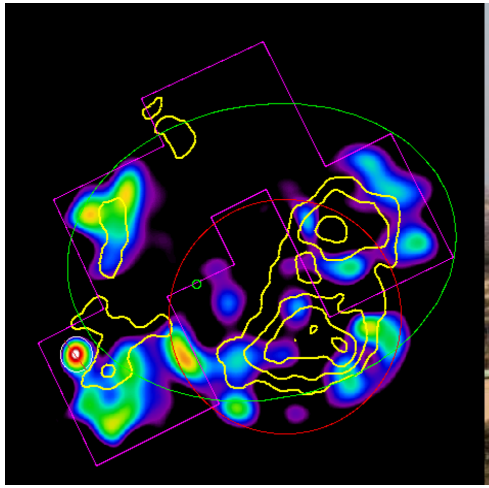
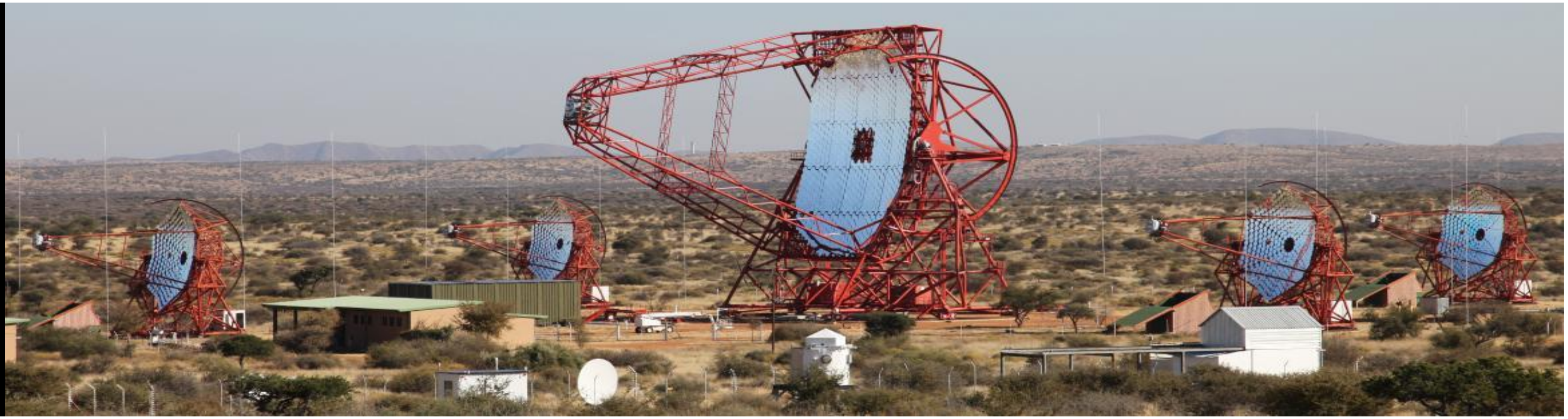
Revealing the cosmic ray activities at the site of the TeV-discovered SNR HESS J1534-571





Speaker: **Nhan T. Nguyen-Dang**

XMM-Newton observations of the TeV-discovered supernova remnant HESS J1534-571

N. T. Nguyen-Dang[1], G. Pühlhofer[1], M. Sasaki[2], A. Bamba[3,4,5], V. Doroshenko[1], and A. Santangelo[1]

Outline

1. Introduction
    1.1. Cosmic rays and their origin
    1.2. Supernova remnants (SNRs)
    1.3. HESS J1534-571
2. Results
    2.1. X-ray continuum emission
    2.2. 6.4 keV emission
    2.3. Broadband SED analysis
3. Conclusion

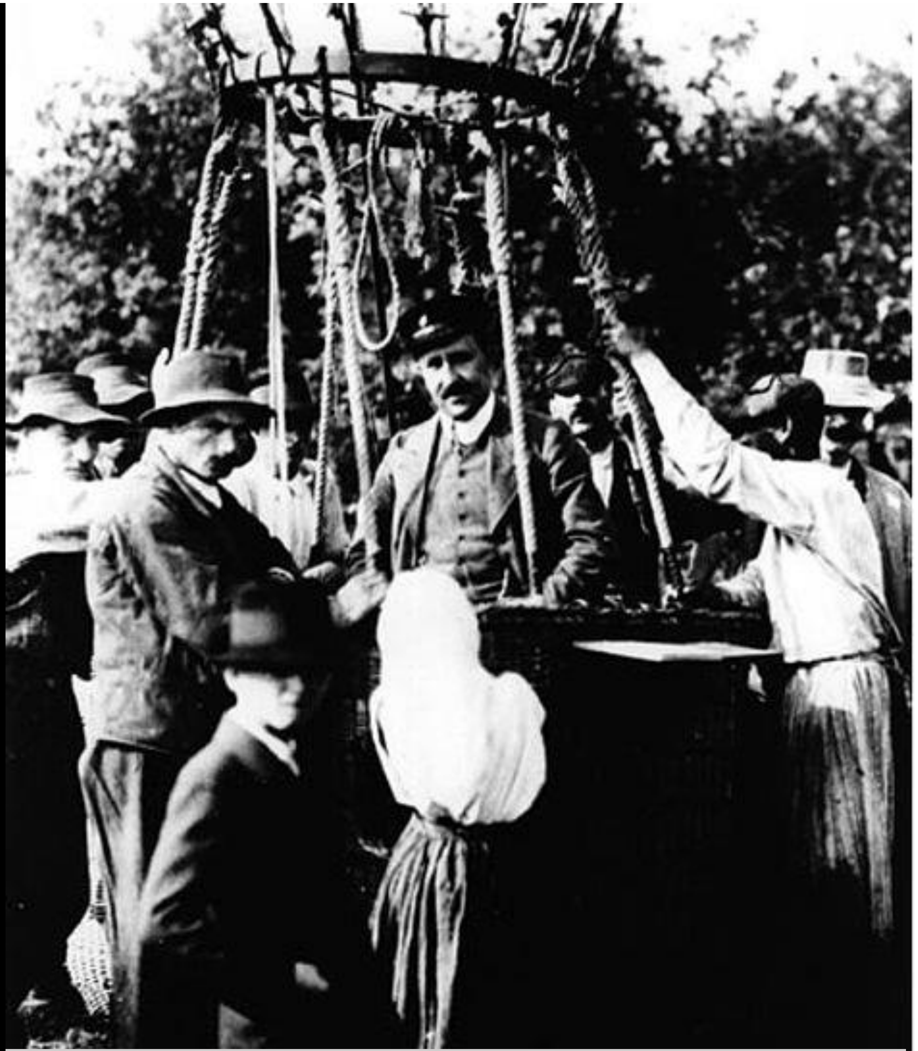
1. Introduction
1.1. Cosmic rays and their origin

- Discovered in 1912 by Victor Hess: the ionization rate at 5300 m is ~3 times higher than at sea level.

➔ High-energy particles/radiations coming from outer space!

- First time ever observed particles, e.g. positrons, muons.

- Open a new era for particle physics study.



Austrian physicist Victor Hess and the balloon in 1912.
Source: wikipedia

1. Introduction

1.1. Cosmic rays and their origin

Composition:

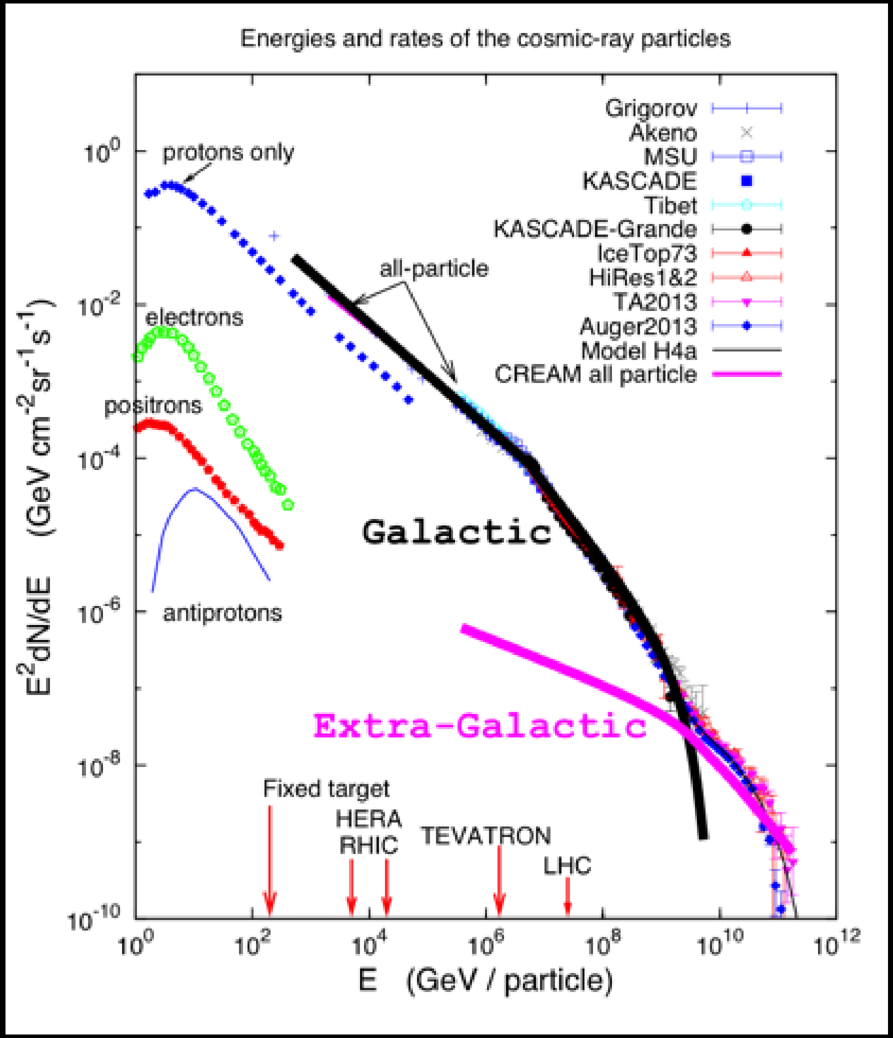
- Primary: protons, ions, electrons.
- Secondary: anti particles, neutrinos, gamma rays.

High energy density:

- In our galaxy: 1 – 2 eV cm^{-3}

Energy source:

- Supernova remnants, pulsars.



Credit: https://masterclass.icecube.wisc.edu/

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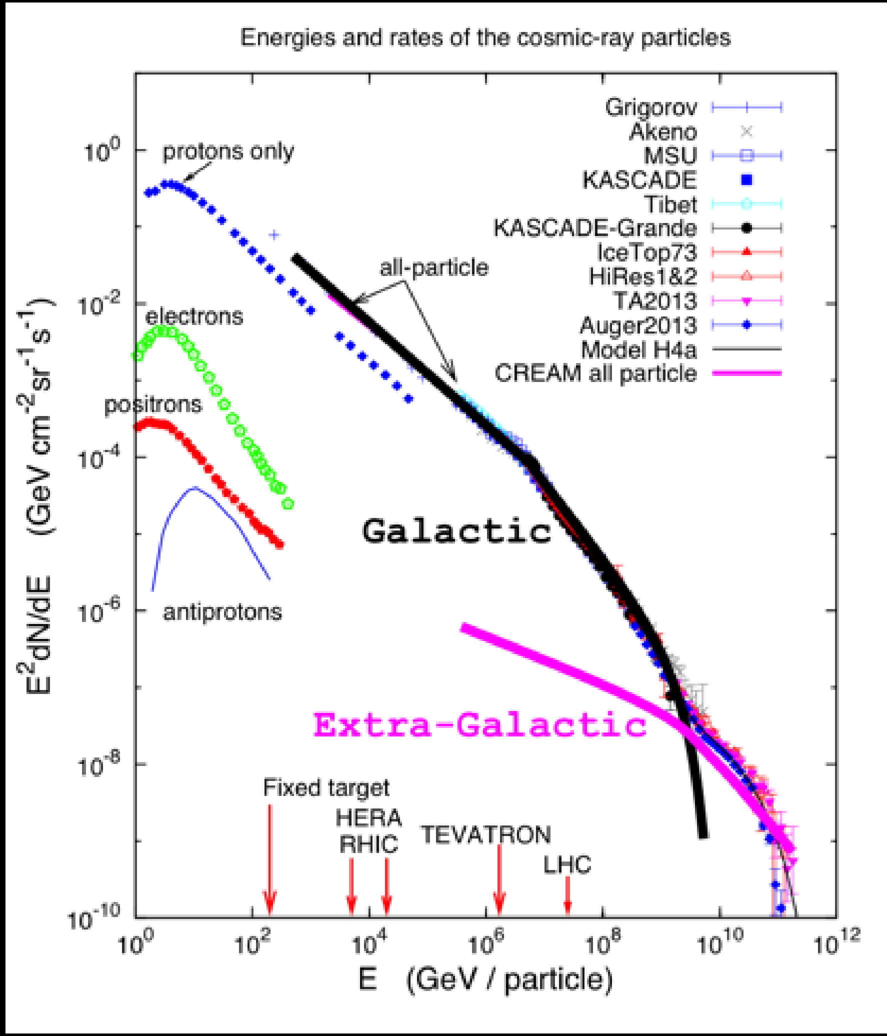
Prediction:

- CR production total power = 10^{41} erg s^{-1}
- SN average explosion energy = 10^{51} erg
- SN rate in our galaxy = 2-3/century

→ 10% of SNRs' energy goes into CRs.



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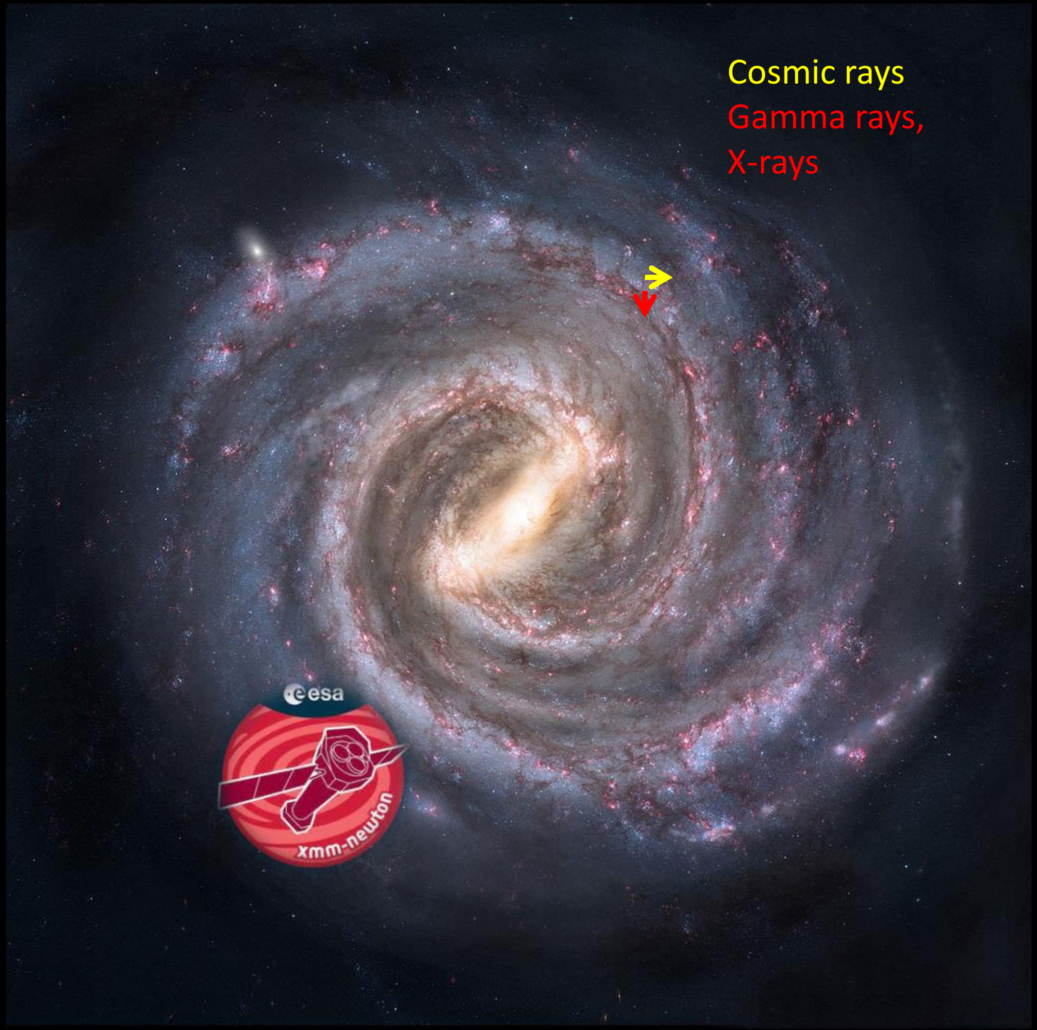

The Milky way
Credit: https://www.universetoday.com/

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

東京大学 THE UNIVERSITY OF TOKYO

H.E.S.S.

