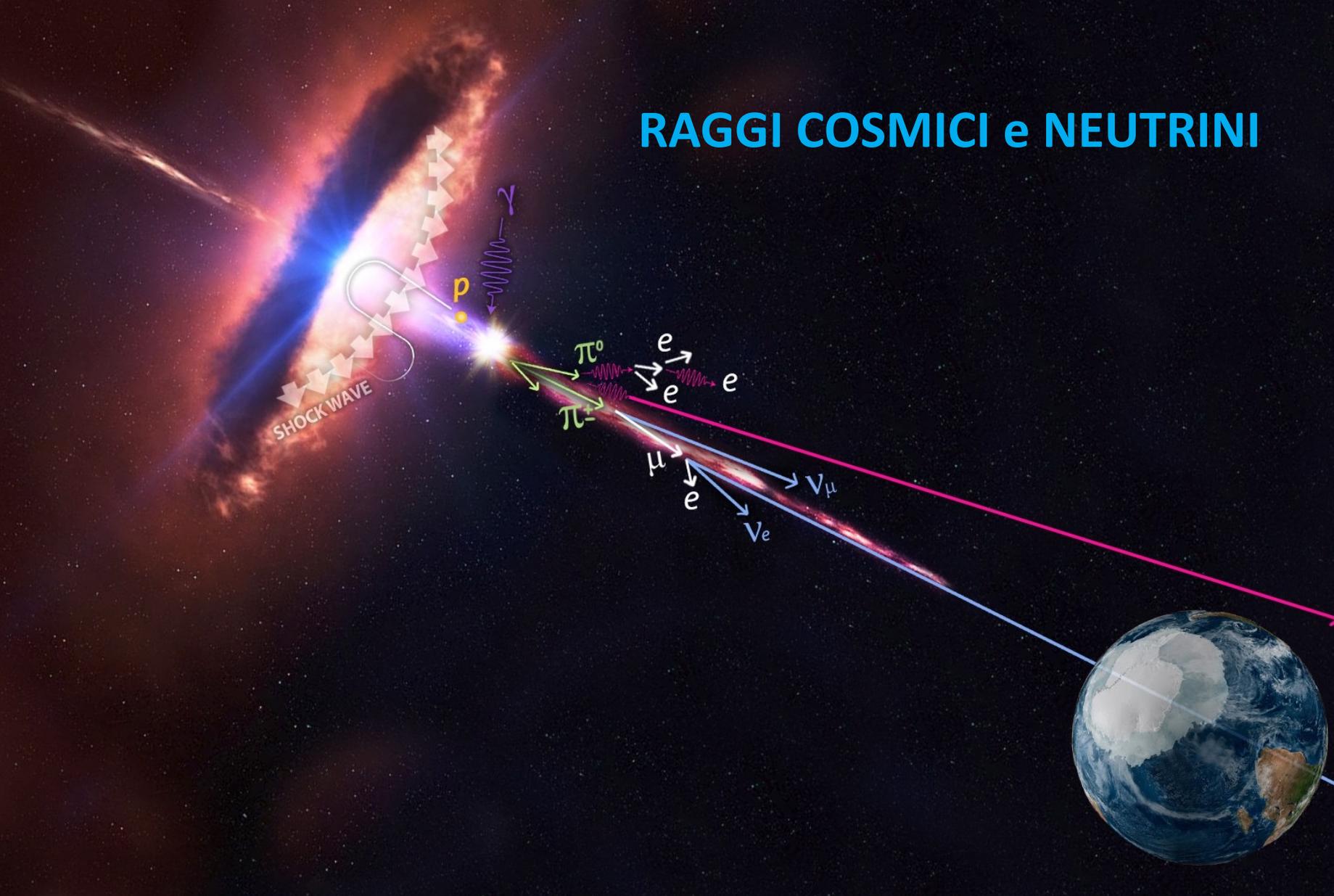
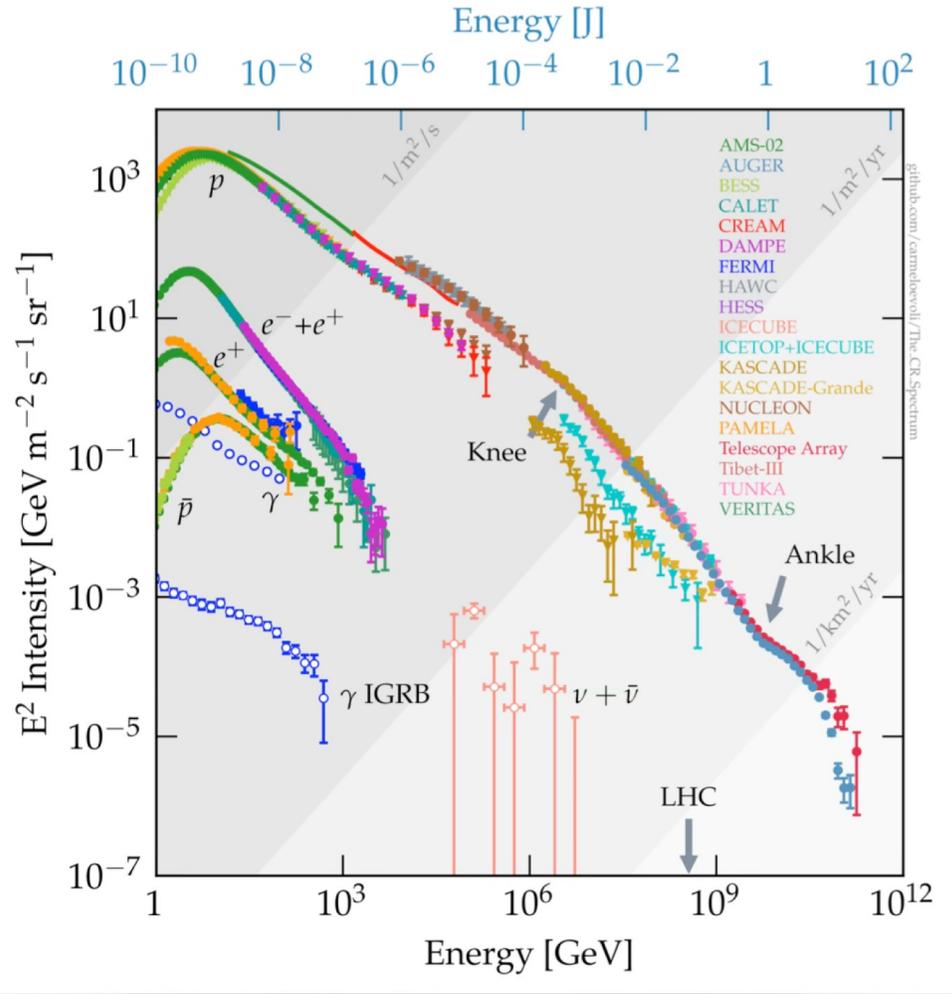


RAGGI COSMICI e NEUTRINI



ELENA AMATO
INAF-OAA

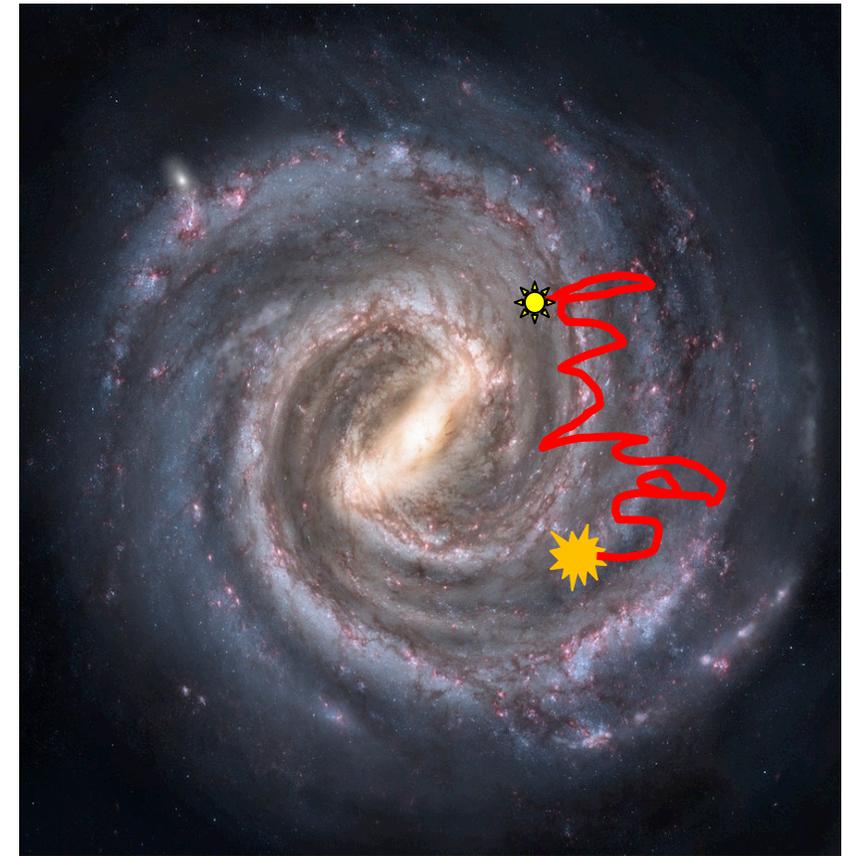
COSMIC RAYS



98% PROTONS AND NUCLEI
 87% PROTONS
 12% He
 1% HEAVIER NUCLEI

2% ELECTRONS

0.1% ANTIMATTER
 ($e^+ - e^- - \bar{p}$)

