Gamma-rays and the sources of galactic cosmic rays (with a focus on PeVatrons)

Stefano Gabici
APC, Paris
SuperNova Remnants, Cosmic Rays, γ-rays

SN explosions -> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)
SuperNova Remnants, Cosmic Rays, $\gamma$-rays

**SN explosions $\rightarrow$ enough power to explain CRs**

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**SNR shocks $\rightarrow$ acceleration sites**

Shklovsky 1954, Ginzburg & Syrovatskii 1964
SuperNova Remnants, Cosmic Rays, γ-rays

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Diffusive Shock Acceleration

BOBALSKy 1977-1978 (Blandford, Ostriker, Bell, Axford, Leer, Skadron, Krymskii)
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γ-rays from pp interactions
Drury, Aharonian & Völk 1994

<- Cherenkov telescope

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<- Cherenkov telescope

very popular but not proven yet!
Are SNRs proton PeVatrons?

- Knee: few PeV
- Graph: log(FLUX * E^3 in eV^2 m^-2 s^-1 sr^-1) vs. log(ENERGY in eV)

---

**Intro** | **SNRs** | **Gal Centre** | **SNRs?** | **Conclusions**
Are SNRs proton PeVatrons?

Hillas criterium

\[ E_{\text{max}} \approx u \frac{R}{Pc} \frac{B}{\mu G} \text{ TeV} \]

Intro | SNRs | Gal Centre | SNRs? | Conclusions
Are SNRs proton PeVatrons?

$E_{max}$

100 TeV

Hillas criterion

$E_{max} \approx u R B$

$\approx 1 \left( \frac{u}{10^3 \text{ km/s}} \right) \left( \frac{R}{\text{ pc}} \right) \left( \frac{B}{\mu \text{G}} \right) \text{ TeV}$

$\sim 10$  $\sim 3$  $\sim 3$

Lagage & Cesarsky 1983
Are SNRs proton PeVatrons?

30 years later…

Hillas criterium

\[ E_{\text{max}} \approx u R B \]

velocity
size
magnetic field

B-field amplification

\[ \left( \frac{B}{\mu \text{G}} \right) \text{TeV} \approx 10 \]

100 TeV

\[ E_{\text{max}} \approx 10^3 \text{km/s} \]

\[ v = 4.7 \text{ km/s} \]

\[ \sqrt{v} = 15 \text{ km/s} \]

\[ v_w = 1000 \text{ km/s} \]

Schure & Bell 2013

Intro        SNRs        Gal Centre       SNRs?        Conclusions
Are SNRs proton PeVatrons?

30 years later...

current driven, non-resonant instability (Bell 2004, 2013) -> PeV particle acceleration possible in the very early (tens of years) stage of a SNR evolution -> ejecta dominated phase -> is there enough power to feed the PeV CR population?

Hillas criterium

\[ E_{\text{max}} \approx u R B \]

\[ B \left( \frac{B}{\mu \text{G}} \right) \sim 10 \]

\[ R \sim 3 \]

\[ u \sim 3 \]

Intro SNRs Gal Centre SNRs? Conclusions
Are SNRs proton PeVatrons?

30 years later...

Hillas criterium

\[ E_{\text{max}} \approx u R B \]

velocity

size

magnetic field

B-field amplification

\[ \left( \frac{B}{\mu \text{G}} \right) \text{TeV} \]

~10

~3

~3

Drury instability might also play a role \( \rightarrow \) Drury, Downes 2012, 2014

current driven, non-resonant instability (Bell 2004, 2013) \( \rightarrow \) PeV particle acceleration possible in the very early (tens of years) stage of a SNR evolution \( \rightarrow \) ejecta dominated phase \( \rightarrow \) is there enough power to feed the PeV CR population?

Intro  SNRs  Gal Centre  SNRs?  Conclusions
Indirect detection of PeVatrons?