1. Introduction

1.. Cosmic rays and their origin

Gamma ray production

Hadronic origin

CRp + p - - -> CRp + p + π^0/ $\pi^{\pm}$

π^0 (decay) - - -> γ

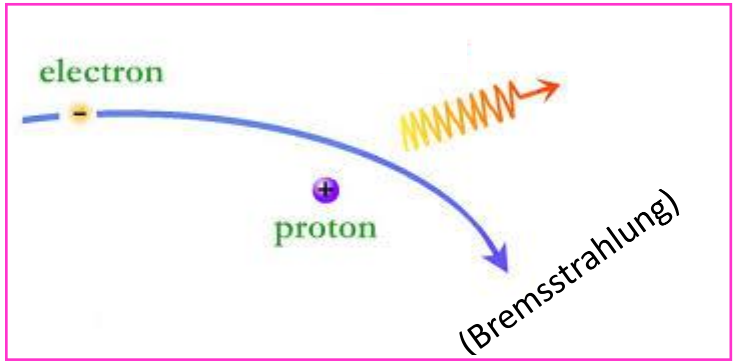
Leptonic origin

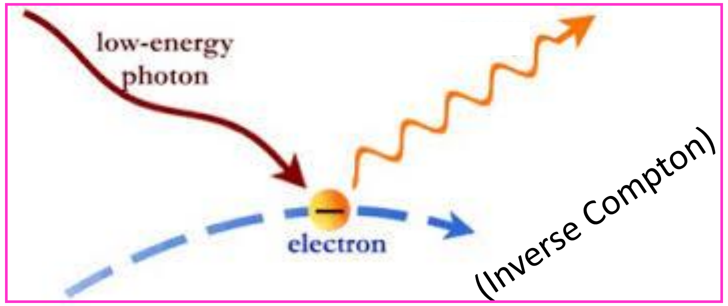
CRe + p - - -> CRe + p + γ

CRe + γ (CMB) - - -> e + γ'

CRe + B-field - - -> CRe + γ

Also:
$\pi^{\pm}$ (decay) - - -> e$^{\pm}$ ...





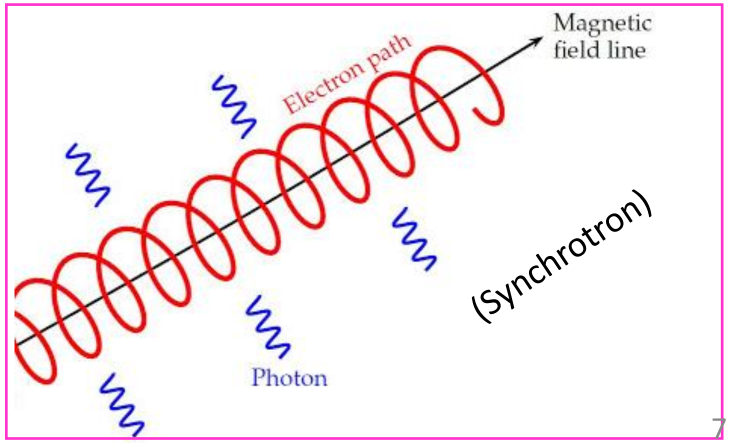


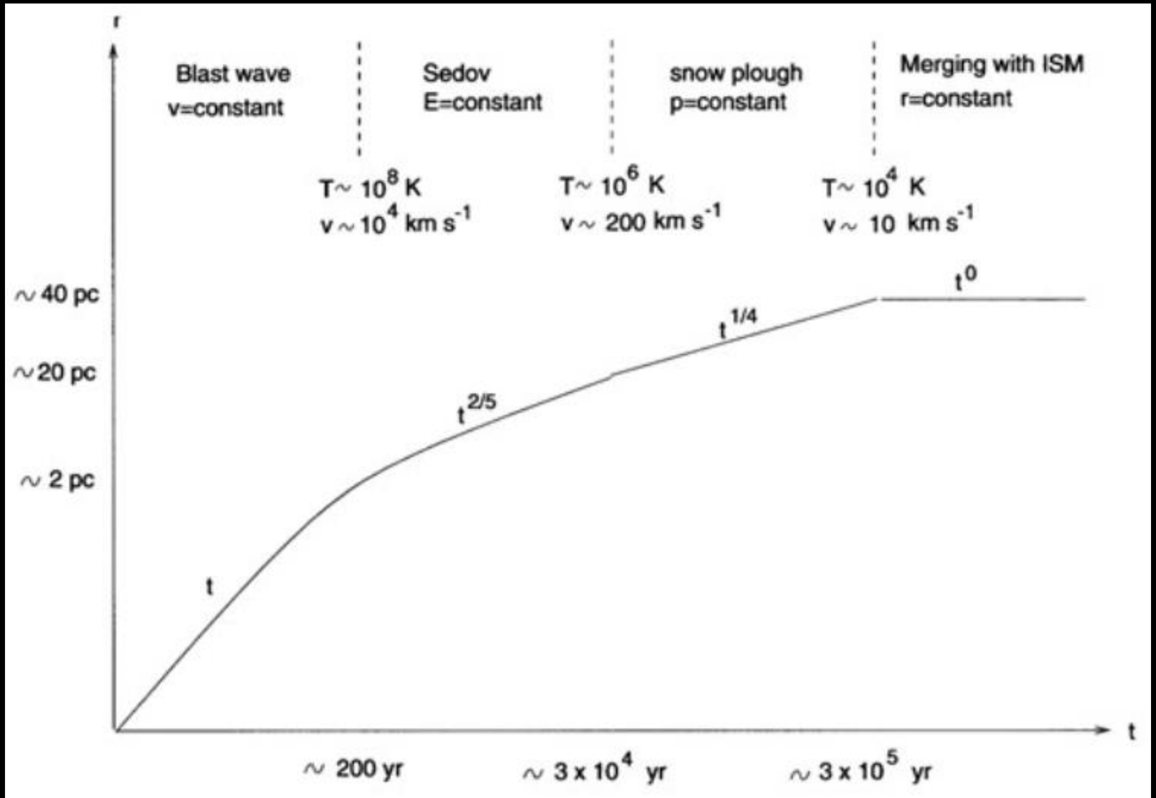
Image credit: https://chandra.harvard.edu/, https://indico.cern.ch/, http://spiff.rit.edu/

1. Introduction
1.2. Supernova remnants (SNRs)

Supernovae (SN):
- Tremendous explosions at the end of a star life cycle (core collapse or thermonuclear).
- Create strong shock, which can interact with circumstellar matter.

Supernova remnants:
- Ingredients: expanding shock wave from the SN, ejected material, swept up ISM.
- Properties: low density, high temperature gas (~10^7 K).
- Eventually merge with the ISM.

1. Introduction
1.2. Supernova remnants (SNRs)



Credit: Rosswog and Brüggen (2007)

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1. Introduction

1.2. Supernova remnants (SNRs)

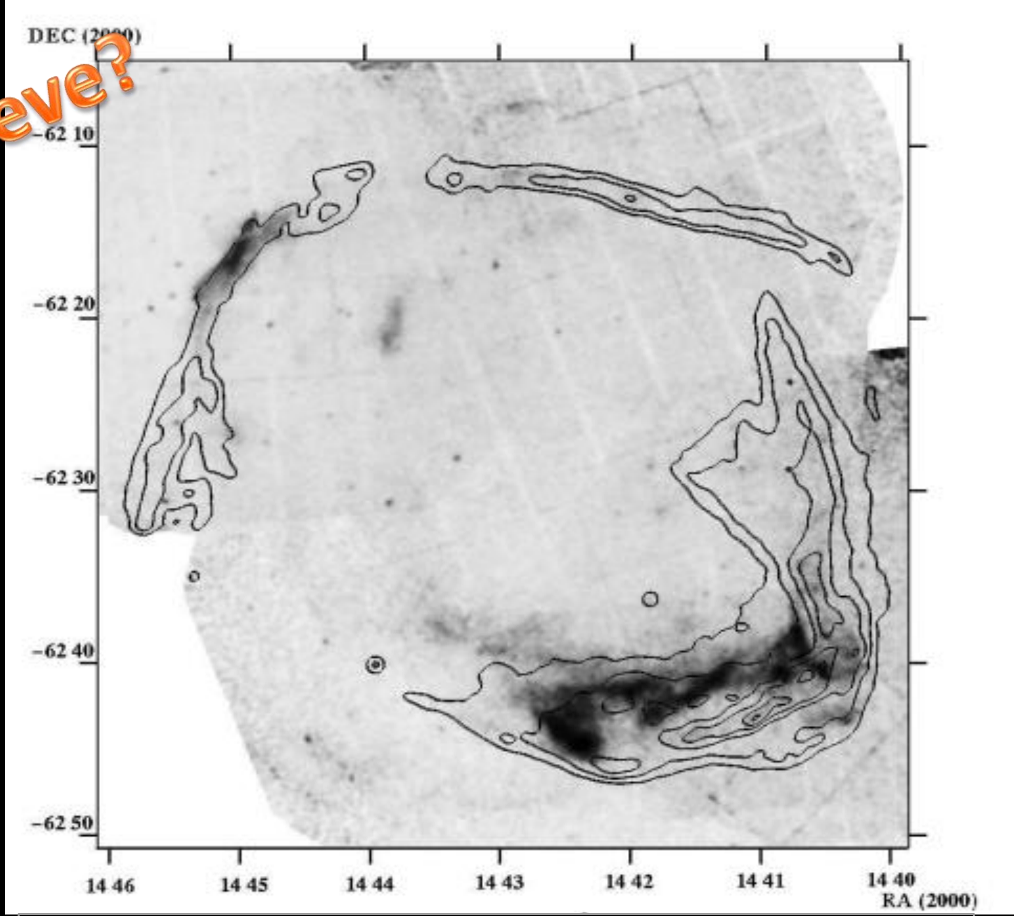
How to obsereve?

Emission from SNRs:

- Radio: synchrotron radiation at the shock front, where the shock gives rise to B-field.
- Optical: line emission from interaction with the ISM.
- X-ray:
    - From **shock heated gas**: collisionless, “violent relaxation”.
    - **Synchrotron** from 10-100 TeV electrons at the CR acceleration sites.
- VHE: From the cosmic ray (CR) particles.
    - Electrons induced: **inverse Compton (IC).**
    - Protons induced: **pion decay.**

Leptonic

Hadronic



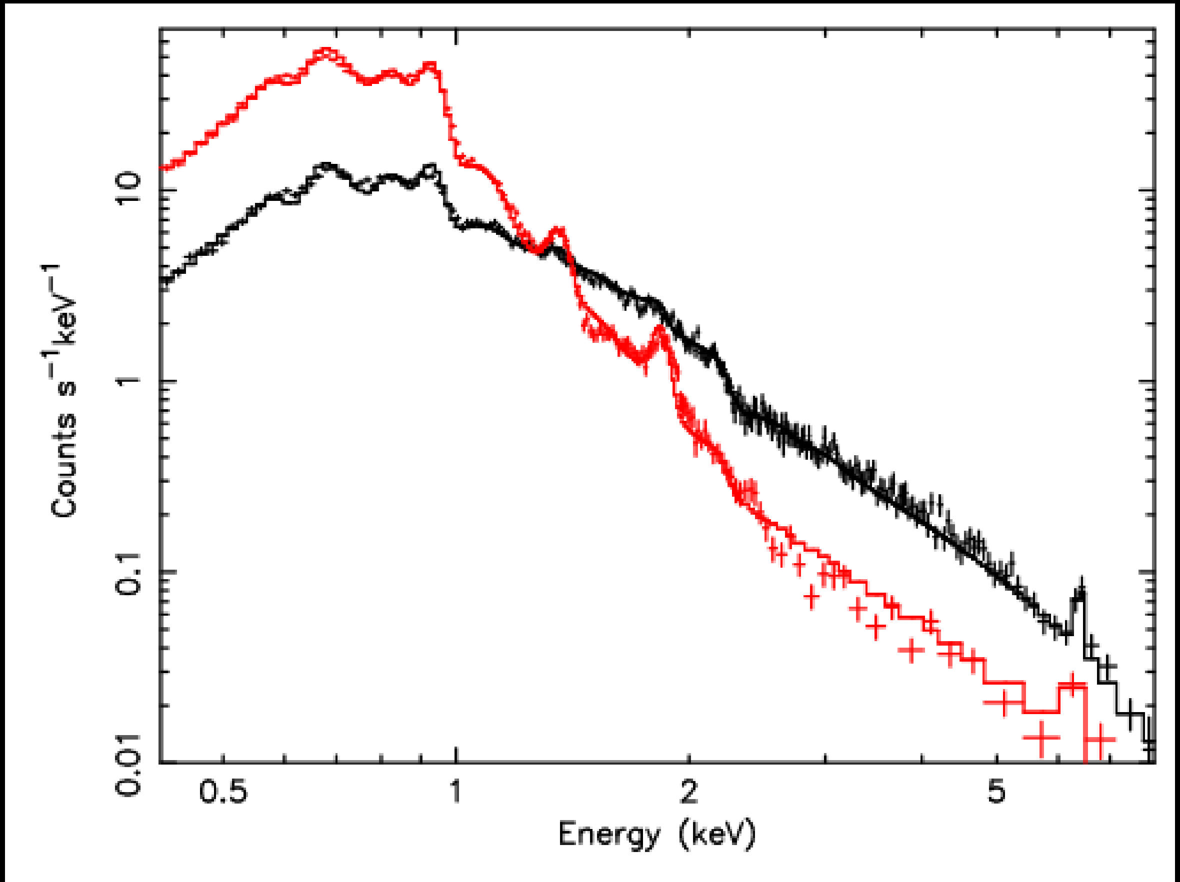
XMM-Newton mosaic image of **RCW86** in the band 1.95-6.8 keV, with 0.5-1.0 keV as contours.
Credit: Vink 2004

1. Introduction

1.2. Supernova remnants (SNRs)

X-ray emission from SNRs

- **Thermal X-ray emission:**
  - Shock heated plasma
  - Dominated by thermal bremsstrahlung and line emission.

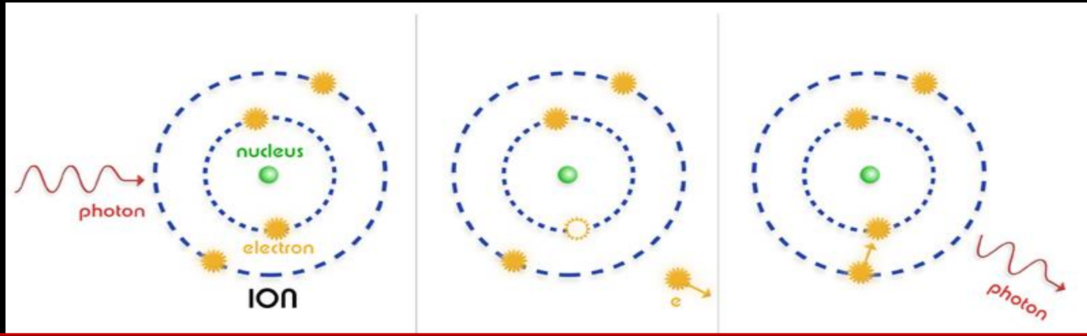


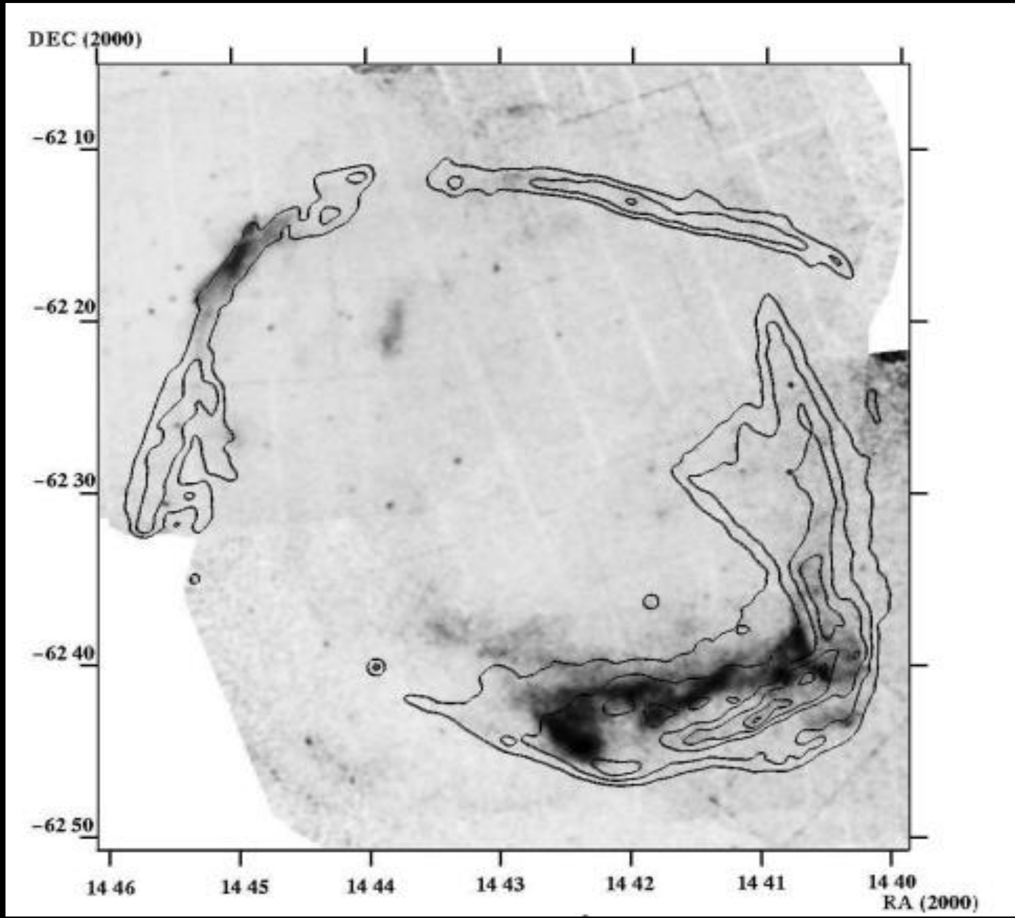
Spectra from a thermal dominated emission region **(red)** and a nonthermal dominated region **(black)**. *Credit: Vink 2004*

1. Introduction
1.2. Supernova remnants (SNRs)

X-ray emission from SNRs:

- **Non-thermal:**
  - Synchrotron (mostly).
  - Non-thermal bremsstrahlung, but hardly contribute (can only see narrowly near the shock front or where the ionization age is low.)
  - Fluorescence from low energy cosmic rays, e.g: Fe Kα at 6.4 keV.

