INSTITUT DE CIÈNCIES DE L'ESPAI

ICE CSIC IEEC

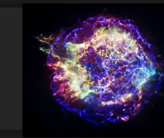
An energy cutoff in the TeV gamma-ray spectrum of the SNR Cassiopeia A

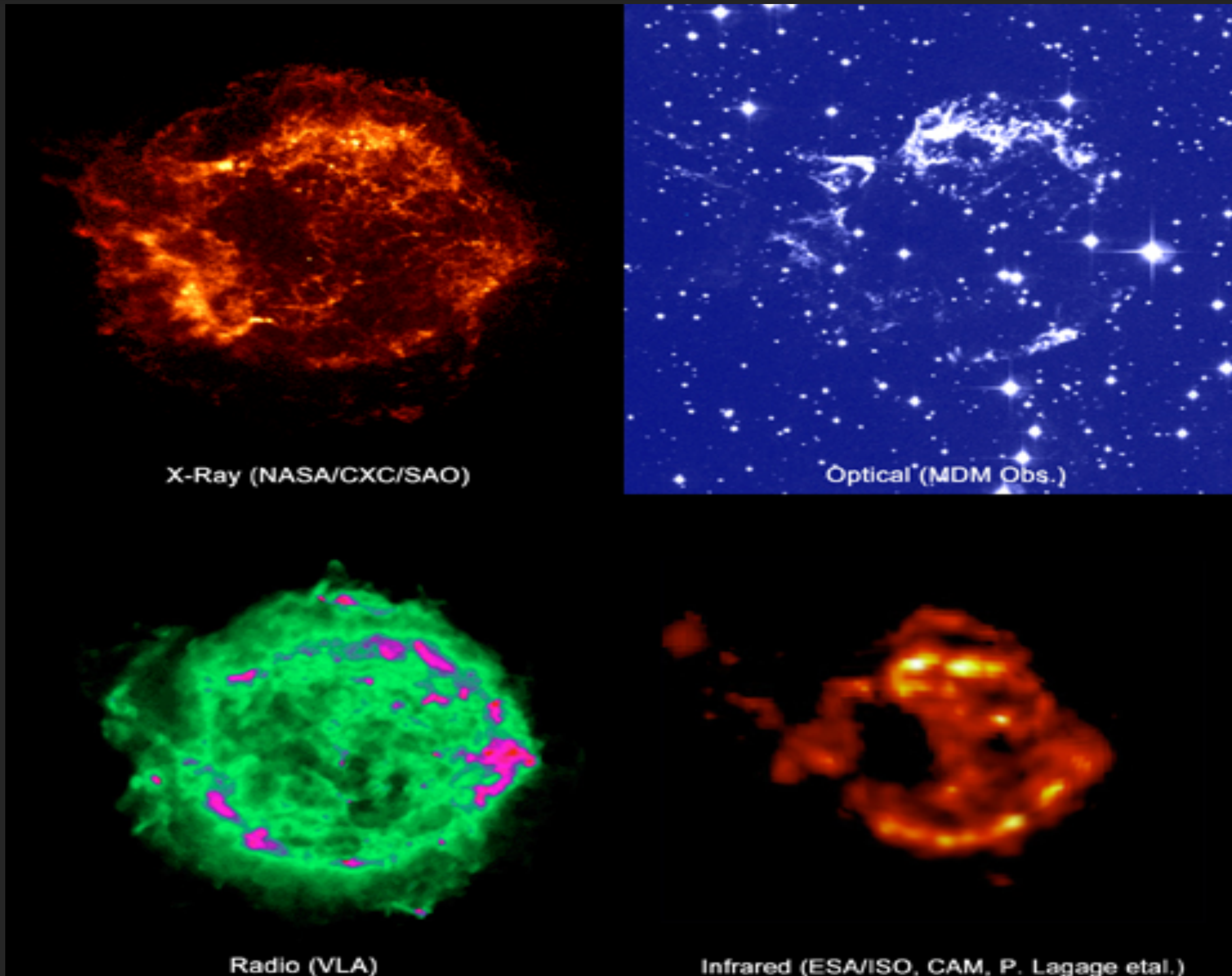
Emma de Oña Wilhelmi*, Daniel Guberman, Daniel Galindo, Juan Cortina and Abelardo Moralejo for the MAGIC collaboration

*Ramon y Cajal Fellow

Institute of Space Sciences, IEEC-CSIC, Barcelona

TeVPA 2017 7-11 August, Columbus, Ohio





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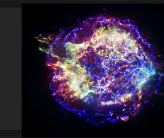
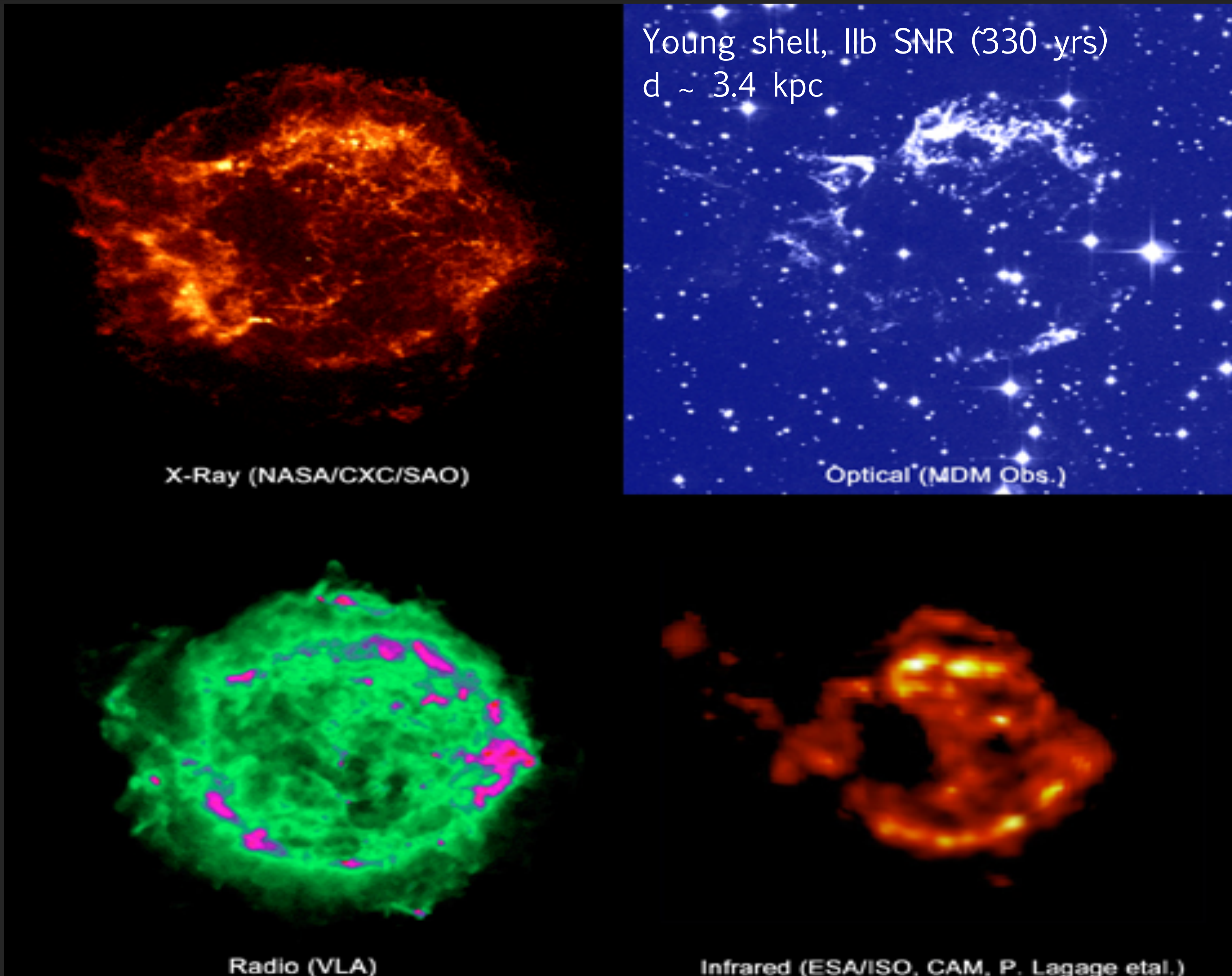
Lastochkin et al. 1963; Medd & Ramana 1965; Allen & Barrett 1967; Parker 1968; Braude et al. 1969; Hales et al. 1995, Anderson et al. 1991, Gotthelf et al. 2001; Maeda et al. 2009; Grefenstette et al. 2015; Wang & Li 2016, Uchiyama & Aharonian 2008, Metzger et al 1986

Cassiopeia A the remnant





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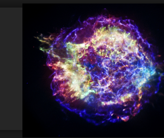

