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Constraints in the TeV Halo Population of M31

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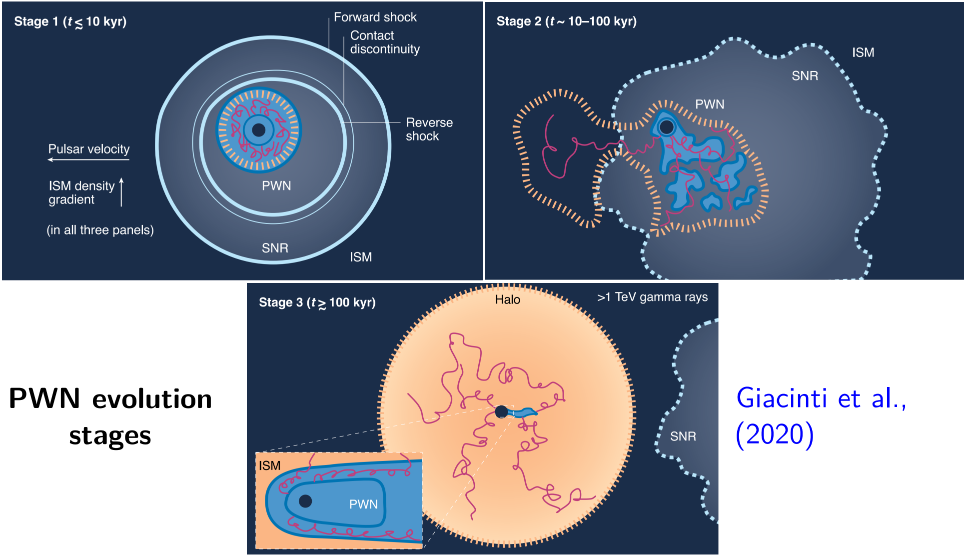
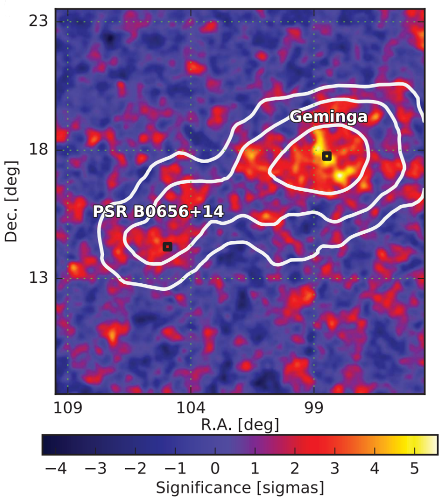
What are TeV halos?



PWN evolution stages

Giacinti et al., (2020)

Discovery of Geminga TeV halo



Abeysekara et al, (2017)

TeV halos discovery by HAWC observatory

- Geminga
- PSR B0656+14 (Monogem)

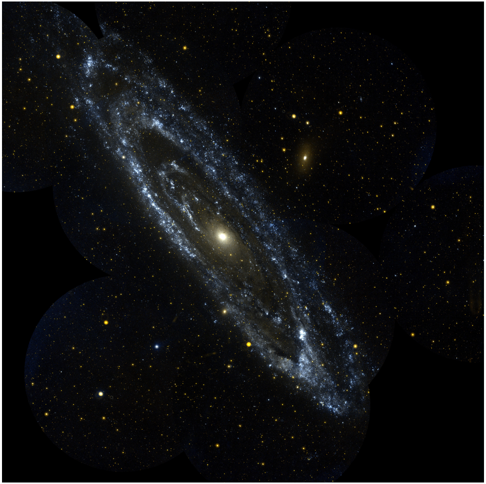
Modeled with a power law with an exponential cutoff

- Sudoh et al (2019) predicted ~ 160 TeV halos detectable by HAWC
- TeV halos are significant contributors to the TeV emission in our Milky Way (or any other galaxy?)

Why to study Andromeda?

- Closest major spiral galaxy to the Milky Way
- A star-forming galaxy
- It emits in the gamma-ray band

- Diffuse gamma-ray excess in the GeV band, as seen by *Fermi*-LAT
- This excess might be explained by a population of millisecond pulsars



Credits:NASA/GALEX Telescope

Milky Way and Andromeda

Properties*	Milky Way	Andromeda
Morphology	SbcI-II	SbI-II
Mass ($10^{10} M_\odot$)		
Visible	5	5.9 – 8.7
Total	40 – 55	107 – 140
Disk		
Total SFR ($M_\odot$ yr^{-1})	$\sim 1 - 5$	0.35 – 1.0
Pulsar birth rate† (pulsar year^{-1})	1.4×10^{-2}	
Mass ($10^{10} M_\odot$)		
disk	3.5	7
stellar	3.0	6
gas	0.7	0.6
HI	0.4	0.5
HII	0.11	0.02 – 0.04

*Data taken from Yin (2009) and references therein.
†Lorimer et al., (2006)

TeV observations in M31

Some work has been performed regarding TeV emission from M31.