CRs escape the SNR

\[ t_{\text{diff}}^{\text{PeV}} \approx 5000 \left( \frac{d}{100 \, \text{pc}} \right)^2 \left( \frac{D_{\text{PeV}}}{10^{29} \, \text{cm}^2/\text{s}} \right)^{-1} \, \text{yr} \]

\[ t_{\text{PeV}}^{\text{acc}} \approx 30 \, \text{yr} \]

MCs enhance the gamma ray emission

SG & Aharonian 2007
data recently presented by the VERITAS collaboration (Acciari et al. 2011). The half of the shock is expanding in a denser medium with density

Because of the various self-regulation processes that take place somewhat higher because of the faster shock motion, although the results of pions for the proton spectra shown in Fig. 3. It was first shown by Berezhko et al. 2013 that the electron spectrum in the Tycho SNR ~450yr, which compare well with data from Fermi-LAT (Reynoso et al. 1997). This amplified field would have lighted the radio emissivity and limit the inverse Compton contribution to the observed gamma ray emission to half of the remnant. Observations in the spatially integrated radio emission seem to suggest that even the radio emission could be stabilities (e.g. Kothes et al. 2006, Katz-Stone et al. 2000). However, the accretion and ionisation of the manuscript. This work was partially funded through Grant PRIN.

The existence of spectra of accelerated particles that are steeper spectra of accelerated particles. The electron spectrum in the Tycho SNR (Caprioli 2012), and we pointed out that the steeper spectra range from morphological considerations (see Morlino et al. 2013). Since the medium of the remnant is about twice as bright as the faster region. The only attempt to carry out a spatially resolved measure the spatially resolved spectrum of the radio emission is when both the NRF and the dynamical reaction of accelerated particles. The non-linear theory of particle acceleration, DSA is recovered. The non-linear theory of particle acceleration, which compare well with data from Fermi-LAT (Reynoso et al. 1997), and we pointed out that the standard spectrum of accelerated particles. The e- spectrum of accelerated particles steepens. At high enough energies, the standard spectrum of accelerated particles steepens. At high enough energies, the standard spectrum of accelerated particles steepens.

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SNRs in gamma rays

very young

middle aged

old

Tycho ~450yr

no PeVatron detected

FERMI-MAGIC-VERITAS

are SNRs proton PeVatrons?

hundreds of yrs

thousands of yrs

\(10^4...10^5\) yr

Intro  SNRs  Gal Centre  SNRs?  Conclusions
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~1600 yr?
Y-ray shells

are SNRs proton
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which production
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Y-ray shells

SN1006

HESS

W44

effect of interactions with ISM?

are SNRs proton PeVatrons?

which production spectrum?

hundreds of yrs

thousands of yrs

10^4...10^5 yr

Intro SNRs Gal Centre SNRs? Conclusions
data recently presented by the VERITAS collaboration (Giordano et al. 2011). The half of the shock is expanding in a denser medium with density $p_{\text{H}}$, which is somewhat steeper than the average density. This suggests that the electron spectrum in the region where neutral hydrogen is absent may strongly increase with energy $E$. On the other hand, the CR acceleration efficiency can become higher than $\sim 20\%$.

It was first shown by Giacalone & Jokipii (2004) that the gamma ray emission from the faster region of the remnant is about twice as bright as the slower region. The radio morphology of the remnant shows that the slower NE region is moving appreciably slower than the average velocity ($\sim 0.1$). However, the effect of interactions with ISM is necessary.

Explanations of the steeper spectra range from morphological considerations (see Caprioli, D., & Spitkovsky, A. 2014a, Morlino et al. 2015). As discussed above, this amplified field would have lasted for hundreds of years. Observations in the spatially integrated radio emission seem to point to a possible SNR, but the question remains of whether limiting the inverse Compton contribution to the observed gamma ray emission is possible. Nevertheless, the question remains of whether limiting the gamma ray emission is possible.