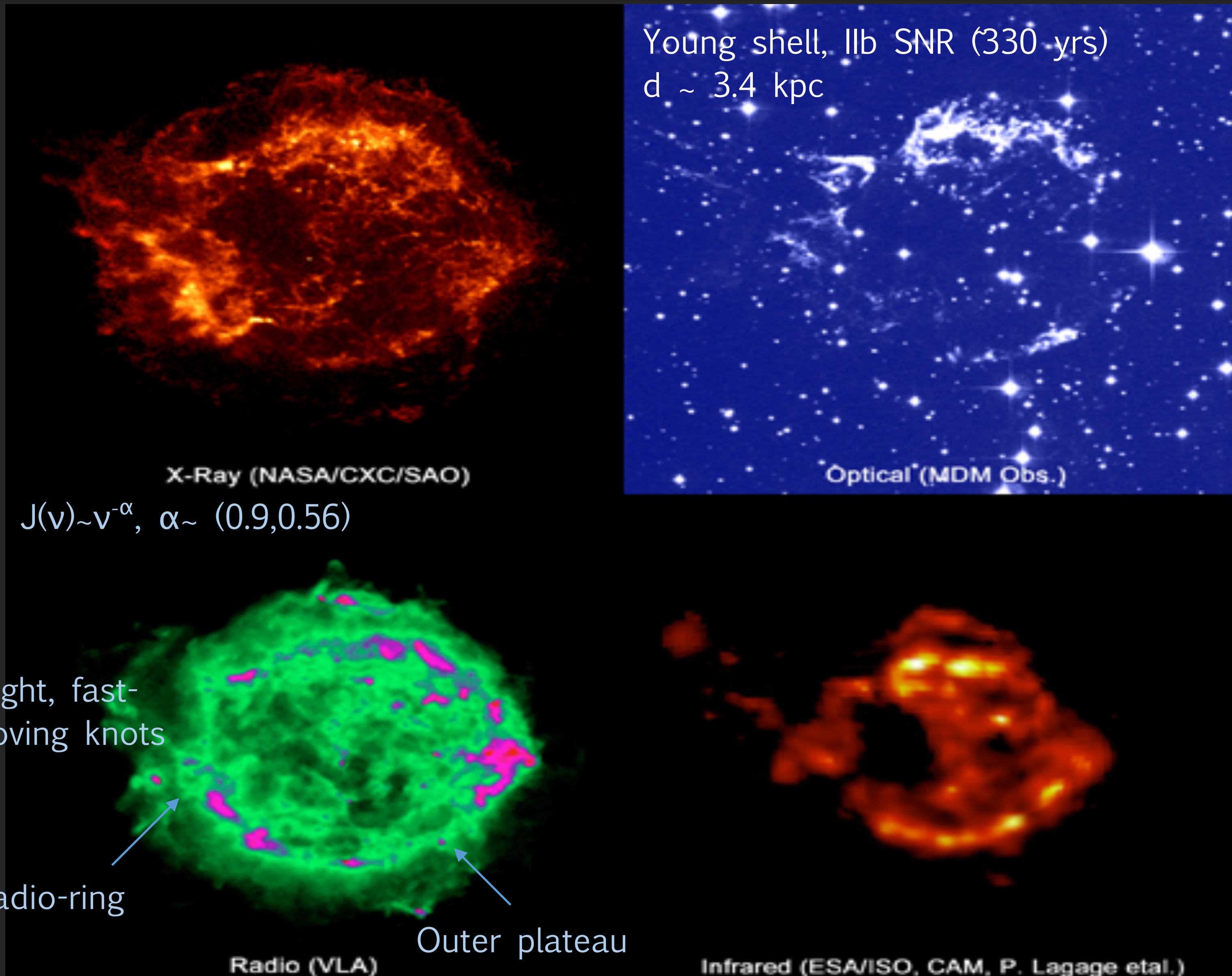

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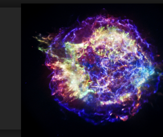

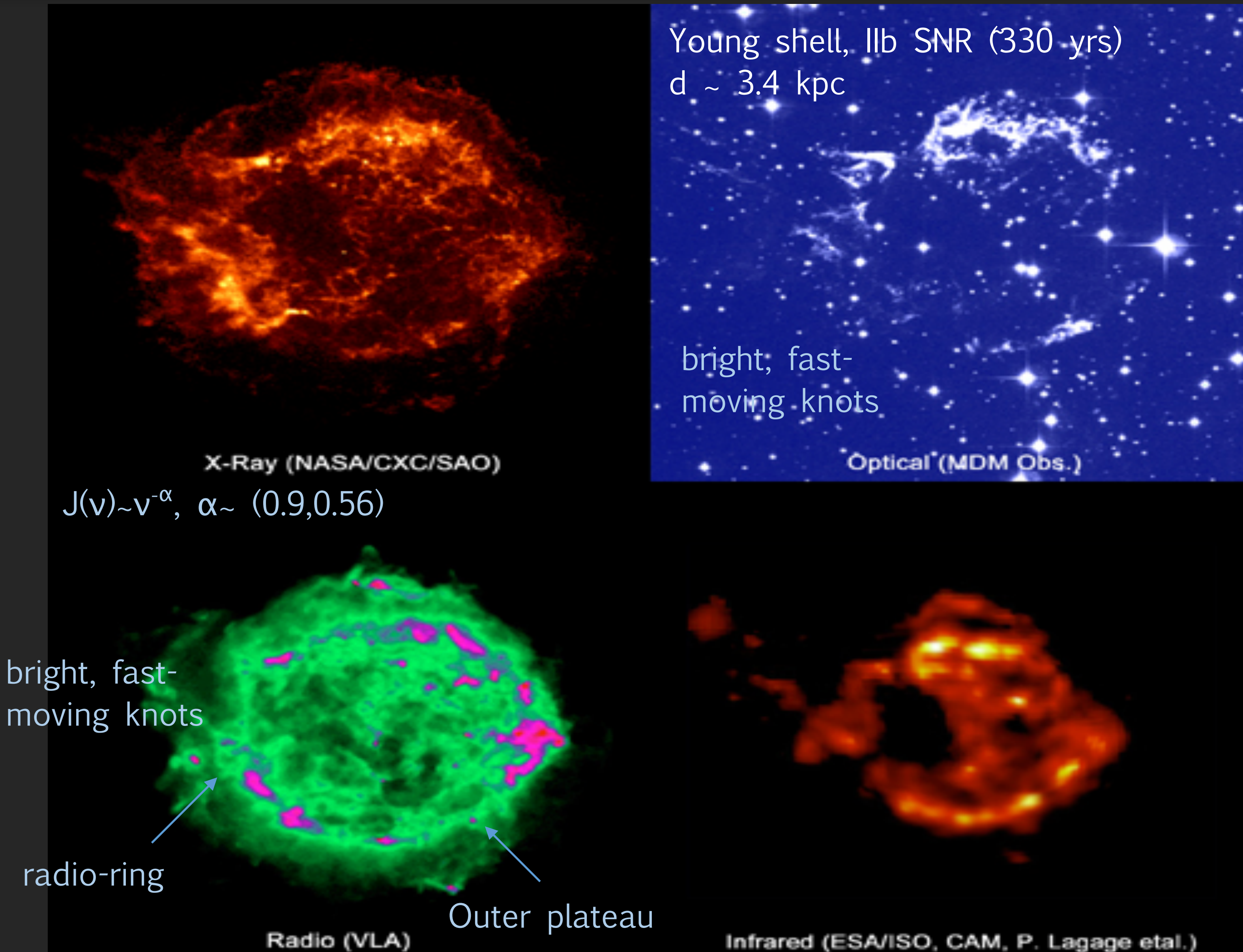

$J(\nu) \sim \nu^{-\alpha}$, $\alpha \sim (0.9, 0.56)$

Image credit: NASA/CXC/SAO

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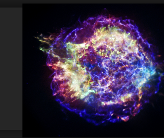