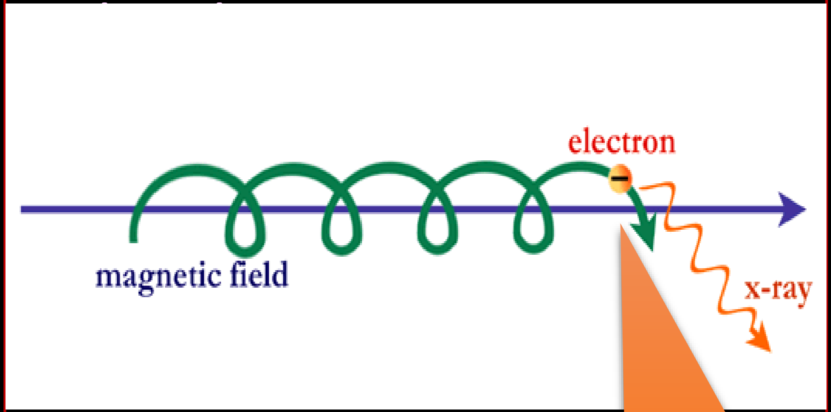




XMM-Newton mosaic image of **RCW86** in the band 1.95-6.8 keV, with 0.5-1.0 keV as contours. *Credit: Vink 2004*

1. Introduction
1.2. Supernova remnants (SNRs)

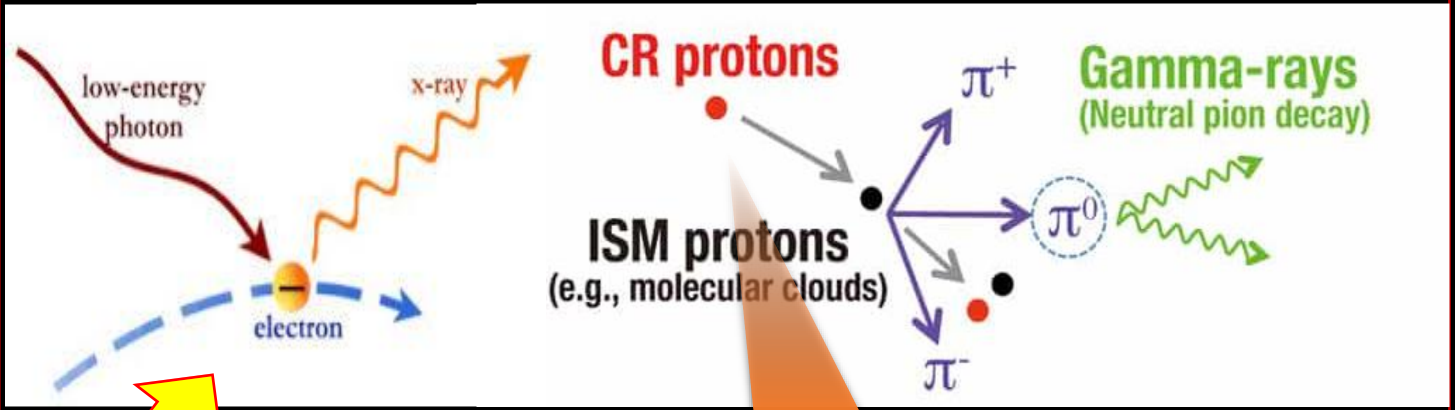
X-ray emission from SNRs:



~10-100 TeV e⁻ (same populations that produce TeV via **IC**)

Credit: http://Chandra.harvard.edu.

High energy gamm-ray emission from SNRs:



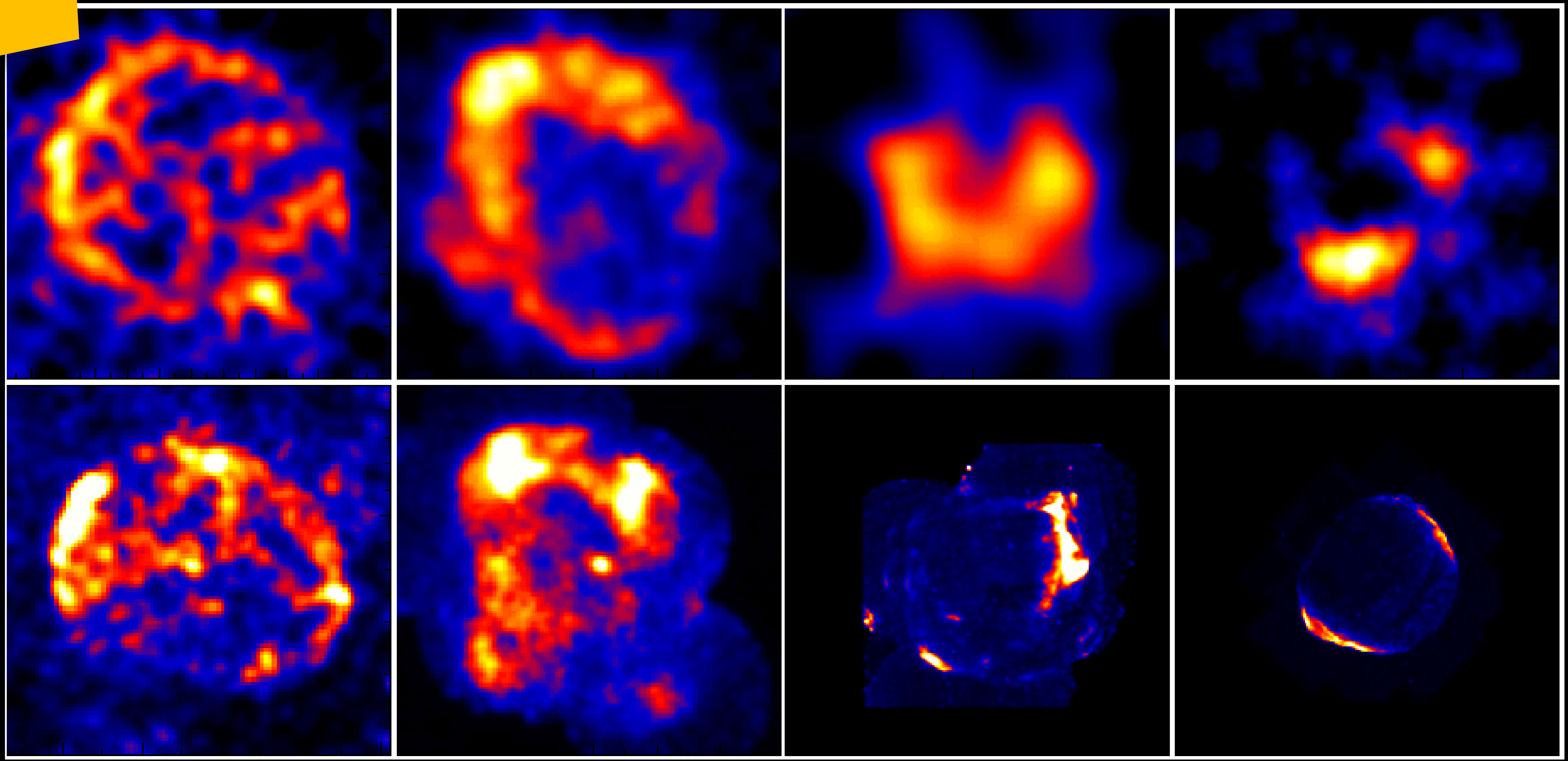
But **pion decay** also produces TeV gamma too!

Credit: Astrophysics Laboratory, Nagoya University

Key questions

Resolved shell-type supernova remnants in the TeV band

Young, resolved (in TeV), TeV-dominated (in γ-rays)



X-ray synchrotron emission, correlated with TeV profile

Key questions

Which CR population is responsible for the VHE gamma radiation from SNRs? Is it CR electrons by IC? Or CR protons by pion decay?

Probing the CR protons/ ions acceleration in SNRs? => important population to explain the Galactic cosmic ray sources.

Here's an idea!

TeV emission is **hadronic**
(low e-density, high B-field)

TeV emission is **leptonic**
(high e-density, low B-field)

Example: SNR RX J1713.7-3946

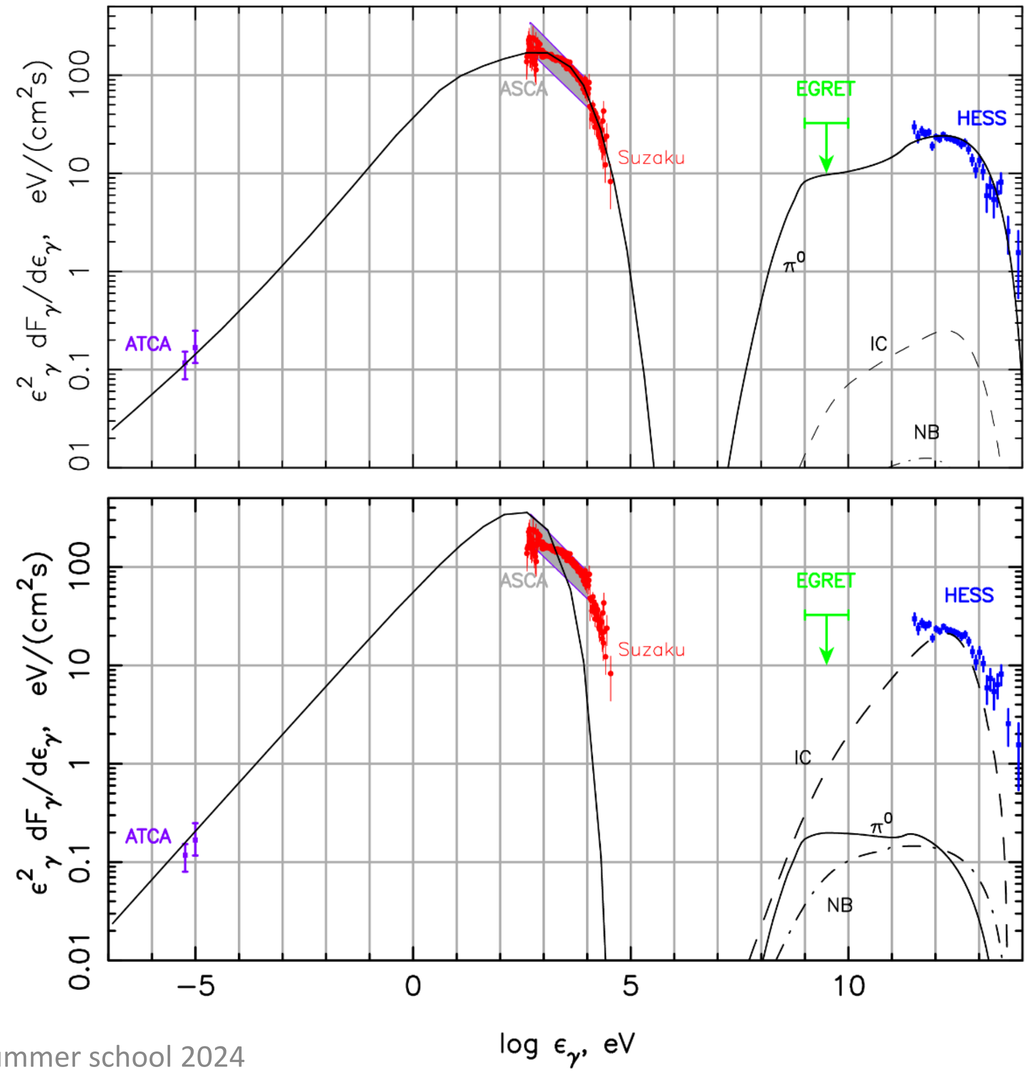


Image credit: Berezhko & Völk, astro-ph/0801.0988

1. Introduction

1.2. Supernova remnants (SNRs)

VHE + X-rays in case of a hadronic source

*emitted power of IC and SYN:

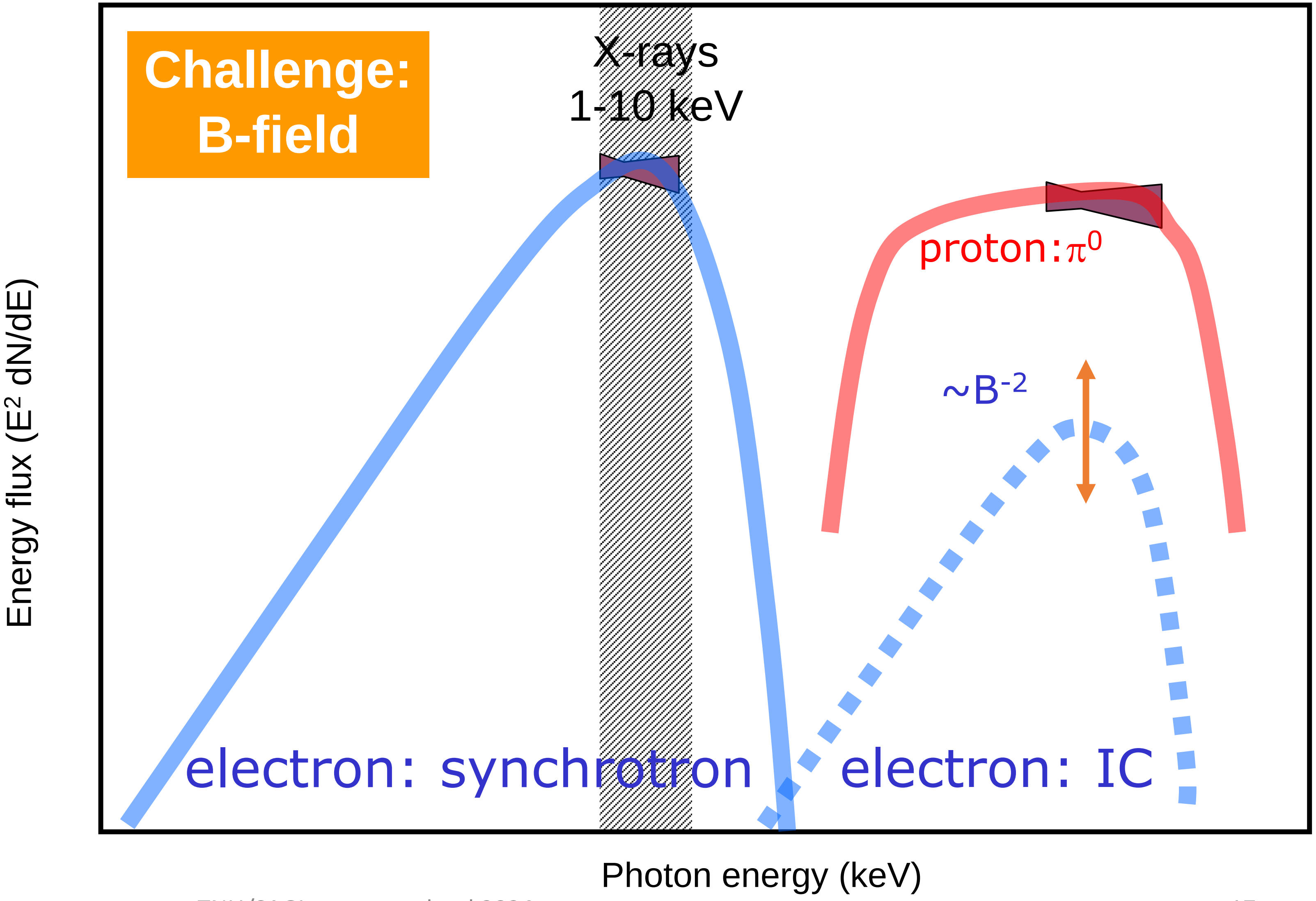
$$P_{IC} \sim \gamma^2 . u_{phot}$$

$$P_{SYN} \sim \gamma^2 . u_B$$

$$P_{IC} \sim \frac{u_{phot}}{u_B} P_{SYN}$$

*energy density of magnetic field:

$$u_B \sim B^2$$



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1.2. Supernova remnants (SNRs)

