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The GeV Gamma-Ray Emission Detected by Fermi-LAT Adjacent to SNR Kesteven 41

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IAUS 331 : SN 1987A, 30 years later

February 20-24, 2017, Saint-Gilles-Les-Bains, La Reunion, France

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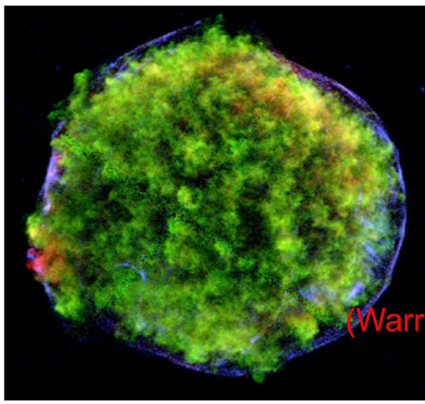
Introduction

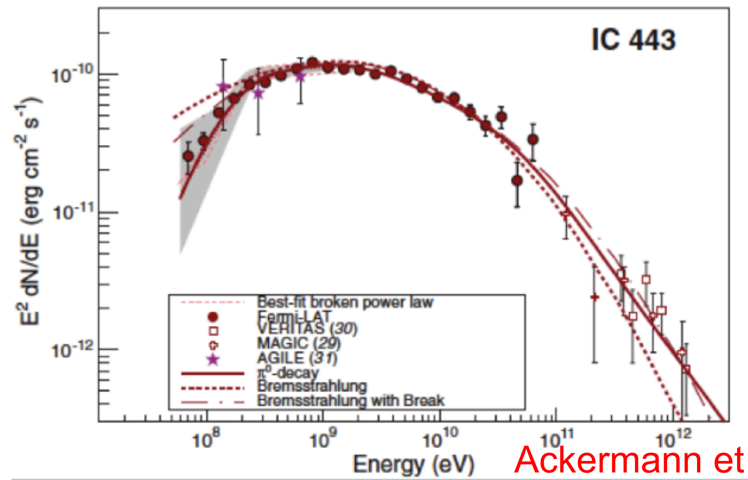
The Origin of Cosmic Rays (CRs)

Supernova remnants (SNRs)
---One of the main accelerators of Galactic CRs



(Warren et al, 2005).

Electron acceleration in SNRs



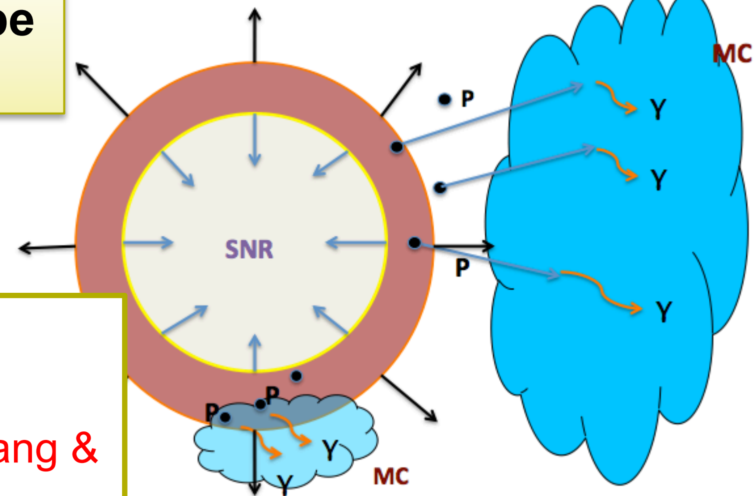
Ackermann et al. 2013

Proton acceleration in SNRs

It is often difficult to distinguish between the **hadronic** γ-ray emission and the **leptonic** γ-ray emission.

Introduction

There are generally two scenarios that describe how hadronic γ-rays are produced in SNRs.



(1) The accelerated protons frozen in the shock efficiently collide with target cloud gas (e.g., Blandford & Cowie 1982; Uchiyama et al. 2010; Tang & Chevalier 2014).

(2) Interactions between the relativistic protons escaping from the SNR shock and adjacent Molecular Clouds (MCs) (e.g., Aharonian & Atoyan 1996; Gabici et al. 2009; Li & Chen 2010; Ohiraet al. 2011).

The SNRs interacting with MCs are crucial probes in the search for the signatures of proton acceleration.

Introduction

- The hadronic γ-ray emission from SNR-MC systems is usually bright around GeV, and a series of GeV-bright SNRs interacting with MCs have recently been discovered with Fermi-LAT.