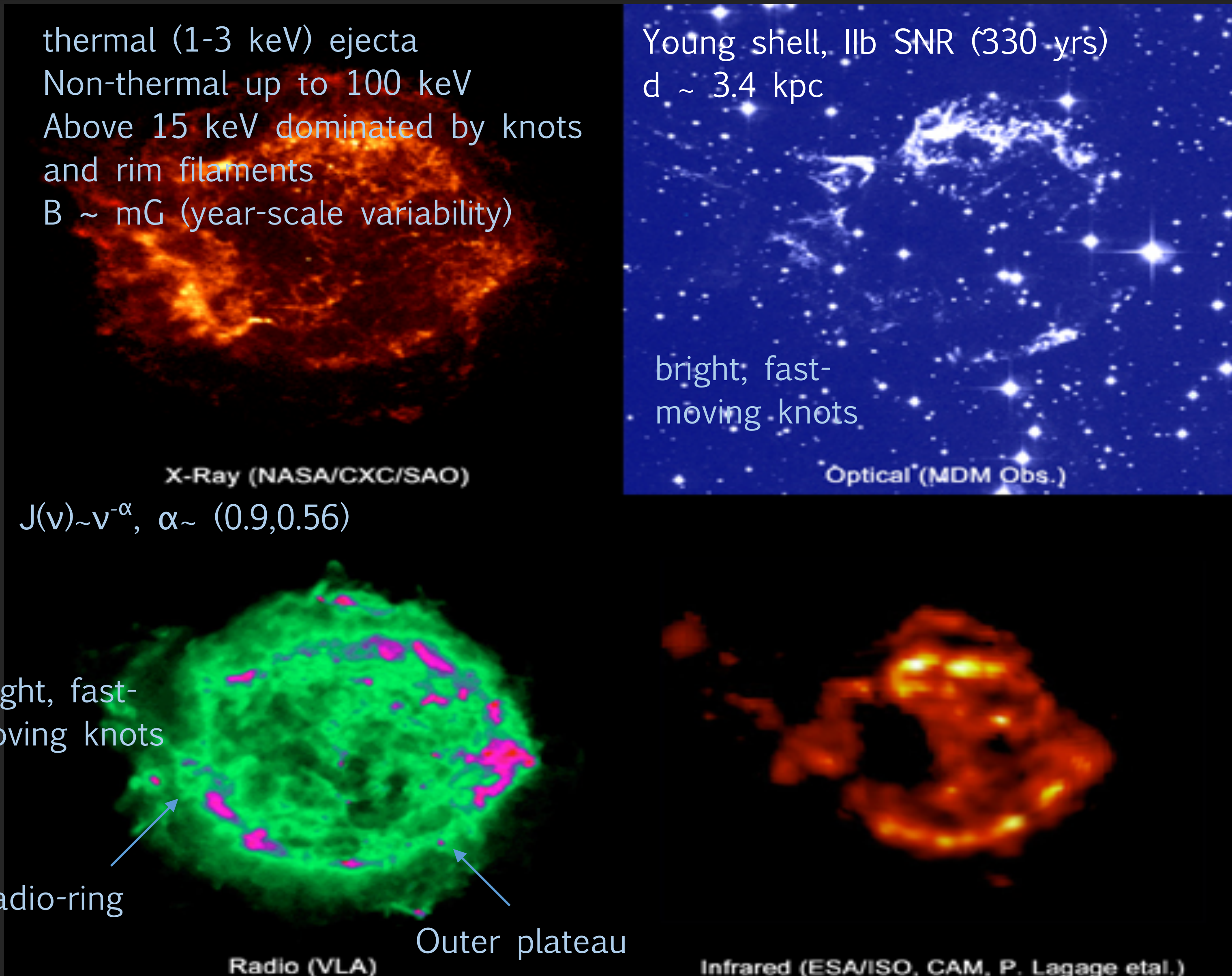

thermal (1-3 keV) ejecta
Non-thermal up to 100 keV
Above 15 keV dominated by knots and rim filaments
B ~ mG (year-scale variability)

Young shell, IIb SNR (330 yrs)
d ~ 3.4 kpc

bright, fast-moving knots

$J(\nu) \sim \nu^{-\alpha}$, $\alpha \sim$ (0.9,0.56)

bright, fast-moving knots

radio-ring

Outer plateau

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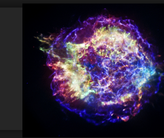

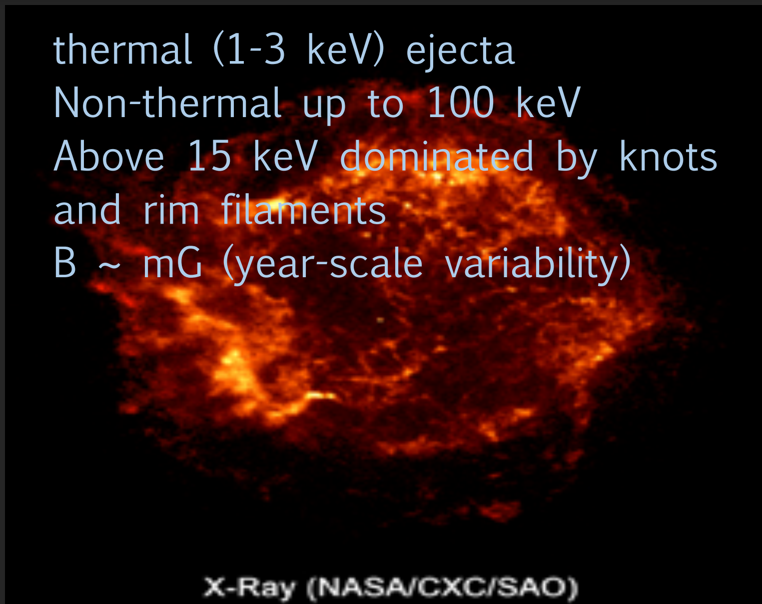

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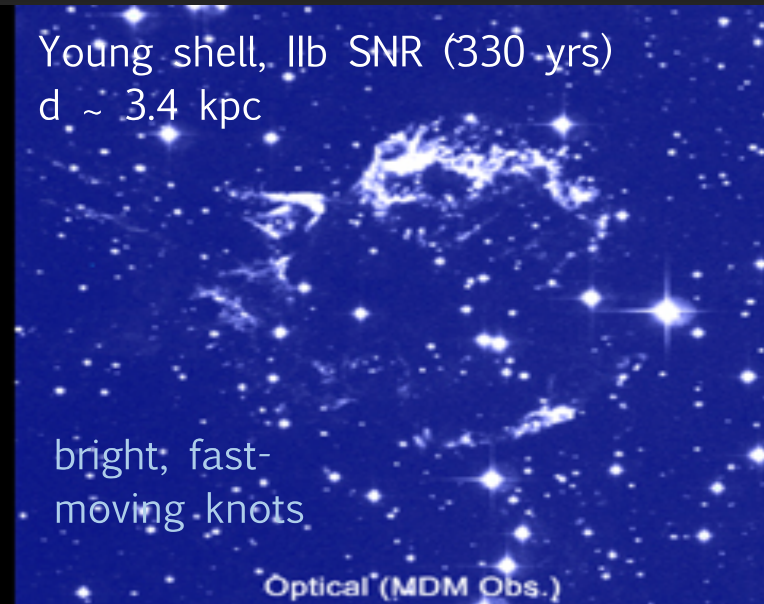

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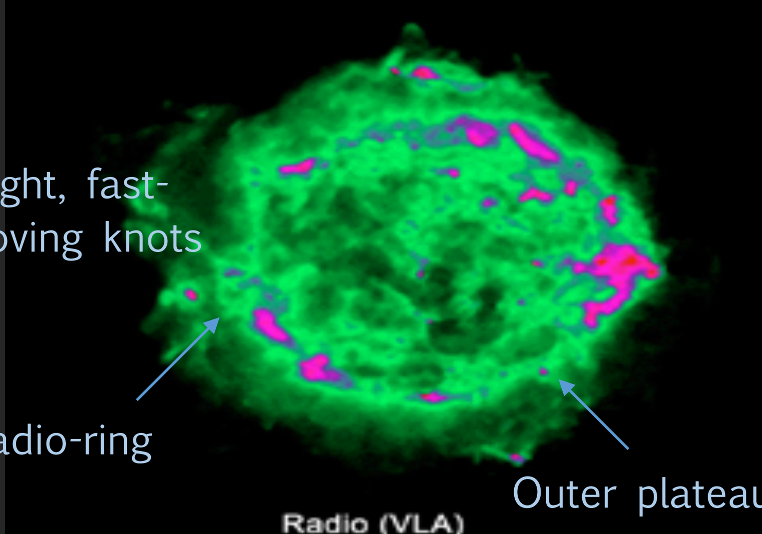