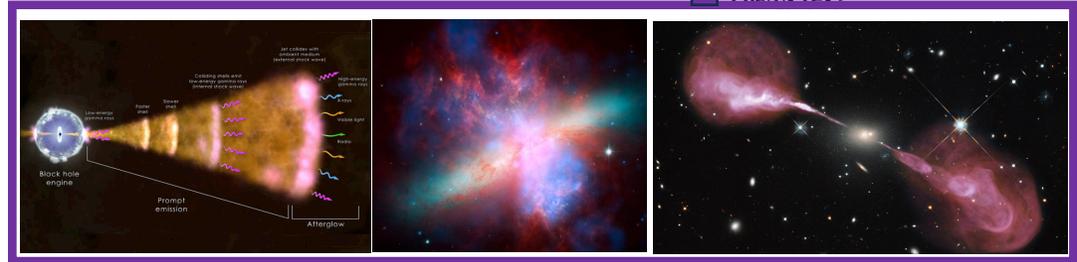
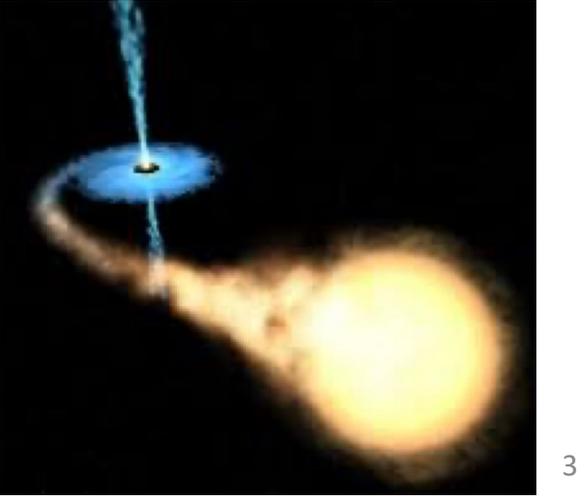
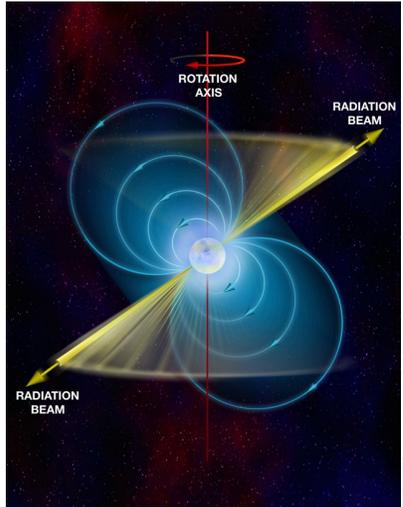
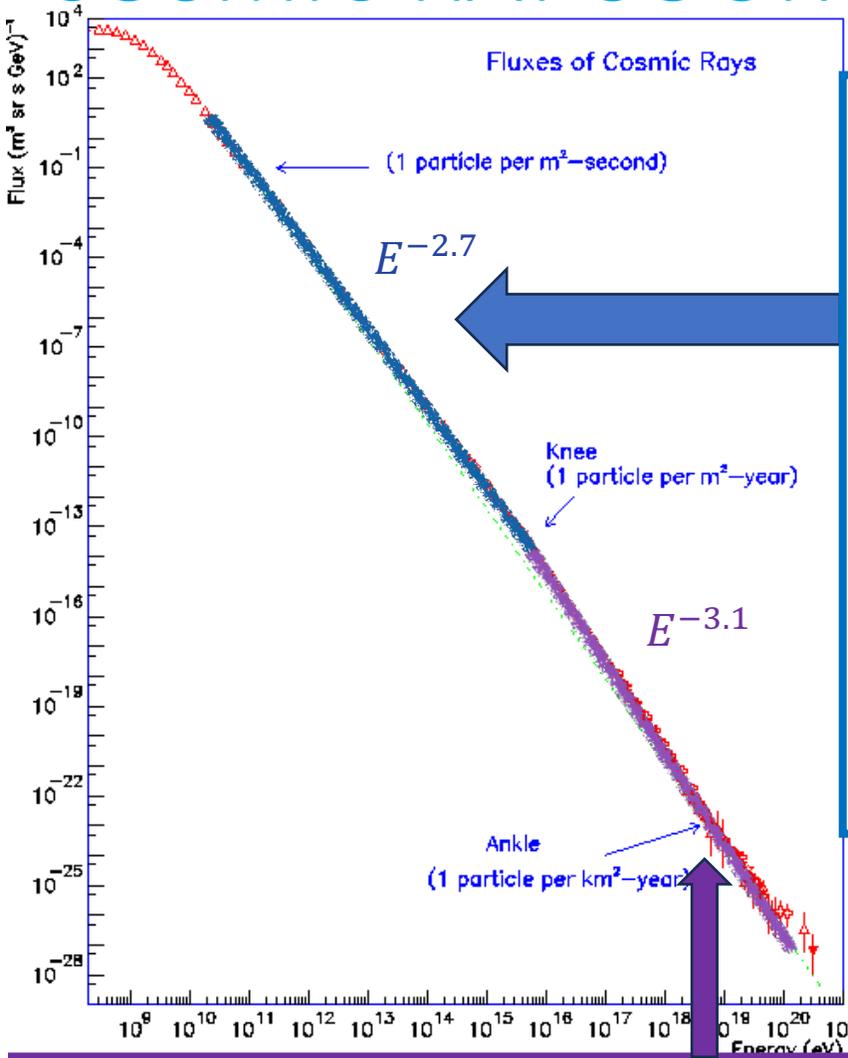


- SOURCE IDENTIFICATION MADE DIFFICULT BY DIFFUSION
- GAMMA-RAYS & NEUTRINOS MOST DIRECT PROBES

FUNDAMENTAL COMPONENT OF THE ISM
 ENERGY DENSITY:

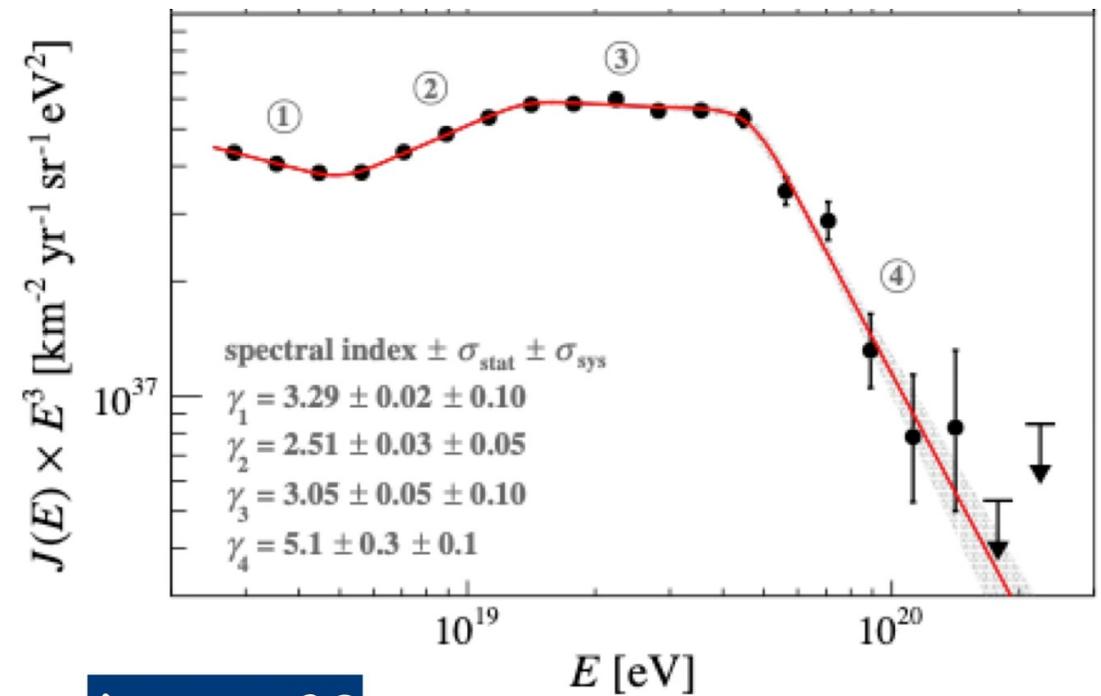
$$W_{CR} \approx W_{CMB} \approx U_B \approx U_{sl} \approx 0.5 \text{ eV}$$