For closer SNRs, where spatially resolved gamma-ray observations may be possible, a similar test can be performed in the gamma ray band.

Acknowledgements.

We are grateful to E. Amato for a careful reading of the manuscript. This work was partially funded through Grant PRIN-2010-65X8. A special thanks to the anonymous referee, Don Ellison, for raising several interesting problems with the initial version of this manuscript.
**SNRs in gamma rays**

**very young**

Tycho ~450yr
no PeVatron detected

**middle aged**

~1600 yr?

**old**

effect of interactions with ISM?
pion decay→hadronic

are SNRs proton PeVatrons?
which production spectrum?

**Intro**

**SNRs**

**Gal Centre**

**SNRs?**

**Conclusions**

**SN1006**

y-ray shells

HESS

W44

steep

Fermi

10⁴...10⁵ yr

hundreds of yrs

thousands of yrs

RXJ1713

FERMI-HESS

FERMI-MAGIC-VERITAS

Fermi

De Palma et al. 2015

Bell, A. R. 2004,

Blasi, P., Gabici, S., & Vannoni, G. 2005,

Caprioli, D., & Spitkovsky, A. 2014a,

Caprioli, D., & Spitkovsky, A. 2014b,

Giordano et al. 2012

Giordano et al. (2011)

Blasi et al. 2011

Blasi, P., Morlino G., Bandiera R., Amato, E., & Caprioli, D. 2012,

Berezhko, E. G., Ksenofontov, L. T., & Völk, H. J. 2013,

Reynoso et al. 1997

VERITAS

VERITAS ICRC 2015

VERITAS

VERITAS

VERITAS

VERITAS

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SNRs in gamma rays

very young

middle aged

old

Tycho \(\sim 450\) yr

no PeVatron detected

FERMI-MAGIC-VERITAS

\(\sim 1600\) yr?

\(E^2 F(E)\) [eV/cm\(^2\)/s]

effect of interactions with ISM?
pion decay\(\rightarrow\)hadronic

are SNRs proton PeVatrons?

which production spectrum?

hadronic or leptonic?

FERMI-HESS

hundreds of yrs

thousands of yrs

Fermi

10\(^4\)…10\(^5\) yr

SN1006

Y-ray shells

HESS

W44

 References

- Caprioli, D. 2012, JCAP, 07, 038
- Kothes et al. 2006, A&ARv, 21, 70
- Acciari et al. 2011; circled). The shaded area represents the preliminary findings is necessary. Explanations of the steeper spectra range

\(E^2 F(E)\) [eV/cm\(^2\)/s]

\(E\) [eV]

\(10^8 \ 10^9 \ 10^{10} \ 10^{11} \ 10^{12} \ 10^{13} \ 10^{14}\)

\(0.1 \ 0.01 \ 0.001\)

\(1 \ 10 \ 100\)

\(\sim<\)

\(\gamma\) -decay

\(E\)\(_\text{eff}\) effective,\(\gamma\) decay,\(\gamma\) production and decays of neutral nucleons and pions for the proton spectra shown in Fig.

Fig. 3.

The data recently presented by the VERITAS collaboration (Acciari et al. 2011). While detailed fits to the data would have revealed a strong dependence on spectral index, the overall qualities of the fits were not conclusive.

The effect of the various self-regulation processes that take place during the acceleration process is somewhat steeper than expected from DSA. This also reflects in steeper gamma ray spectra, which production and decays of neutral nucleons and pions for the proton spectra shown in Fig.

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Fig. 3.
Is the paradigm consistent with γ-ray data? Tests for CR origin

GeV domain

Intro             SNRs             Gal Centre              SNRs?              Conclusions

Acero+ 2016

10-100% E
SN
converted into CRs

FERMI: 30 likely, 14 marginal, 245 u.l.
Is the paradigm consistent with γ-ray data? Tests for CR origin

How many SNRs should we detect in the HESS galactic plane survey?
Is the paradigm consistent with γ-ray data? Tests for CR origin

How many SNRs should we detect in the HESS galactic plane survey?