Such as W51C (Abdo et al. 2009), W44 (Abdo et al. 2010c), IC 443 (Abdo et al. 2010d), W28 (Abdo et al. 2010a), W41 (Castro et al. 2013), RCW 103 (Xing et al. 2014)…

Basic information of SNR Kesteven 41(Kes 41)

- A southern-sky SNR (**G337.8−0.1**)
- First discovered with the Molonglo Observatory Synthesis Telescope (MOST) at 408 MHz (Shaver & Goss 1970)
- **Age**: 4~100 kyr, estimated from the ionization timescale of the X-ray emitting gas (Zhang et al. 2015)
- **Distance**:~12 kpc (OH maser, Koralesky et al. 1998).

Introduction

Kes 41

A *thermal composite (or mixed-morphology)* SNR interacting with MC

It is found to ***be associated with a giant MC*** and **confined in a cavity**

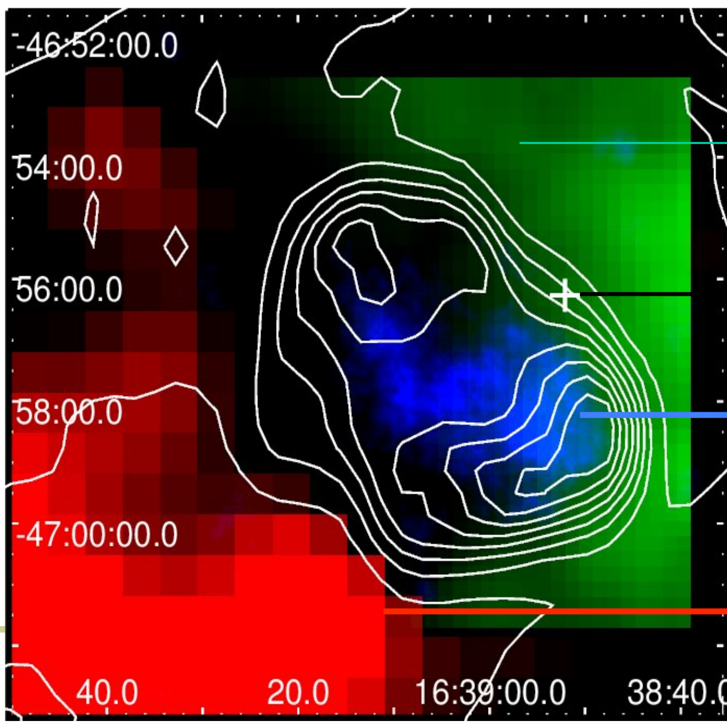


Figure 1 from Zhang et al (2015)

$^{12}CO(J = 1–0)$ integrated map (V_{LSR} = −70 to −40 km/s)

The 1720 MHz OH maser (Koralesky et al. 1998)

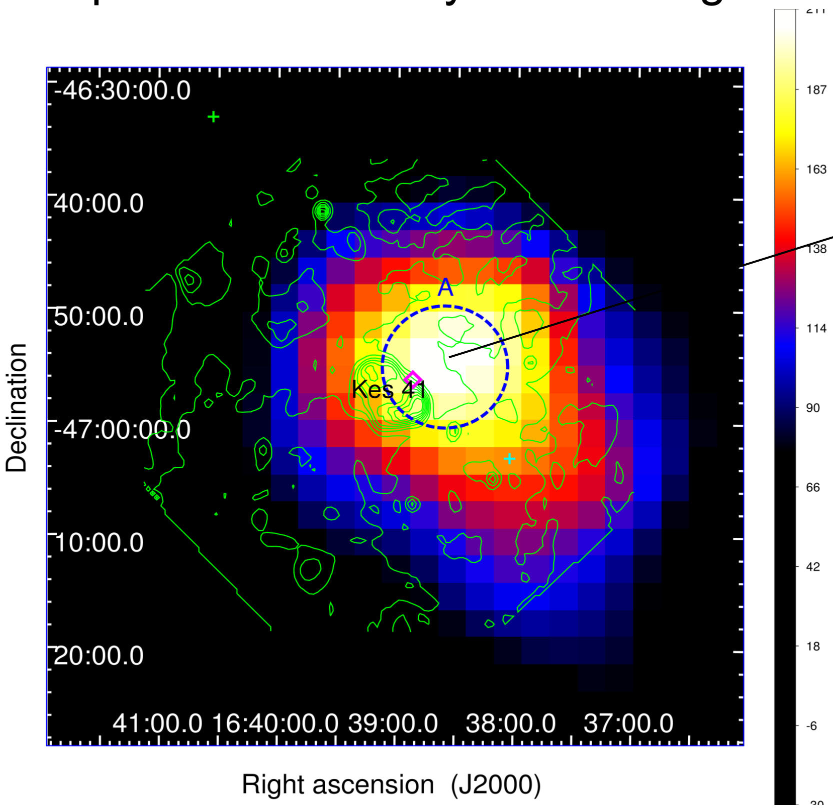
XMM-Newton X-ray image (2.0–7.2 keV)

HI line emission from the SGPS integrated map (V_{LSR} = −55 to −50 km/s)

The image is overlaid with MOST 843MHz radio contours

Fermi-LAT Data Analysis and Results

- Data: 5.6 years data from Fermi-LAT (0.2-300 GeV)
- We select the LAT events inside a 14° X14° region of interest (ROI) centered at the position of Kes 41
- We perform our analysis following the standard binned likelihood analysis procedure.