COSMIC RAY SOURCES

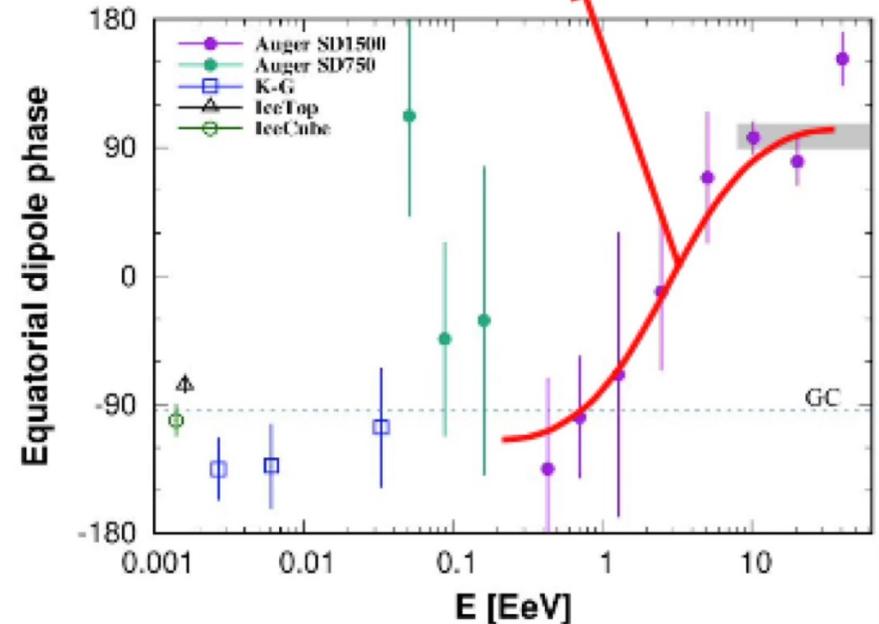


EXTRAGALACTIC COSMIC RAYS

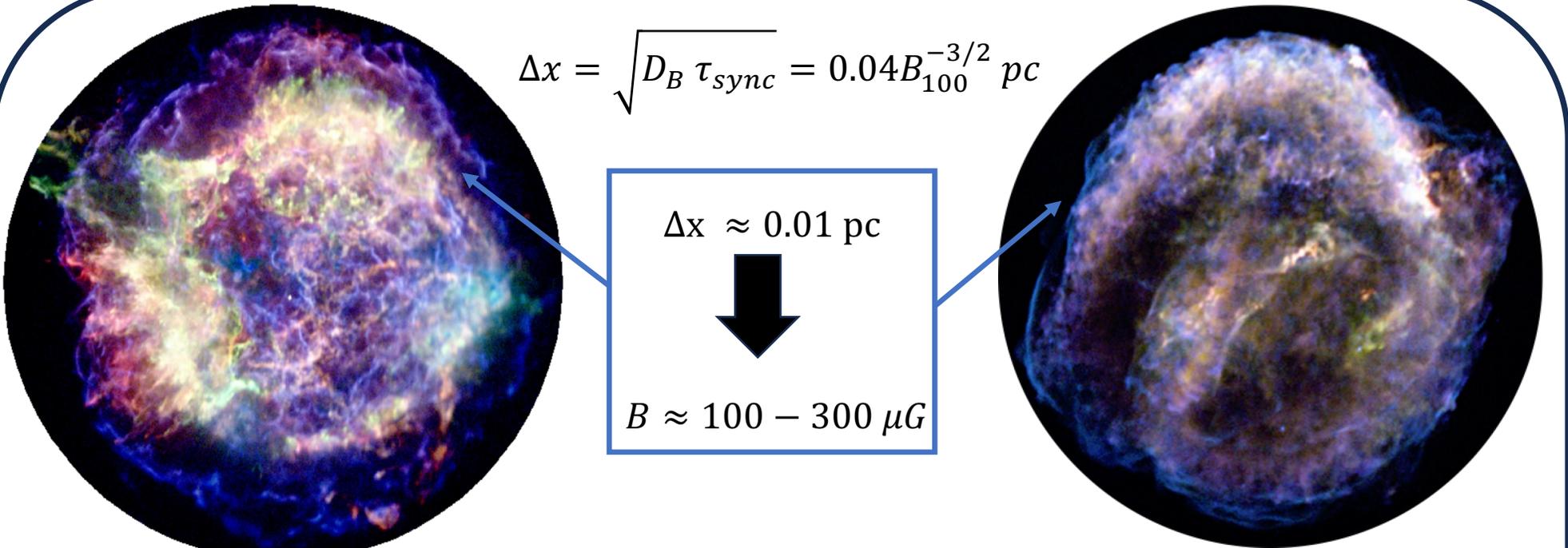
- MASS COMPOSITION: BECOMES HEAVIER ABOVE FEW $\times 10^{18}$ eV BUT NOT UP TO Fe
- EGAL DOMINANCE ABOVE FEW $FEW \times 10^{18}$ eV
- CORRELATIONS: AGN:2.7; AGN+SBG: 3.7; SBG: 4
- INFERENCE ON CLOSEST SOURCES: MANY UNKNOWNNS (IGM and ISM B!!)



Auger 20



THE SNR-CR CONNECTION



$E_e \approx 10 TeV \epsilon_{\gamma, keV} B_{100}^{-1/2}$
 $\epsilon_{\gamma} \approx keV$



[Vink 12, EA & Casanova 21 for review]

THE CHALLENGE OF PeV ENERGIES

ABSOLUTE LIMIT	IN NUMBERS
$E_{\max} = qE_{\text{el}}R = q \frac{v}{c} BR$	$E_{\max} = 100 \text{ PeV } (v/c) B_{-4} R_{\text{pc}}$

FOR PROTONS LOSSES IRRELEVANT

TIME LIMITED MAXIMUM ENERGY:

$$t_{\text{acc}}(E_{\max}) = \min[t_{\text{age}}, t_{\text{loss}}]$$

FOR DIFFUSIVE SHOCK ACCELERATION

$$t_{\text{acc}} = \frac{D}{v_s^2}$$

WHERE

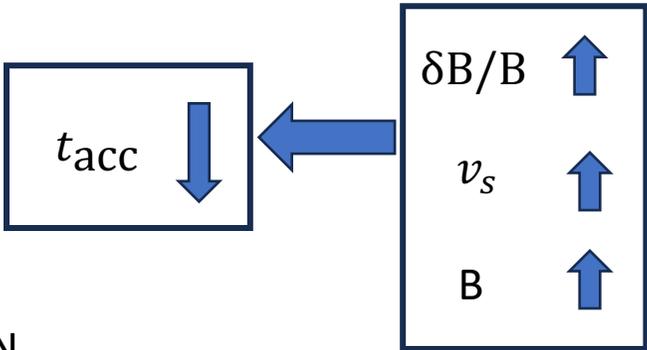
$$D(E) = \frac{cr_L}{(\delta B/B)_{r_L}^2} = \frac{D_B}{(\delta B/B)_{r_L}^2}$$

BEST CASE

$$t_{\text{acc}}(E) = \frac{\eta c E}{B v_s^2}$$

$$\eta = (B/\delta B)^2$$

MUST BE CLOSE TO 1 FOR EFFICIENT ACCELERATION



- **YOUNG SNRs** CAN ACCELERATE PROTONS TO THE **KNEE IF FIELDS ARE IN THE 100 μG RANGE**
- THE **KNEE** CAN BE REACHED IN PRINCIPLE **ALSO IN PULSARS, PULSAR WIND NEBULAE, STAR CLUSTERS AND MQs**

ELECTRONS TYPICALLY

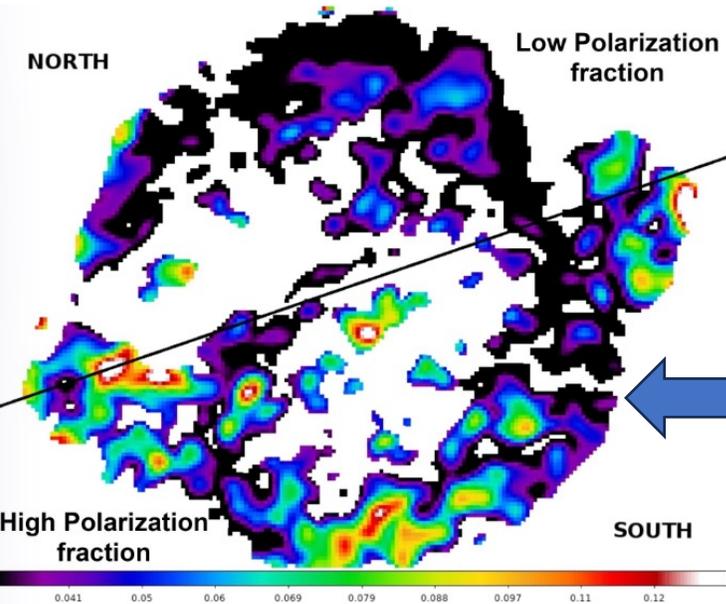
SYNCHROTRON LOSS-LIMITED

$$E_{\max} = 5 \text{ PeV } (v_s/c) \eta^{-1/2} B_{-4}^{-1/2}$$

$$v_{\max} = \frac{2.5}{\eta} \left(\frac{v_s}{5000 \text{ km/s}} \right)^2 \text{ keV}$$

X-RAY OBSERVATIONS OF SNRS: KEPLER

RADIO POLARIZATION



SNR INTERACTING WITH A CLOUD

$$\nu_{\max} = \frac{2.5}{\eta} \left(\frac{v_s}{5000 \text{ km/s}} \right)^2 \text{ keV}$$

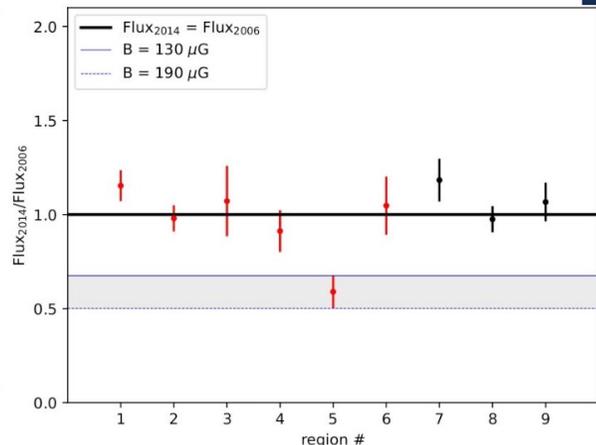
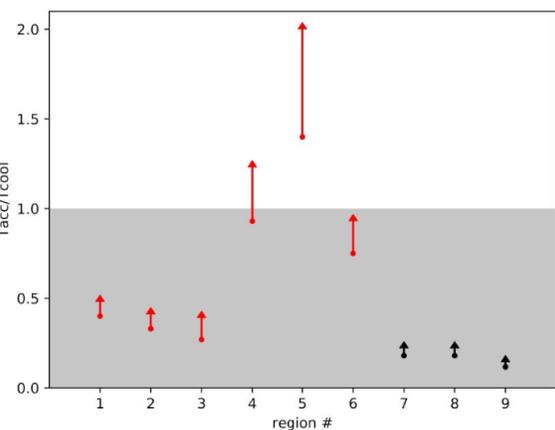
MAPPING $\nu_{\max}(v_s) \longrightarrow \delta B/B$

