Supernova Remnant G106.3+2.7 – a likely proton PeVatron

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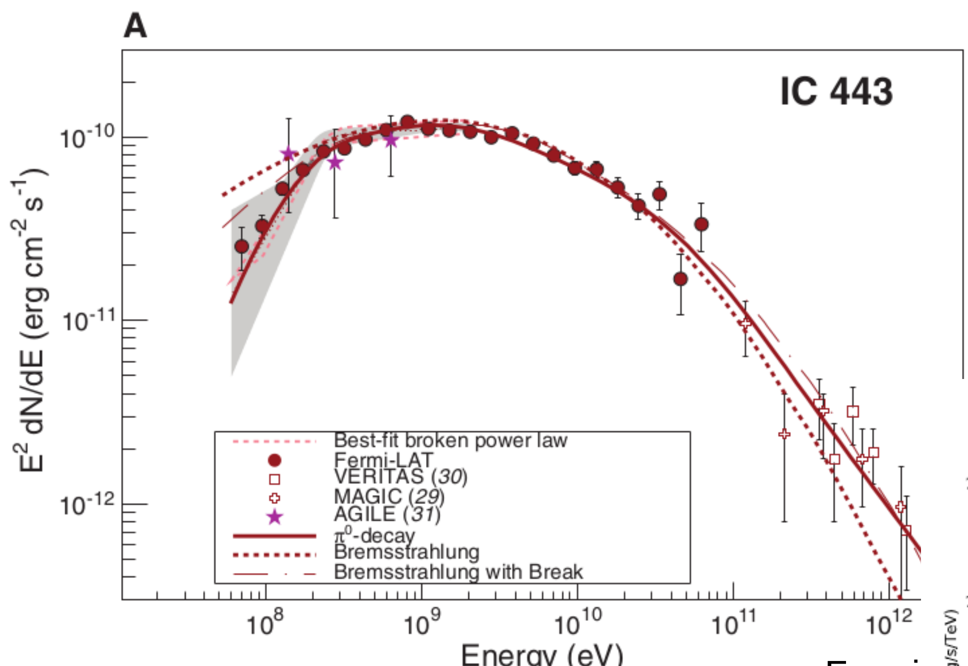
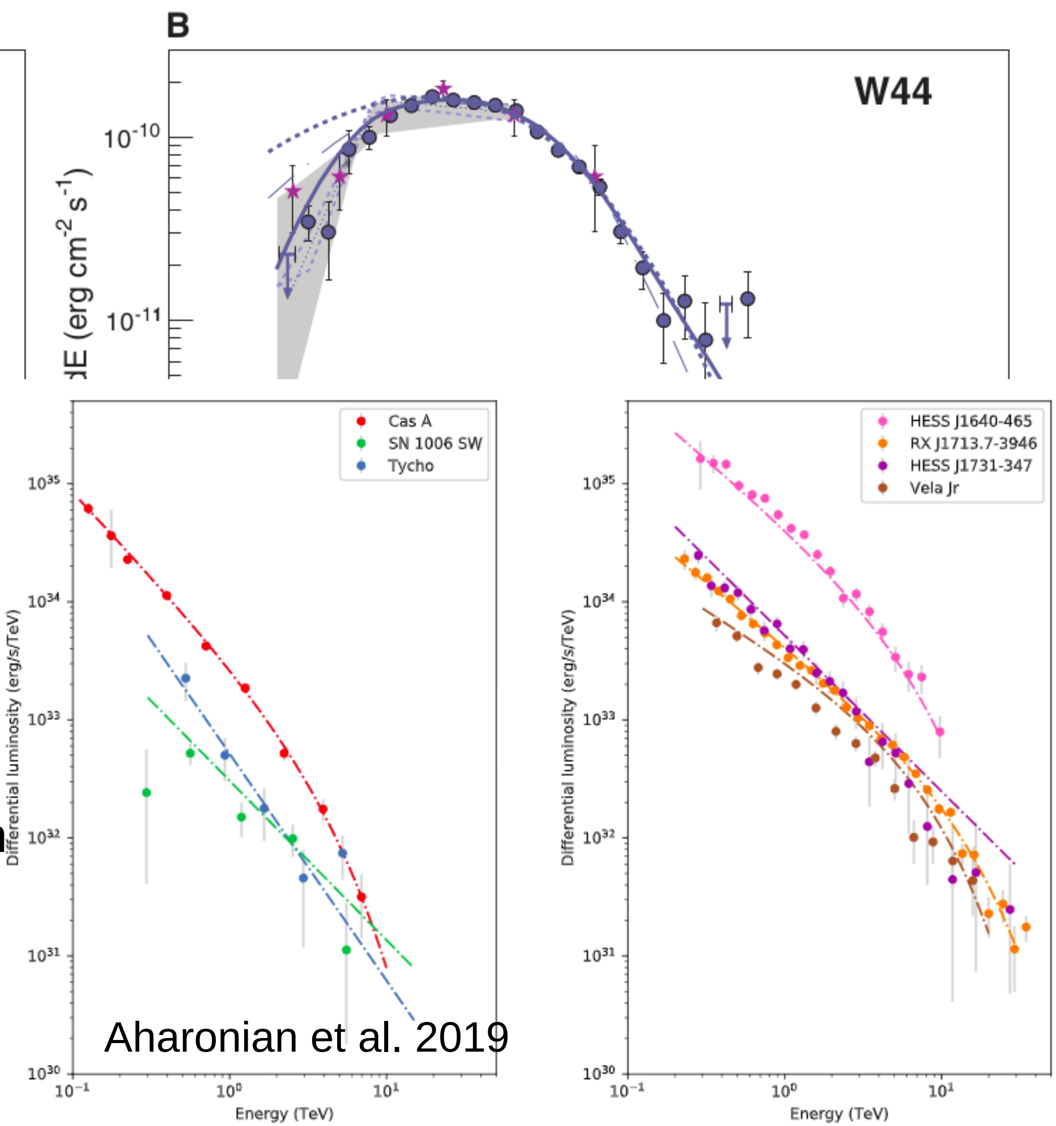
Evidence of proton acceleration at SNRs