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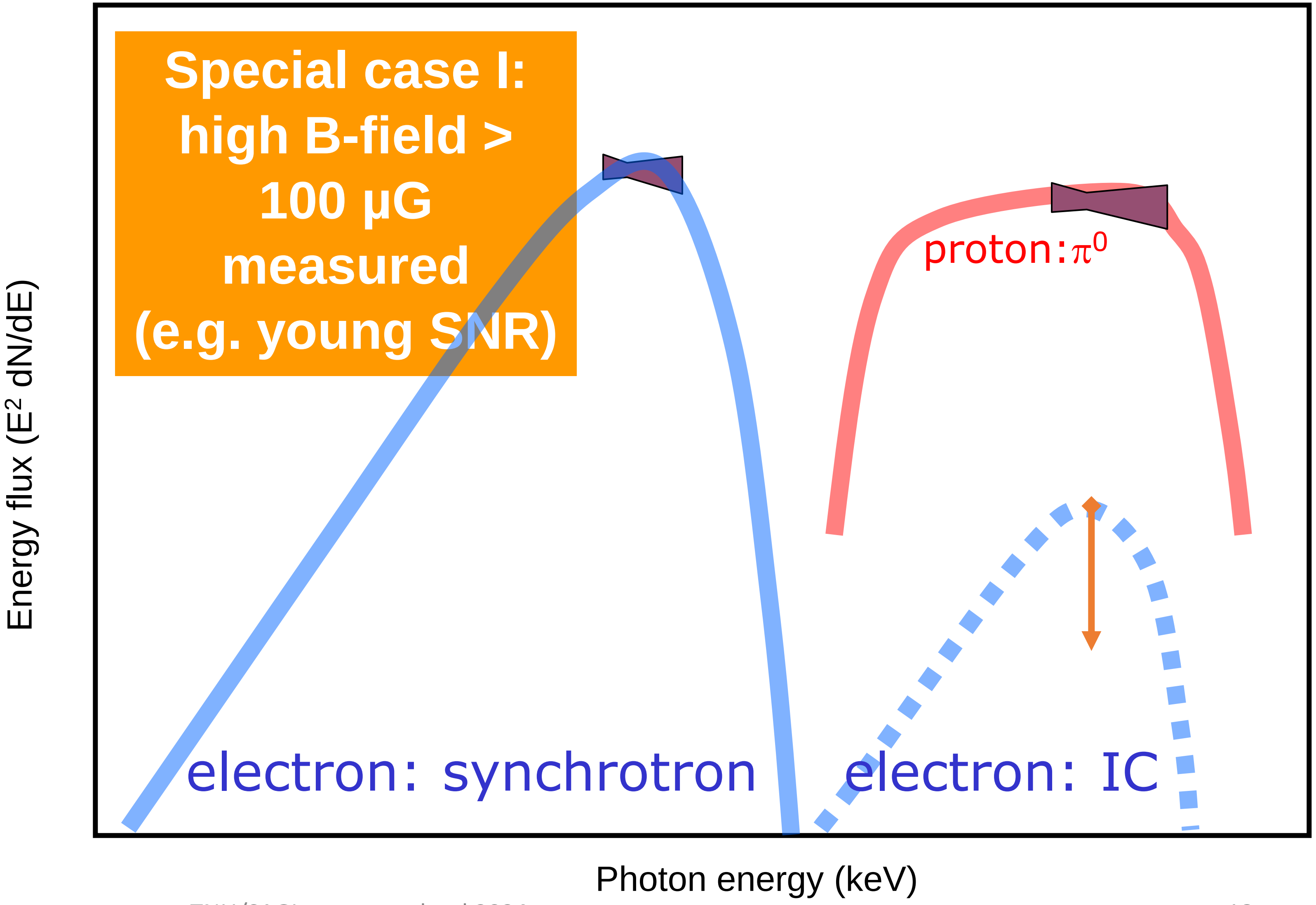

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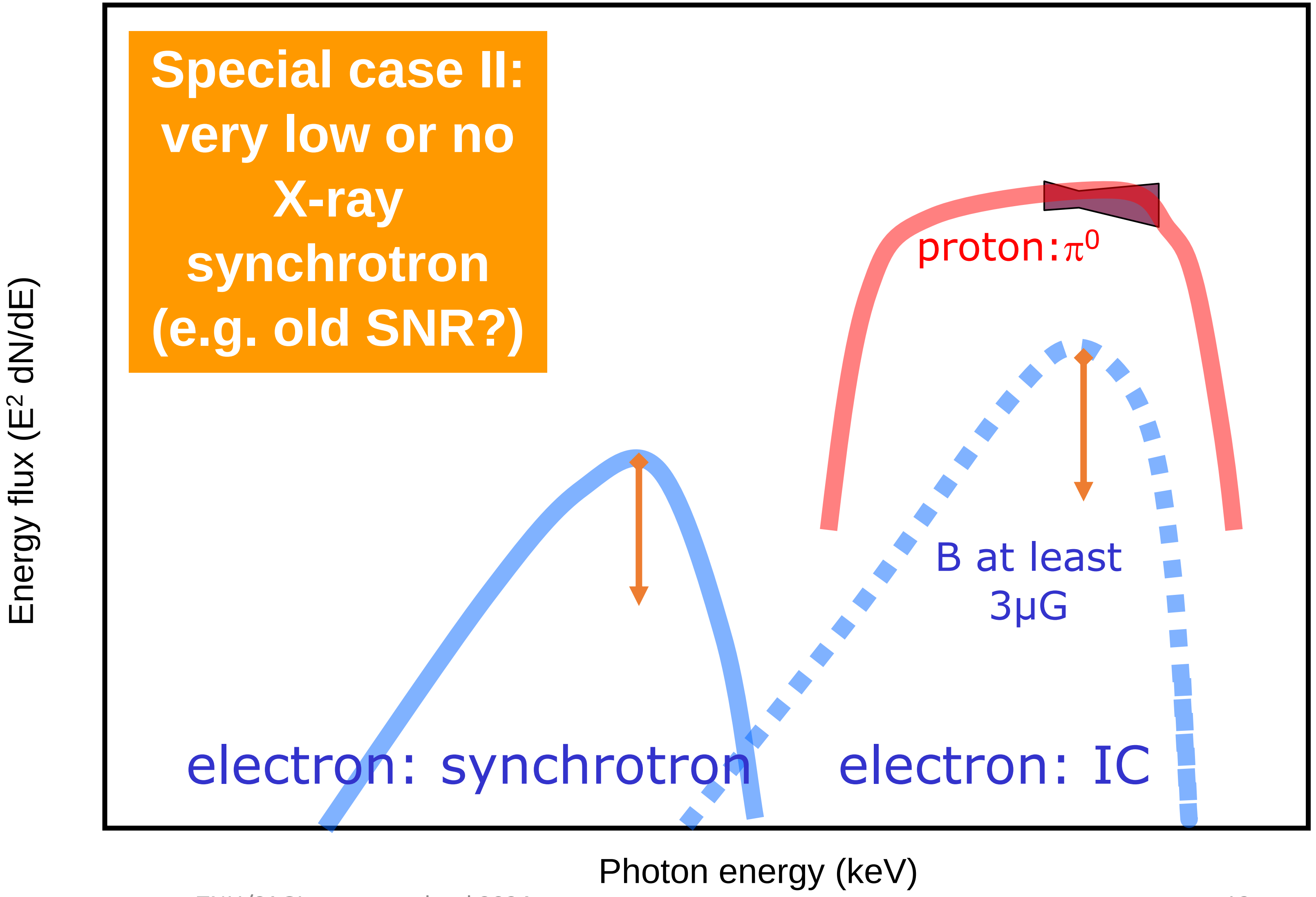
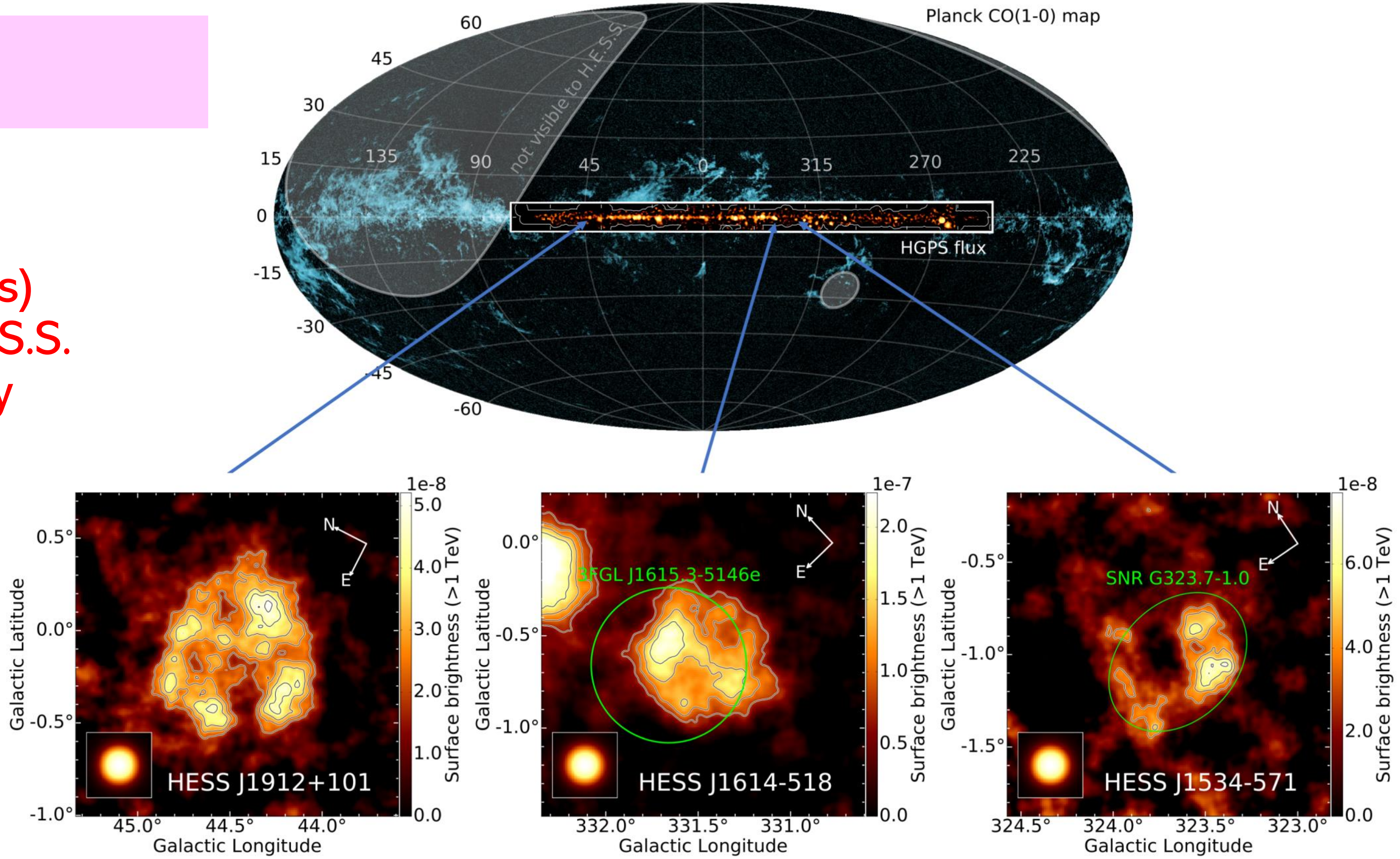
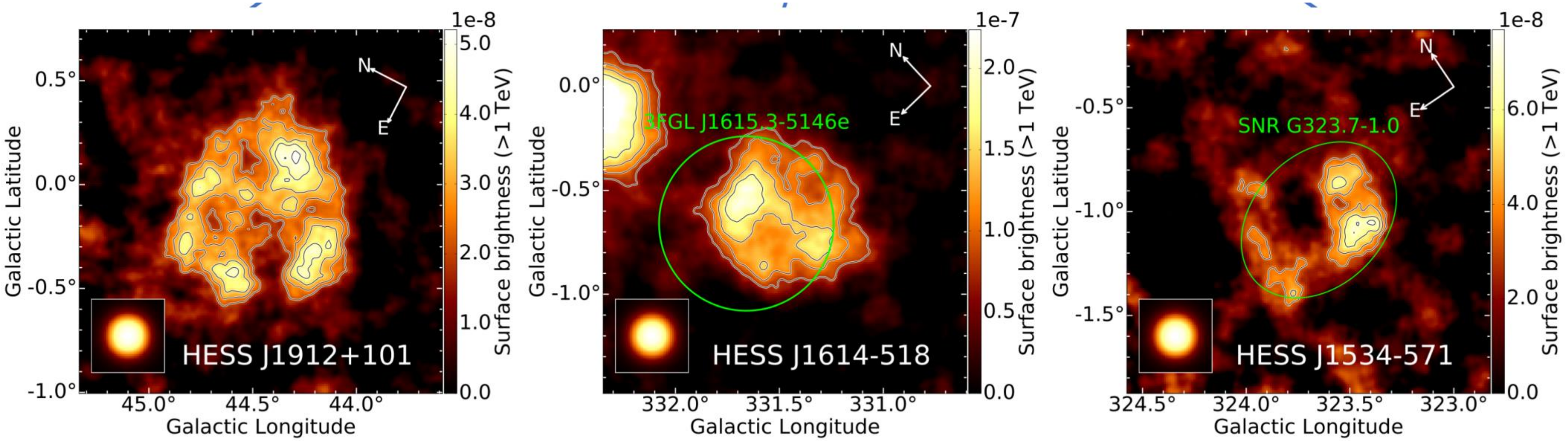


1. Introduction
1.3. HESS J1534-571

New SNR (candidates) identified in the H.E.S.S. Galactic plane survey



1. Introduction
1.3. HESS J1534-571



-Bright in TeV
-No radio/X-ray counterpart?

- Radio/X-ray observational limit?
- Good candidates for hadronic gamma-ray emission?
- Possible scenarios: evolved SNR, TeV acceleration from π^0 decay(CRp) or IC (CRe).

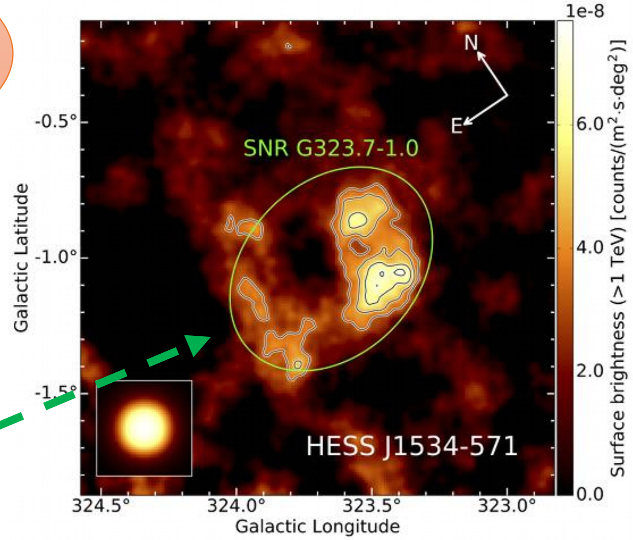
1. Introduction
1.3. HESS J1534-571

2006	[Aharonian et al.] **Initial discovery of galactic TeV shells**
2008	[Matsumoto et al.] Suzaku observation of HESS J1614-518
2011	[Sakai et al.] XMM-Newton observation of HESS J1614-518
2014	[Green et al.] **radio SNR candidate G323.7-1.0 at 834 MHz**
2015, 2016	[Acero et al., Ackermann et al.] Fermi-LAT catalogs with HESS J1614-518 possible counterpart.
2017	[Araya] **GeV counterpart of HESS J1534-571 is discovered**
2018	[H.E.S.S Collaborations] **3 TeV selected SNR candidates for the first time: HESS J1534-571, HESS J1614-518 and HESS J1912+101.**
2018	[Saji et al.] **reanalysis of G323.7-1.0 by Suzaku archival data**
2023	[Nguyen-Dang et al.] **XMM-Newton observations of the TeV-discovered SNR HESS J1534-571 (2023)**
	[Pühlhofer, Michailidis, Nguyen-Dang et al.] eROSITA study of HESS J1614-518 (in prep.)

