWNe can be resolved in great detail.

If all of them at the same distance:

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Looking at the inner part of the nebula:

- Large nebula: no cooling?
- Faint, not so large

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PWNe: Test-bench for particle acceleration and propagation

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Looking at the inner part of the nebula

Large nebula: no cooling?

Faint, not so large

Observing particles cooling

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Gamma-ray Emission Regions

Emission from the pulsar and/or the wind
Emission from the interaction with the companion
Emission from the PWNe
Emission from the Shell

Steady emission
Synchrotron and thermal Emission
Inverse Compton or/and Proton-proton

Radio MPGS
X-ray XMM
Gamma-ray HESS

SNR G327.1-1.1
Acero et al (HESS Col) 2011
 Gamma-ray Emission Regions

Emission from the pulsar and/or the wind
Emission from the interaction with the companion
Emission from the PWNe
Emission from the Shell
Emission from the Shell in Dense Medium

Steady emission
Old SNRs or in dense region
Thermal Emission
Proton-proton
Question since 1912: What is the origin of Galactic Cosmic Rays?

Non-linear diffuse shock acceleration theory (Fermi first order acceleration) in shells provides the right spectral index, high $P_{\text{CR}}$, magnetic field amplification and $E_{\text{max}} \sim E_{\text{knee}}$
Large GeV & TeV data set has revealed two type of gamma-ray emitter SNRs

GeV: high luminosity in old SNRs, pion decay peak found!
This trend is not present at TeV energies:
Leptonic dominant? Escape of CR in old SNRs? Maximum energy of accelerated particles?
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Uchiyama et al (Fermi LAT), 2013
Fernandez et al (HESS), 2013

See also Hewitt talk TeVPA 2017
Young (bright TeV) SNRs

GeV counterpart / Spectral Index

- Yes/1.5
- Yes/1.85
- No/2.32
- Yes/2.0
- Yes/2.6
- Yes/1.8
- No/2.0

Density [cm$^{-3}$]

- <0.02
- <0.03
- <0.02
- 0.1-1
- 0.1-1
- 0.01-1
- <0.05

see also Auchettl, Slane in TeVPA 2017
TeV Remnants with low $B_{\text{field}}$

- Bfield $\sim$ few uG, low density medium
- Different emission region? forward vs reverse shock, clumps…
- Energy cutoff measured for several of them ($E_p \sim 100$ TeV)
**TeV Remnants with high $B_{\text{field}}$**

B = 0.3-0.5 mG is inferred from the width of X-ray filaments and X-ray time-variability. If hadronic origin $E_{\text{CR}} \approx 10-20\%$ of SNR energy. Energy Cutoff at $\sim 3.5$ TeV.
Where are the PeVatrons?

Hypothesis: PeV particles are accelerated at the beginning of Sedov phase (~200 yrs), when the shock speed is high but the SNR is faint
Look at the surroundings, or somewhere else?

- VHE in the vicinity of G318.2+0.1 with a flat spectrum ranging from a few 100 MeV to few tens of TeV
- G318.2+0.1 radio bright North and South shell filled up with thermal emission
- Enhancement of Molecular Content observed by NANTEN and with Fermi LAT
- D~3.5 (9.2) kpc -> 50 pc if related to the SNR

HESS Col. 2016

Correlation between clouds and TeV emission
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Correlation between clouds and TeV emission
Astrophysical compact objects provide optimal conditions to accelerate particles to GeV/TeV energies

New, sensitive instruments in the last years such FermiLAT, AGILE, H.E.S.S., MAGIC & VERITAS have stirred up the field with a plethora of exciting results

Thanks to the large pulsar population obtained, we have significantly advanced in our understanding of pulsar magnetospheres (current sheets, pair production, etc)

They are the most powerful steady (up to PeV=1x10^{15} eV) and relatively nearby accelerators (and sometime not-steady!)

They last thousands of years, providing clues about historical evolution of radiative plasma and transport of particles/fields

They flare! -> efficient & rapid particle acceleration (like in AGNs or GRBs): common mechanisms (magnetic reconnection or shock acceleration)

The future is bright! stay tune for new results obtained with new detectors (IXPE/XIPE, CTA, eASTROGAM, etc)
Thanks!
Spectral variation with distance from the pulsar could result from:

(i) energy loss of particles during propagation, with radiative cooling of electrons propagating outward from the pulsar termination shock

(ii) energy dependent diffusion or convection speeds

(iii) variation of the shape of the injection spectrum with age of the pulsar which, after propagation, translates into a spatial variation of spectra.

If $\alpha =$ electron index $\rightarrow$ synchrotron cooling ($\tau_{\text{syn}} \sim 400 \text{ B}^{-2} \text{G}^{-1} \text{E}^{-1} \text{TeV s}$)

$\Delta \alpha = 1 \rightarrow \Delta \Gamma = 1/2$
Which PWNe we see?
- Large density regions
- Middle age (right size!)
- Energetic PSR