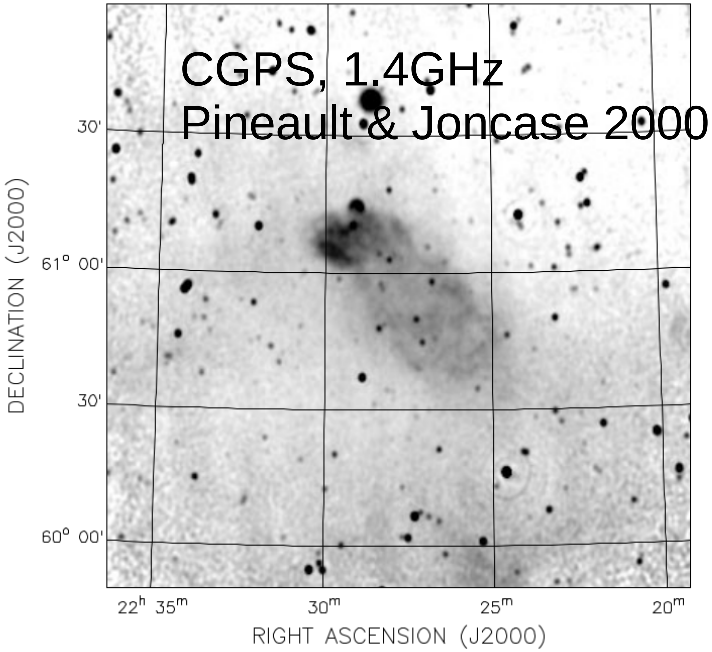


Fermi



Aharonian et al. 2019

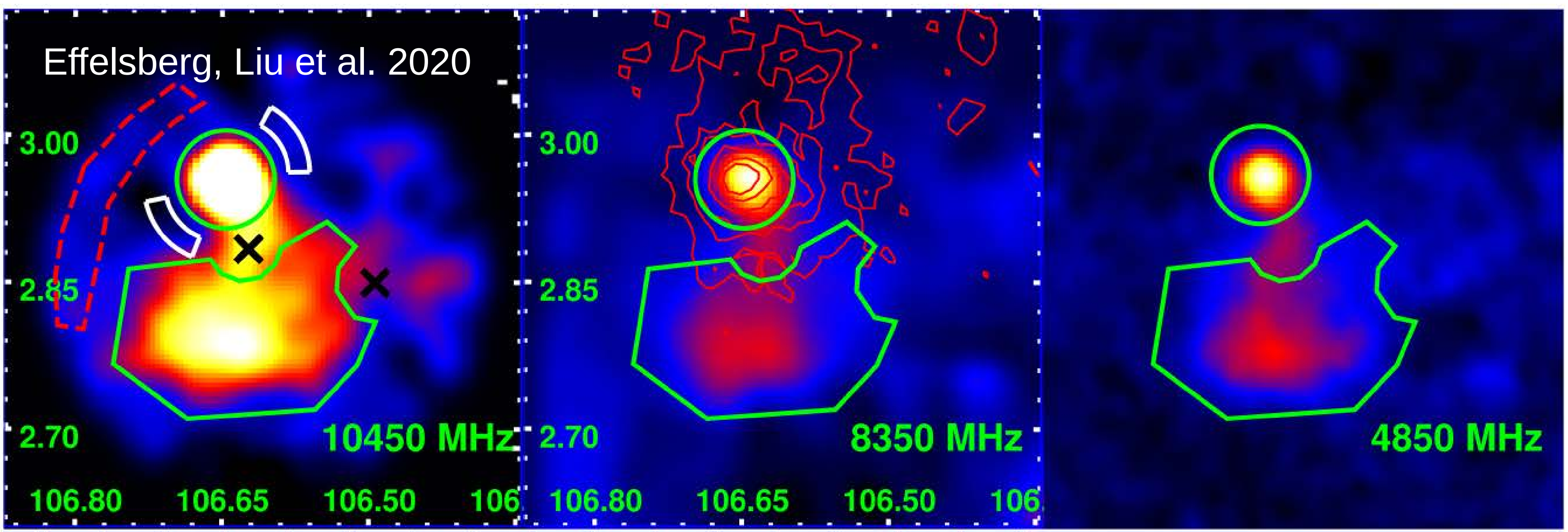
- no evidence for PeV proton acceleration
- spectral cutoff/break below 10TeV

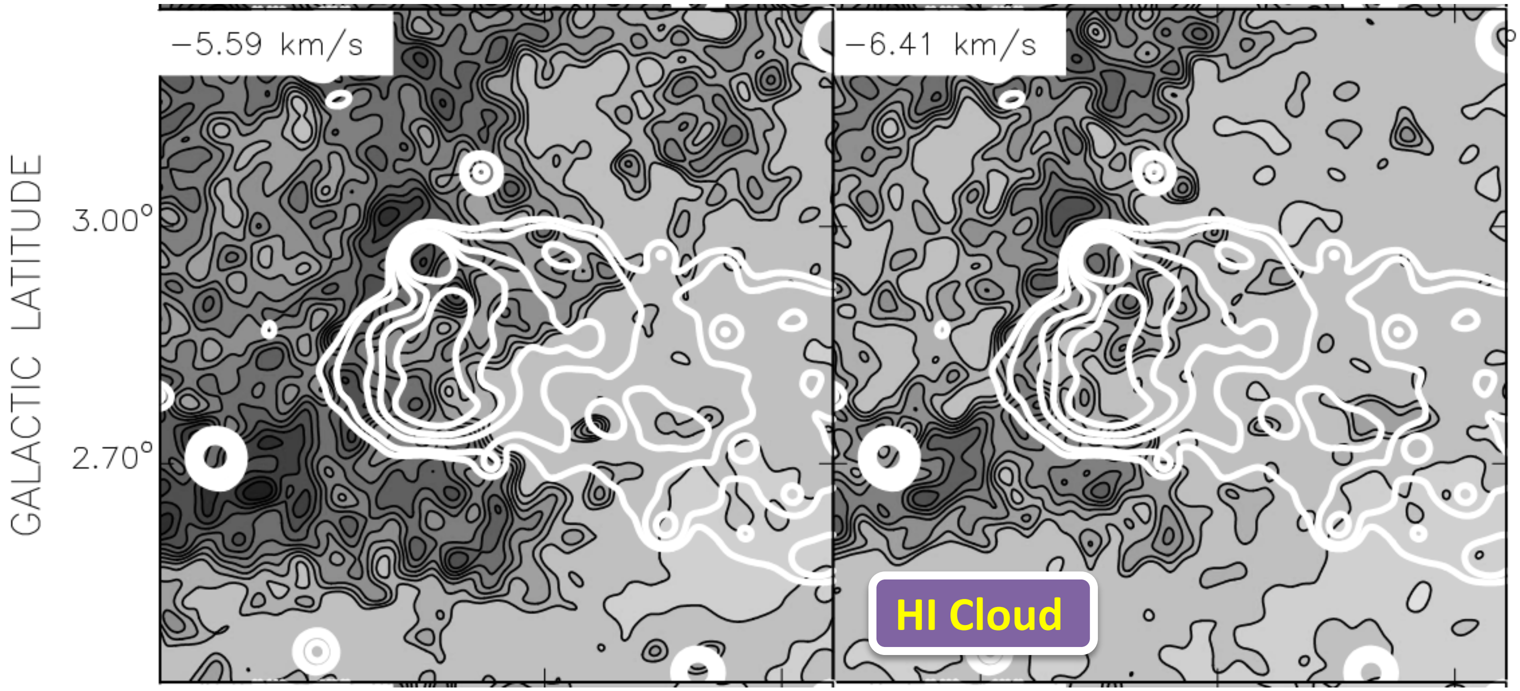


Radio Observation on SNR G106.3+2.7

Compact, bright **Head**
(including energetic pulsar PSR J2229+6114
of ~10kyr and its PWN Boomerang)