1. Introduction
1.3. HESS J1534-571

+ Age: ~ 10^4 yrs (?)
+ Distance: ~ 3-5 kpc (?).
+ Multiwavelength study:
    - **Radio**: *faint ellipse shell* (834 MHz), other name G323.7-01.0
    - **GeV**: hard spectra, partially looks like a uniform disk.
    - **TeV**: *shell, non symmetric*.

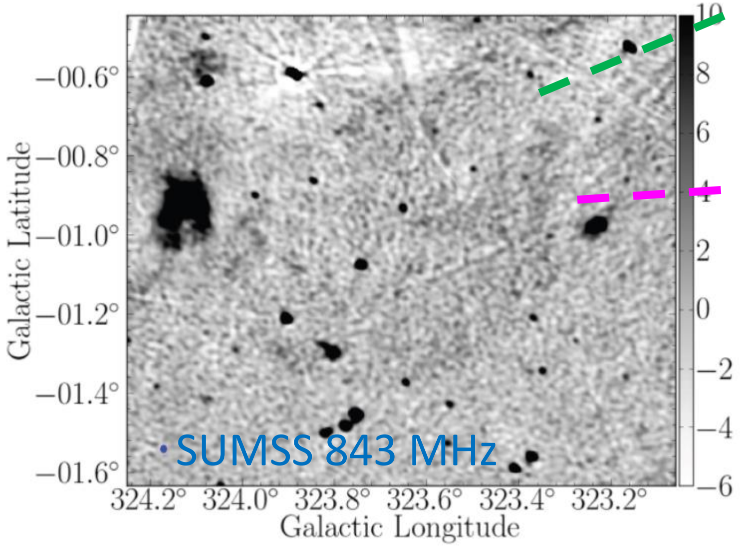
TeV

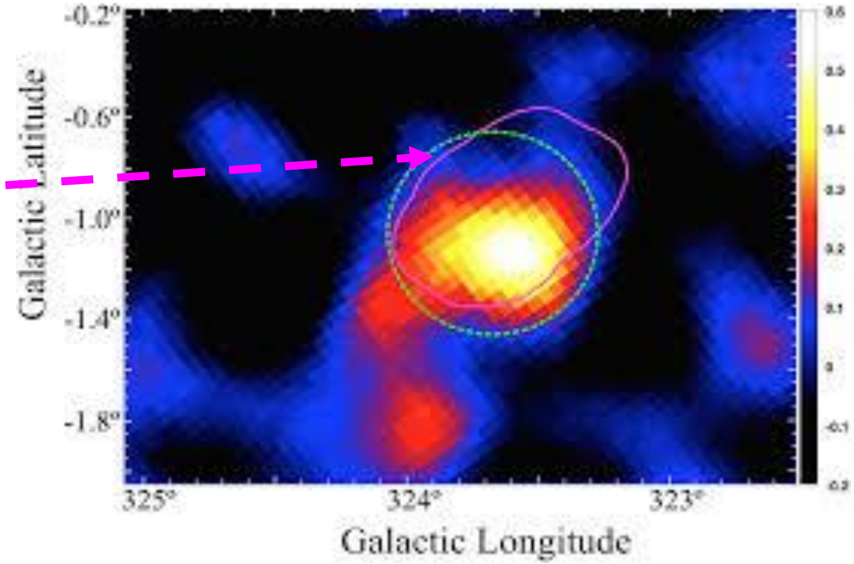


Credit: https://www.mpi-hd.mpg.de/

Radio

Credit: Green et al. 2014





Credit: Miguel Araya 2017

GeV

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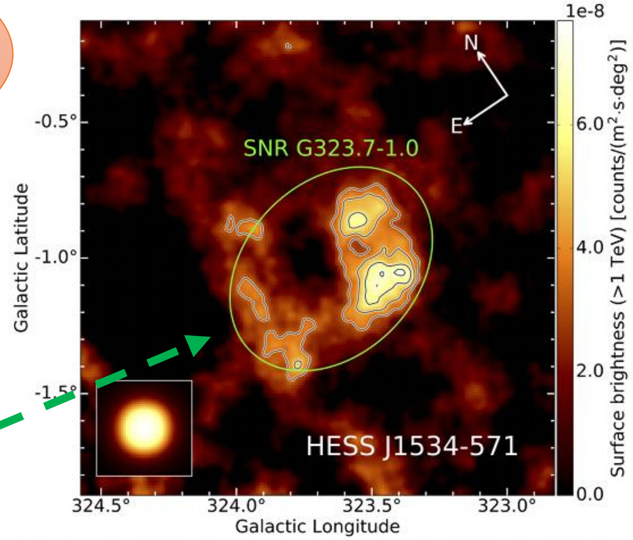
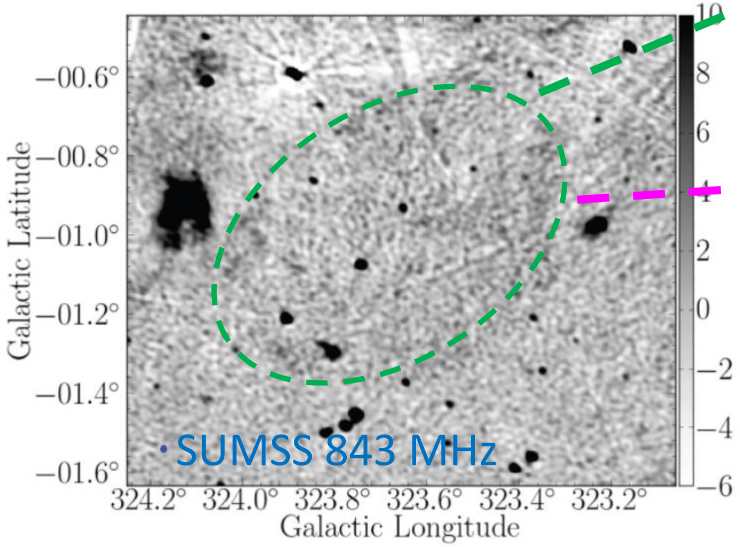
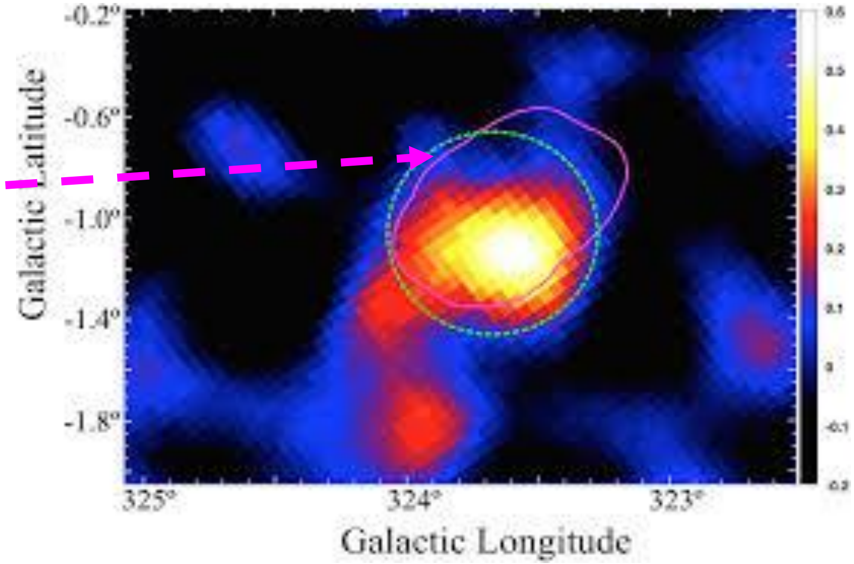


Credit: https://www.mpi-hd.mpg.de/

Radio

Credit: Green et al. 2014





Credit: Miguel Araya 2017

GeV

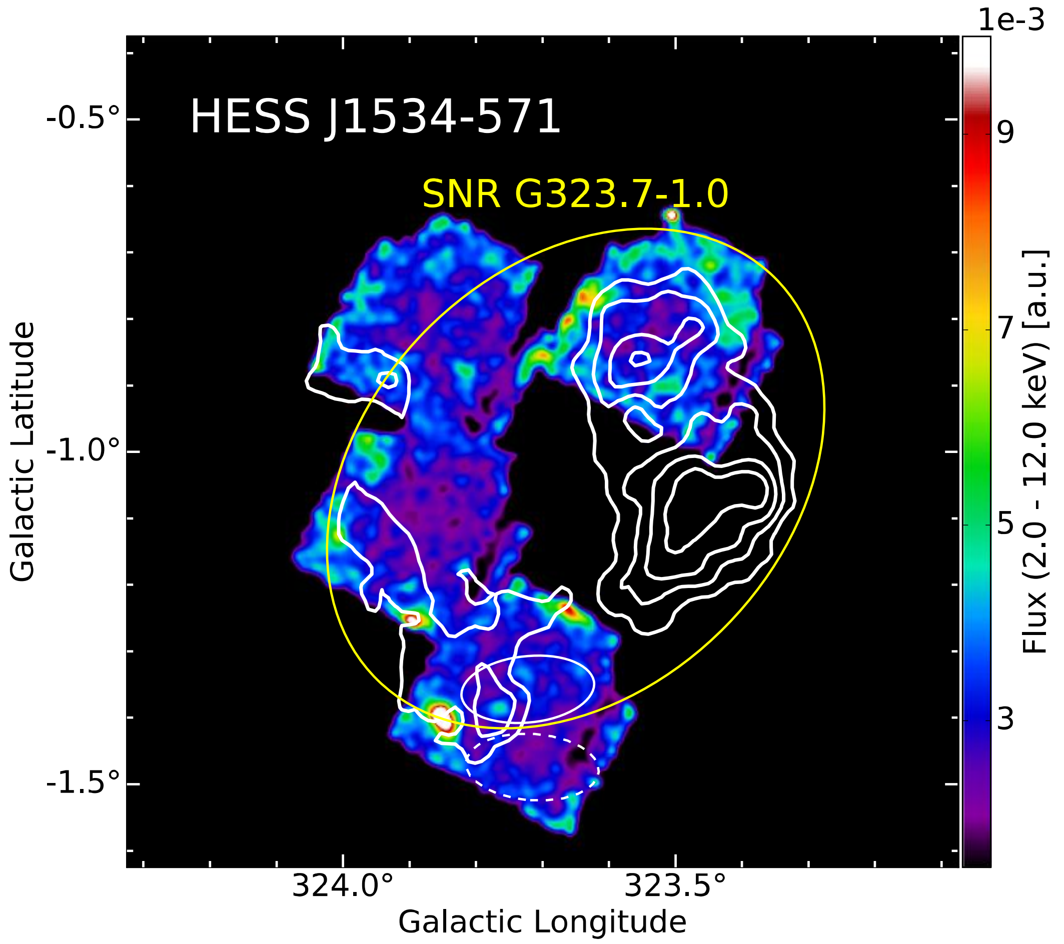
1. Introduction
1.3. HESS J1534-571

PI: Aya Bamba

Suzaku XIS (XIS0 + XIS3) mosaic of the pointings toward HESS J1534−571, in 2 keV- 12 keV, point sources not removed.

Upper flux limit* (2 – 12 keV):
2.4×10^{-11} erg cm^{-2}s^{-1} for $\Gamma = 2$;
1.9×10^{-11} erg cm^{-2}s^{-1} for $\Gamma = 3.1$

*Additional (unabsorbed) power-law component

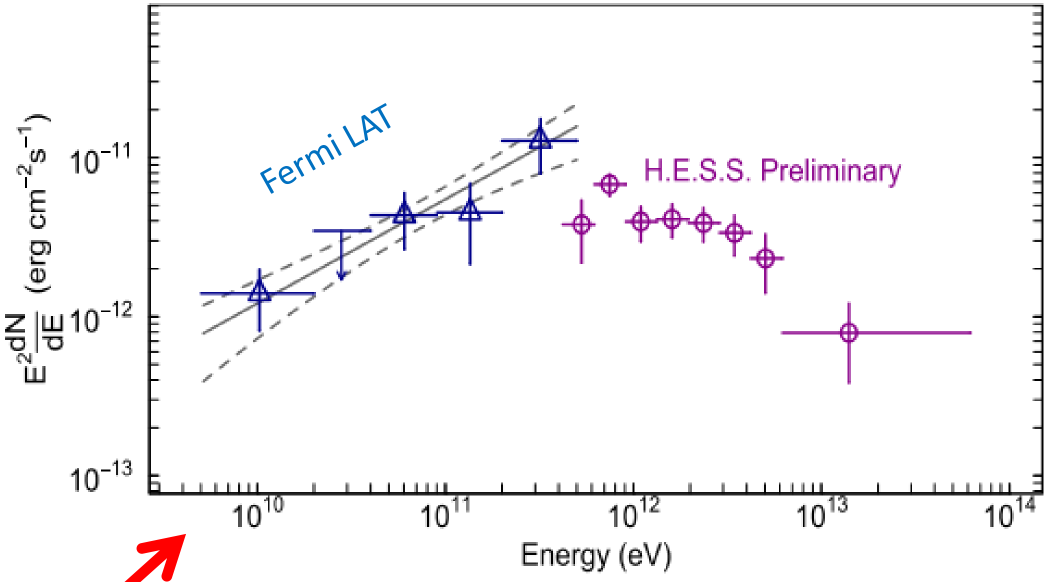


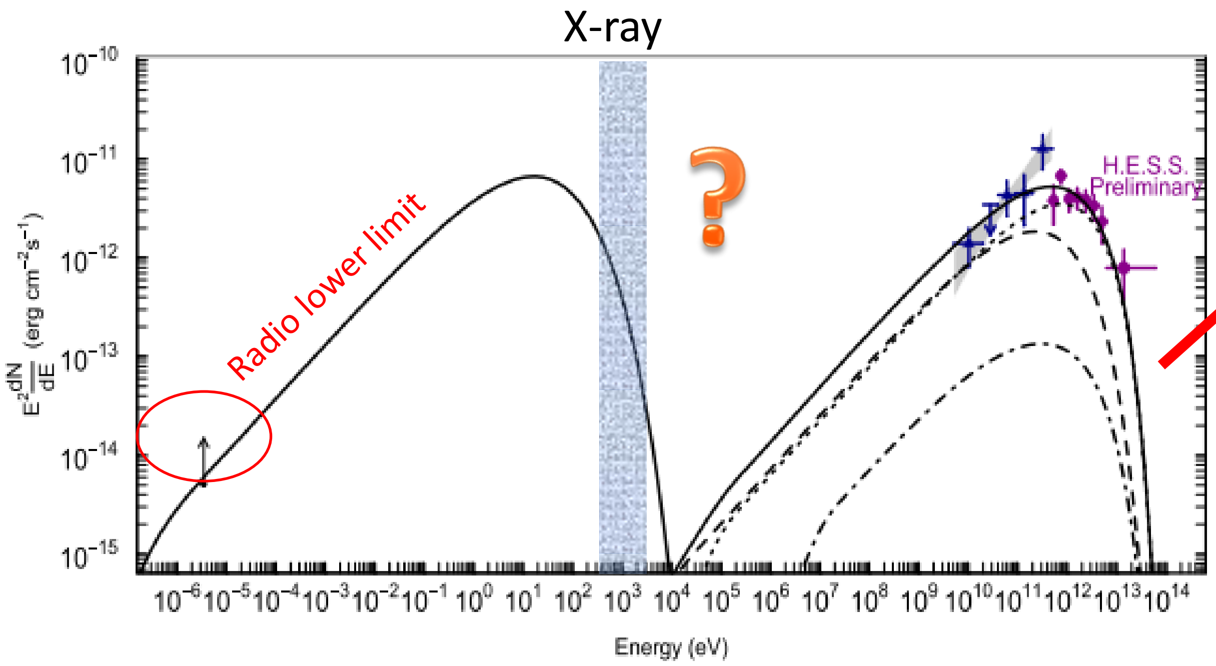
Credit: HESS collaboration, A&A, 612 (2018) A8