Source Detection

- We detected a γ-ray source (hereafter **source A**) with a significance of 24σ in 0.2-300GeV energy range.
- The best-fit position :
  (R.A. (J2000) = $16^h38^m36^s.00$,
  decl. (J2000) = −46°55′06″. 96)

<u>Green contours</u>: the MOST 843 MHz radio contours
<u>The dashed blue circle</u> : the 3σ error circle of the best-fit position of source A.

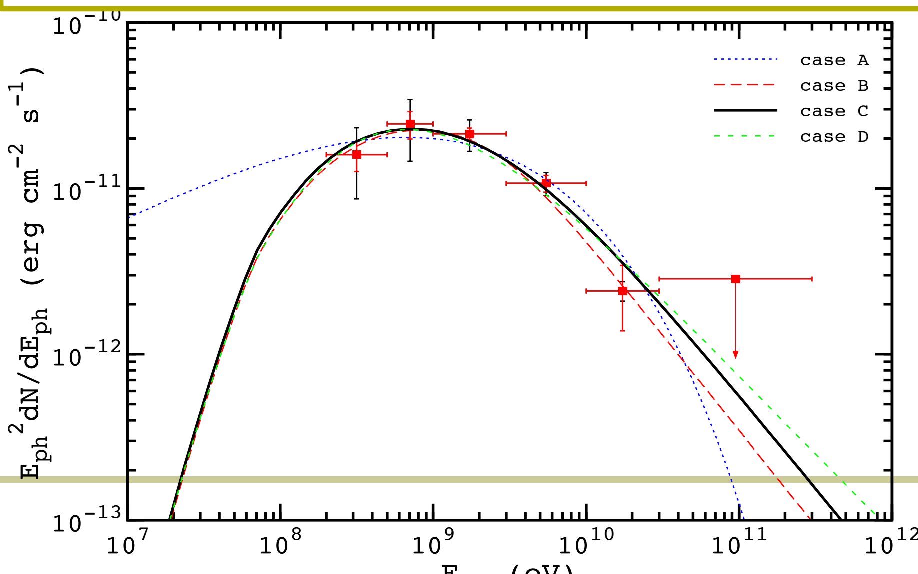
Residual test statistic (TS) map of 1° × 1° region centered at Kes 41. (energy range: 2–300 GeV)

Fermi-LAT Data Analysis and Results

Spectral Analysis

- We fit the 0.2–300 GeV spectral data of source A with a power-law model.
- The obtained spectral shape is relatively flat with photon index of = 2.38 ± 0.03.
- Flux :(9.2 ± 1.0)X10^{-11} erg cm^{-2} s^{-1}
- Luminosity : ~1.6X10^{36} d^2_{12} erg s^{-1}

d_{12} = d/12 kpc, the distance to the MC associated with SNR Kes 41 in units of the reference value estimated from the maser observation (Koralesky et al. 1998)..