Diffusive, faint **Tail**

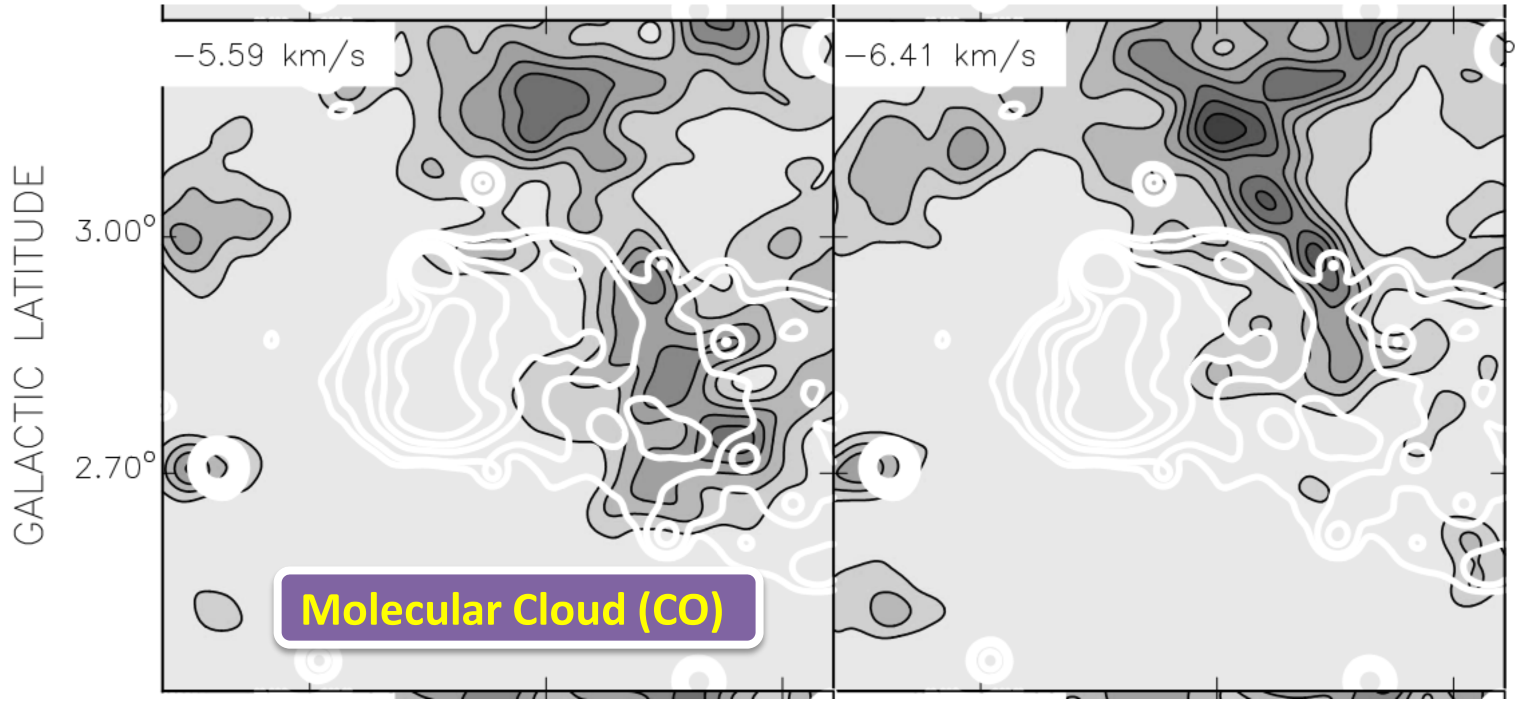




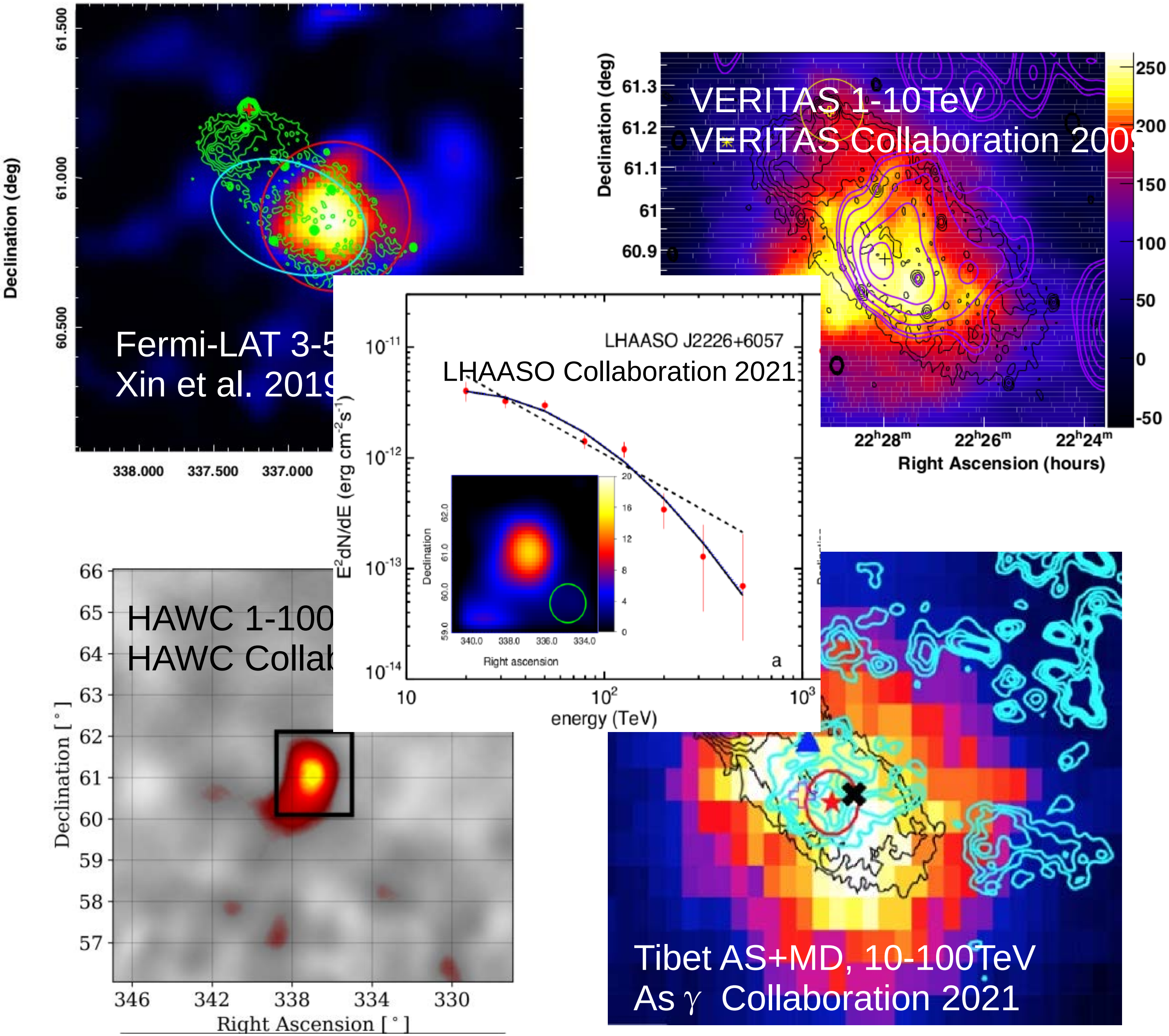
Distance ~800 pc

HI cavity in the tail region

Kothes et al. 2001



CO line data of IRAM 30m telescope does not show clear evidence for direction interaction between SNR and the clouds by Q.C. Liu & Y. Chen, to be submitted



Gamma-ray observation on SNR G106.3+2.7 region

Centroid of the gamma-ray emission coincident with **Tail**

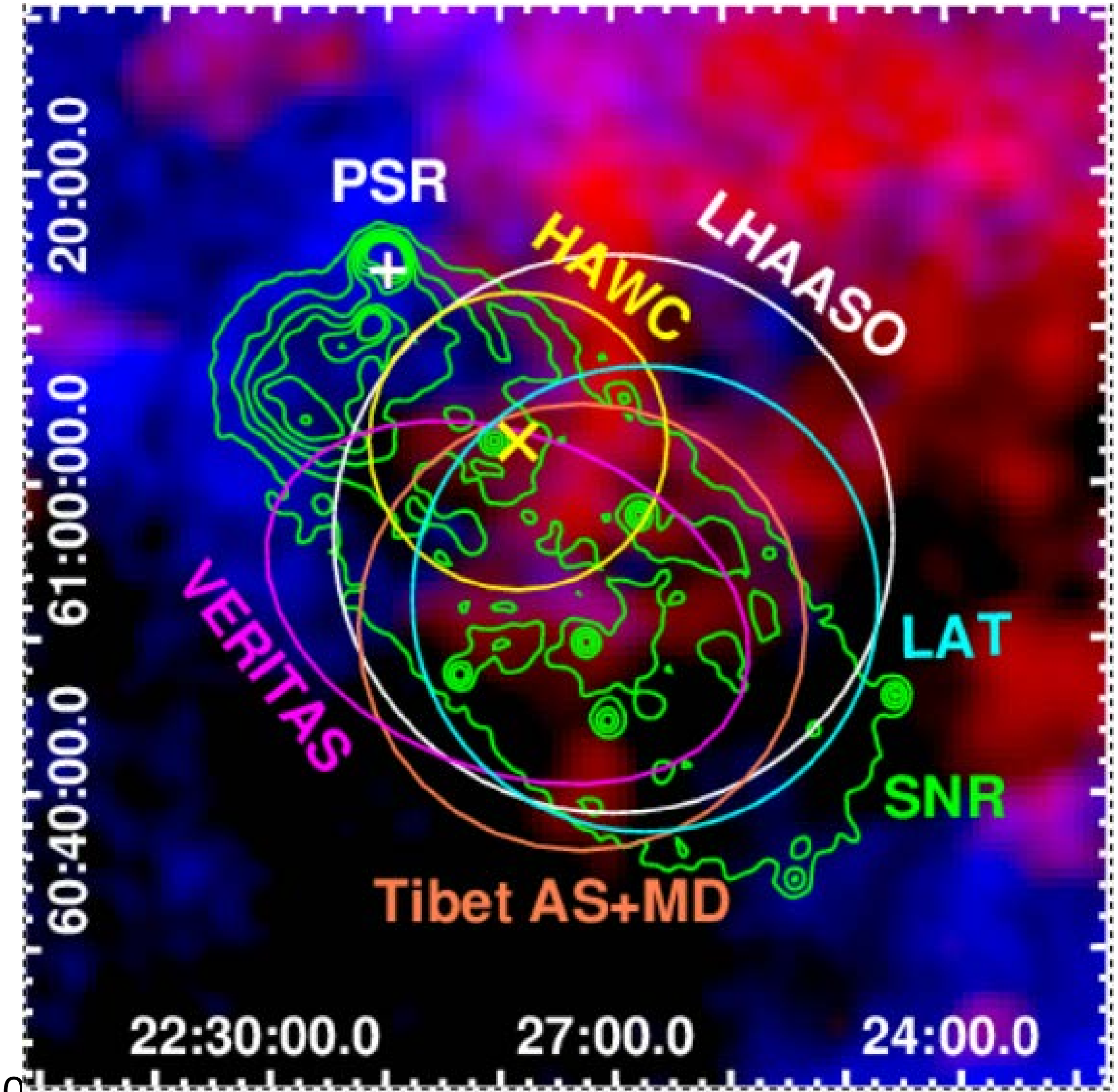
“We estimate that our emission centroid deviates from the pulsar location at a confidence level of 3.1σ”

Also seen by MILAGRO

Blue: Atomic (HI) Cloud
Red: Molecular Cloud

Head: Interacting with HI Cloud
Tail: Expanding into a Cavity

Gamma-ray coincident with the molecular cloud



Fermi-LAT 3-500GeV (Xin et al. 2019)

HAWC 1-100TeV (HAWC Collaboration 2020)