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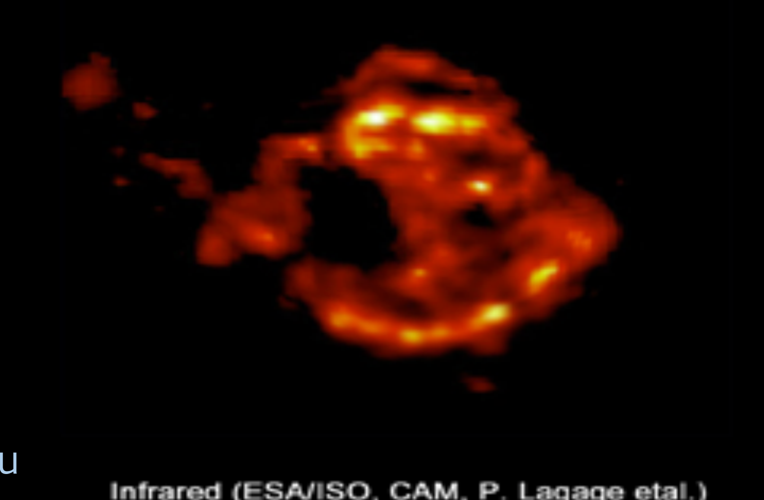
Outer plateau

photon field~2 eV/cm^3, T ~97 K



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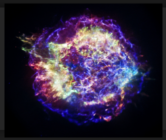
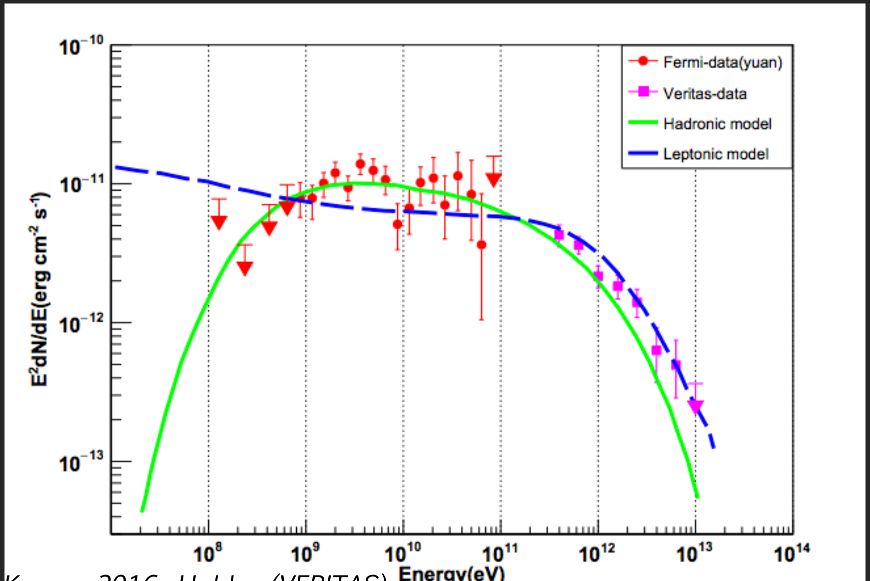


Aharonian et al, 2001, Albert et al 2007, Kumar 2016, Holder (VERITAS) 2016, Yuan et al 2013, Bell et al 2013, Zirakashvilli et al 2014

At high energies:

- detected by HEGRA, MAGIC, VERITAS and FermiLAT
- energy turn-off at ~1.7 GeV, evidence of change of slope among GeV/TeV data
- current models suggest GeV-TeV emission is mainly of hadronic origin
- Also suggest it might "only" be able to accelerate protons up to a few hundred TeV



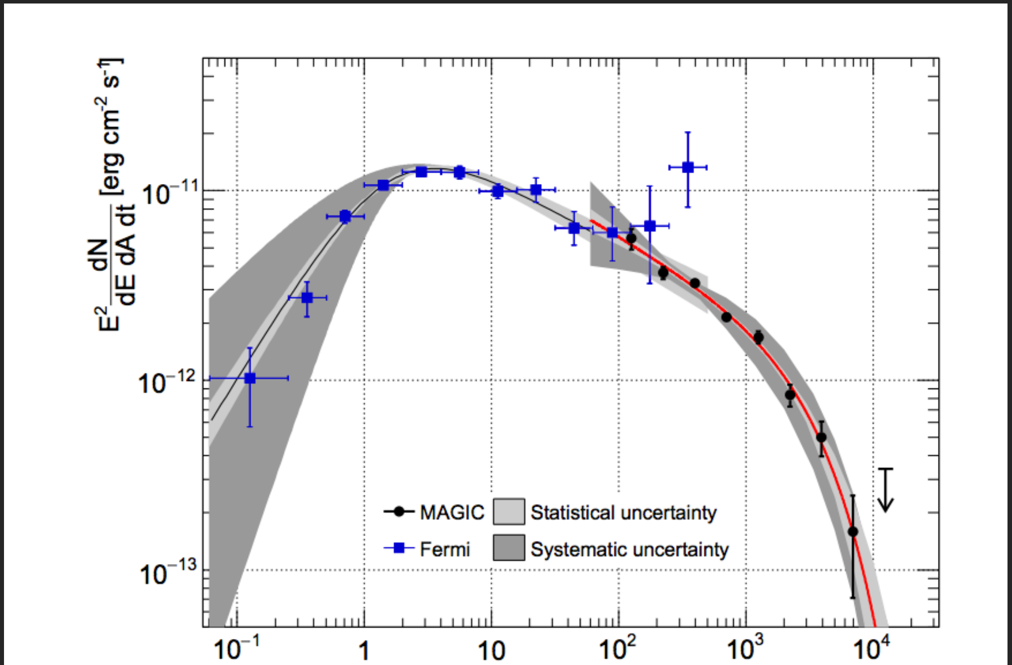
Kumar 2016, Holder (VERITAS)

MAGIC campaign to investigate the extension of the spectrum by accurate spectral measurements at TeV energies:
What is the maximum energy of particles in Cassiopeia A?

MAGIC is a system of two 17m diameter IACT telescopes designed to observe very high energy (VHE, ≥ 50 GeV) γ rays, located in La Palma (Spain),at Roque de los Muchachos observatory.

- We accumulated ~160 hr of good quality data (Dec 2014 - Oct 2016)
- All data for zenith angles Zd: ~30-50º
- ~70% of data taken under moonlight (see arXiv:1704.00906)
- Also analyzed more than 8 yr of Fermi data, combining multiple data selections (EDISP) into a joint likelihood

*see Vovk, Rodriguez-Garcia, Vanzo, Satalecka



MAGIC Col. 2017

Fitted MAGIC spectrum assuming:

- Pure power-law (PWL)
- Power-law with exponential cut-off (EPWL)

EPWL preferred over PWL with 4.6σ significance.

Ecut = 3.5 TeV

Fermi spectral index:

Γ_1 = (0.90±0.08)

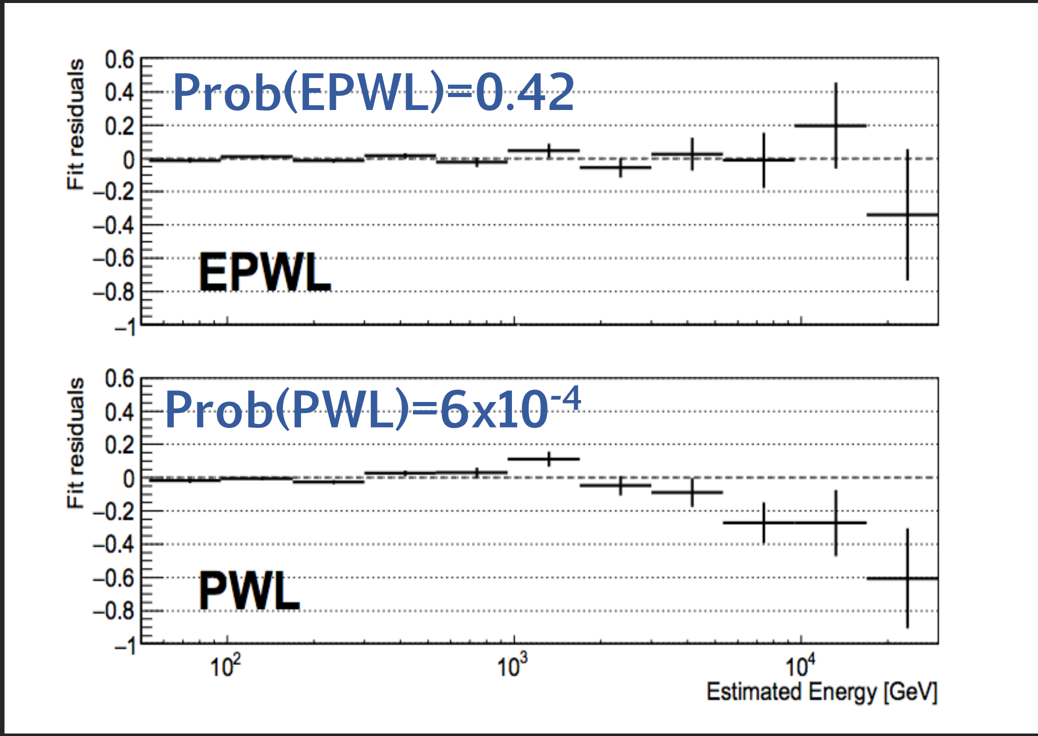
Γ_2 = (2.37±0.04)

MAGIC Fit:

$f(E) = N0\ (E/E0)^{-\Gamma} \exp(-E/E_c)$

$\Gamma_1 = (2.40 \pm 0.1_{sta} \pm 0.2_{sys})$

$E_c = 3.5(^{+1.6}_{-1.0})_{sta}(^{+0.8}_{-0.9})_{sys}$ TeV



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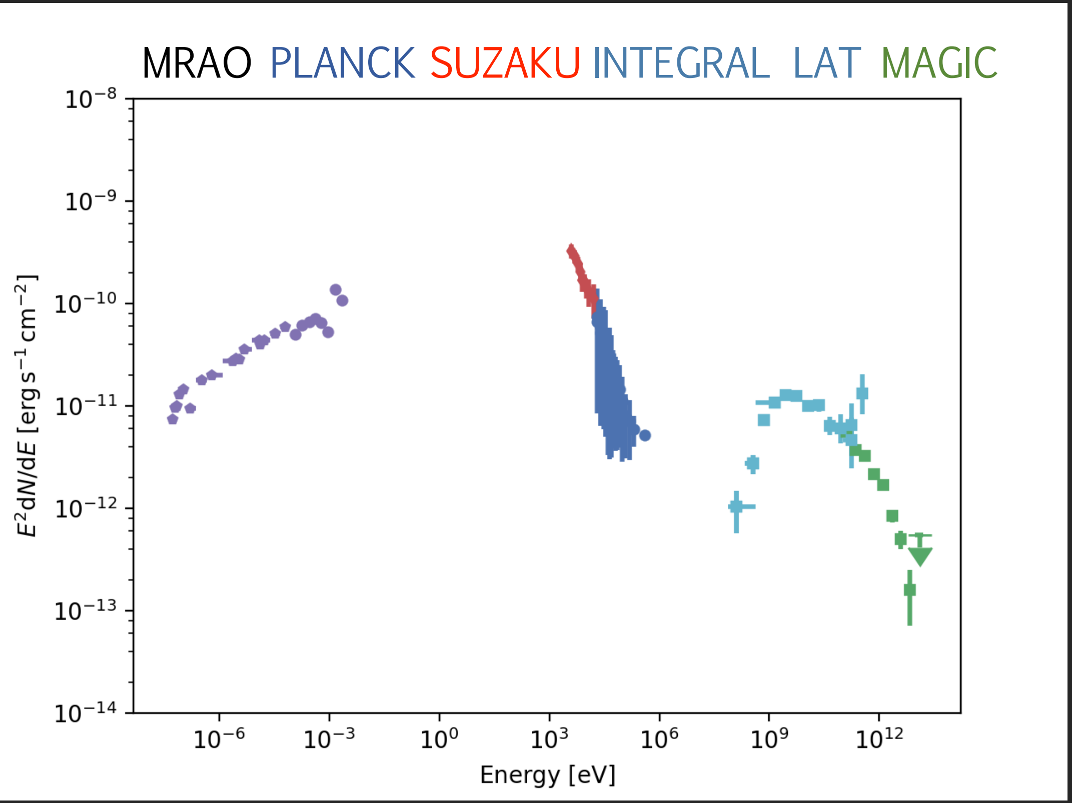
Spectral Energy Distribution

Zabalza 2015, Kafexhiu et al 2014, Aharonian et al 2010, Khangulyan et al 2014, Baring et al 1999

Multi-Wavelength SED fit using Naima*
Parent population: electron/positrons described by a power-law function plus exponential cutoff



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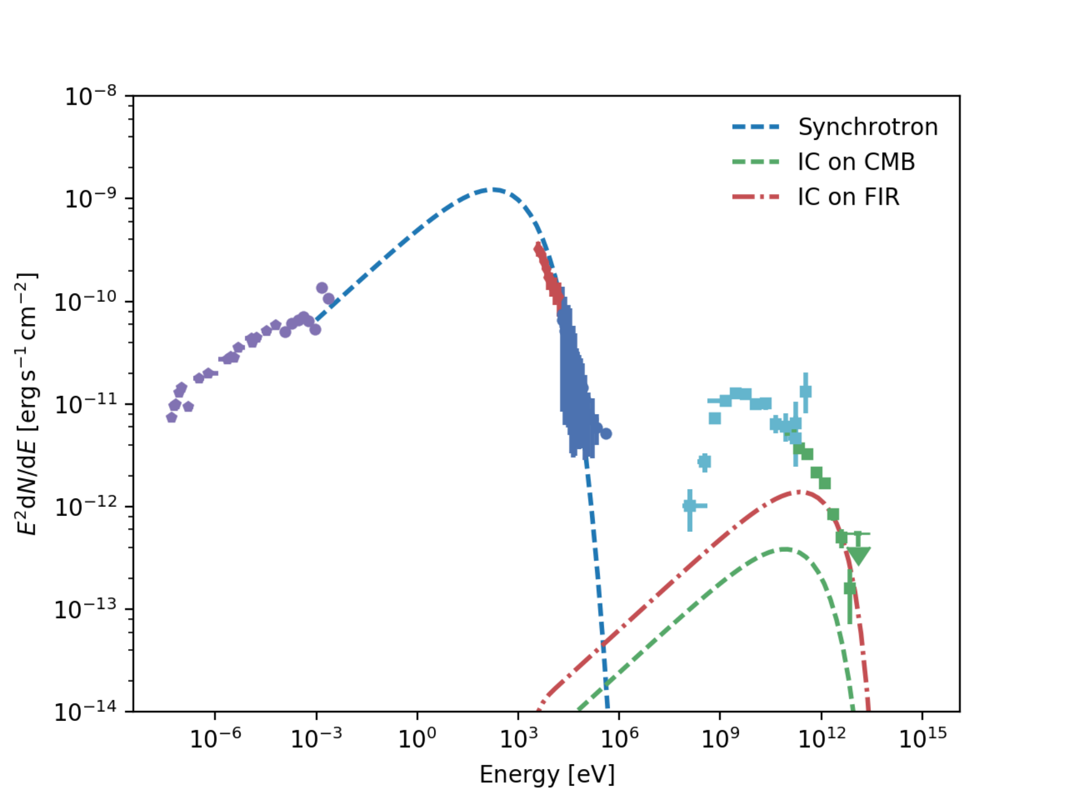

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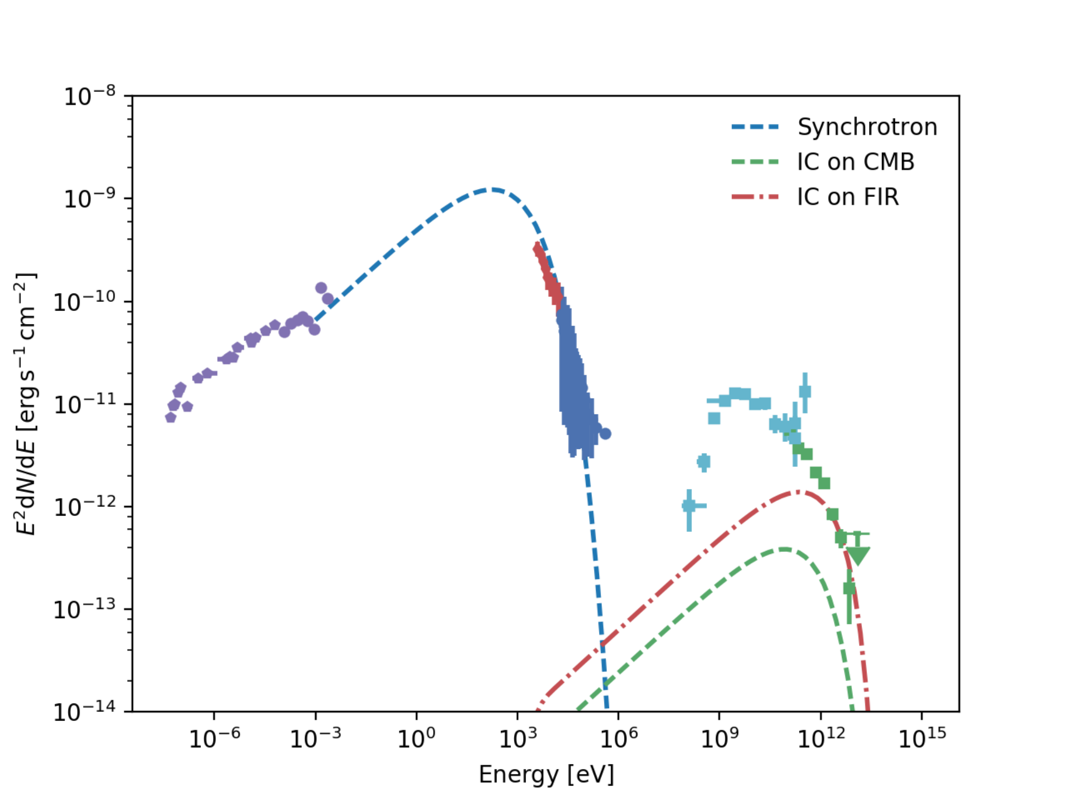

- **Inverse Compton & Synchrotron**
  $B < 180$ μG
  $\alpha \sim 2.4$
  $E_c \sim 8$ TeV
  N_e (1 TeV) $\sim 2 \times 10^{34}$ eV^{-1}

