Deep observations of the starburst galaxy M82 with VERITAS

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Smithsonian Astrophysical Observatory

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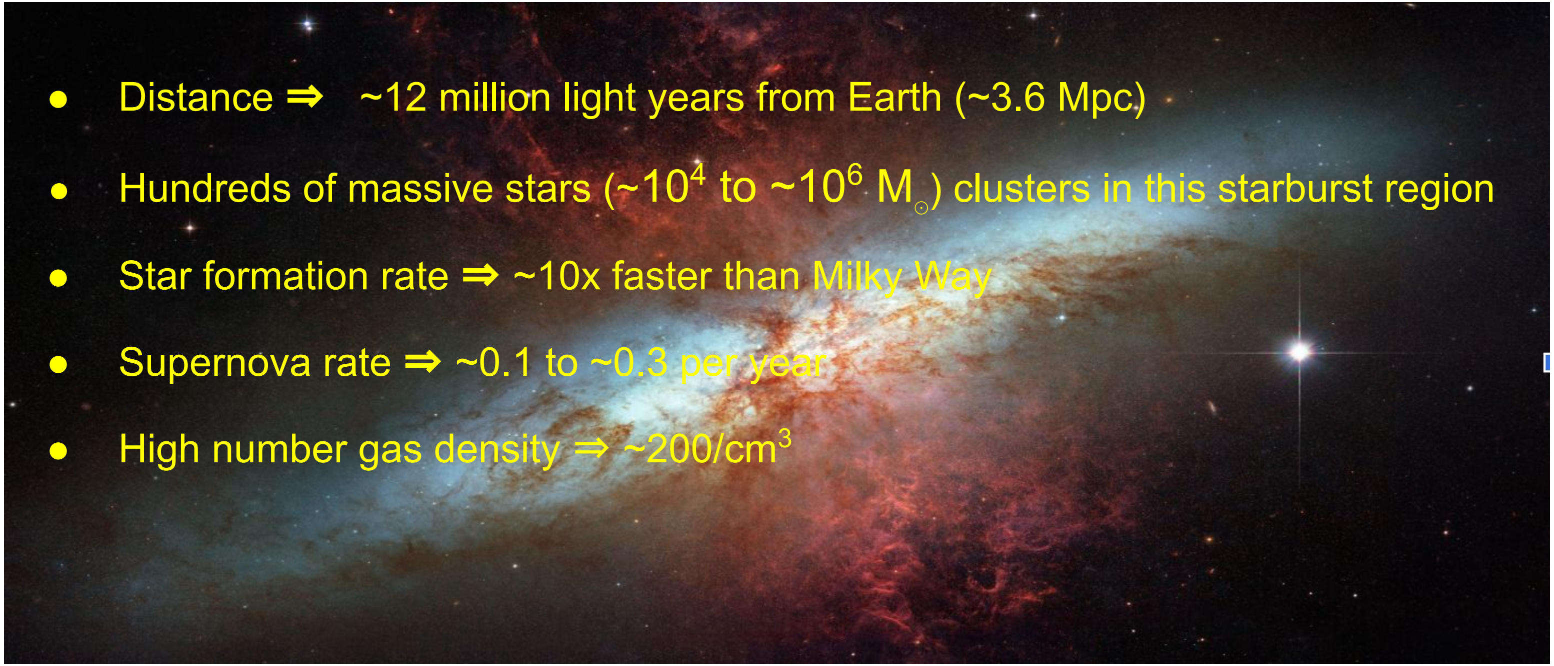
About the source M 82 (also known as NGC 3034 or Cigar Galaxy)



- Distance ⇒ ~12 million light years from Earth (~3.6 Mpc)
- Hundreds of massive stars (~10^4 to ~10^6 $M_\odot$) clusters in this starburst region
- Star formation rate ⇒ ~10x faster than Milky Way
- Supernova rate ⇒ ~0.1 to ~0.3 per year
- High number gas density ⇒ ~$200/cm^3$