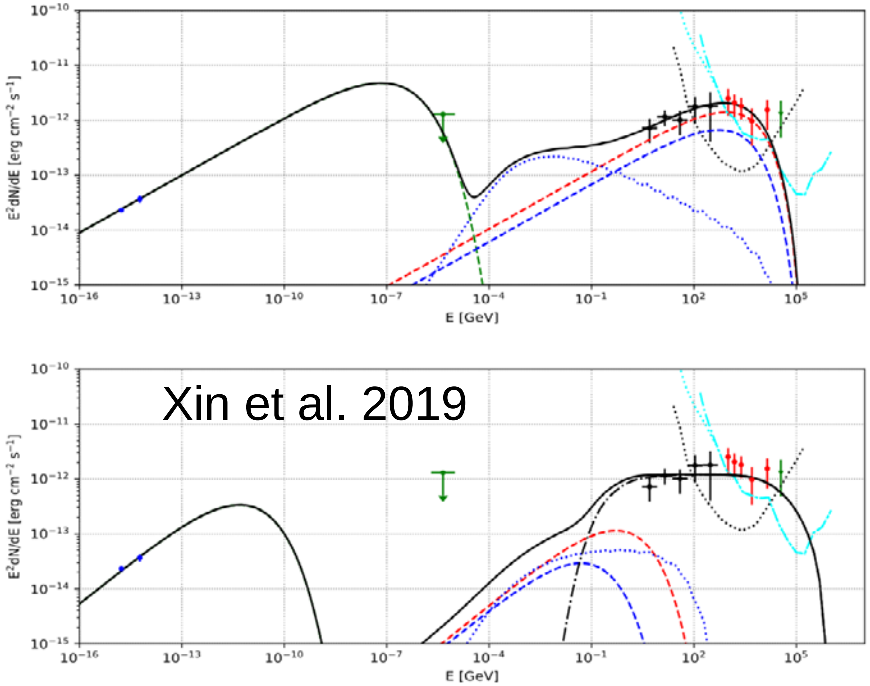
VERITAS 1-10TeV (VERITAS Collaboration 2009)

Tibet AS+MD, 10-100TeV (As γ Collaboration 2021)

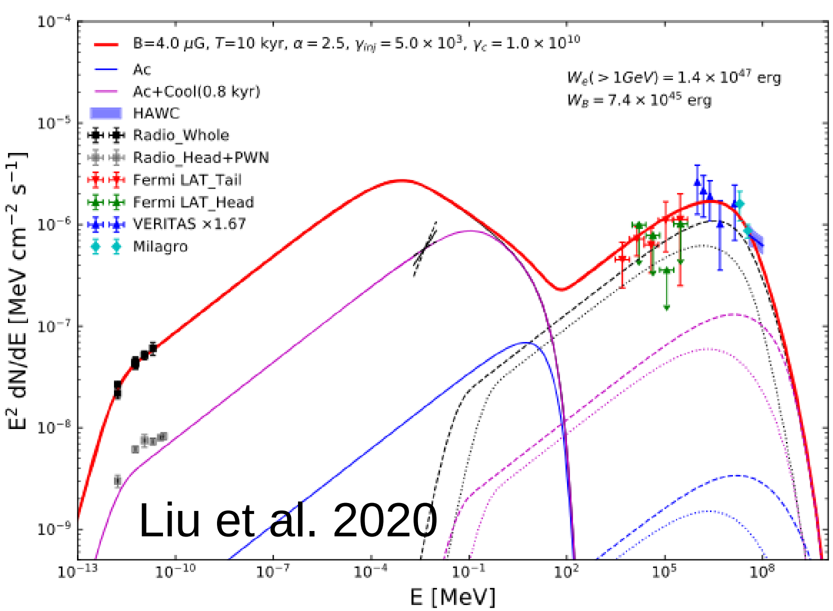
LHAASO, >100TeV (LHAASO Collaboration 2021)

Ge, **RYL,** Niu, Chen & Wang 2021, *The Innovation*, 2, 100118

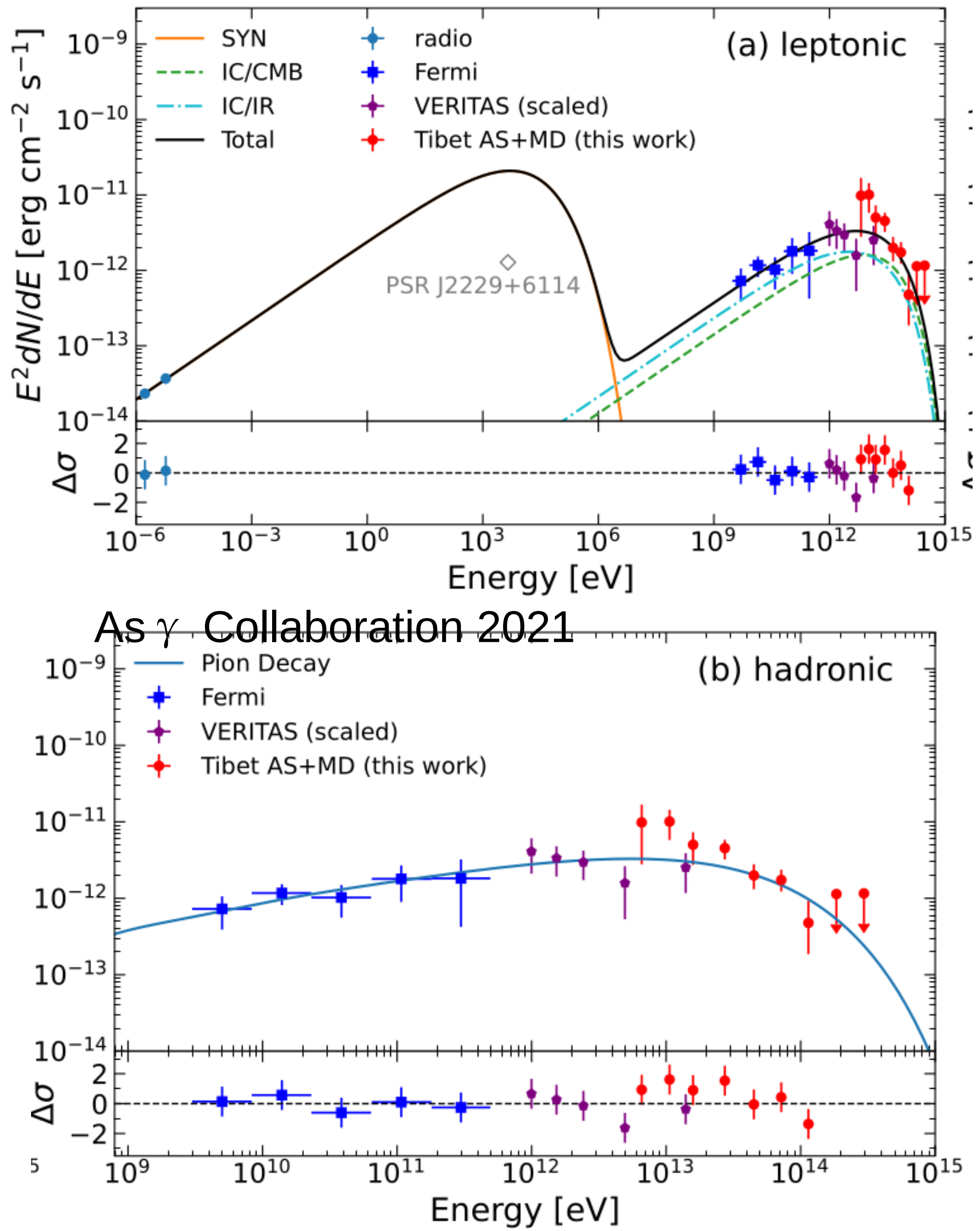
Both leptonic and hadronic scenario work