1. Introduction
1.3. HESS J1534-571

Gamma ray SED analysis

- Hadronic/ Leptonic origin?
- ISM parameters (B field, radiation field…)





- **HESS J1534-571**
- prefer the leptonic scenario
- require **6 μG** for B-field
- adopt FIR field of **20 K** and **0.8 eVcm^{-3}**

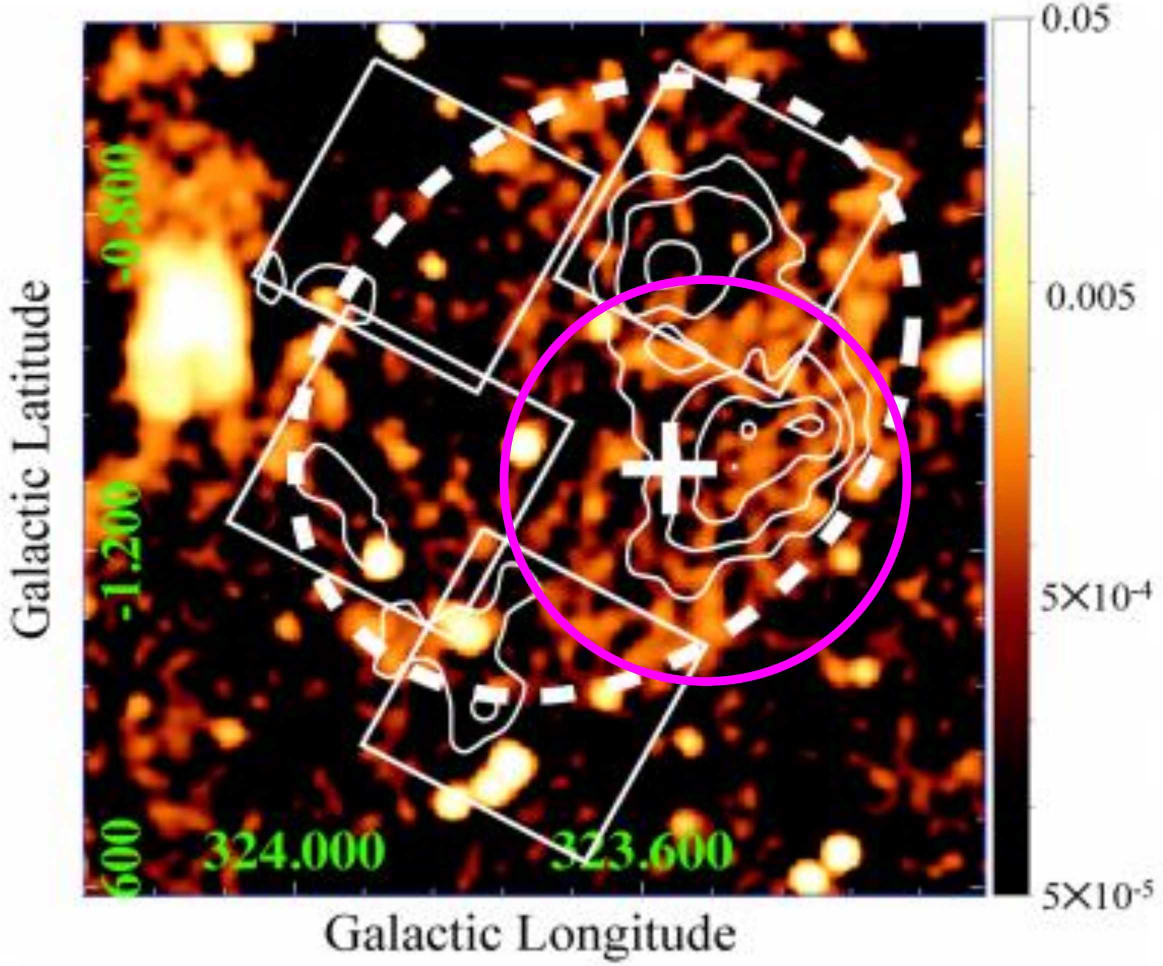
Credit: Miguel Araya 2017

1. Introduction
1.3. HESS J1534-571

XMM-Newton, PI: Gerd Puehlhofer.
- **2017 - 2018**: observation cancelled due to MAXI J1535-571outburst.
- **29/01/2020**: rescheduled (again) due to instrumental issues.
- **03/03/2020**: observed (finally).

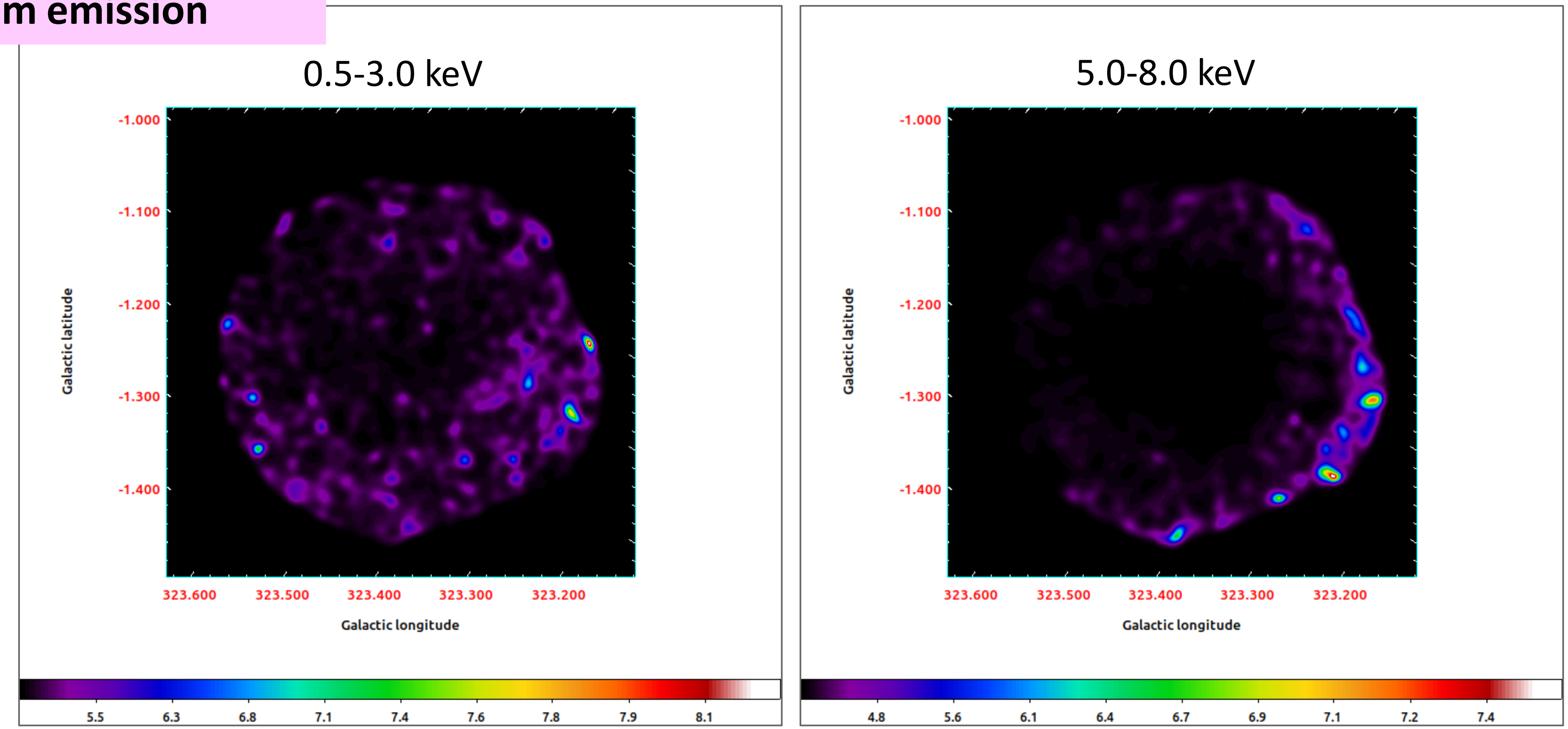
Observation ID	**0841440101**
Observation date	2020-03-03
XMM-Newton Pointing	$15^h34^m04^s$
Duration, ks	30
Exposure (M1/M2/PN), ks	24.07/24.51/17.07

XMM-Newton's FOV



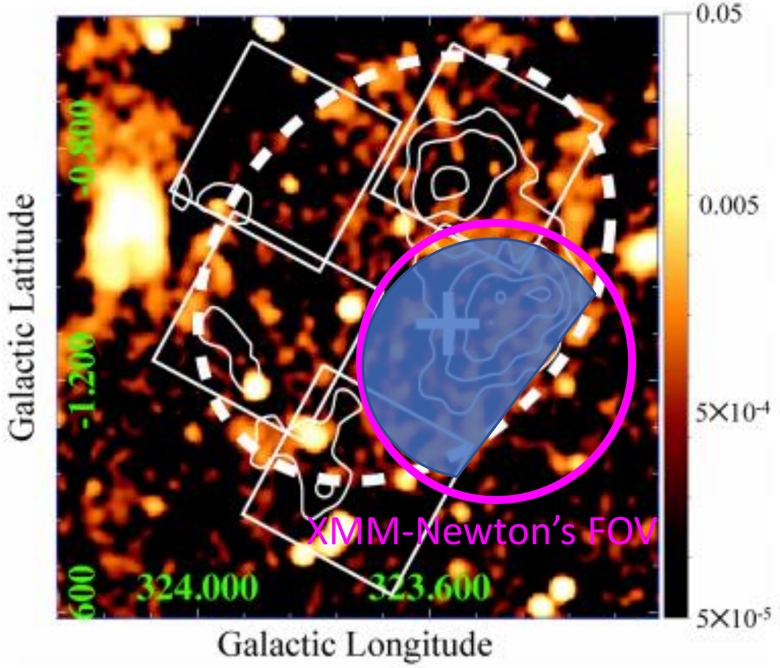
2. Results
2.1. X-ray continuum emission

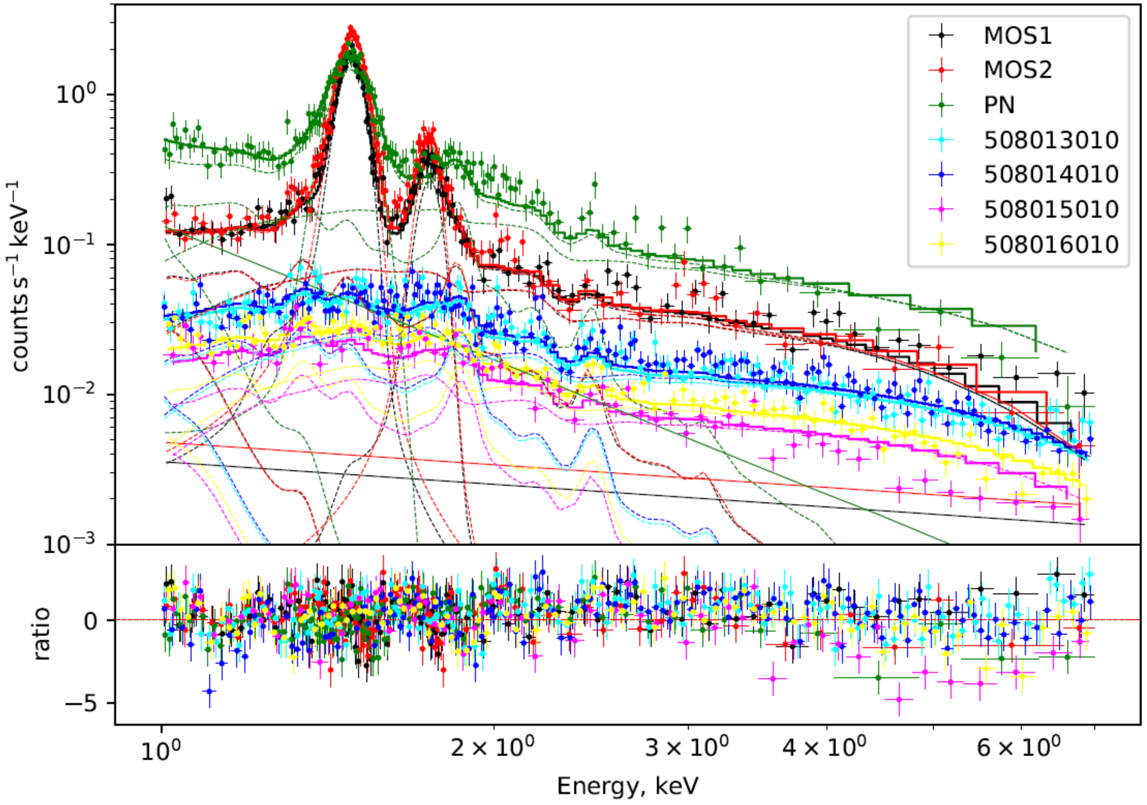
➔ No prominent source found, border effect could be instrumental fluctuation



HESS J1534-571 images in the soft (0.5-3.0 keV) and the hard (5.0-8.0 keV) band

2. Results
2.1. X-ray continuum emission





Scale factor:
radio ellipse area/ XMM covered area

Spectra model:
Cosmic background

+ absorbed power-law

Red χ^2 = 3421/2930

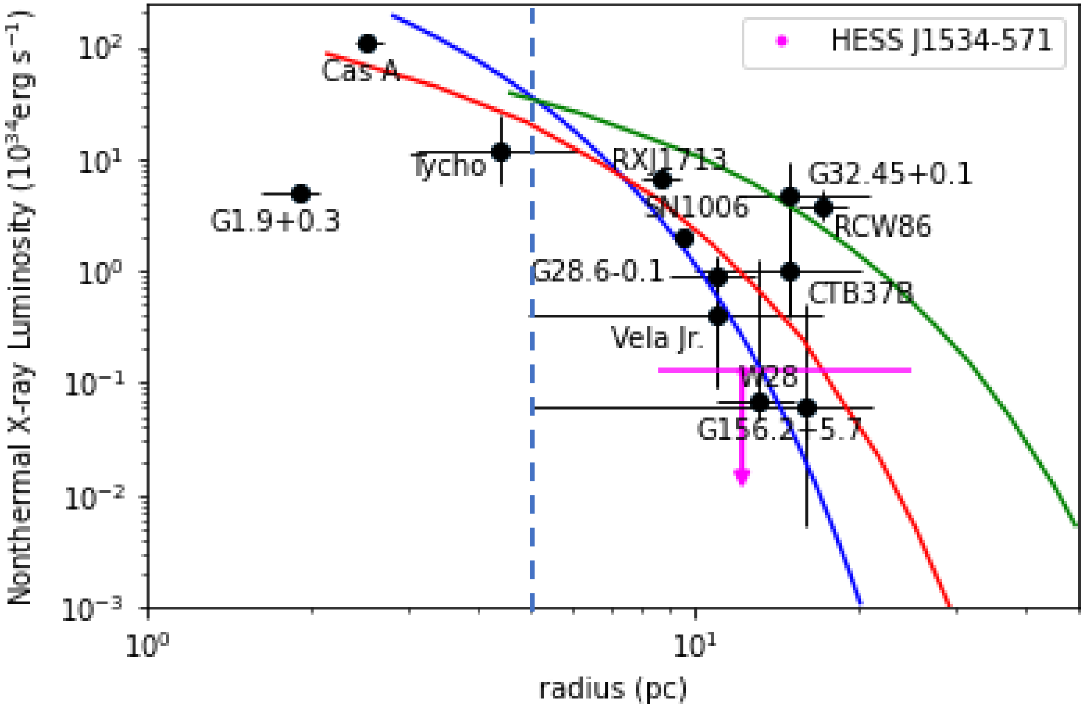
➔ Upper limit flux $F_{2\text{-}10keV} = 5.62 \times 10^{-13}$ erg/cm^2/s at 95% c.l.

2. Results
2.1. X-ray continuum emission

Relation between **Nonthermal X-ray luminosity** and galactic **SNR's radius**. Plotted in green, red, blue are predicted models of time evolution of SNR synchrotron X-rays for different density at 5.0 cm^{-3} (blue), 1.0 cm^{-3} (red), and 0.1 cm^{-3} (green) [Nakamura et al. 2012].