Fermi LAT Flux Measurements of Source A in the Kes 41 Region

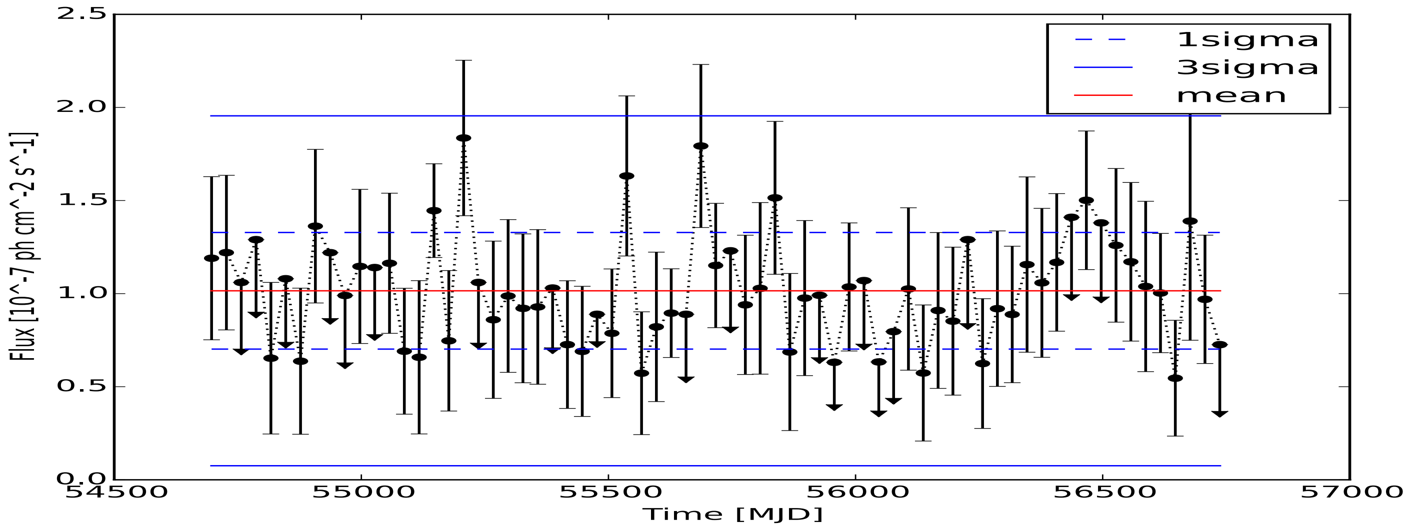
E_{ph} (Energy Band) (GeV)	$E_{ph}^2\, dN(E_{ph})/dE_{ph}$ [a] (10^{-12} erg cm^{-2} s^{-1})	TS Value
0.32 (0.20–0.50)	15.9 ± 3.3 ± 7.3	39
0.71 (0.50–1.00)	24.4 ± 4.6 ± 9.9	113
1.73 (1.00–3.00)	21.3 ± 1.8 ± 4.6	224
5.48 (3.00–10.0)	10.7 ± 1.2 ± 1.7	105
17.3 (10.0–30.0)	2.4 ± 1.0 ± 0.3	9
94.9 (30.0–300)	$\leqslant$2.9[b]	2

Fermi γ-ray spectral energy distribution of source A fit with various models.

Fermi-LAT Data Analysis and Results

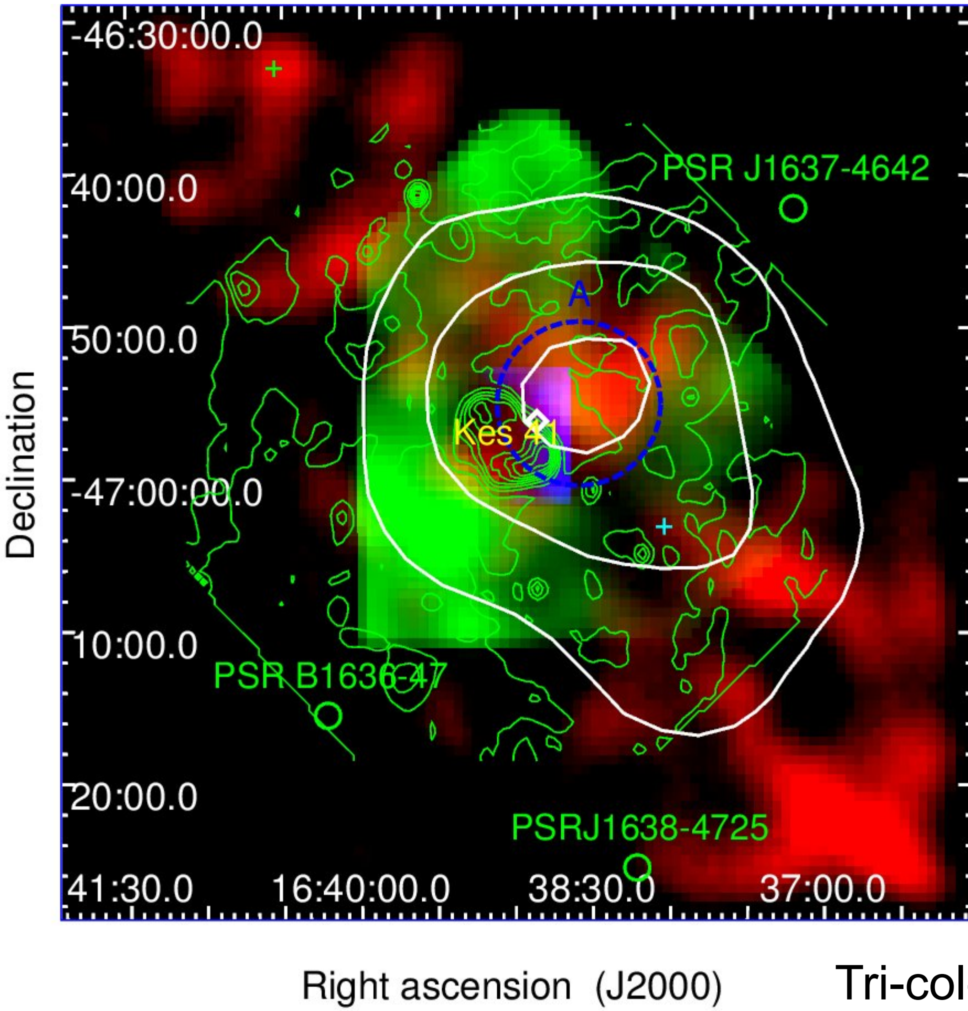
Timing Analysis

- Variability Index (TS_{var})=65.2 (Nolan et al. 2012).
  The threshold is 98.0 corresponding to 99% confidence.
- No significance long-term variability is observed.
- No periodic signals is found through Fermi-LAT aperture photometry analyses..