A potential target for gamma-ray observations

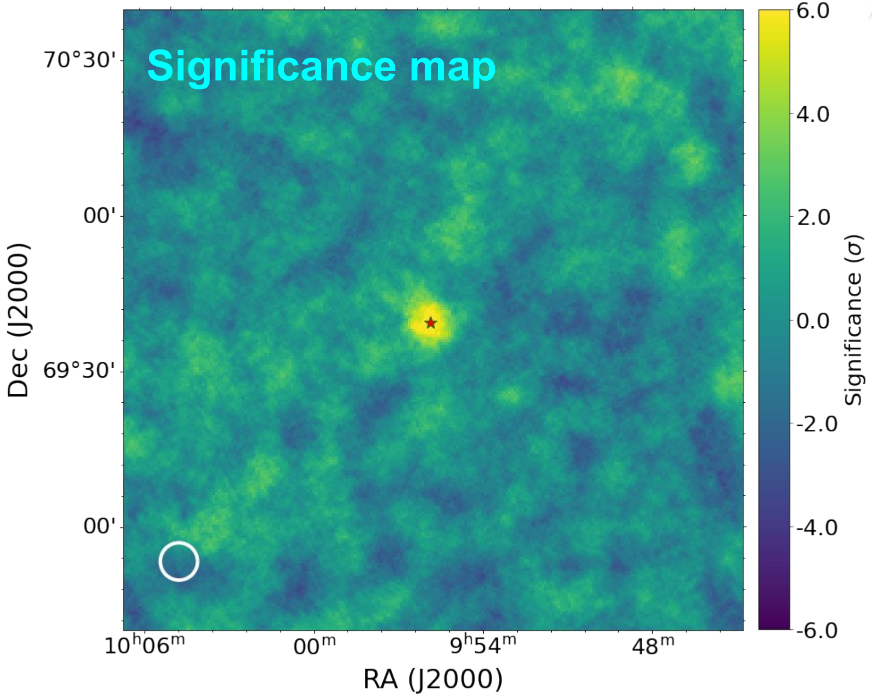
Results

~254 h good-quality data in **~15 yrs**

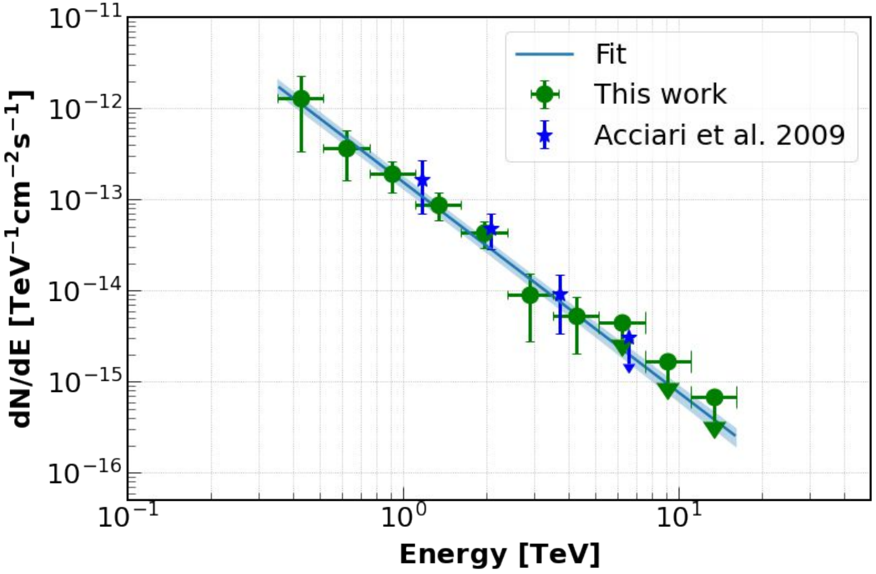
# of gamma events: **~135**

# of background events: **~372**

Significance(σ): **6.5**



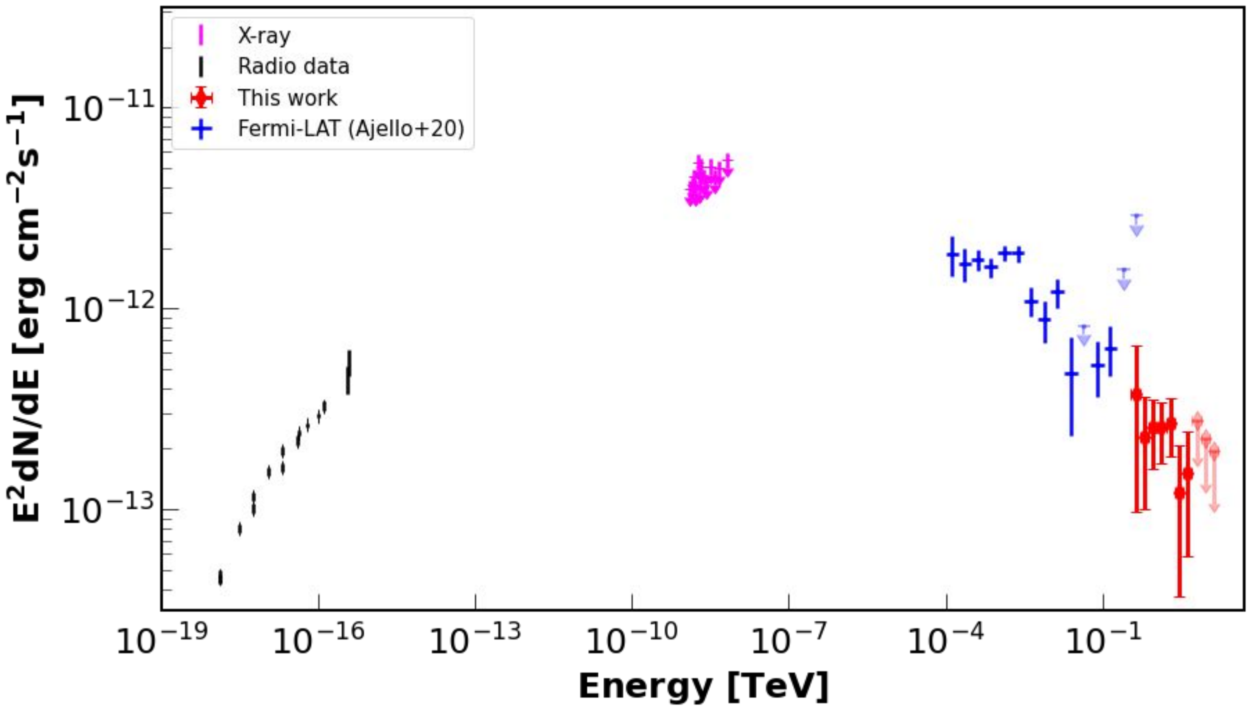
Results



Γ = 2.31 ± 0.26
Norm @ 1.4 TeV = $(7.17 \pm 1.23)\times10^{-10}$ $TeV^{-1}\ m^{-2}\ s^{-1}$

Flux > **450 GeV**: **~0.4% of Crab Nebula flux**

Multi-wavelength observations