Xin et al. 2019

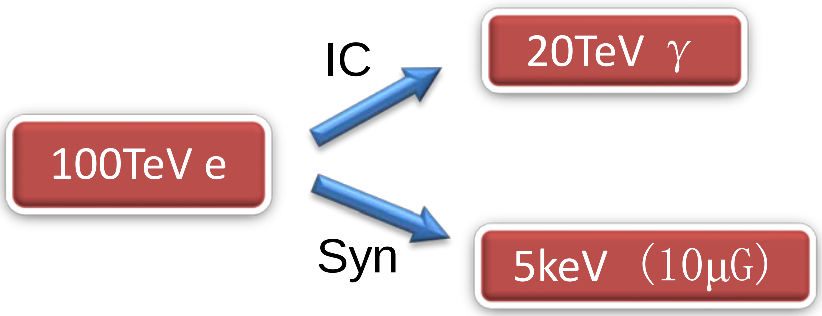


Liu et al. 2020



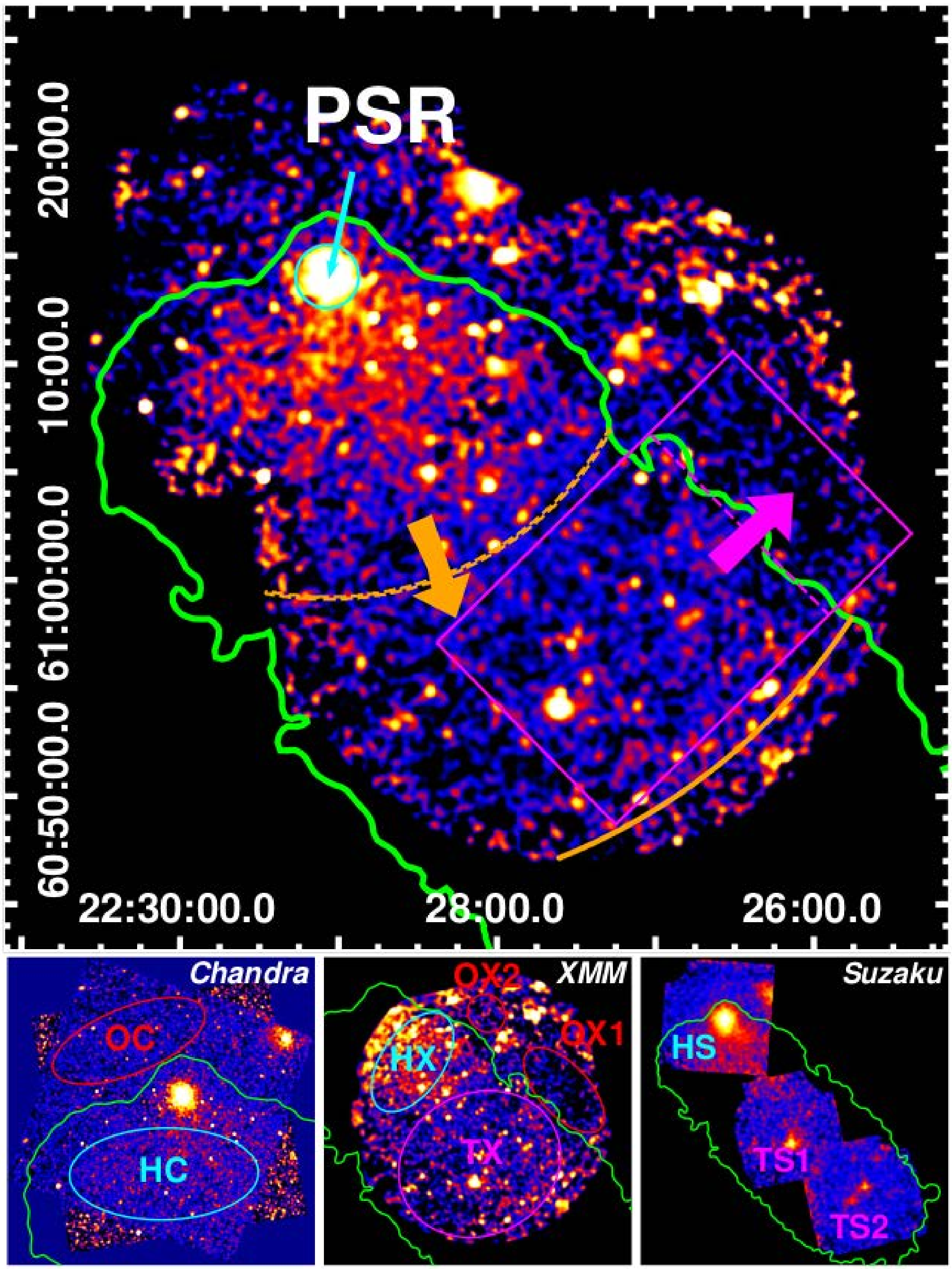
Asγ Collaboration 2021

X-ray observation is helpful!



Better angular resolution & more statistics

Nonthermal X-ray emission from SNR G106.3+2.7-Boomerang complex



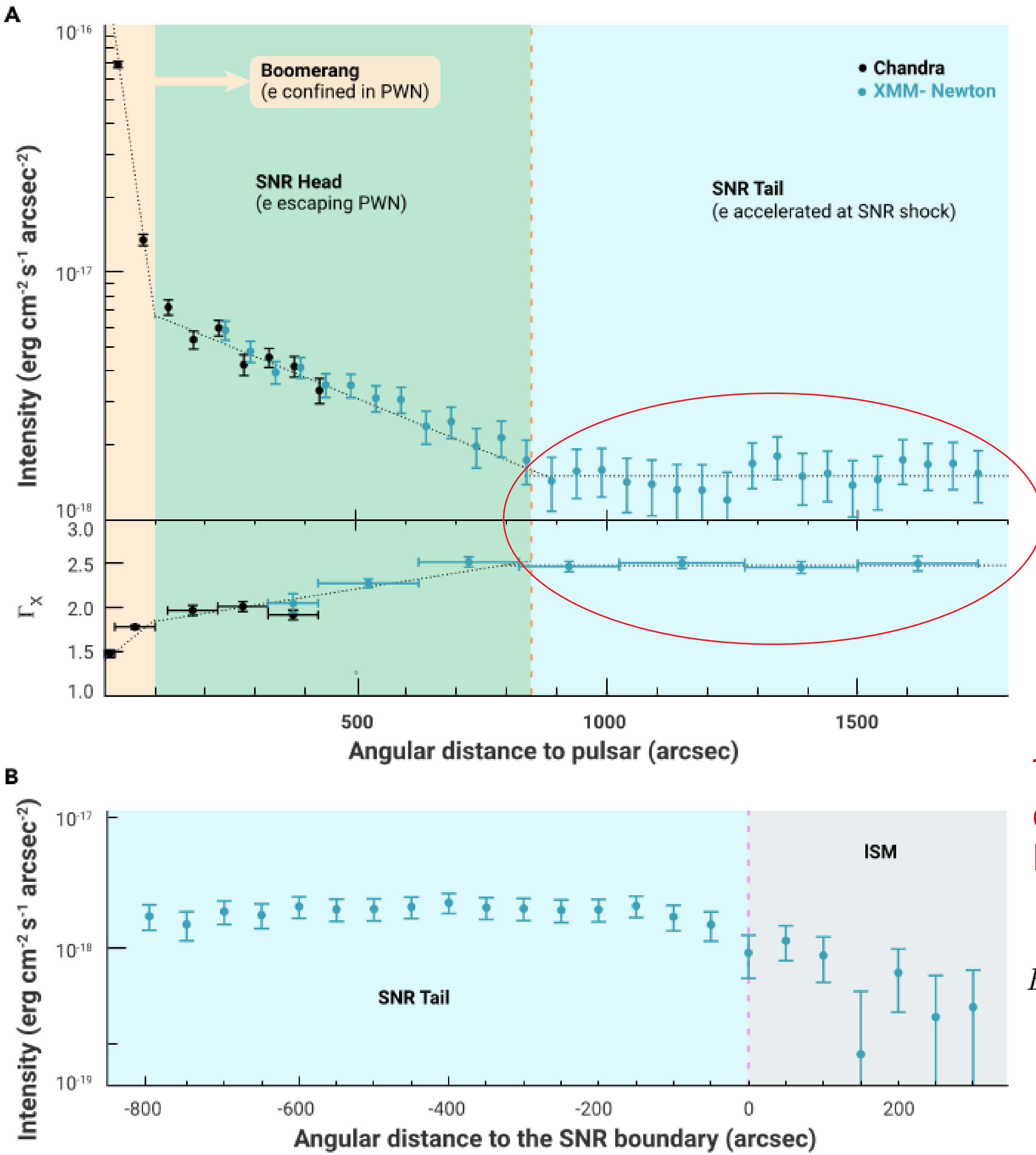
Reg[a]	PL index	Intensity[b] (erg cm^{-2} s^{-1} arcmin^{-2})	χ^2/DOF
PWN	1.7 ± 0.1	$(1.1 \pm 0.1) \times 10^{-13}$	307.6/303
HC	1.9 ± 0.1	$(1.3 \pm 0.1) \times 10^{-14}$	734.9/606
HX	2.2 ± 0.1	$(1.3 \pm 0.1) \times 10^{-14}$	230.7/192
HS	2.0 ± 0.1	$(1.2 \pm 0.1) \times 10^{-14}$	207.6/240
TX	2.4 ± 0.1	$(5.4 \pm 0.5) \times 10^{-15}$	1122.0/892
TS1	2.0 ± 0.1	$(7.2 \pm 0.4) \times 10^{-15}$	98.8/113
TS2	2.0 ± 0.1	$(5.7 \pm 0.3) \times 10^{-15}$	181.5/166
OC	2.6 ± 0.5	$(1.3 \pm 0.9) \times 10^{-15}$	399.6/364
OX1	4.5 ± 0.7	$(1.0 \pm 0.8) \times 10^{-15}$	224.6/185
OX2	5.8 ± 1.2	$(1.9 \pm 1.8) \times 10^{-15}$	156.9/134
BKG	-	$(5.6 \pm 1.0) \times 10^{-15}$	-