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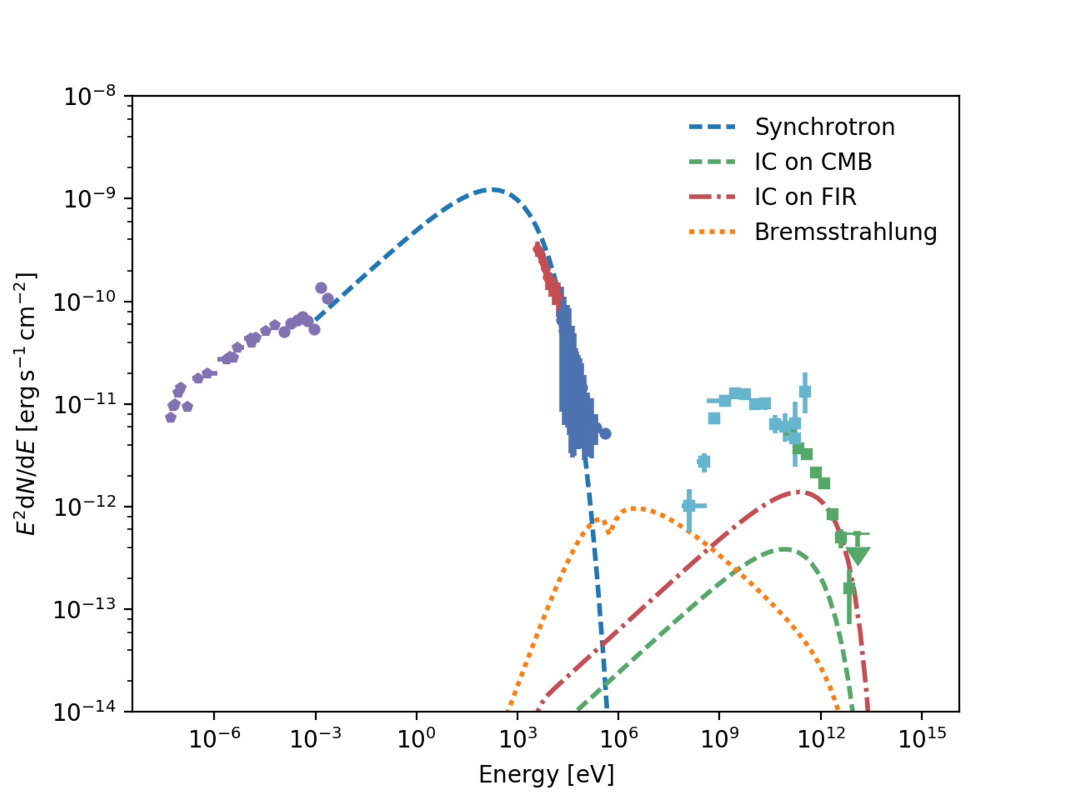

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  n_e < 1 cm^{-3}

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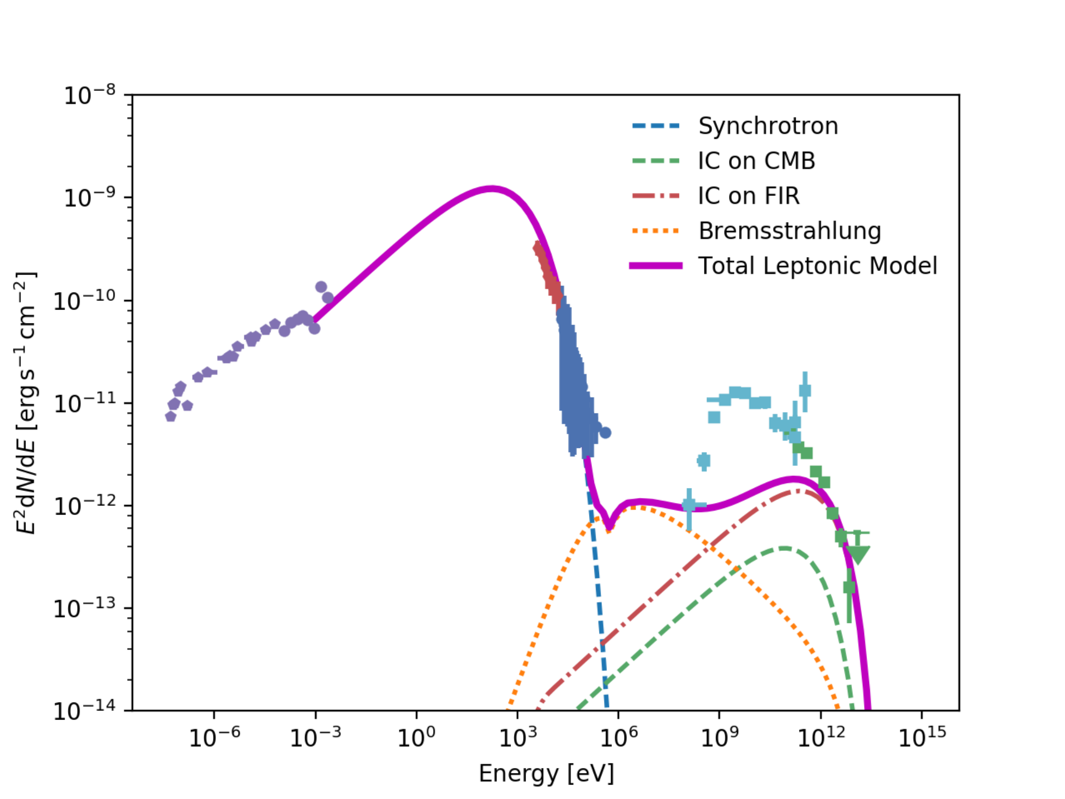

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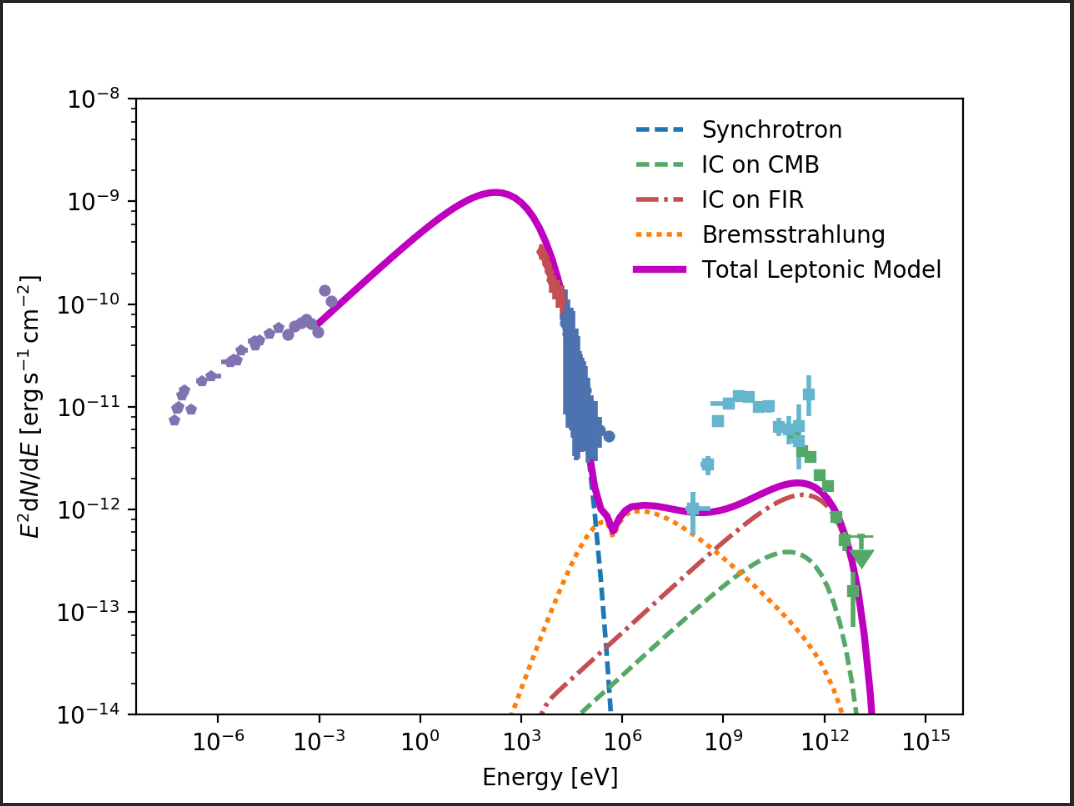

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If leptonic: Relative low magnetic field in large photon field, possible in a thin, clumpy ejecta medium