RED and BLACK regions -> with or without Inverse Compton contribution

Number of detections vs Spectral index

Intro SNRs Gal Centre SNRs? Conclusions
Is the paradigm consistent with γ-ray data? Tests for CR origin

How many SNRs should we detect in the HESS galactic plane survey?

RED and BLACK regions -> with or without Inverse Compton contribution

allowed range of spectral slopes from CR propagation studies!

Intro SNRs Gal Centre SNRs? Conclusions
### A proton PeVatron in the galactic centre

**Observational signature**

- **p-p interactions** -> $E_{max}^p \approx 1 \text{ PeV } \rightarrow E_{max}^\gamma \approx 100 \text{ TeV}$

- **inverse Compton** -> suppressed in the multi-TeV domain (Klein-Nishina effect)

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A proton PeVatron in the galactic centre

Observational signature

unattenuated γ-ray spectrum extending to the multi-TeV domain

\[ p-p \text{ interactions} \rightarrow E_{\text{max}}^{p} \approx 1 \text{ PeV} \rightarrow E_{\text{max}}^{\gamma} \approx 100 \text{ TeV} \]

inverse Compton\rightarrow suppressed in the multi-TeV domain (Klein-Nishina effect)
A proton PeVatron in the galactic centre

Observational signature

p-p interactions → \( E_{max}^p \approx 1 \text{ PeV} \) → \( E_{max}^\gamma \approx 100 \text{ TeV} \)

inverse Compton→ suppressed in the multi-TeV domain (Klein-Nishina effect)

unattenuated γ-ray spectrum extending to the multi-TeV domain

the first PeVatron is not a SNR but is located in the Galactic centre!

diffuse emission from the GC

no cutoff!

H.E.S.S. Coll. 2016
A proton PeVatron in the galactic centre

Observational signature

unattenuated $\gamma$-ray spectrum extending to the multi-TeV domain

$p$-$p$ interactions $\rightarrow E_{p,\text{max}}^{p} \approx 1 \text{ PeV} \rightarrow E_{\gamma,\text{max}}^{\gamma} \approx 100 \text{ TeV}$

inverse Compton $\rightarrow$ suppressed in the multi-TeV domain (Klein-Nishina effect)

the first PeVatron is not a SNR but is located in the Galactic centre!

H.E.S.S. Coll. 2016

Intro \hspace{1cm} SNRs \hspace{1cm} Gal Centre \hspace{1cm} SNRs? \hspace{1cm} Conclusions
The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006

Intro             SNRs             Gal Centre              SNRs?              Conclusions

55 h

color scale -> γ-rays
contours -> gas (CS)
The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006

Intro  SNRs  Gal Centre  SNRs?  Conclusions

[Diagram showing various astronomical objects and data analysis processes, including gamma rays, gas (CS), and corrected excess counts.]
The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006

morphology of gas and γ-rays -> spatial distribution of CR

quite good correlation except for the edges of the ridge -> hadronic emission

histogram -> γ-rays
red -> gas (CS)

Intro       SNRs   Gal Centre   SNRs?       Conclusions
The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006

The morphology of gas and γ-rays is quite well correlated except for the edges of the ridge, which exhibit hadronic emission.

55 h

Histogram → γ-rays  
Red → gas (CS)

Spatial distribution of CRs

Source

CRs

Intro  SNRs  Gal Centre  SNRs?  Conclusions
Where is the source?

CR spatial distribution

Sgr A*

one source
impulsive injection of CRs
Where is the source?

CR spatial distribution

Sgr A*

one source
impulsive injection of CRs

diffusion length

$l_d \sim \sqrt{D \times t}$

Intro  SNRs  Gal Centre  SNRs?  Conclusions
Where is the source?