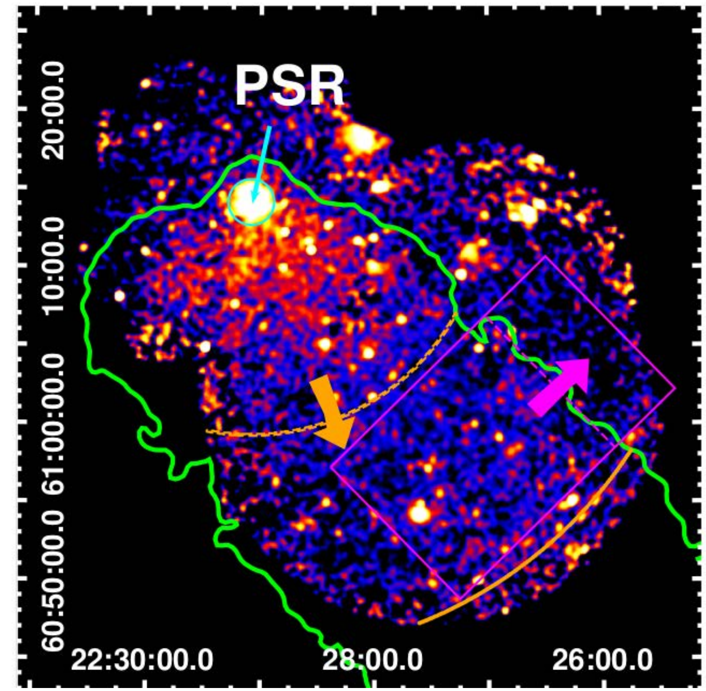
H for Head (excluding Boomerang)
T for Tail
O for Outside

Significant contrast of X-ray surface brightness inside and outside the SNR

Ge, **RYL,** Niu, Chen & Wang 2021,
The Innovation, 2, 100118

See also Fujita et al. 2021 for analysis of Suzaku data

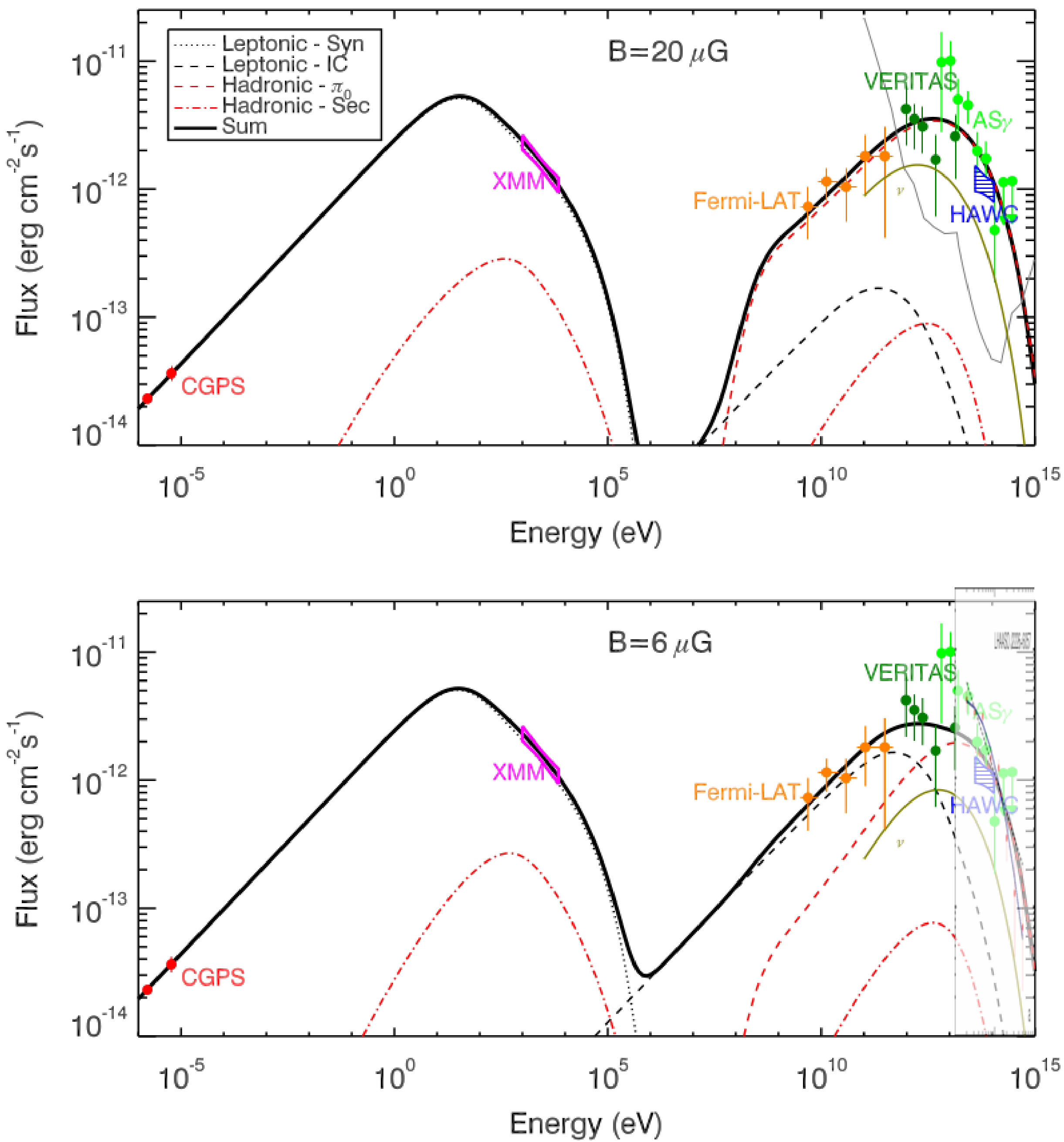




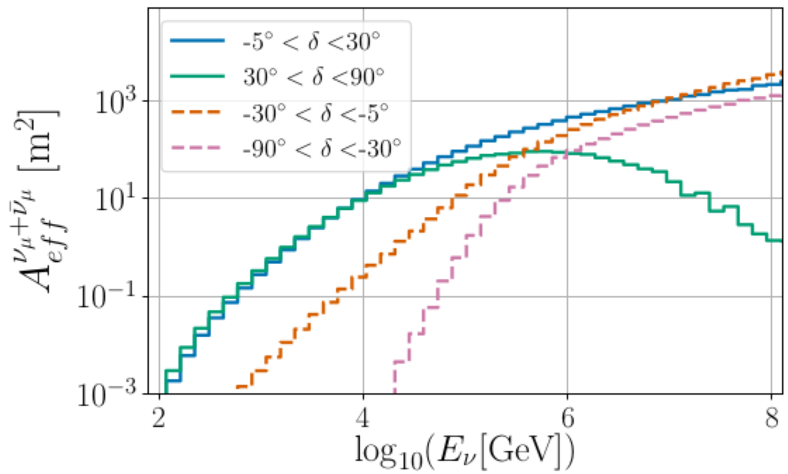
$$\epsilon_{\rm syn,max} \approx 7\eta(v_s/3000{\rm km\ s^{-1}})^2\,{\rm keV}$$

The inferred high shock velocity empowers the shock to accelerate PeV protons!

$$E_{p,\rm max} \approx 3\left(\frac{T_{\rm age}}{10\,{\rm kyr}}\right)\left(\frac{B}{10\mu{\rm G}}\right)\left(\frac{\epsilon_{\rm syn,max}}{7\,{\rm keV}}\right)\,{\rm PeV}$$