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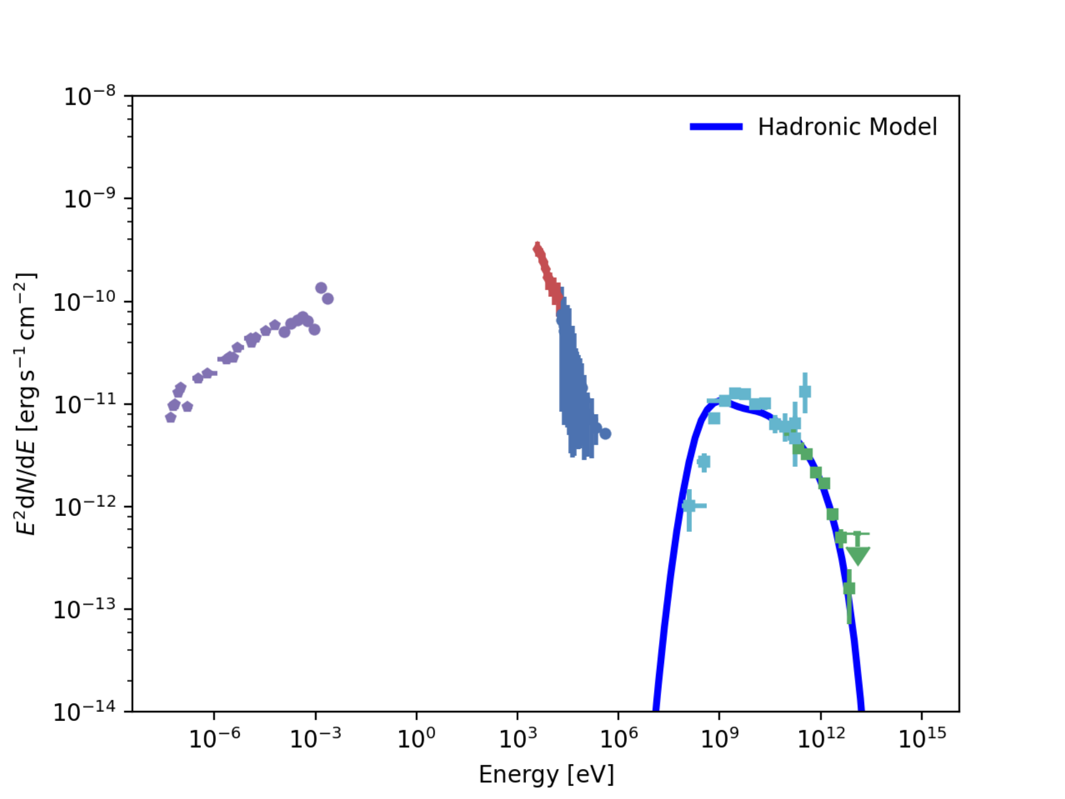

- **Proton-proton Interactions**
  Np ~ 10 cm^{-3}
  α ~ 2.21
  E_c ~ 12 TeV
  Wp (>1 TeV) ~ 5.1x10^{48} erg
  (0.2% of Esn (=2x10^{51} erg))
  Wp (>100 MeV) ~ 9.9x10^{49} erg

If hadronic: Extremely inefficient accelerator! escape?

$$E_c^p \simeq 450\left(\frac{B}{1\ \mathrm{mG}}\right)\left(\frac{t_0}{100\ \mathrm{yr}}\right)\left(\frac{u_s}{3000\ \mathrm{km/s}}\right)^2 \eta^{-1}\ \mathrm{TeV},$$

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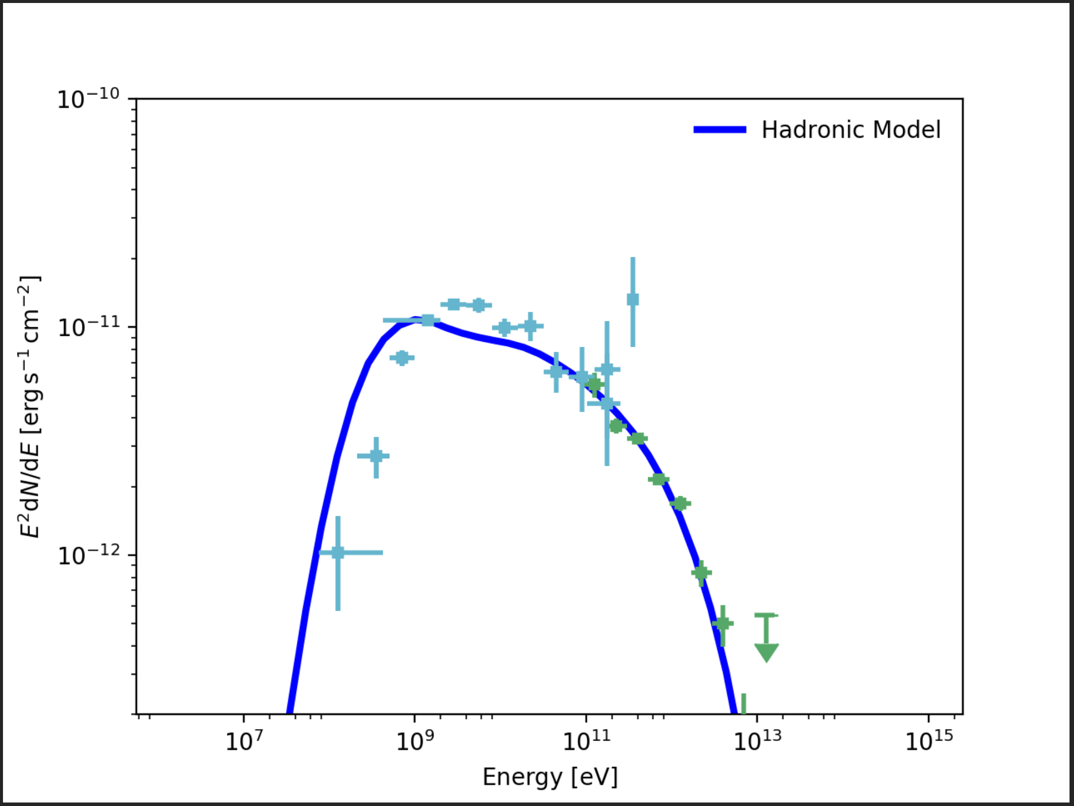

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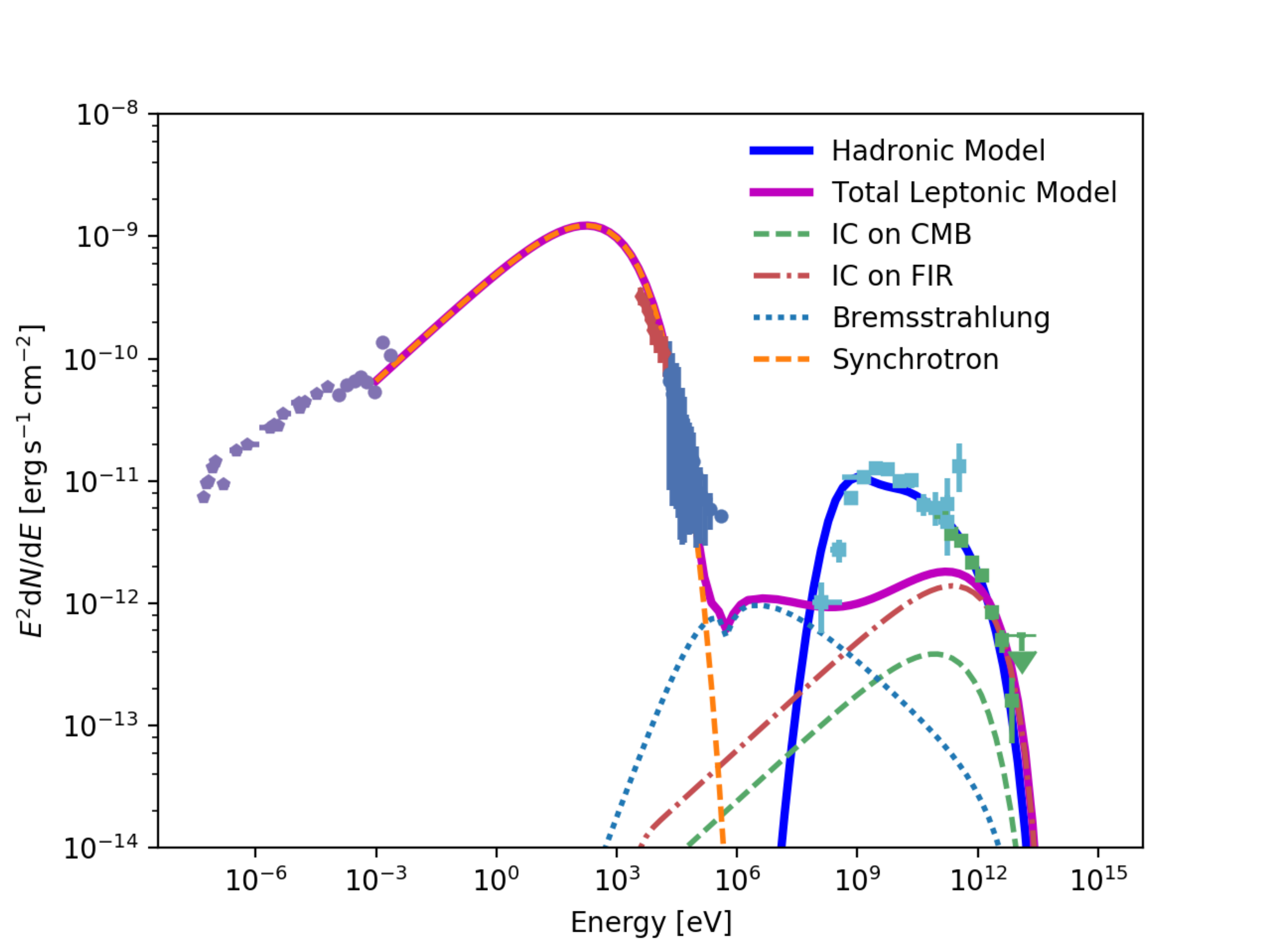


Summary

For the first time, we proved evidence of a cut-off in Cas A, located at 3.5 TeV, with a significance of 4.6 sigma

We derived the most precise spectral measurement at TeV energies available

The MWL SED cannot be explained by a single population of electrons.