CONSISTENT WITH RADIO POLARIZATION

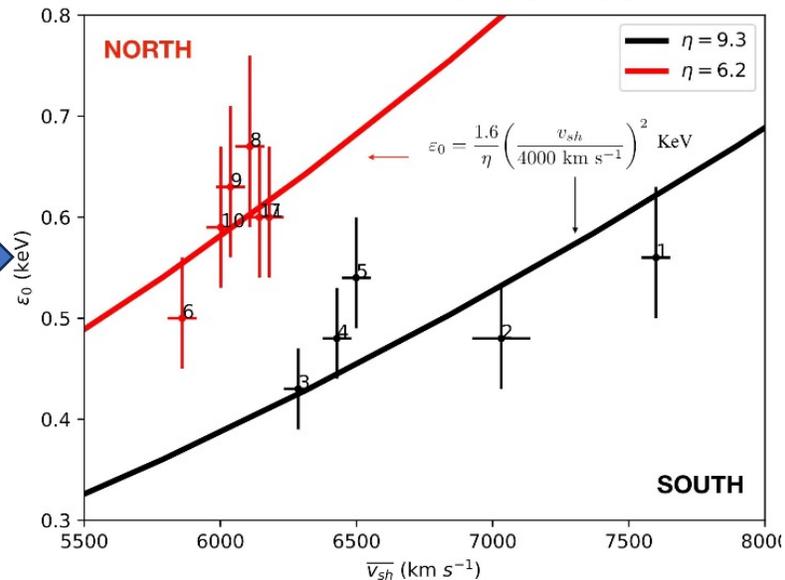
FLUX VARIATION WHERE $t_{\text{acc}} > t_{\text{loss}}$

HADRONIC GAMMA-RAYS

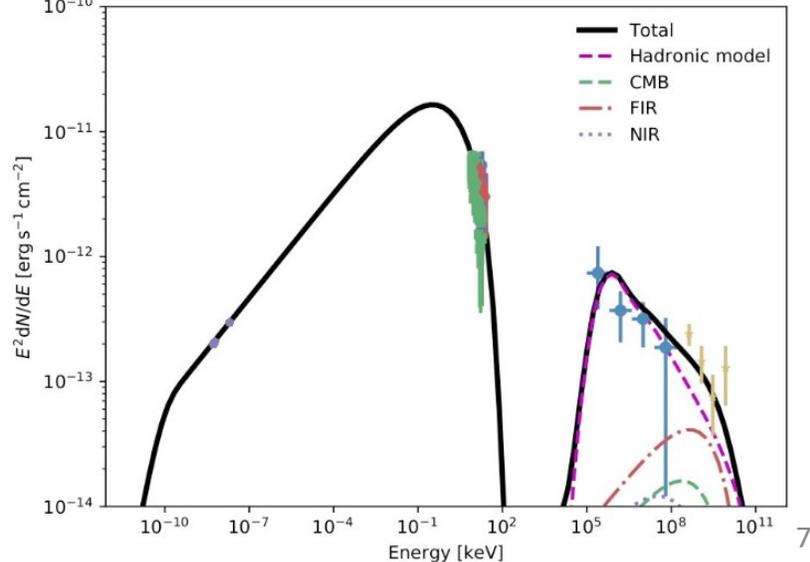
Chandra: TWO EPOCHS



XMM-NEWTON & NuSTAR



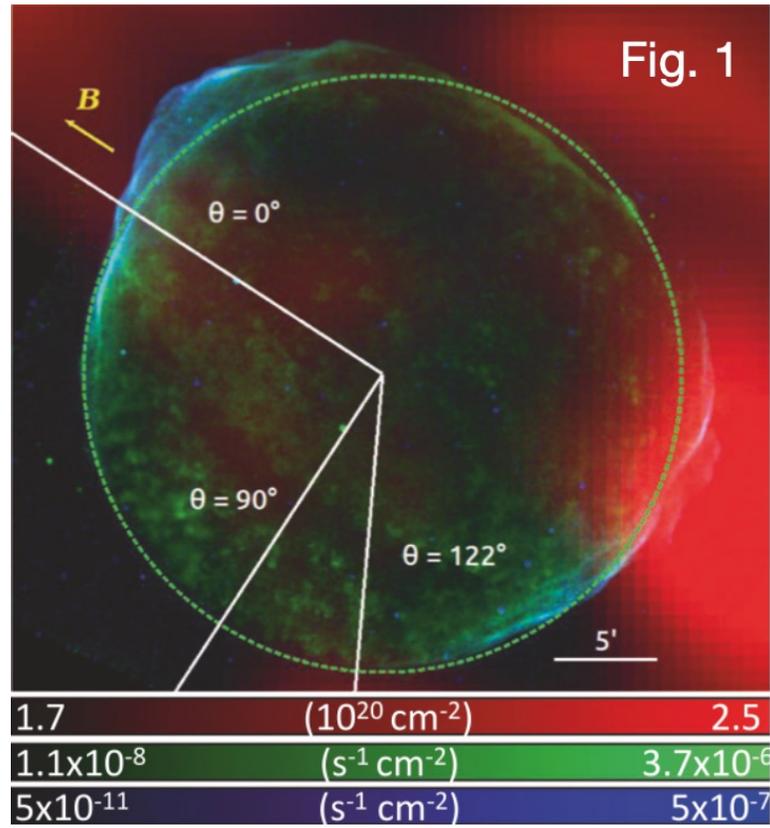
SPECTRAL ENERGY DIOSTRIBUTION



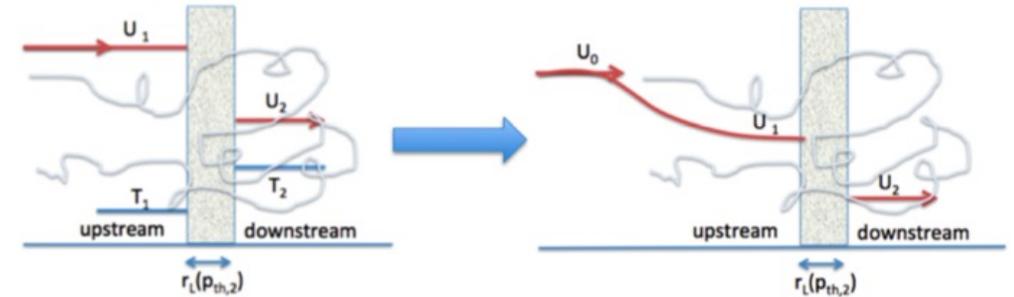
[Sapienza + 22, 24]

X-RAY OBSERVATIONS OF SNRs: SN 1006

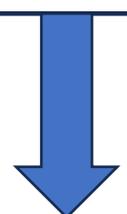
CLEAN ENVIRONMENT ALLOWS TESTS OF SHOCK GEOMETRY



INCREASED COMPRESSION RATIO EXPECTED FOR EFFICIENT DSA [e.g. EA & Blasi 05,06]

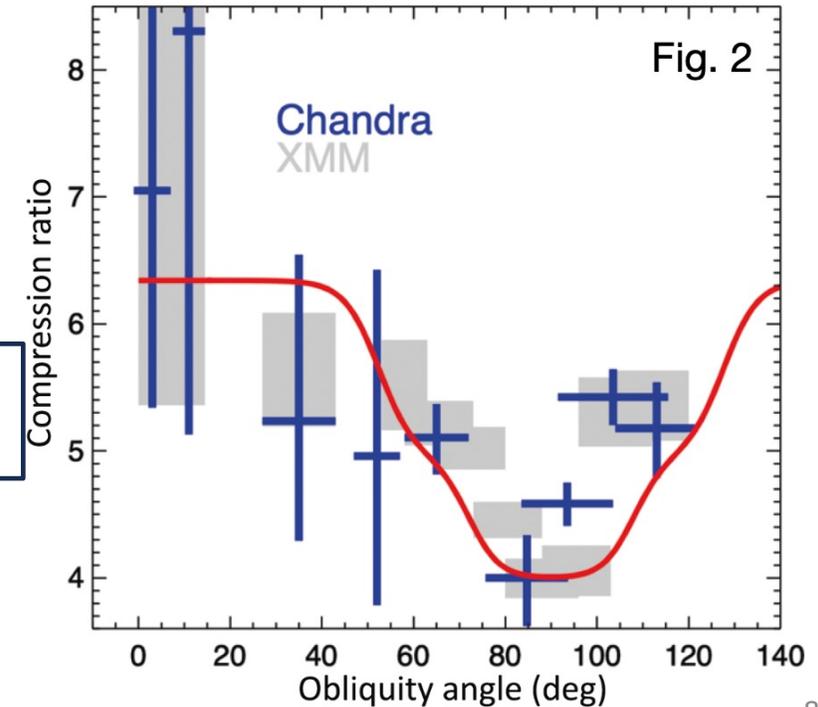


TRACING COMPRESSION RATIO ALONG SHOCK SURFACE



PARTICLE ACCELERATION MORE EFFICIENT WHERE SHOCK IS PARALLEL

CR ACCELERATION EFFICIENCY 12%



[Giuffrida+ 22]