CR spatial distribution

Sgr A*

one source
continuous injection of CRs

Intro   SNRs    Gal Centre   SNRs?   Conclusions
Where is the source?

CR spatial distribution

one source
continuous injection of CRs

$n_{\text{CR}} \propto 1/R$

Sgr A*

Intro SNRs Gal Centre SNRs? Conclusions
Where is the source?

CR spatial distribution

$n_{\text{CR}} \propto 1/R$

$l_d \sim \sqrt{D \times t}$

one source
continuous injection of CRs

Intro            SNRs            Gal Centre            SNRs?            Conclusions
Where is the source?

CR spatial distribution

Sgr A*

many sources
-> any distribution

Intro          SNRs          Gal Centre          SNRs?          Conclusions
The source is at the GC

H.E.S.S. Coll. 2016

Intro             SNRs             Gal Centre              SNRs?              Conclusions

226 h
The source is at the GC

The source is located in the inner ~10 pc, as indicated by the 1/R profile.
The source is at the GC

H.E.S.S. Coll. 2016

226 h

1/R profile -> source located in the inner ~10 pc!

accelerator must be active for:

\[
\Delta t > \frac{R^2}{6 \times D} \sim 2 \times 10^3 \left( \frac{D}{10^{30} \text{cm}^2/\text{s}} \right)^{-1} \text{yr}
\]

Intro             SNRs             Gal Centre              SNRs?              Conclusions
The source is at the GC

226 h

1/R profile $\rightarrow$ source located in the inner ~10 pc!

accelerator must be active for:

$$\Delta t > \frac{R^2}{6xD} \sim 2 \times 10^3 \left( \frac{D}{10^{30} \text{ cm}^2/\text{s}} \right)^{-1} \text{ yr}$$

multi-source scenarios require excessive fine-tuning/unrealistic number of sources
Supermassive black hole as a PeVatron

Sgr A* is the best bet candidate source of PeV cosmic rays
Supermassive black hole as a PeVatron

Sgr A* is the best bet candidate source of PeV cosmic rays

~10 TeV cutoff → inconsistency? no...

- emission could be unrelated
- time dependent effect
- γγ-absorption w. IR photons? (Celli+ 2016)
Supermassive black hole as a PeVatron

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\[ W_p \sim 10^{49} \text{erg} \]

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Sgr A* is the best bet candidate source of PeV cosmic rays

Diffuse Sgr A* ~10 TeV cutoff -> inconsistency? no...

gas mass

1/R profile

\( W_p \sim 10^{49} \text{erg} \)

\( \dot{Q}_p \sim 4 \times 10^{37} \left( \frac{D}{10^{30} \text{cm}^2/\text{s}} \right) \text{erg/s} \)

~10 TeV cutoff -> inconsistency? no...

- emission could be unrelated
- time dependent effect
- \( \gamma\gamma \)-absorption w. IR photons? (Celli+ 2016)

Intro SNRs Gal Centre SNRs? Conclusions
BH activity, cosmic rays, neutrinos

the GC activity highly variable (Ponti+2013) \(\to\) what if the CR acceleration efficiency was larger in the past?

Intro SNRs Gal Centre SNRs? Conclusions
to explain all CRs >10 TeV we need

\[ L_{CR} \approx 10^{39} \text{ erg/s} \]

for \( \sim 10^6 \) - \( 10^7 \) yrs

the GC activity highly variable (Ponti+2013) \( \rightarrow \) what if the CR acceleration efficiency was larger in the past?
Fermi bubbles ~200 kpc

evidence for a huge reservoir of ionized gas (> $10^{10}$ $M_{\odot}$) in the halo from X-ray observations (Gupta+ 2012)

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BH activity, cosmic rays, neutrinos

Intro SNRs Gal Centre SNRs? Conclusions

speculations

IceCube neutrinos
Taylor, SG, Aharonian 2014
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to explain all CRs >10 TeV we need $L_{\text{CR}} \approx 10^{39}$ erg/s for ~$10^6$-$10^7$ yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?