X-ray spectrum constrains IC contribution to gamma rays above 10TeV



0.4 track-like events above 50 TeV for the 10-year operation of the IceCube

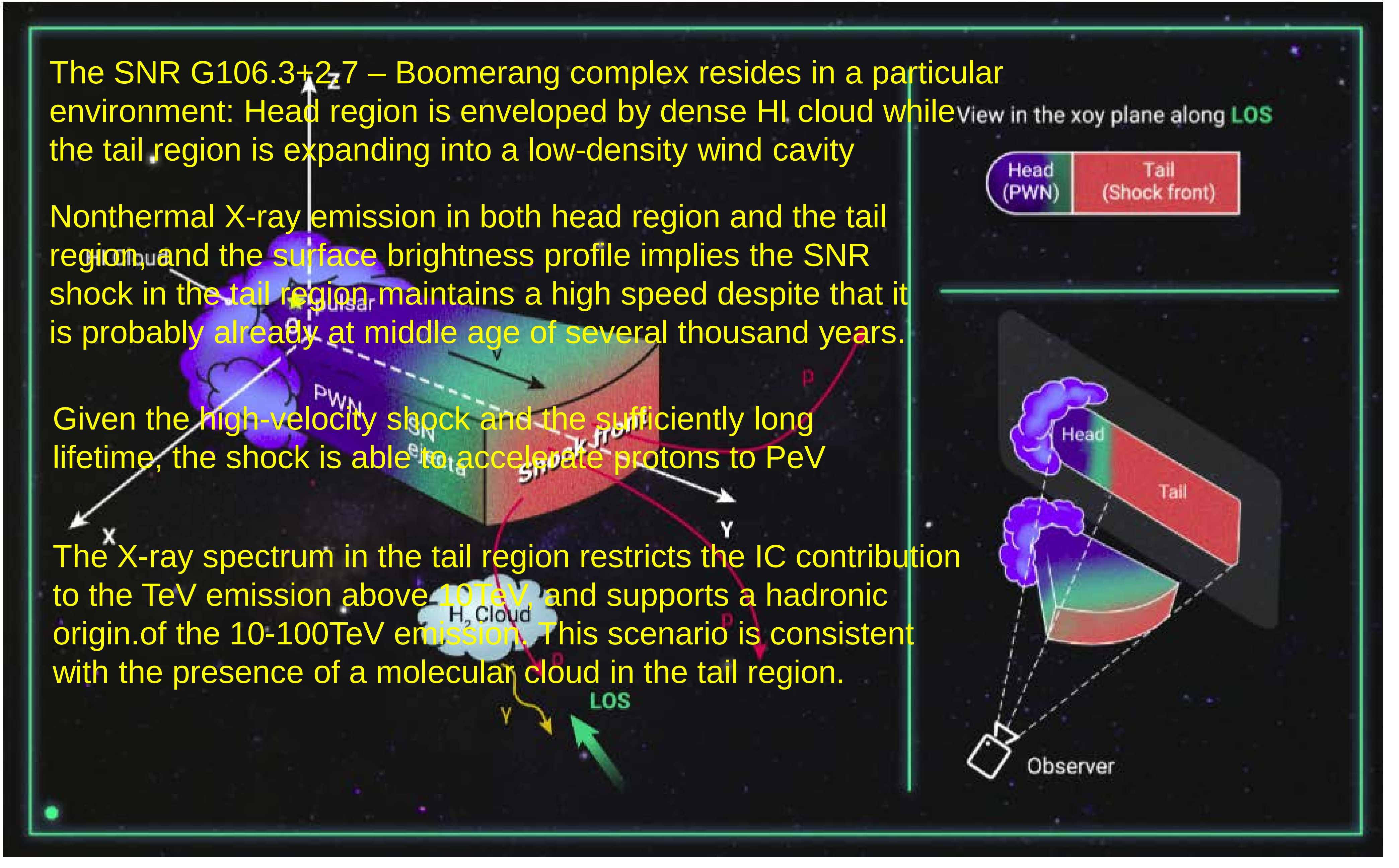
Summary

The SNR G106.3+2.7 – Boomerang complex resides in a particular environment: Head region is enveloped by dense HI cloud while the tail region is expanding into a low-density wind cavity

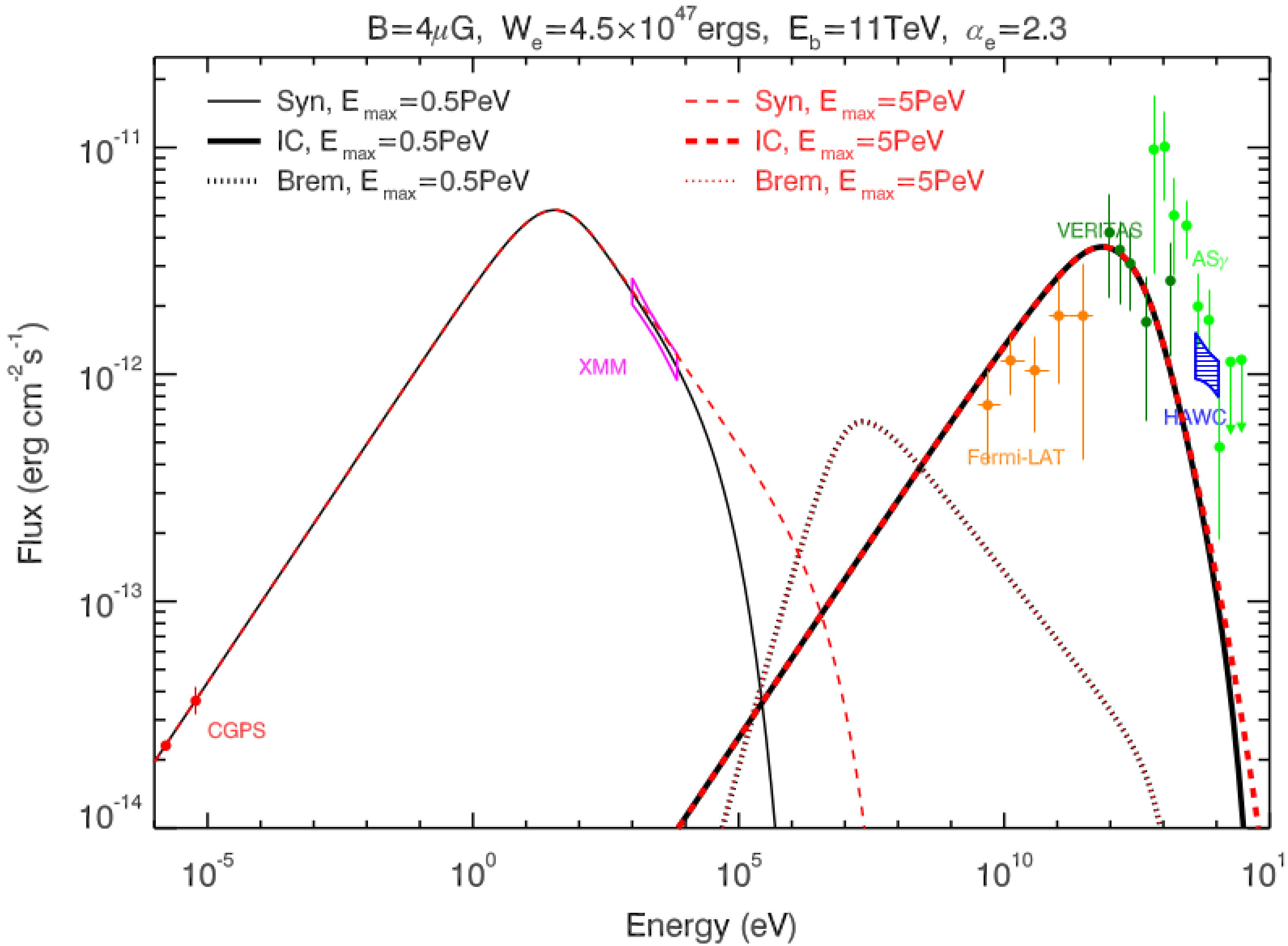
Nonthermal X-ray emission in both head region and the tail region, and the surface brightness profile implies the SNR shock in the tail region maintains a high speed despite that it is probably already at middle age of several thousand years.

Given the high-velocity shock and the sufficiently long lifetime, the shock is able to accelerate protons to PeV

The X-ray spectrum in the tail region restricts the IC contribution to the TeV emission above 10TeV, and supports a hadronic origin.of the 10-100TeV emission. This scenario is consistent with the presence of a molecular cloud in the tail region.