X-RAY POLARIZATION OF SNRs

SN1006

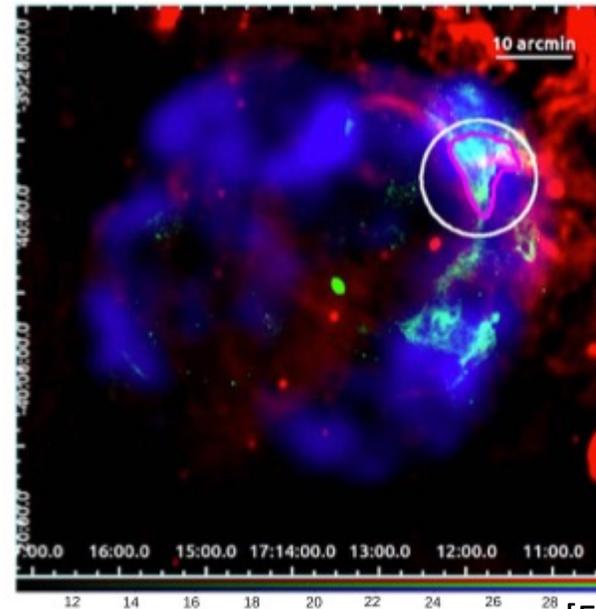
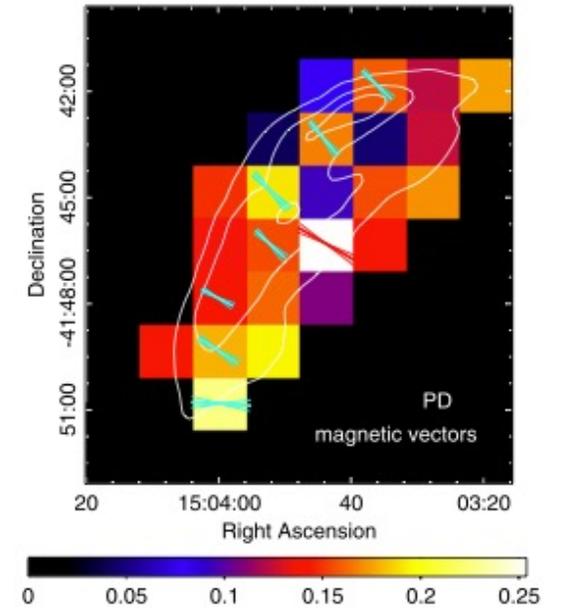
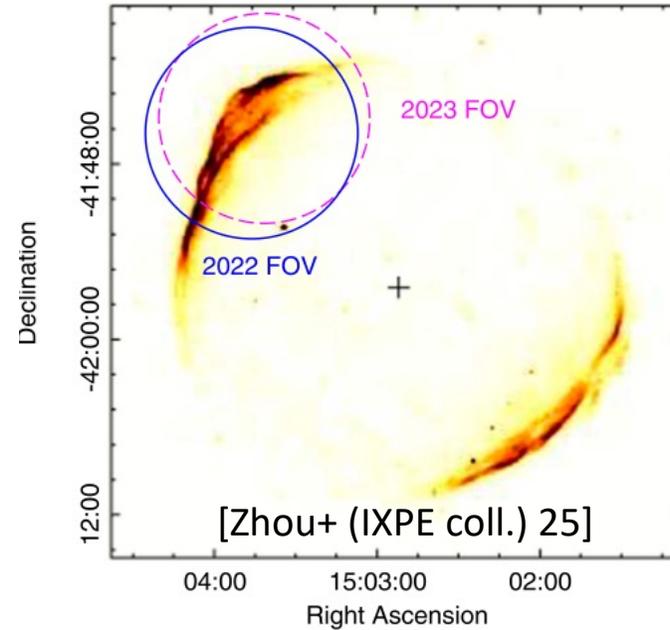
YOUNG SNRs IN CLEAN ENVIRONMENT
AND WITH HIGH SHOCK SPEED
(CAS A, TYCHO, SN1006)
RADIAL MAGNETIC FIELD



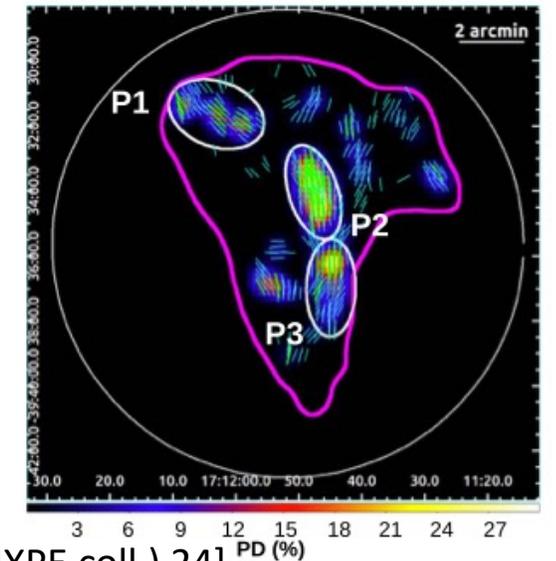
EFFICIENT PARTICLE ACCELERATION
AND
B-FIELD AMPLIFICATION
[Bykov+ 25]

SNrs INTERACTING WITH CLOUDS
AND WITH SLOWER SHOCKS
(RX J1713.3, VELA JR)
TANGENTIAL MAGNETIC FIELD

HOWEVER ONLY ELECTRONS PROBED DIRECTLY...



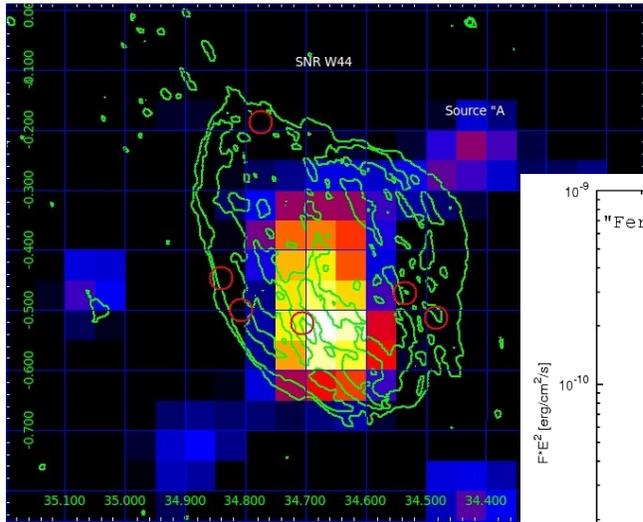
RX J1713.3



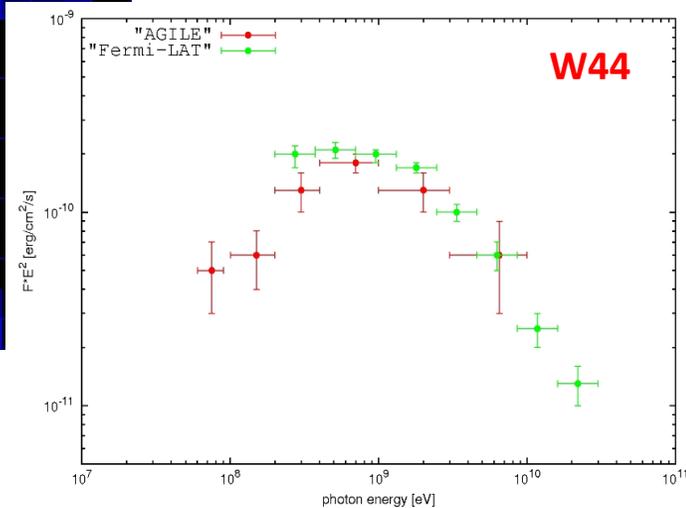
[Ferrazzoli+ (IXPE coll.) 24]

GAMMA-RAY OBSERVATIONS OF SNRs: W44

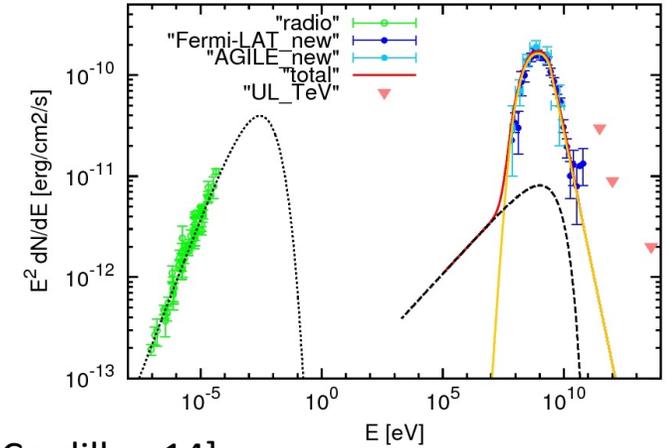
MIDDLE AGED SNRs ($t \sim 10^4$ yr), SLOW SHOCK ($v_s \sim 100$ km/s)
INTERACTING WITH MC ($n \sim 200$ cm $^{-3}$)