Monthly γ-ray light curve of source A in the energy range of 0.2–300 GeV.

The Origin of the Detected γ-Ray Emission



Red: smoothed Fermi-LAT counts map (2–300 GeV)
Blue: ^{12}CO(J = 1–0) integrated map with a field of view of 11´X 10´ (V_{LSR} = −70 to −40 km/s)
Green: HI line emission from the SGPS integrated map (V_{LSR} = −55 to −50 km/s)

Green contours: the MOST 843 MHz radio contours
White contours :TS value=100, 144, 196 (significance= 10σ, 12σ, and 14σ).

Tri-color image of Kes 41 in multi-wavelengths.

The Origin of the Detected γ-Ray Emission

(1) A Pulsar?

- We fit the spectrum of source A with a power-law model with an exponential cutoff, $dN_{ph}/dE_{ph} = KE_{ph}^{-\Gamma} \exp(-E_{ph}/E_{ph,cut})$,
  $E_{ph,cut} = 4.0 \pm 0.9$ GeV, $\Gamma = 1.9 \pm 0.1$
  The spectral shape of source A is similar to those of the detected γ-ray pulsars (Abdo et al. 2013)

- No known pulsar within the 3σ error circle of the best-fit position of Source A
  A kicked pulsar?

- No periodic signals is found through Fermi-LAT aperture photometry analyses.
  (this method is statistically limited and the periodicity is hard to detect due to the massive diffuse background photons in a low galactic latitude).

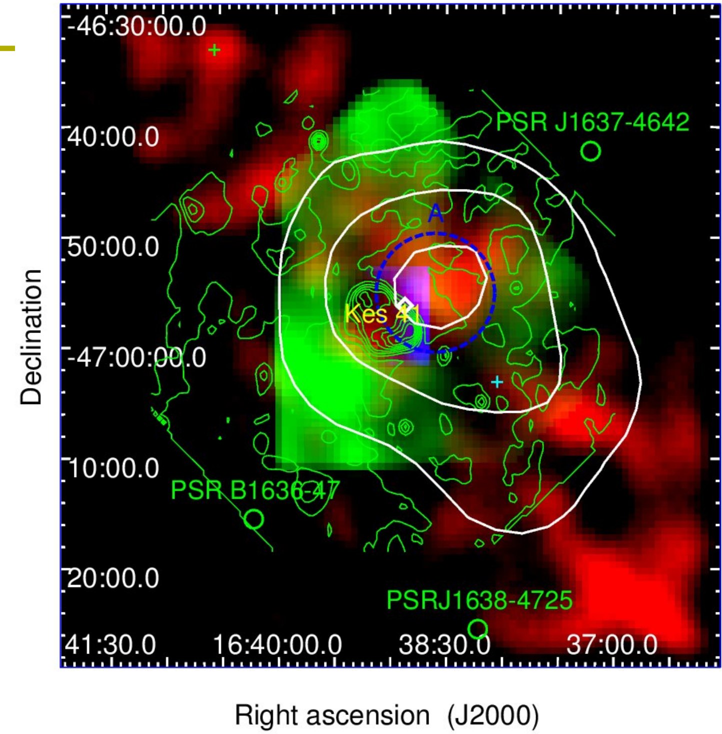
We cannot rule out the possibility.

The Origin of the Detected γ-Ray Emission

2) Emission from Particles Accelerated by Kes 41?

The 3σ error circle is

- on the northwestern boundary of SNR Kes 41
- consistent with the shock-MC interaction region
- covers the OH maser (V_{LSR} = −45 km/s) and the northwestern MC (V_{LSR} = −50 km/s)



- We searched in the SIMBAD Astronomical Database (Wenger et al. 2000) within a 3σ error circle of the source to find possible counterpart for the γ-ray emission .
  objects:Kes 41, several dark clouds, a young stellar object candidate, an infrared source

It is very possible that the γ-ray emission arises from relativistic particles accelerated by the SNR shock waves.

Leptonic Scenario-**Case A**

Inverse Compton emission of relativistic electrons accelerated by the SNR.

- We only consider the cosmic microwave background as the seed photons
- We fit a power-law electron spectrum with a cutoff to the spectral data.