CR bursts from GC Ptuskin & Khazan (1981) see also Fujita+ 2016
CR in Gal. breeze Taylor & Giacinti 2016

Intro SNRs Gal Centre SNRs? Conclusions

IceCube neutrinos Taylor, SG, Aharonian 2014
Another scenario: SNOBs, superbubbles...

- chemical composition -> CRs originate in a source which is a mixture ~20% stellar outflow/SN ejecta and ~80% interstellar medium (Murphy+ 2016 and references)
- stars form in clusters -> SN explosions -> SNOBs and superbubbles
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**Star clusters in γ-rays**
- westerlund 1 and 2, HESS

**Superbubbles in γ-rays**
- Cygnus, Fermi
- 30 Dor C, LMC, HESS

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**Stars Clusters in γ-rays**

- westerdlund 1 and 2, HESS
- Cygnus, Fermi
- 30 Dor C, LMC, HESS

- the acceleration mechanism might be completely different (Bykov&Fleishman92)
- particle spectrum not universal, large $E_{\text{max}}$ (large size!)

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The SNR hypothesis for the origin of galactic CRs is widely accepted...but it is not proven!

tested against Fermi and HESS observations -> OK
one crucial question is: where are PeVatrons?
the only known proton PeVatron in the MW is the galactic centre!
needs to explore alternative scenarios to the standard SNR hypothesis
Backup slides
The importance of being a SNOB
Montmerle 1979

 tentative spatial association between SNOBs and COS B hot spots

Intro  SNRs  Gal Centre  SNRs?  Conclusions
The importance of being a SNOB

Montmerle 1979

tentative spatial association between SNOBs and COS B hot spots

OB stars

supernovae

SuperNovae

OB associations

Intro | SNRs | Gal Centre | SNRs? | Conclusions
The importance of being a SNOB

Montmerle 1979

tentative spatial association between SNOBs and COS B hot spots

Intro SNRs Gal Centre SNRs? Conclusions
The importance of being a SNOB

Montmerle 1979

Tentative spatial association between SNOBs and COS B hot spots

OB stars
Supernovae
CR acceleration

Molecular cloud

Black & Fazio 1973
The importance of being a SNOB

Montmerle 1979

tentative spatial association between SNOBs and COS B hot spots

OB stars
supernovae

associations between SNRs and MCs are expected, and are ideal targets for gamma-ray observations due to the enhanced rate of CR interactions with the gas

Black & Fazio 1973

Intro SNRs Gal Centre SNRs? Conclusions
Molecular Clouds: boosting γ-ray emission


Shock/MC interaction

Intro | SNRs | Gal Centre | SNRs? | Conclusions

see L. Nava's talk
Molecular Clouds: boosting $\gamma$-ray emission


shock/MC interaction

runaway CRs


see L. Nava’s talk
From SNRs to the galactic pool

- Hard injection spectrum: $\propto E^{-2}$
- Soft observed spectrum: $\propto E^{-2.7}$

Ptuskin+ 2013

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Fluxes of Cosmic Rays

- Knee: (1 particle per $m^2\cdot$year)
- Ankle: (1 particle per $km^2\cdot$year)
From SNRs to the galactic pool

Ptuskin+ 2013

hard injection spectrum

\[ \sim E^{-2} \]

soft observed spectrum

energy dependent escape from the MW

Intro             SNRs             Gal Centre              SNRs?              Conclusions
From SNRs to the galactic pool

- **Hard injection spectrum**
- **Soft observed spectrum**

$\sim E^{\gamma - 2.7}$

Energy dependent escape from the MW

Production of stable secondary particles:
- \(\gamma\)-rays, nuclei (\(\rightarrow\) B/C), \(e^+, e^-\), \(\bar{p}\), ...