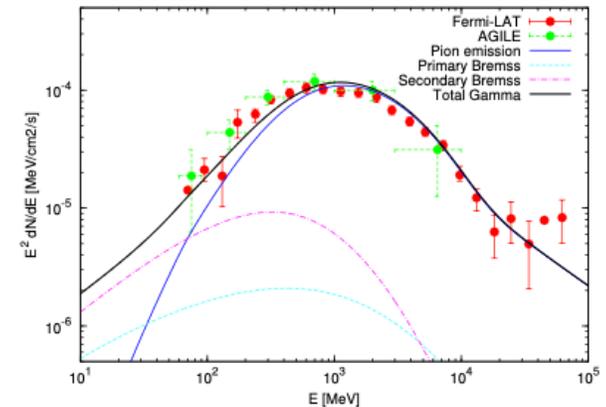
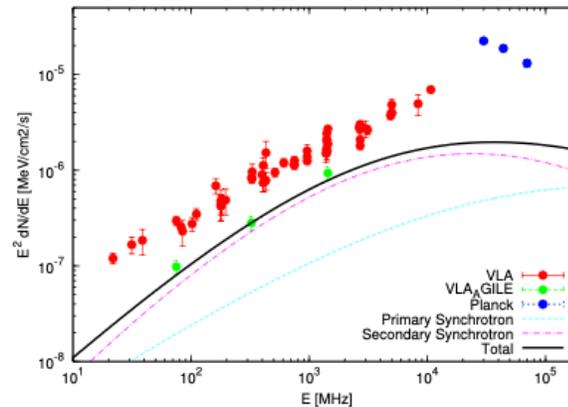
[Giuliani, Cardillo + 11]



CLEAR SIGNATURES OF
ACCELERATED HADRONS
DETECTED BY
Agile AND Fermi
[Giuliani+ 11, Ackermann + 13, Cardillo+ 14]



- BUT POSSIBLY MOSTLY RE-ACCELERATION
[Uchiyama+ 10, Lee + 15, Cardillo, EA, Blasi 16]
- ALTHOUGH SEE RECENT MAGIC RESULTS
[Abe+ 25]



MORE SNRs AND CLOUDS: Puppis A AND W51C

MIDDLE-AGED SLOW SNR INTERACTING WITH CLOUD IN THE EAST

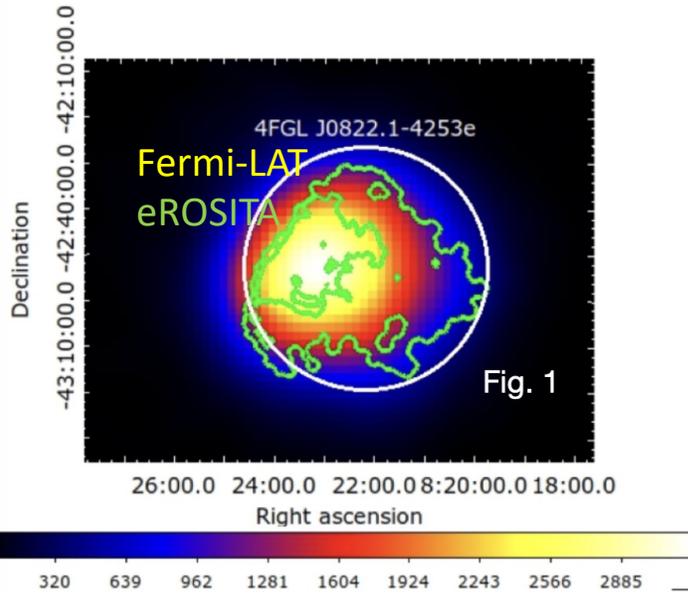


Fig. 1

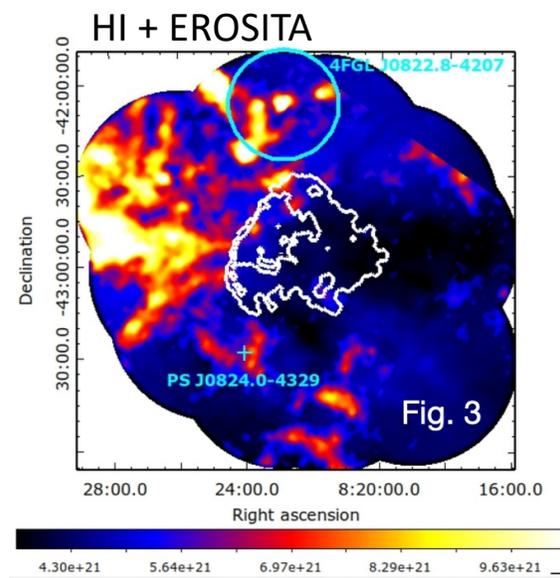


Fig. 3

PUPPIS A

[Giuffrida+ 25]

AGAIN MOSTLY REACCELERATION

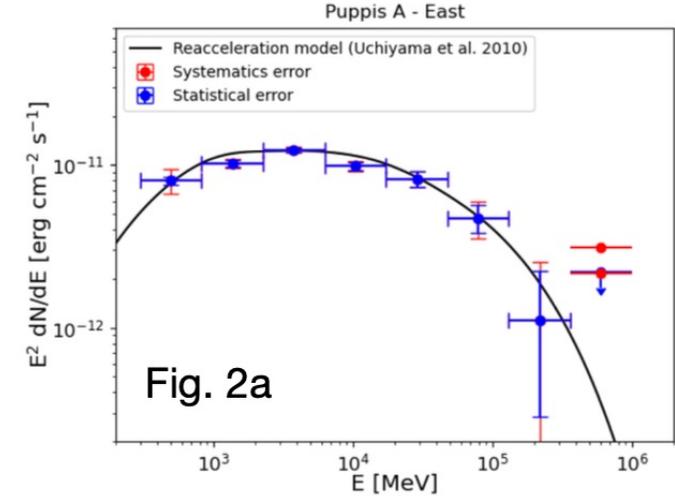


Fig. 2a

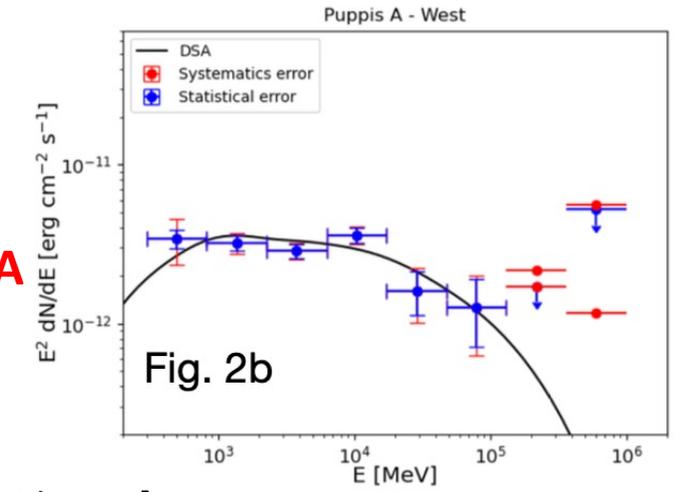
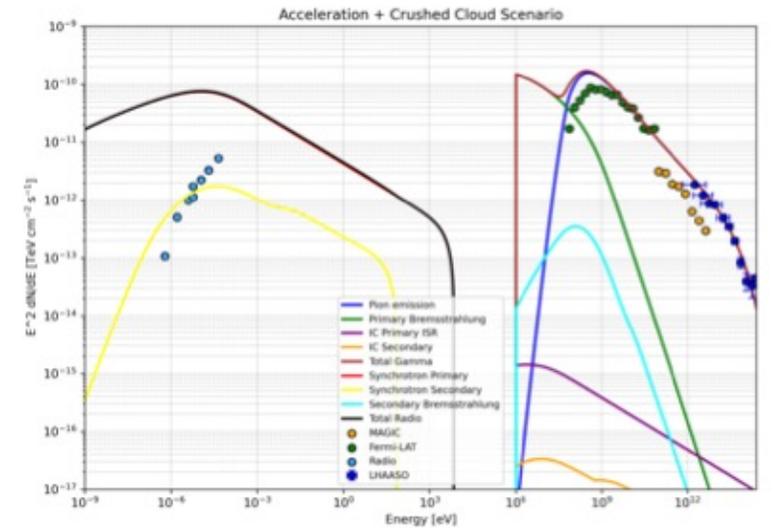
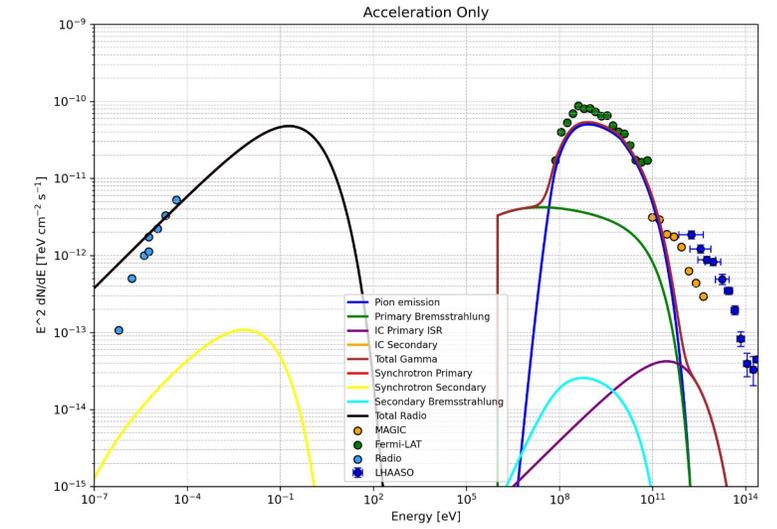