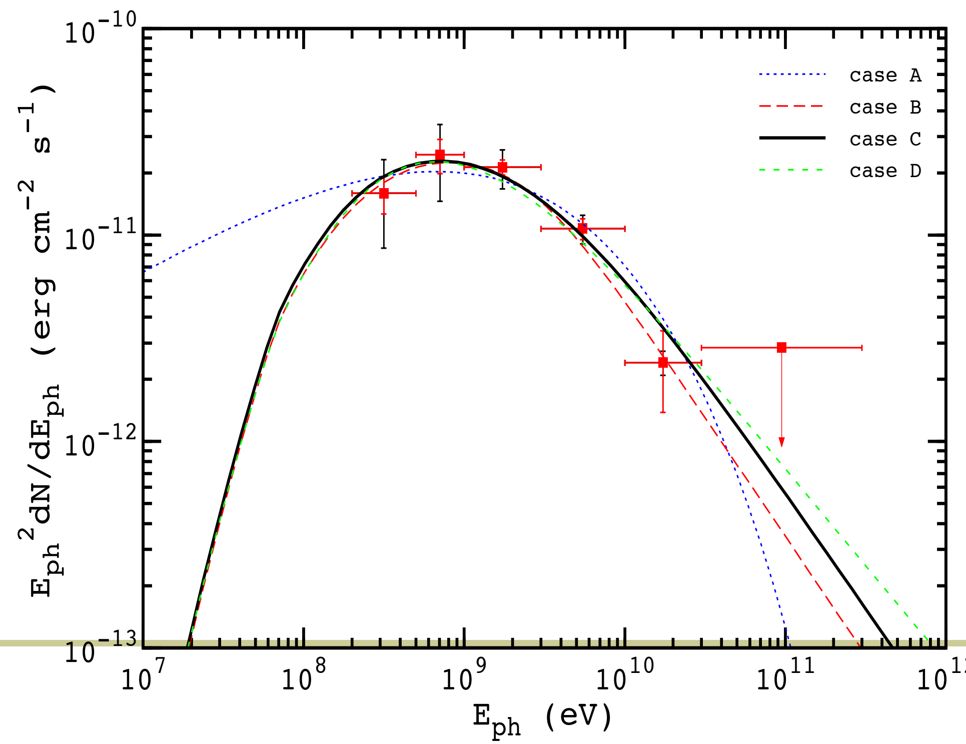
$$dN_e/dE_e \propto E_e^{-\alpha_e} \exp(-E_e/E_{e,cut})$$

α_e	$E_{e,cut}$ (GeV)	W_e (>1 GeV) (10^{51} erg)
2.0	400	1.3

As the order of the canonical SN explosion energy :10^{51}erg

Extremely high

Not favorable



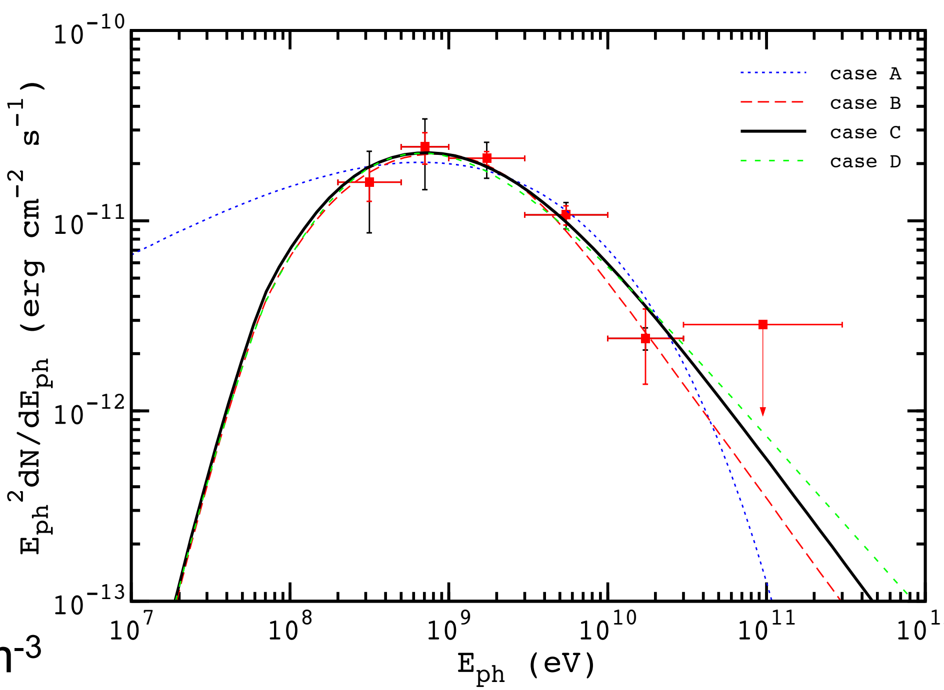
Hadronic Scenario-**Case B**

The shock accelerated protons collide with dense molecular gas
(p-p inelastic collision → π^0-decay)