Emission mechanisms:

- Leptonic
- Hadronic

Multi-wavelength modelling

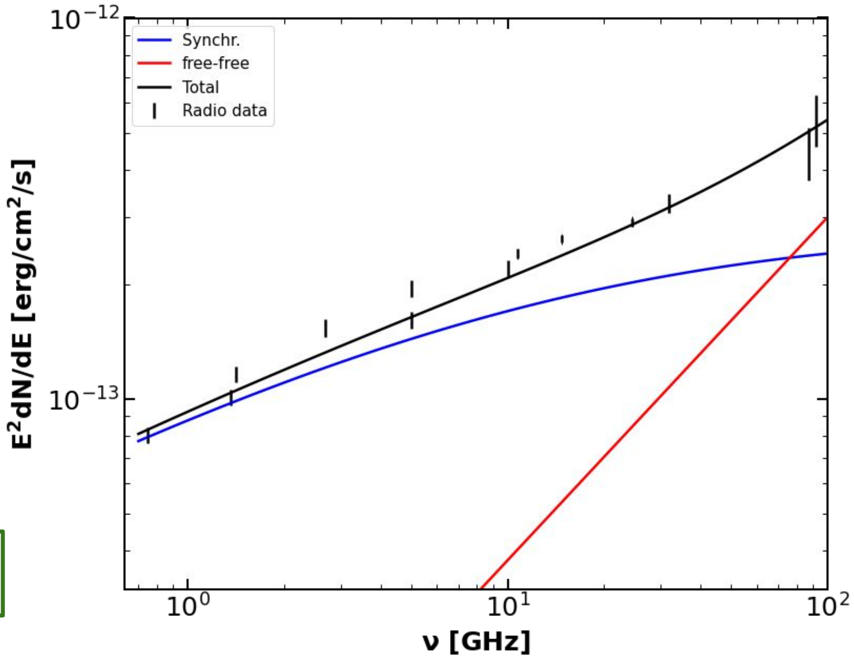
Leptonic scenario

- **Parameters of the radiation modelling**
  - Neutral gas density**: 200 cm^{-3}**
  - Ionized gas density: **50 cm^{-3}**
  - Magnetic energy density: **500 eV cm^{-3}**
  - Particle energy density: **500 eV cm^{-3}**

- **Fit to radio data/spectrum**
  - Synchrotron emission
  - Free-free emission
  - Electron injection with **Q~E$^{-2.25}$**