Consistent with other SNRs

A few hundred years



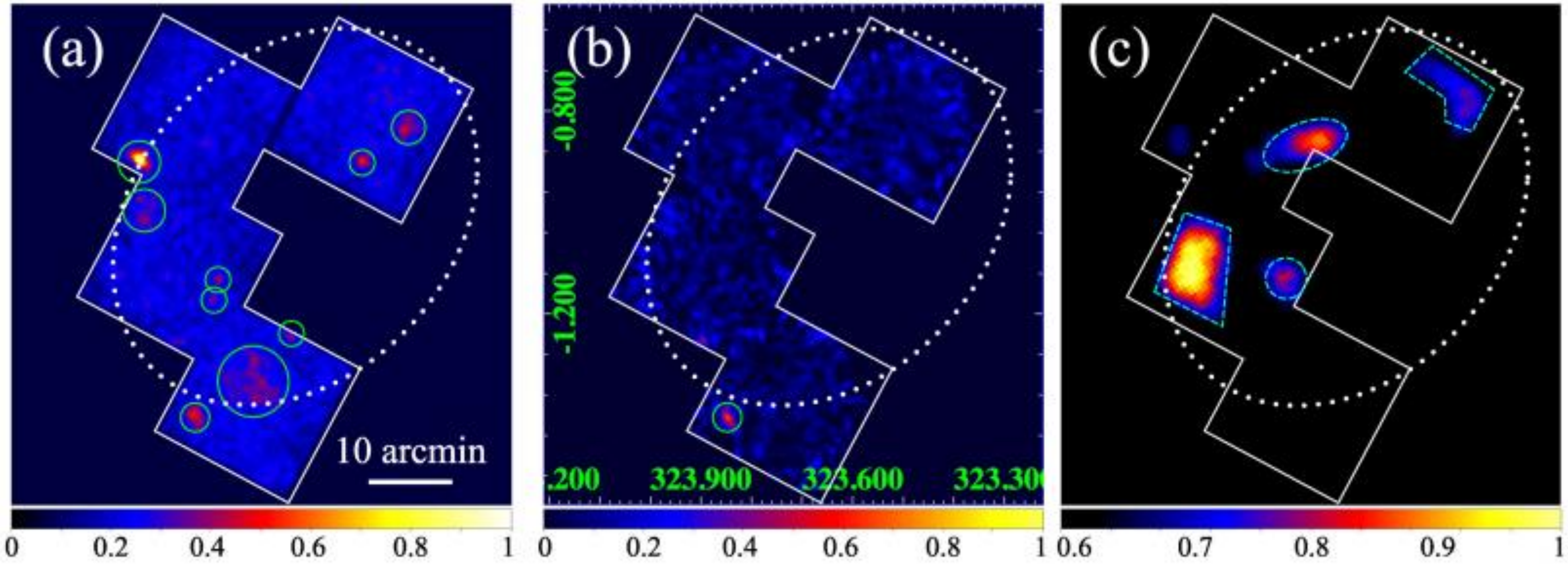
Upper limit flux $F_{2\text{-}10keV}$ = 5.62 x 10^{-13} erg/cm^2/s at 95% c.l.

2. Results
2.2. 6.4 keV line emission

Credit: Saji et al. 2018

Saji et al. 2018

- **SUZAKU** archive data
- Partially cover the radio shell
- Some diffuse **soft** (0.5-3 keV) sources
- No **hard** (5-8 keV) X-ray emission
- "strong" 6.4 keV **Fe Kα line** emission at 4σ.



0.5 – 3.0 keV

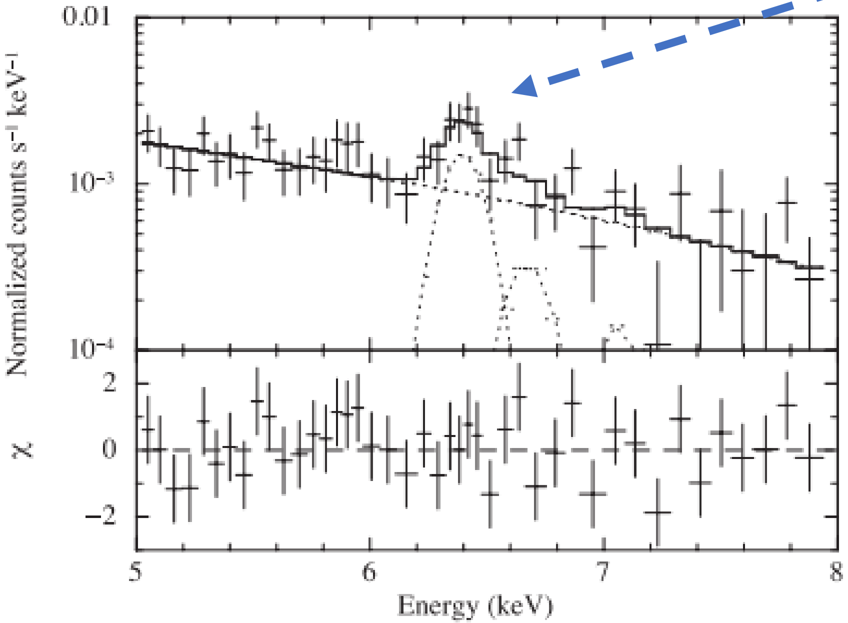
5.0 – 8.0 keV

6.3 – 6.5 keV

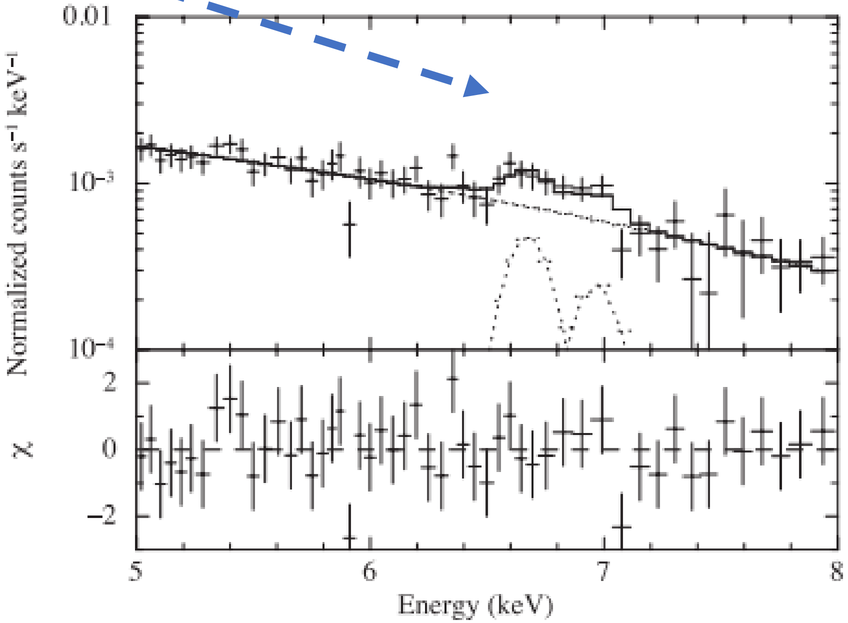
2. Results
2.2. 6.4 keV line emission

probing MeV cosmic rays

Line intensity > 4 times that of the reference region



"Enhanced" region



Reference region

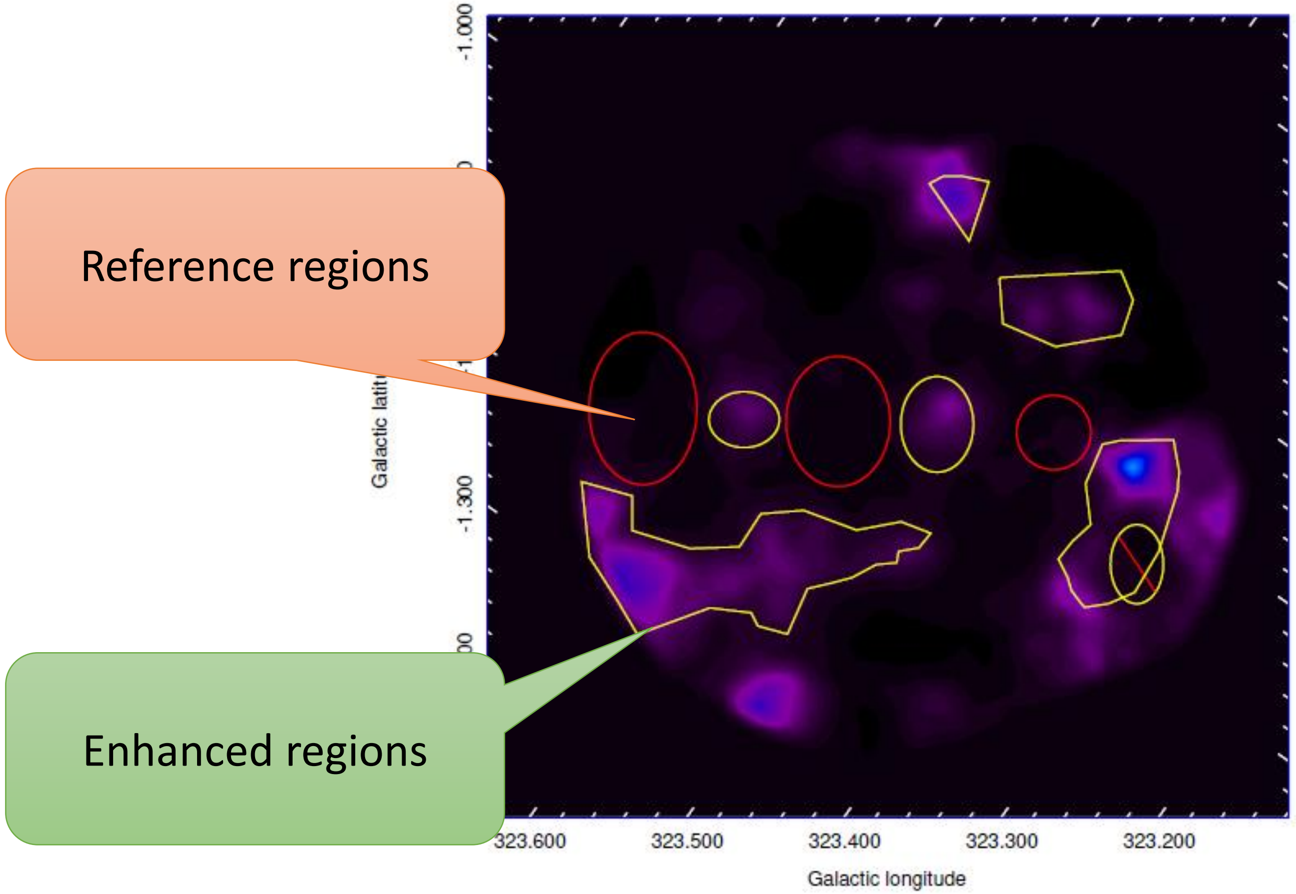
Credit: Saji et al. 2018

2. Results
2.2. 6.4 keV line emission

XMM adaptively smoothed combined image (MOS1+MOS2+PN) in the **6.3-6.5 keV** energy band.

➔ There are some bright clumps.

➔ Let's look at the spectra!



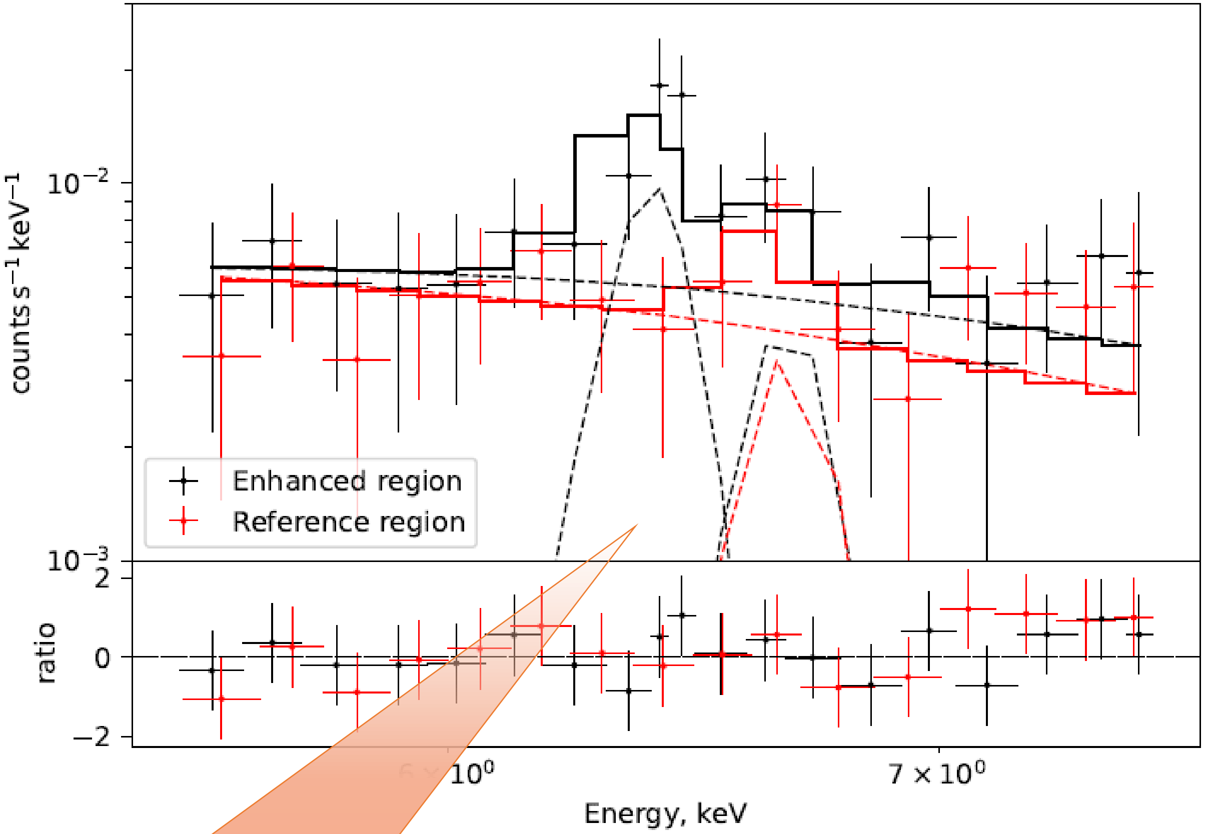
2. Results
2.2. 6.4 keV line emission

MOS1+MOS2 stacked spectra.

- In **black**: enhanced region, in **red**: reference region.

- Model: power law + **gauss (6.4 keV)** + gauss (6.68 keV) + gauss (6.97 keV) + gauss (7.06 keV).

- Signature **6.4 Fe Kα keV line** and Galactic Ridge X-ray Emission.



+ MCMC simulation:
➔The significance of the line: ~3σ

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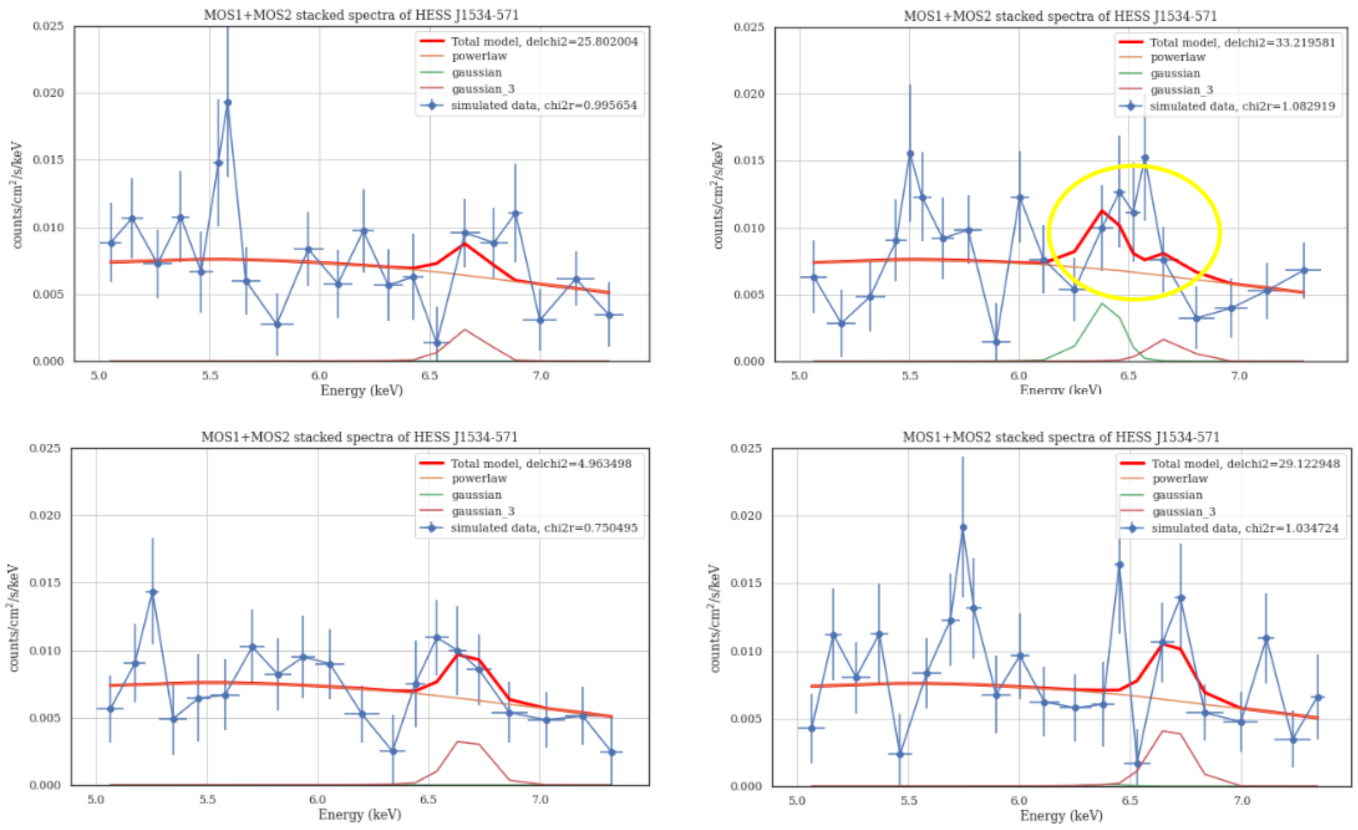
2. Results
2.2. 6.4 keV line emission

Parameters	Enhanced region	Reference region
Energy (keV)	6.4 (fixed)	6.4 (fixed)
σ (keV)	0 (fixed)	0 (fixed)
normalization[a]	$1.892^{+1.017}_{-0.959}$	< 0.679
Equivalent width[b]	549	212
Energy (keV)	6.68 (fixed)	6.68 (fixed)
σ (keV)	0.023 (fixed)	0.023 (fixed)
normalization	$1.096^{+1.121}_{-0.811}$	$0.762^{+0.785}_{-0.628}$
Equivalent width	275	504
Energy (keV)	6.97 (fixed)	6.97 (fixed)
σ (keV)	0 (fixed)	0 (fixed)
normalization	$0.157^{+1.352}_{-0.106}$	< 0.578
Equivalent width	224	172

[a] Photon flux in units of 10^{-5} photons cm^{-2} s^{-1}
[b] keV at 95% level of significance.