We assume for the protons a broken power-law distribution to fit the spectral data

$$dN_p/dE_p \propto E_p^{-\alpha_p}(1+(E_p/E_b)^2)^{-\Delta\alpha_p/2}$$

α_p	$\Delta\alpha_p$	E_b (GeV)	$n_t E_{51}^{-1} W_p(>1\ \mathrm{GeV})$ (10^{51} erg cm^{-3})
2.0	1.2	18	7



Assuming mean target density n_t~100 cm^{-3}
➔W_p~0.7x10^{50}erg
➔the fraction of the SN explosion energy (10^{51}erg) converted to protons :η~0.1

Reasonable

Hadronic Scenario-**Case C**

The diffusive relativistic protons escaping from the SNR shock front “illuminate” the adjacent MC.

- The SNR Kes 41 evolves in a cavity and may have drastically decelerated and entered the radiative phase as soon as the blast wave encountered the cavity wall, after a Sedov evolution lifetime t_{enc}. (Zhang et al. 2015).

$$t_{\rm enc} = 4 \times 10^3 (n_{\rm H}/0.3\ {\rm cm}^{-3})^{1/2} E_{51}^{-1/2} (R_s/11\ {\rm pc})^{5/2}$$

- The particle acceleration process **is not significant** after this time.

- The γ-rays arise from an MC which is in contact with the shock surface.

Assumption:

- Energy conversion fraction η= 0.1
- E_{SN} = 10^{51} erg.

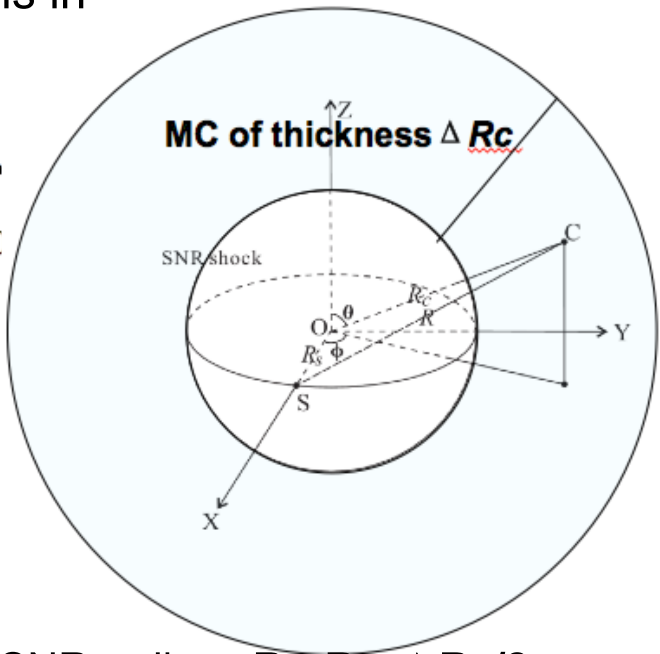
Hadronic Scenario-**Case C**

The diffusive relativistic protons escaping from the SNR shock front "illuminate" the adjacent MC. .

The average distribution of the cumulative escaping protons in the MC at the remnant age t_{age} :

$$F_{\rm ave}(E_{\rm p}, t_{\rm age}) = \int_{R_c-\Delta R_c/2}^{R_c+\Delta R_c/2} r^2 dr \int_0^{t_{\rm enc}} \int_0^{2\pi} \int_0 f(E_{\rm p}, R_{\rm bet}(R_c, t_i, \theta, \varphi), t_{\rm dif}) R_s^2(t_i) \sin\theta \, d\theta \, d\varphi \, dt_i \Big/ \int_{R_c-\Delta R_c/2}^{R_c+\Delta R_c/2} r^2 dr,$$

The distribution function at a given point of the protons that escape from the unit area at an arbitrary escape point.



t_i the time at which a proton escapes from the SNR shock **R_s** the SNR radius **$R_c = R_s + \Delta Rc/2$**

$t_{dif} = t_{age} - t_i$ the diffusion time after escape,

R_{bet} the distance between the escape point on the shock surface and a given point in the cloud

See Li & Chen (2012) and the references therein for details

Hadronic Scenario-**Case C**

Considering the remnant's age range ~4 –100kyr,
we calculate the model with three age numbers, 4, 10, and 100 kyr.

t_{age} (kyr)	α_p	δ	χ	ΔR_c (pc)	M_{cl} ($10^4 M_\odot$)
4	2.4	0.7	0.07	5	4.5
10	2.4	0.7	0.03	10	11
100	2.4	0.7	0.004	13	18

α_p :the photon index

δ : the energy-dependent index of the diffusion coefficient

X: the correction factor of slow diffusion around the SNR

- The ΔRc value :~5–13 pc (~0°. 02–0°. 06) implies that the MC involved in the p–p hadronic interaction is essentially within the 3σ error circle of source A.
- The "illuminated" MC mass (M_{cl}), around $10^5 M_\odot$ is **reasonable** compared with the mass of the molecular gas in the northwest, > a few times $10^5 M_\odot$
(Zhang et al. (2015) estimated the mass from a limited field of view of the CO observation)

Hadronic Scenario–**Case D**

According to Zhang et al. (2015), the cavity wall may send a reflected shock backward when the blast wave collides with it.