---

**Intro** | **SNRs** | **Gal Centre** | **SNRs?** | **Conclusions**
From SNRs to the galactic pool

- **Hard injection spectrum**
- **Energy dependent escape from the MW**
- **Production of stable secondary particles**
- **γ-rays, nuclei (→ B/C), e^+, e^-, p, ...**
- Additional constraints from chemical composition & anisotropy

**Intro** | **SNRs** | **Gal Centre** | **SNRs?** | **Conclusions**
Young/mid aged SNRs: hadronic or leptonic?

strong B-field $\rightarrow$ low ICS $\rightarrow$ soft hadronic

Intro | SNRs | Gal Centre | SNRs? | Conclusions
Young/mid aged SNRs: hadronic or leptonic?

- strong B-field -> low ICS -> **soft hadronic**

- weak B-field -> uncooled $e^-$ spectrum -> **hard leptonic**

*very low level of thermal X-rays from RXJ1713 -> leptonic? (Ellison+ 2010)*
Soft/hadronic & hard/leptonic?


**clumpy ISM**

- diffuse intercloud $n \sim 1 \text{ cm}^3$
- wind bubble $n \sim 0.01 \text{ cm}^3$
- dense clumps survive against wind $n \geq 10^3 \text{ cm}^3$

**stellar wind sweeps the gas and creates a cavity**

**dense clumps survive (unshocked) both the stellar wind and the SNR shock**

**no thermal X-rays!**
**Soft/hadronic & hard/leptonic?**


**Soft/hadronic & hard/leptonic?**

- **clumpy ISM**
  - wind shell
  - wind bubble
  - massive star
  - dense clumps survive against wind
  - diffuse intercloud
  - $n \sim 1 \, \text{cm}^3$
  - $n \sim 0.01 \, \text{cm}^3$
  - high energy CRs penetrate
  - low energy CRs don’t

**starry wind sweeps the gas and creates a cavity**

- dense clumps survive (unshocked) both the stellar wind and the SNR shock

**no thermal X-rays!**

Sub-parsec clumps!
Soft/hadronic & hard/leptonic?


- stellar wind sweeps the gas and creates a cavity
- dense clumps survive (unshocked) both the stellar wind and the SNR shock
- no thermal X-rays!
- high energy CRs penetrate
- low energy CRs don't
- clumps!

- sub-parsec clumpy ISM

Gabici & Aharonian 2014
Soft/hadronic & hard/leptonic?

- Stellar wind sweeps the gas and creates a cavity
  - Dense clumps survive (unshocked) both the stellar wind and the SNR shock
  - No thermal X-rays!
- High energy CRs penetrate
  - Low energy CRs don't

Gabici & Aharonian 2014

Clumpy ISM

Old SNRs -> hadronic, young/mid aged -> still open issue
The MeV domain: CR ionization

(see SG & Montmerle 2015, Padovani+ 2009 for recent reviews)

\[ H_2 + CR \rightarrow H_2^+ + e^- \]

ionizing photons are absorbed

CRs can penetrate

Intro  SNRs  Gal Centre  SNRs?  Conclusions
The MeV domain: CR ionization

(see SG & Montmerle 2015, Padovani+ 2009 for recent reviews)

\[ H_2 + CR \rightarrow H_2^+ + e^- \]

\[ H_3^+, HCO^+, DCO^+... \]

Intro SNRs Gal Centre SNRs? Conclusions
The MeV domain: CR ionization

(see SG & Montmerle 2015, Padovani+ 2009 for recent reviews)

$H_2 + CR \rightarrow H_2^+ + e^-$

CRs can penetrate

ionizing photons are absorbed

molecular cloud

Chemistry

$H_3^+, HCO^+, DCO^+...$

IRAM

UKIRT

see e.g. McCall+, Indriolo+, Ceccarelli+, Vaupré...
the exception of the SE1 point, in all other points in the previous section. First thing to notice is that, with CR ionization rates, derived following the method described Table 5 lists the observed positions and the corresponding visual extinctions of 5 and 100 mag, respectively. On the left lie different values of high and lower limits report the values derived in this work. The filled square shows Fig. 6. Note that for Fig. 5.