Protons are likely to dominate the GeV/TeV emission, still, the fit lead to uncomfortable low values on the acceleration efficiency -> escape?

Even if protons produced all the TeV emission, Cas A cannot be a PeVatron at the present time.

→ *protons cut-off energy* ***~ 10 TeV*** *(~10 times lower compared to current models)*

Backups

Moon-light observations

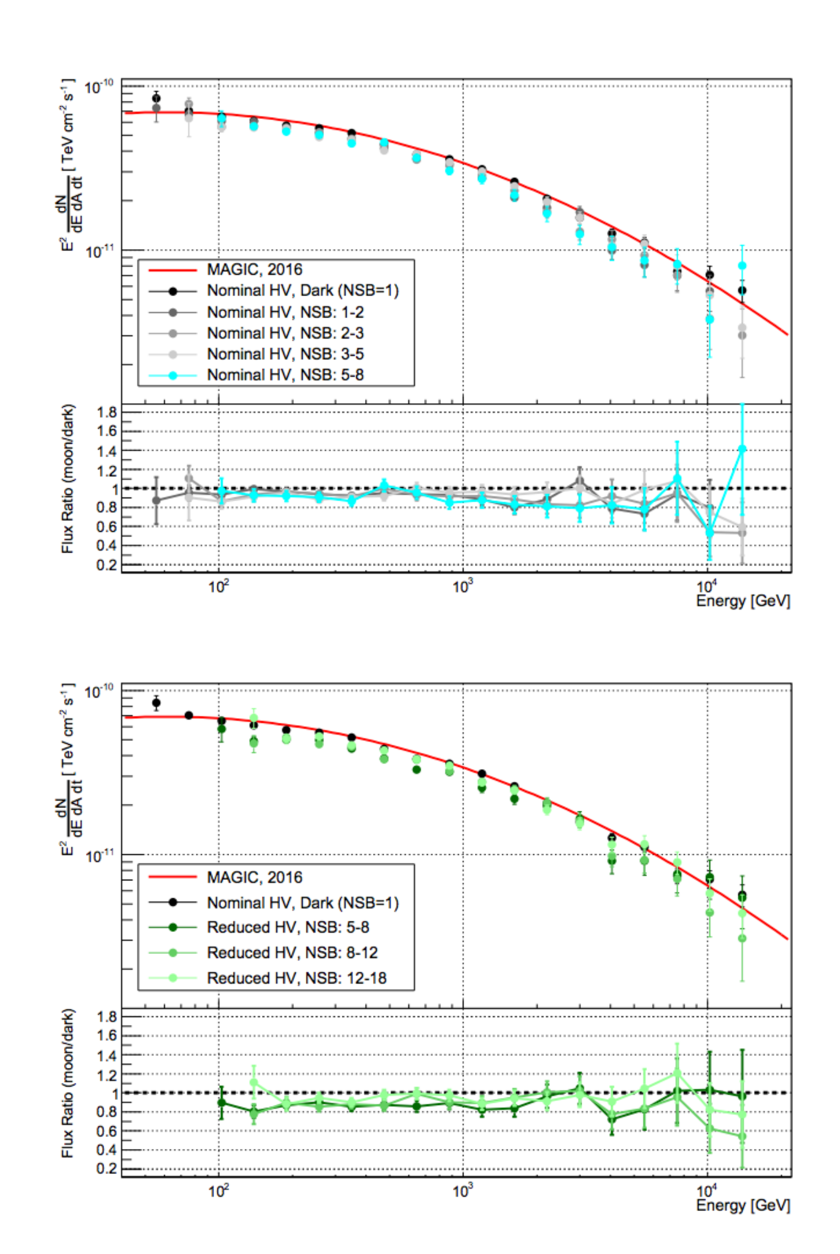
Observation conditions	Time [h]
Dark and Nominal HV	42.2
Moon and Nominal HV	77.7
Moon and Reduced HV	38.1
All configurations	158.0

For moderate moonlight ($NSB<8\times NSB_{Dark}$) with Nominal HV, the additional systematics on the flux is below 10%, raising the flux-normalization uncertainty (at a few hundred GeV) from **11% to 15%.**

For observations with Reduced HV ($NSB<18\times NSB_{Dark}$) the additional systematics on the flux is ~15%, corresponding to a full flux-normalization uncertainty of **19%** after a quadratic addition.

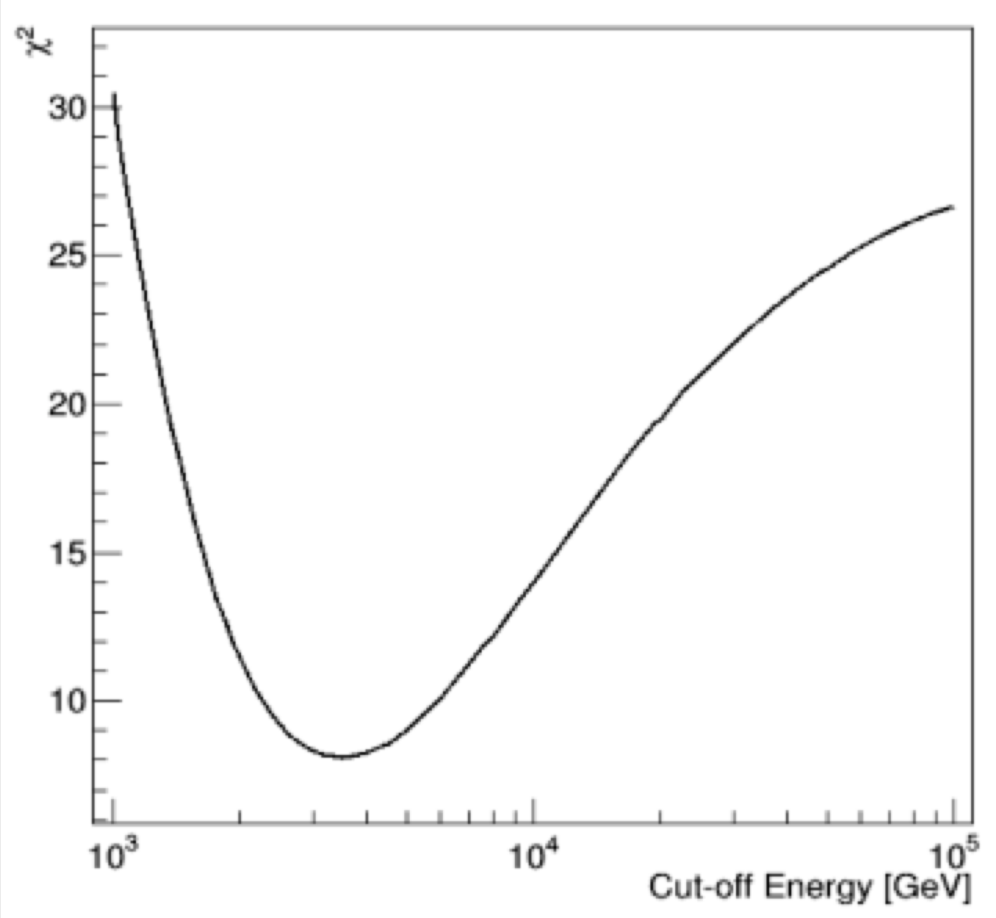
The additional systematics on the reconstructed slope is **negligible (±0.04)** and the overall uncertainty is still **±0.15** for all hardware/NSB configurations.

The uncertainty of the energy scale is not affected by the moonlight.



EPWL → f(E)= N0 (E/E0)-Γ exp(-E/Ec)

Null hypothesis: No cut-off (Ec → ∞, PWL)



Systematic uncertainties due to an eventual mismatch on the absolute energy scale between data and MC < 15%

Modifying the absolute calibration by ±15:

If the average C light in the whole sample was overestimated by 15%: 3.1sigma

If the average C light in the whole sample was underestimated by 15%: 6.5 sigma