What if the reflected shock can still effectively accelerate particles after the forward shock becomes radiative?

We approximate this case as a continuous proton injection from the SNR center and follow the algorithm described in Aharonian & Atoyan (1996)

Assuptions:

- The MC is regarded as a point.
- Energy conversion fraction η = 0.1

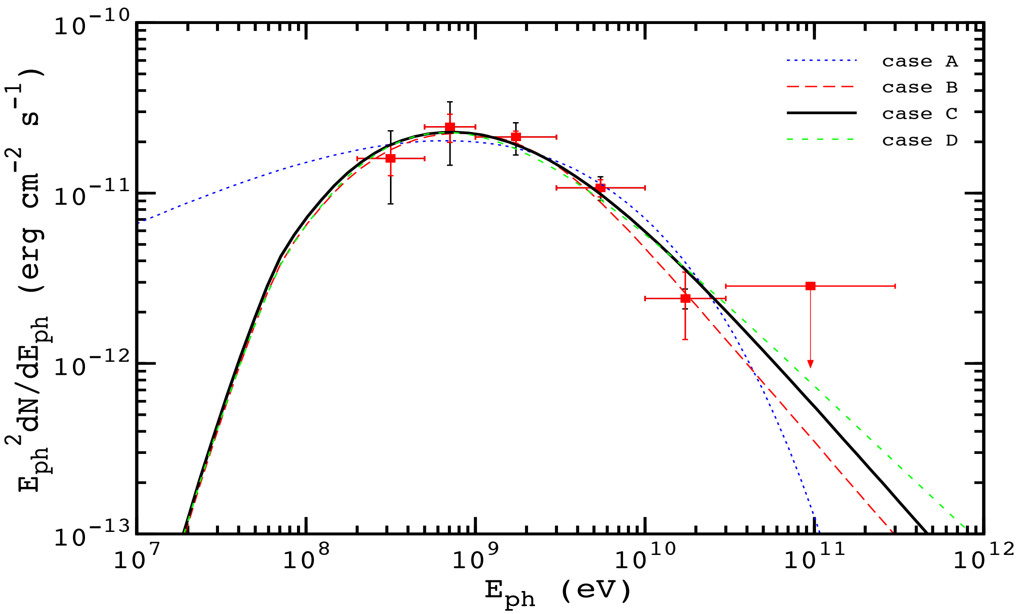
$t_{\rm age}$ (kyr)	$\alpha_{\rm p}$	δ	χ	R_c (pc)	$M_{\rm cl}$ ($10^4 M_\odot$)
4	2.4	0.7	0.25	15	18
10	2.4	0.7	0.45	20	40
100	2.4	0.7	0.05	20	40

A higher mass of the "illuminated" part of MC than Case C is required. **Consistent** with the MC mass estimate from the CO observation in the order of magnitude.

R_c : the distance between the MC and the SNR center

Comparison among different models

Fermi γ-ray spectral energy distribution of source A fit with various models.



- The hadronic scenarios, both the interaction at the shock (Case B) and the illumination by escaping protons (Case C/D), can generally explain the γ-ray properties of source A.
- The escape cases have harder model spectra at 10 GeV than the interaction-at-the-shock case.
- Further TeV observations will likely be of help to distinguish the two scenarios.

Summary

- Using 5.6 years of Fermi-LAT observation data, we find a γ-ray source to the northwest of thermal composite SNR Kes 41 with a significance of 24σ in 0.2–300 GeV.
- The 3σ error circle of the best-fit positon, 0°.09 in radius, covers the OH maser and is consistent with the location of the MC with which the SNR interacts.
- The power-law electron spectrum with a cutoff for inverse Compton scattering would lead to difficulty in the electron energy budget.
- The emission can be naturally explained by the hadronic interaction between the relativistic protons accelerated by the shock of SNR Kes 41 and the adjacent MC.
- By comparison with the hadronic interaction at the shock, which appears off the best-fit position of the source, illumination of the adjacent MC by the protons escaping from the shock front seems more consistent with observations.
- A list of Galactic thermal composite SNRs detected at GeV γ-ray energies by Fermi-LAT is presented in this paper.

Thank you ~