Fig. 2b

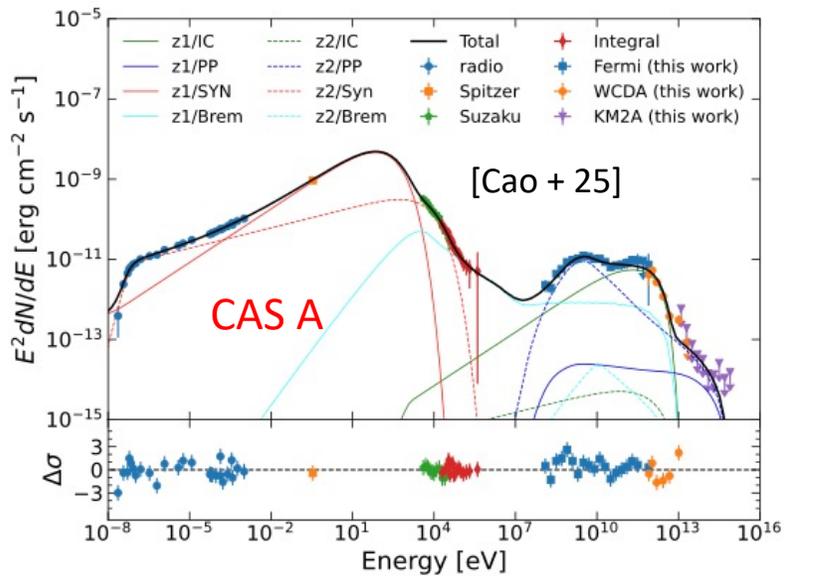
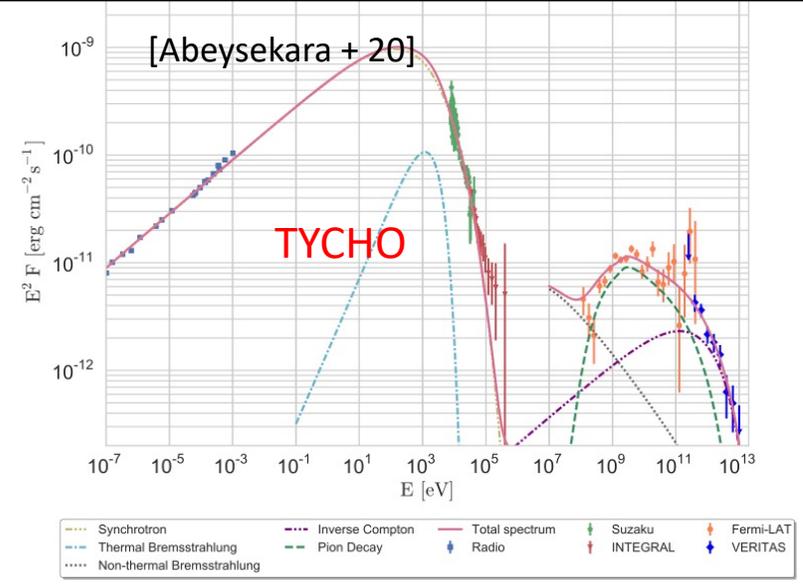
W51c



[Sunny, Cardillo + in prep]

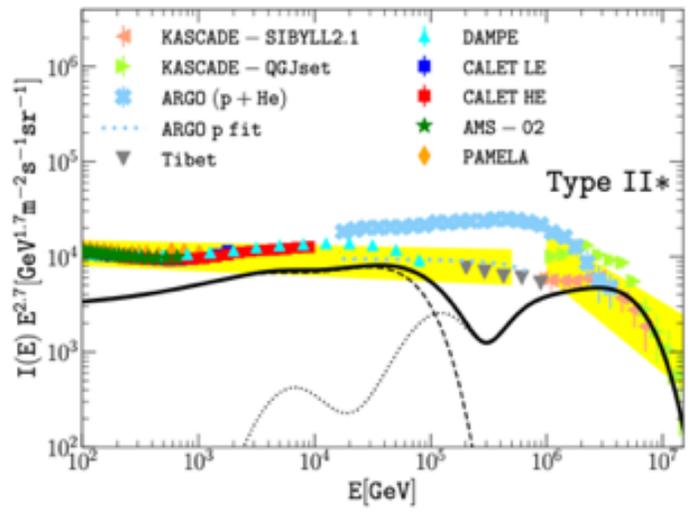
PEVATRON SNRs?

OBSERVATIONS OF YOUNG SNRs : $E_{p,max} < 100 TeV$

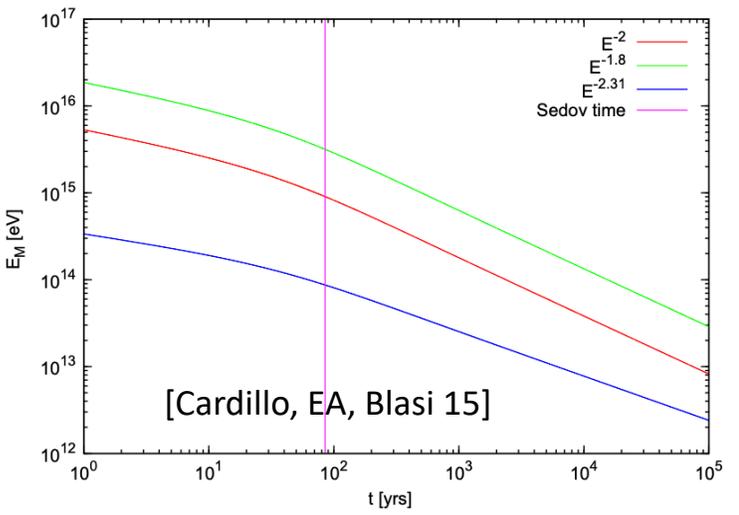
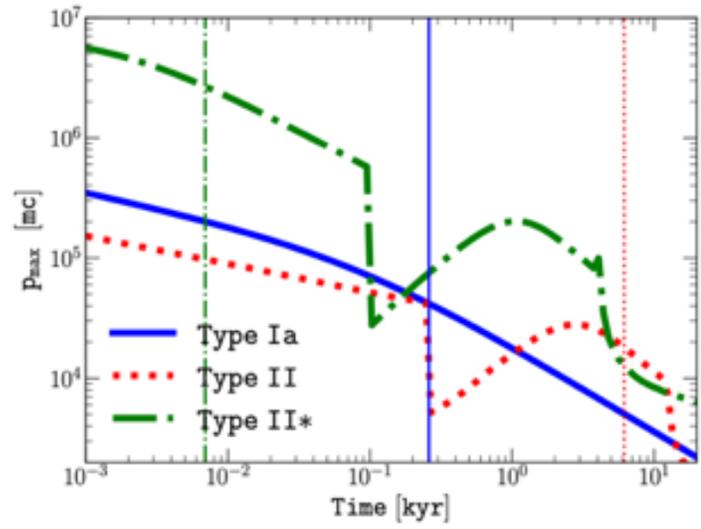


Type	Ia	II	II*
$M_{ej} [M_{\odot}]$	1.4	5	1
$E_{SN} [10^{51} \text{ erg}]$	1	1	10
$\dot{M} [10^{-5} M_{\odot}/\text{yr}]$	-	1	10
$u_w [10^6 \text{ cm/s}]$	-	1	1
$r_1 [\text{pc}]$	-	1.5	1.3

[Cristofari, Blasi, EA 20]