Modeled as a simple power law with index Γ

Only upper limits can be computed!

Model Template	Integral Flux Upper Limit (>1 TeV) [10^{-13} cm^{-2} s^{-1}]
M31 Disk ($\Gamma = -2.0$)	0.85
M31 Disk ($\Gamma = -2.5$)	3.75
M31 Disk ($\Gamma = -3.0$)	5.18

Albert et al, (2020)

Emission by a TeV halo population

We can take an average total flux due to a TeV halo population as (Xu & Hooper, 2022):

$$F_{\gamma,pop} = \Gamma_{p,M31} \langle \eta \rangle \frac{\langle E_{\rm rot} \rangle}{4\pi d_{M31}^2}$$

- $\langle \eta \rangle$ Efficiency
- $\langle E_{\rm rot} \rangle$ rotational energy of a pulsar population
- $\Gamma_{p,M31}$ Pulsar birth rate
- d_{M31} Distance to M31

The efficiency of a TeV halo might be defined as

$$\eta = \frac{F_\gamma}{\dot{E}/(4\pi d^2)},$$

where

- F_γ is the gamma-ray flux between $1-100$ TeV
- d the distance to the TeV halo from Earth.

Emission by a TeV halo population

Pulsar birth rate

Assuming a relation between the SFR ($\Gamma_\star$) and the pulsar birth rate (Γ_p) for both Andromeda (M31) and Milky Way (MW):

$$\Gamma_{p,M31} = \frac{\Gamma_{\star,M31}}{\Gamma_{\star,MW}} \times \Gamma_{p,MW}$$

Average rotational energy

$$\langle E_{\rm rot} \rangle = \frac{4\pi^2 MR^2}{5} \left\langle \frac{1}{P^2} \right\rangle \simeq 7 \times 10^{48} \ {\rm erg},$$

(Xu & Hooper, 2022)

The spectrum of a TeV Halo can be modeled as

$$\frac{dN}{dE} = \Phi_0 \left(\frac{E}{E_0} \right)^{-\alpha} \exp(-E/E_c)$$

Assuming all TeV Halos behave like Geminga, we can use this spectrum for a population of TeV Halos

Geminga and Monogem

Model parameters of Geminga and Monogem

Pulsar parameters*		**Geminga**	**Monogem**
RA, dec	(degrees)	(98.48, 17.77)	(104.95, 14.24)
d	(pc)	250	288
$\dot{E}$	$(10^{34} \mathrm{erg\ s}^{-1})$	3.26	3.8
Adopted model values			
α^{**}		2.23	2.14
E_0	(TeV)	7	
E_c^{***}	(TeV)	50	

* Abeysekara et al., (2017)
** Abeysekara et al., (2017)
*** Sudoh et al., (2019)

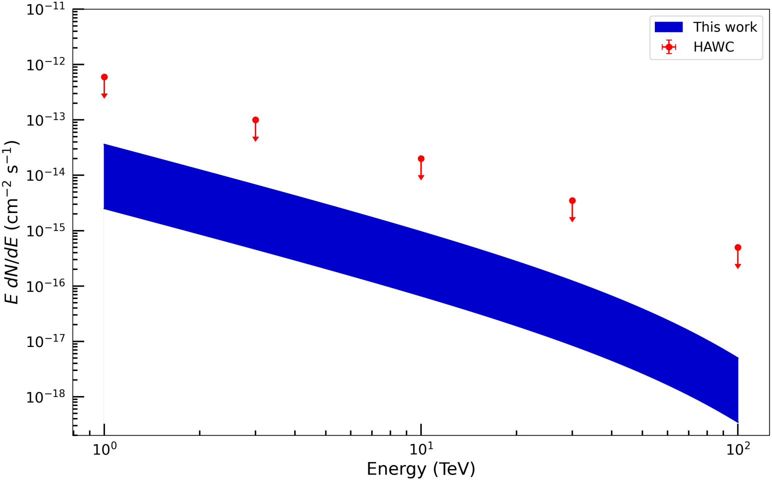
Results

Computed values of the model parameters

Parameter		Value
η	10^{-3}	2.1
$\Gamma_{p,M31}$	(pulsar/century)	$0.01 - 1.40$
Φ_0	$(10^{-17}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	$2 - 28$

These parameters were calculated using the max and min measured values of MW and M31 Star Formation Rate

Results



Gamma-ray emission from M31 assuming a population of TeV halos, compared with HAWC upper limits

Summary and conclusions

- Assuming all TeV Halos behave like Geminga, we have computed the contribution of TeV Halos to the gamma-ray emission of M31
- With a simple model approach, we have found TeV Halo emission might be significantly contributing to the TeV emission from M31.
- Our results are comparable to HAWC upper limits, but warning: contribution from interactions of cosmic rays with the gas of the galaxy still needs to be added.
- Interestingly, TeV Halos may be the only contributor at energies > 10 TeV. This may allow us to constrain the TeV Halo population in M31.
- Better HAWC UL will come out with the new analysis framework and more data.