Intro SNRs Gal Centre SNRs? Conclusions

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<th>Ceccarelli+ 2011</th>
<th>W28</th>
<th>Vaupré+ 2014</th>
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<tr>
<th>10^{-14}</th>
<th>10^{-15}</th>
<th>10^{-16}</th>
<th>10^{-17}</th>
<th>10^{-18}</th>
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<tbody>
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<td>Diffuse</td>
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isolated clouds

\[ N(H_2) \] [cm^{-2}]
SuperNova Remnants & MeV cosmic rays
(for a review see SG & Montmerle 2015)

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1. Discussion

The detection of TeV emission in the vicinity of W51 SNR, W28 SNR, and IC443 is evidence of a physical interaction with different objects, such as infrared dark clouds or protoplanetary disks.

2. Analysis of measured ionization rates

- Indriolo et al. 2010
- Vaupré et al. 2014
- Ceccarelli et al. 2011

The ionization fraction of the dense gas in these objects is at least 10 to 260 times larger than the standard value. This implies an enhanced CR ionization rate as derived following the method described in the text.

3. Compilation of measured CR ionization rates

- High-energy CR (100 GeV - 10 TeV)
- Low-energy CR (100 keV - 1 GeV)

The ionization of UV-shielded gas is mostly due to keV-GeV protons, even in absence of an increased CR flux. The ionization rate in several molecular clouds is at least two orders of magnitude larger than the typical value of the standard rate.

4. Discussion of ionization rates

- The ionization fraction observed in various objects is reported towards one position, W51C-E, which required a CR production of the CRI rate (Indriolo et al. 2010; Indriolo & Vaupré 2011).
- The detection of TeV emission in W51 (Ceccarelli et al. 2011) supports this idea, as the ionizing lower energy CR remain confined closer to the SNR.
- GeV emission from different objects (open bars) is interpreted as being towards the northern region but only to a limited extent (or more, if projection effects play a role) to the southern part of the southern region that escaped the SNR expanding shell and travelled for a distance of 4.6 to 11 pc.

5. Conclusion

Clouds next to SNR are indeed irradiated by 5\(\times\)10\(^{-16}\) cm\(^{-2}\) s\(^{-1}\) \(\leq \zeta\), typical of the W28 association, presented with particularity of the W28 SNR. The paper is organized as follows. In Section 2, the W28 association is presented, with particularity of the W28 SNR. The paper is organized as follows. In Section 2, the W28 association is presented, with particularity of the W28 SNR.
SuperNova Remnants & MeV cosmic rays

\[ \zeta_{\text{CR}} \sim \text{few } 10^{-15} \text{ s}^{-1} \]

\[ \zeta \left[ \text{s}^{-1} \right] \]

\[ N(H_2) \left[ \text{cm}^{-2} \right] \]

- **γ-ray bright clouds next to SNRs**
- **isolated molecular clouds**
- **excess of GeV-TeV CRs associated with excess of MeV CRs**

**Intro**  **SNRs**  **Gal Centre**  **SNRs?**  **Conclusions**

- Discussion
- Such as infrared dark clouds or protoplanetary disks.
- Visual extinctions of 5 and 100 mag, respectively. On the left lie
- Dashed lines show the range of column densities
- Filled square shows
- Di
- Squares), as reported by Padovani & Galli (2013). The black
- Fig. 6.
- Fig. 5.

- Approx. projected distance to SNR shock [pc]
- Typical values in dense clouds
- Standard value in dense clouds

-10 to 260 times larger than the standard value (the exception of the SE1 point, in all other points in the previous section. First thing to notice is that, with

- 10
- 9.4
- 10
- 17
- 10
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- 10
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