Reasonable match between model and data

Radio data



Multi-wavelength modelling

Leptonic scenario

- **Parameters of the radiation modelling**
  - Neutral gas density: **200 cm^{-3}**
  - Ionized gas density: **50 cm^{-3}**
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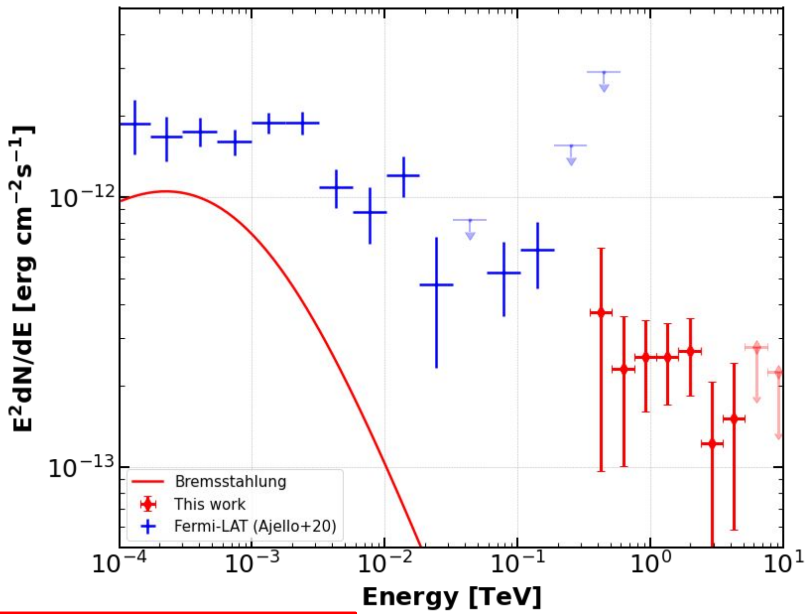
- **Fit to GeV-scale data**
  - non-thermal bremsstrahlung
  - inverse-Compton

- Bremsstrahlung rapidly falls off with energy:
  - 80% of flux at 0.15 GeV
  - 30% of flux at 1 GeV

- Inverse-Compton flux below 10%

Gamma-ray data



The leptonic scenario is disfavored

Multi-wavelength modelling

Hadronic scenario

- **Parameters of the radiation modelling**
  - Neutral gas density**: 200 cm^{-3}**
  - Ionized gas density: **50 cm^{-3}**
  - Magnetic energy density: **500 eV cm^{-3}**
  - Particle energy density: **500 eV cm^{-3}**

- Assume particle spectrum is a **power law** in momentum

- Gamma-ray production calculated with DPMJET III (Bhatt et al. 2020)

- Two different compositions (target gas & cosmic rays)
  - ISM
  - Heavy (enriched by starburst winds + SN explosions)

Components	**ISM**	**Heavy**
Hydrogen	0.909	0.848
Helium	0.090	0.146
Carbon	2.1e-4	5.2e-3
Oxygen	1.6e-4	7.e-4

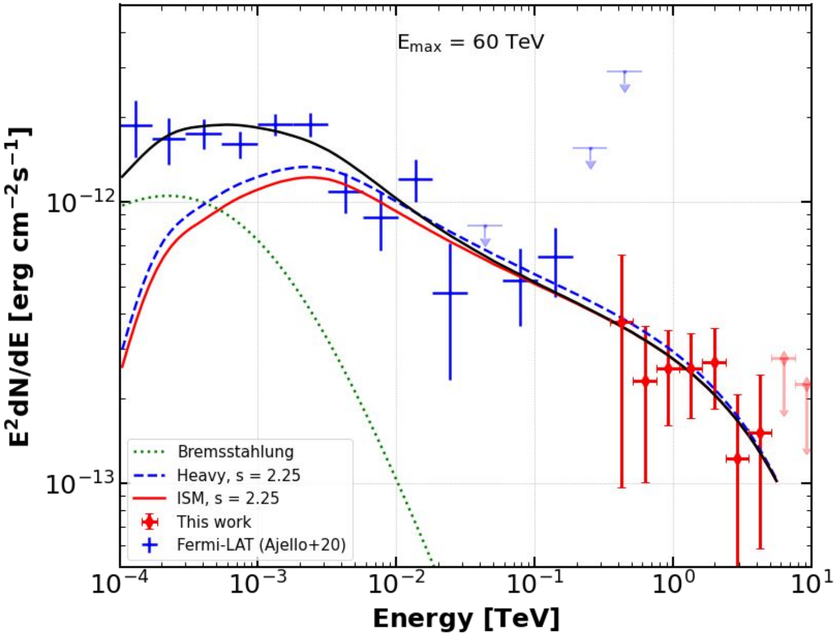
Multi-wavelength modelling

Hadronic scenario

- Heavy Composition:
  - Higher sub-GeV gamma ray flux
  - Uncertainties too large for composition conclusions

- Pion decay+Bremsstrahlung:
  - Reasonable match for a power-law index s=2.25

- The maximum energy is poorly constrained



Summary

- Extensive VERITAS observations: ~6.5σ in ~254 h; Γ = 2.31 ± 0.26; ~0.4% Crab
- Higher significance => Improved spectrum => Better constraints on SED modelling
- Purely leptonic scenario is a poor representation of the gamma-ray SED
- Hadronic scenario is clearly preferred
- A lepto-hadronic scenario with a power-law spectrum (index s ≃ 2.25), and with significant bremsstrahlung below 1 GeV, provides a good match to the observed SED
- CR source spectrum has index s=2.25 (similar to SNRs)