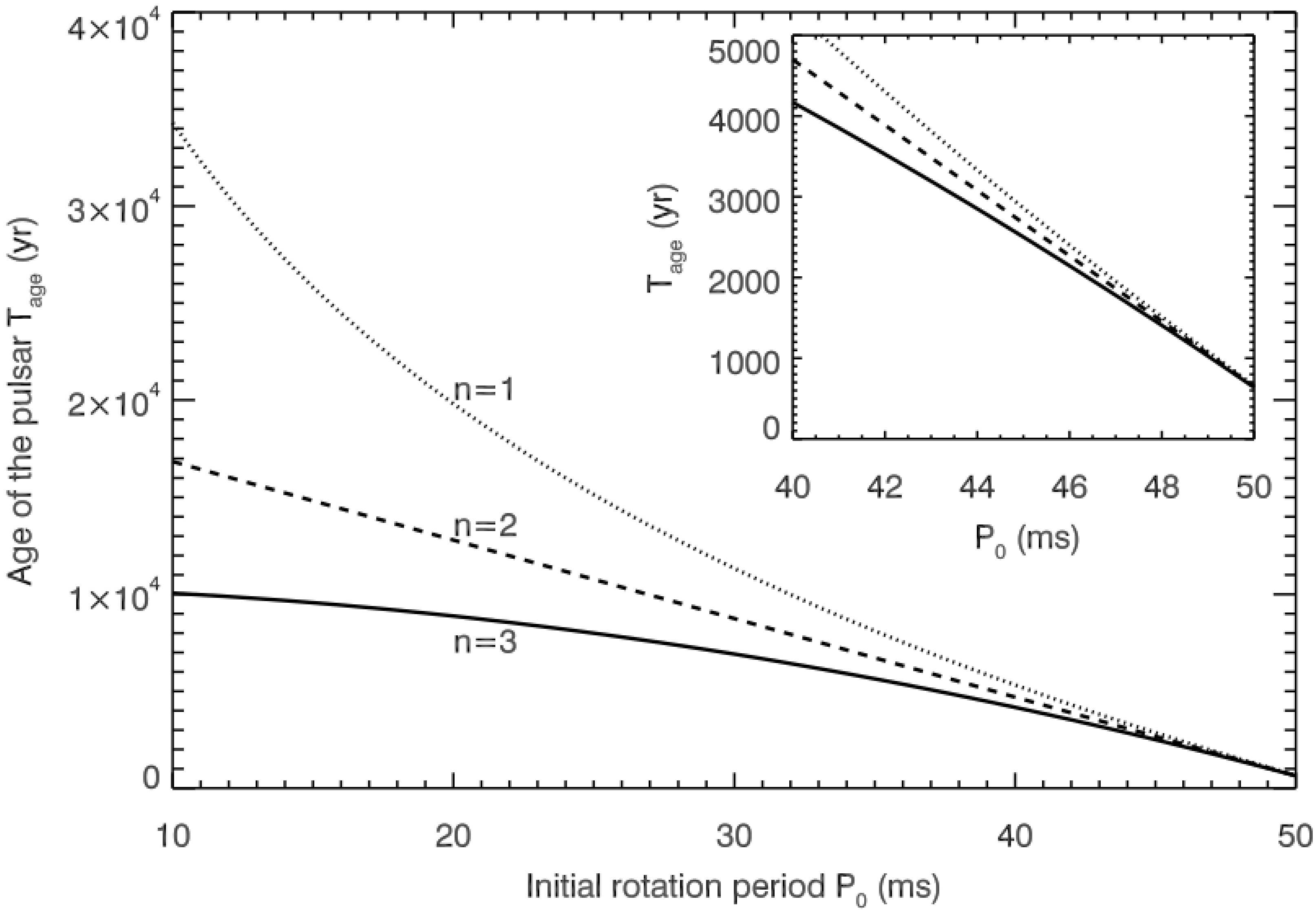


Back-up Slides

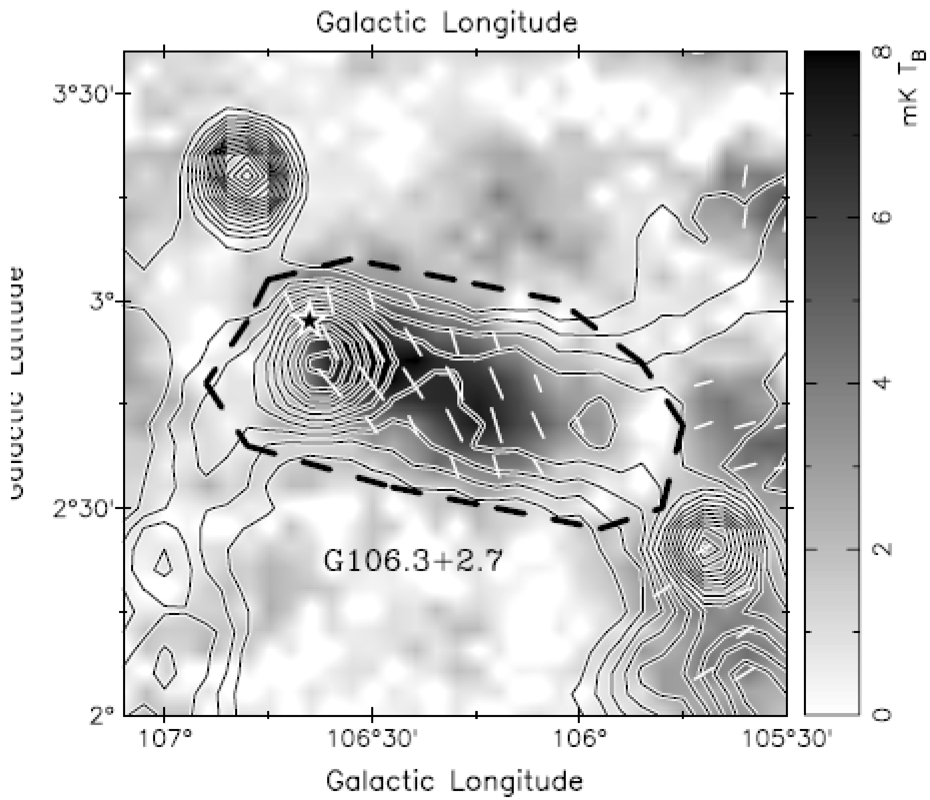


B=4μG, W_e=4.5×10^47 ergs, E_b=11TeV, α_e=2.3
Syn, E_max=0.5PeV
IC, E_max=0.5PeV
Brem, E_max=0.5PeV
Syn, E_max=5PeV
IC, E_max=5PeV
Brem, E_max=5PeV
VERITAS
ASγ
HAWC
Fermi-LAT
XMM
CGPS
Flux (erg cm^-2 s^-1)
Energy (eV)
10^-11
10^-12
10^-13
10^-14
10^-5
10^0
10^5
10^10
10^15

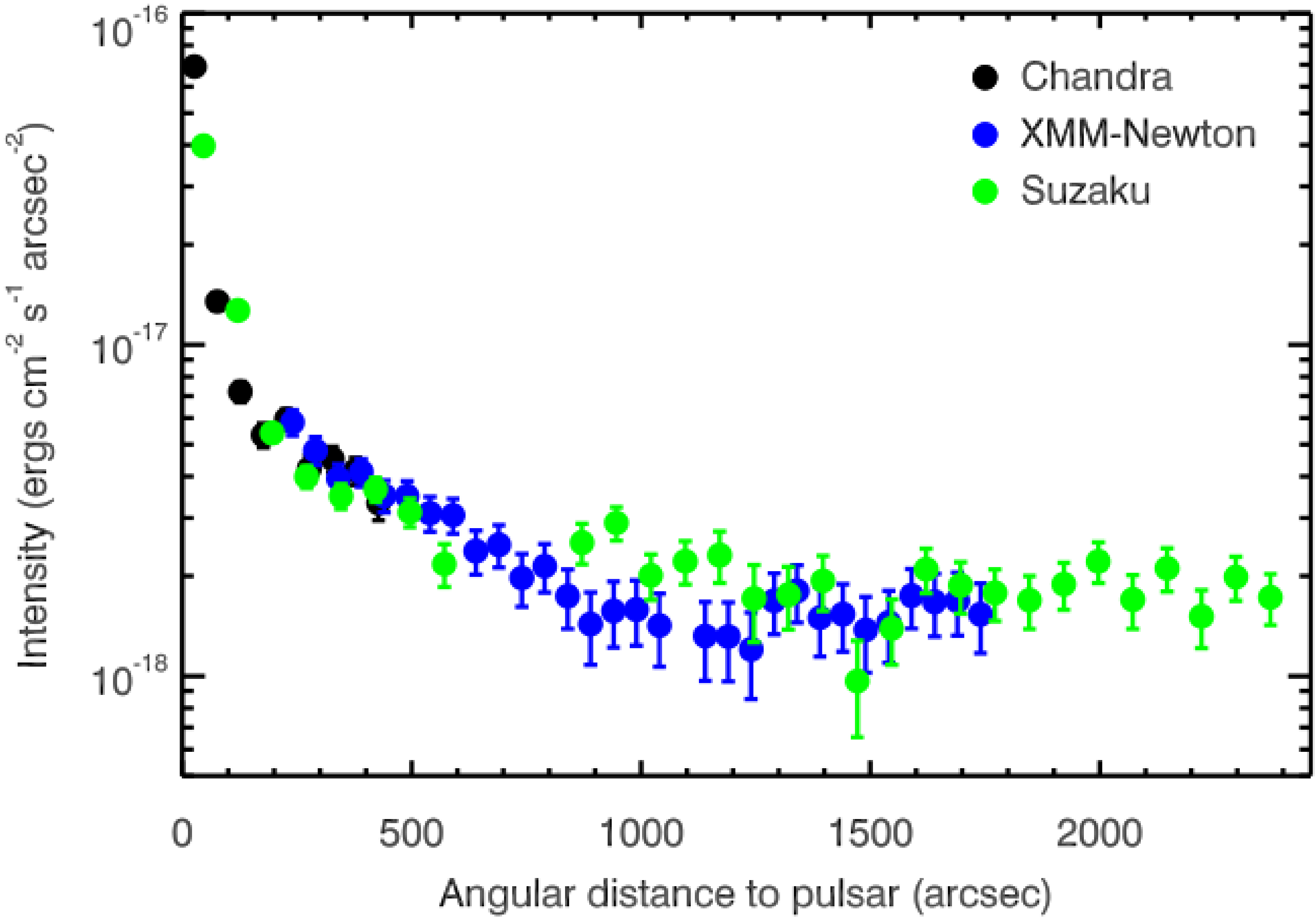
Age of the pulsar



Polarization



Gao et al. 2011



Chandra
XMM-Newton
Suzaku
10^{-16}
10^{-17}
10^{-18}
Intensity (ergs cm^{-2} s^{-1} arcsec^{-2})
0
500
1000
1500
2000
Angular distance to pulsar (arcsec)