Best fit parameters of the spectra analysis of the 6.4 keV clumps. Errors and upper limits are given at 90% c.l.

Significance level of detection

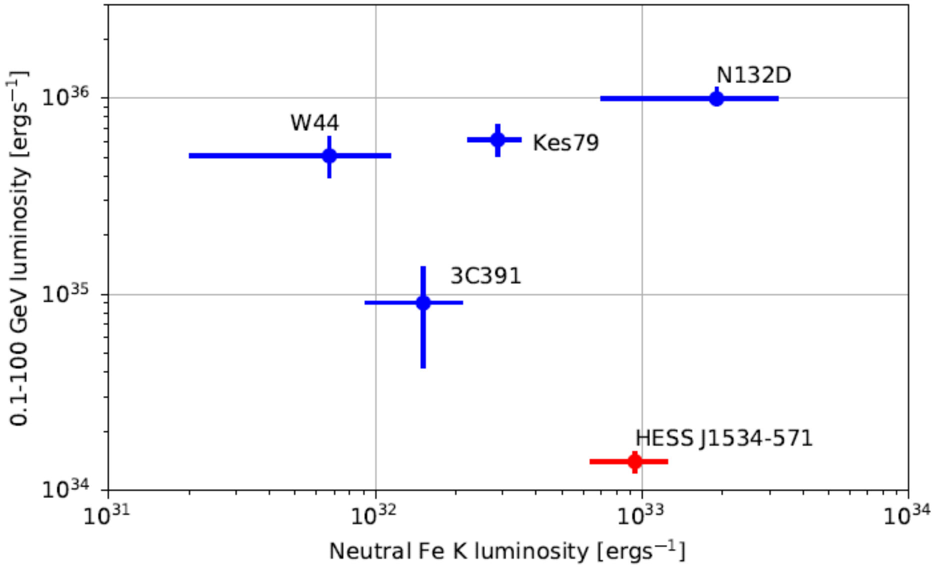


1.000 MCMC simulations => 3σ significant line detection at 6.4 keV

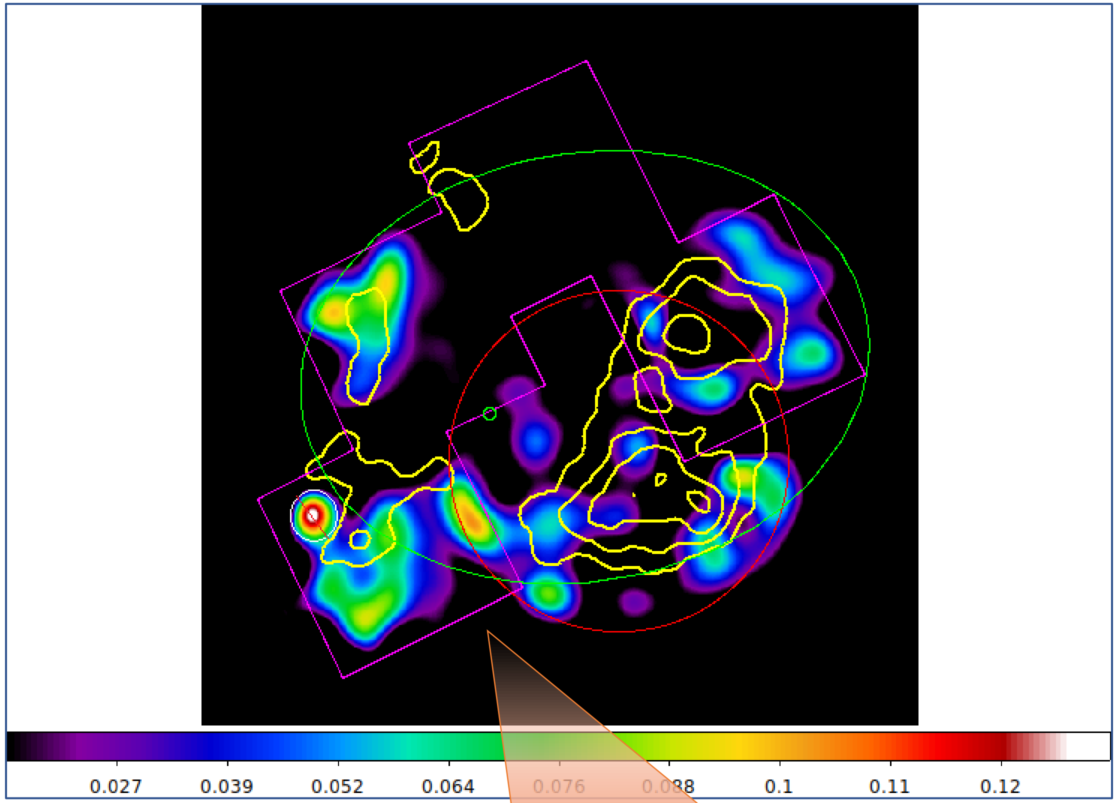
2. Results
2.2. 6.4 keV line emission

XMM – SUZAKU combined image

-TeV surface brightness contour (yellow)
-XMM field of view (red)
-SUZAKU field of view (magenta)
-Molonglo radio boundary (green)



6.3-6.5 keV, without point source removal



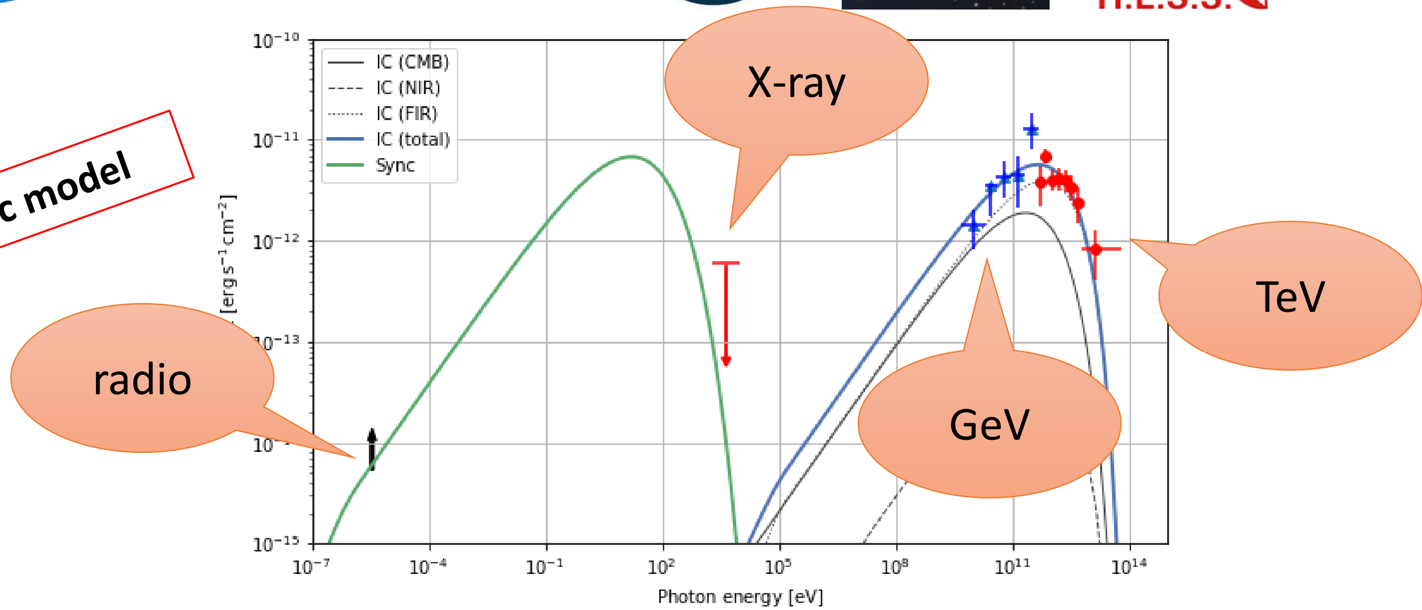
Similarity between TeV profile and Fe Kα emission

2. Results
2.3. Broad band SED analysis

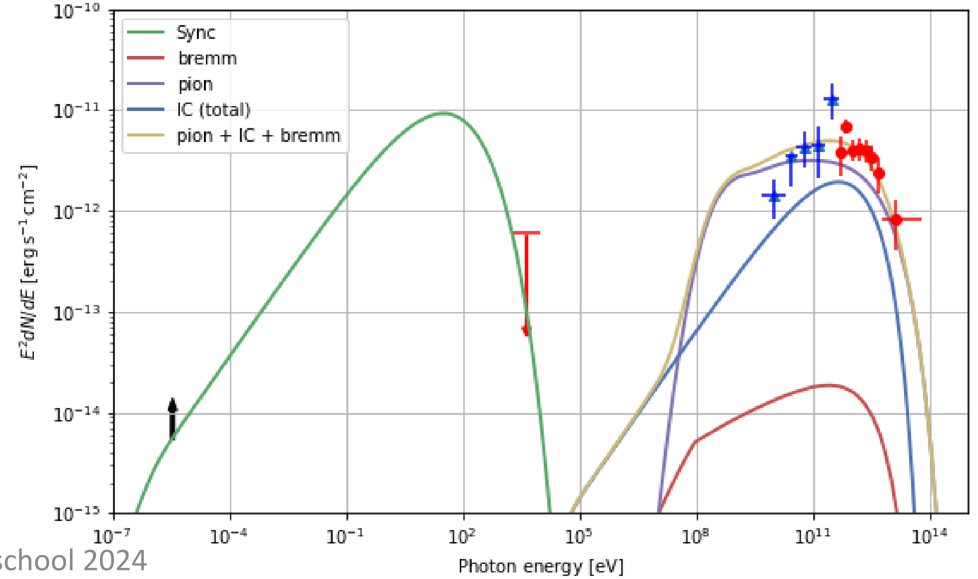
Broad band SED of HESS J1534-571.

-TeV data (red)
-GeV data (blue)
-X-ray upper limit
-Radio lower limit
-Model adapted from Miguel Araya 2017.

Leptonic model



Hadronic model



Not in contradiction to the LEPTONIC model!

2. Results
2.3. Broad band SED analysis

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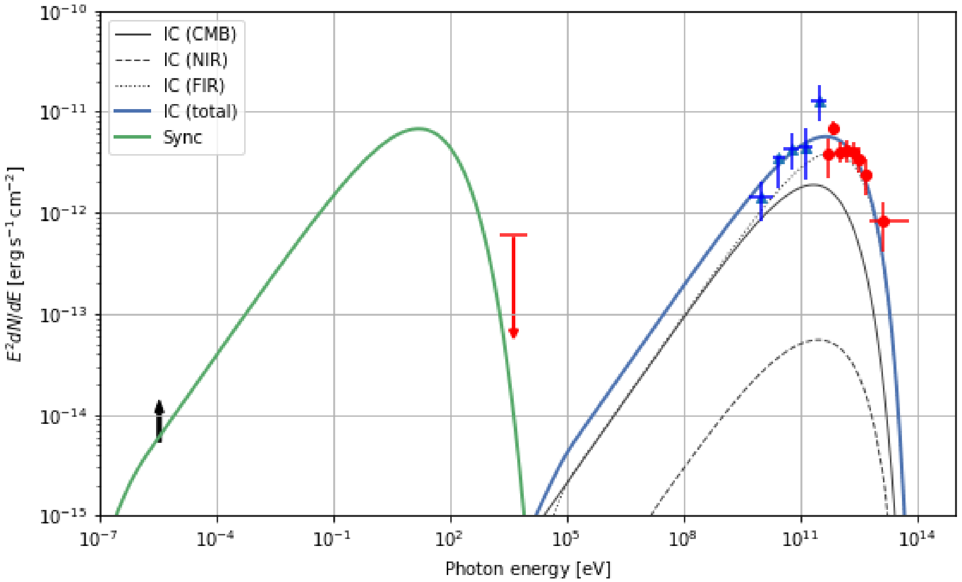
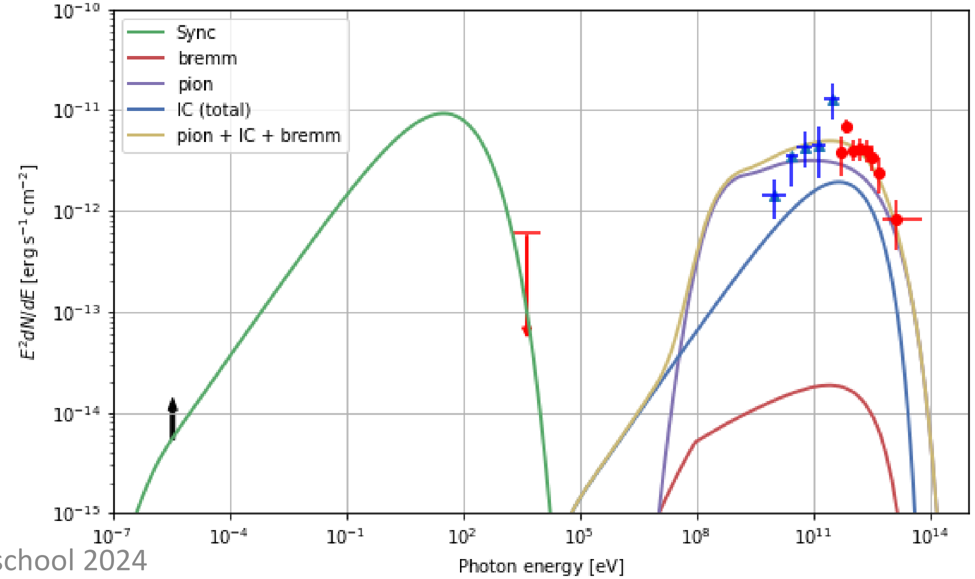


Hadronic model



Not in contradiction to the LEPTONIC model!

3. Conclusion

Which CR population is responsible for the VHE gamma radiation from SNRs? Is it CR electrons by IC? Or CR protons by pion decay?

Revealing the cosmic ray activities at the site of the TeV-discovered SNR HESS J1534-571

Conclusion

- No nonthermal X-ray emission detected at current instruments' sensitivities.
- Clumpy **Fe Kα keV line** emission is found within the SNR, in agreement with previous study of other regions. This provides evidence of **MeV CR protons**, spatially coincident with TeV emission.
- In a one-zone model, the SED analysis of the SNR shows that **gamma rays** are likely produced by **CR electrons.**

What's next?

- Continue to study other galactic TeV shell-type SNRs (e.g: HESS J1912+101, HESS J1614-518…) => look for nonthermal X-ray emission, constrain **the cosmic ray production and acceleration scenarios**.

Thank you for your attention!!!!