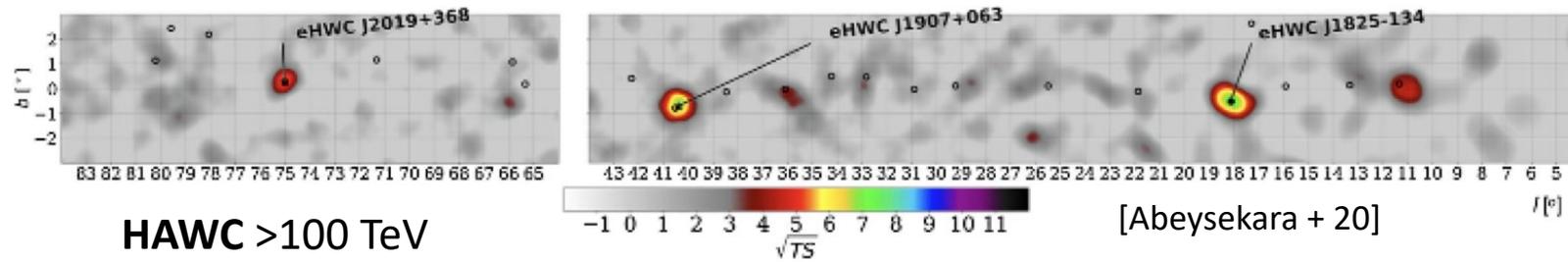


THEORY



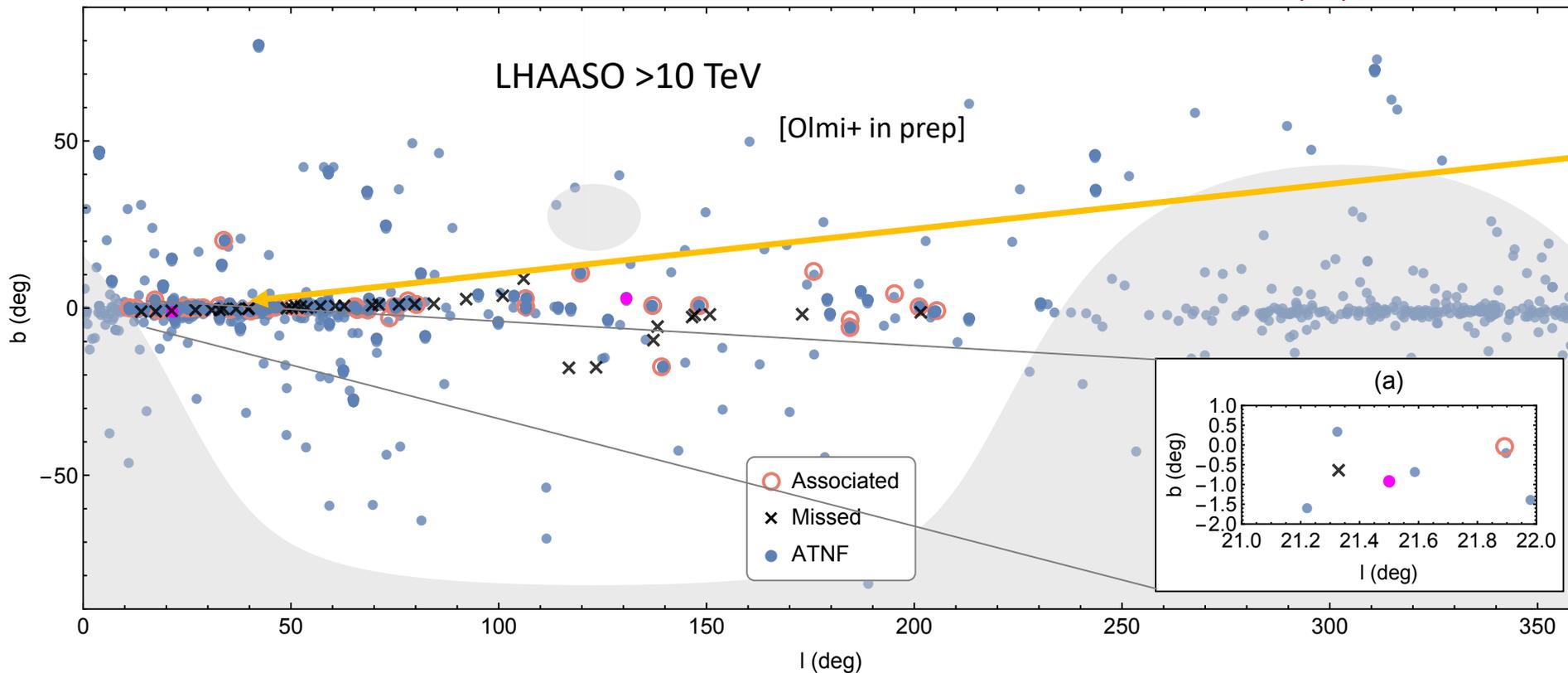
- ONLY SPECIAL EXPLOSIONS (1.5%SN) MAY PRODUCE PeV PROTONS
- THESE WOULD DOMINATE ALSO TeV CRs
- NO HOPE WITH STEEP INJECTION SPECTRA AS ANISOTROPY SUGGESTS

OBSERVED PEVATRONS



LHAASO [Cao+ 24]
 75 SOURCES > 25 TeV: 35 PSRs
 43 SOURCES >100 TeV: 22 PSRs

39 SOURCES OUT OF 75 IN KM2A ASSOCIATED TO PSRs [Olm+ in prep]

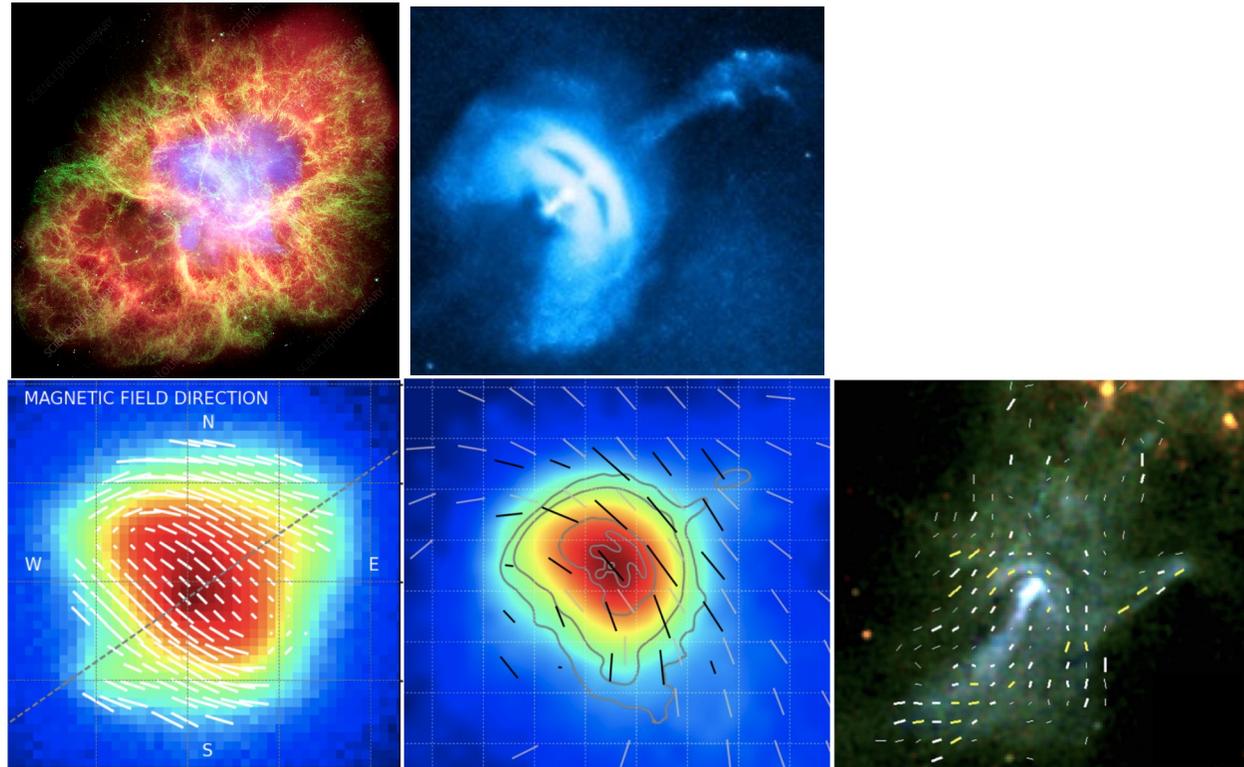
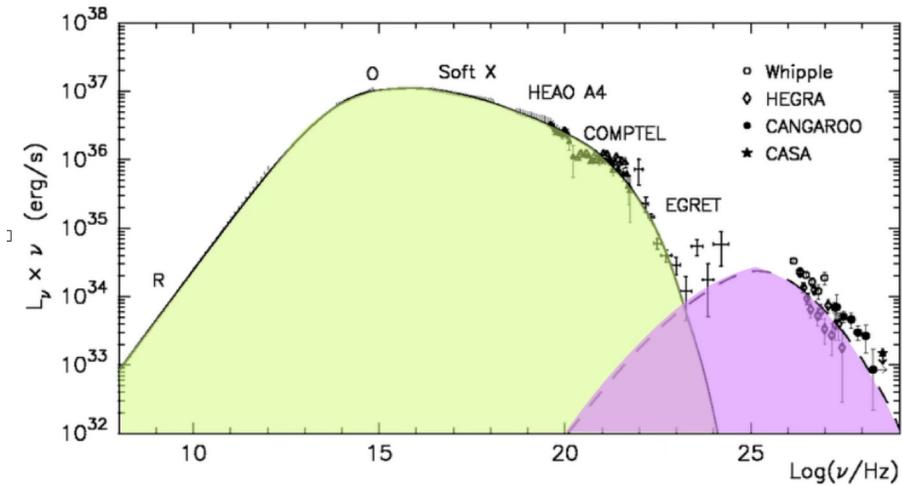
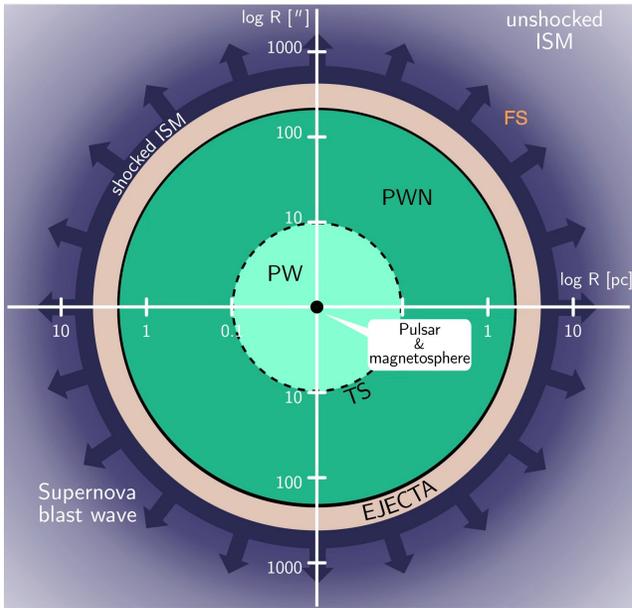


IN MANY CASES SOLID ASSOCIATION IMPOSSIBLE BECAUSE CROWDED FIELD!!!!

POTENTIALLY ALL PULSAR RELATED?

OBSERVED PEVATRONS: PULSAR WIND NEBULAE

- **MOST EFFICIENT (>20%!) AND FASTEST (PeV ELECTRONS!) EVER PARTICLE ACCELERATION AT THE ULTRARELATIVISTIC WIND TERMINATION SHOCK IS AN UNSOLVED MYSTERY!**
[e.g. EA & Olmi 21]
- **IXPE RESULTS MAKE IT WORSE!** [Bucciantini+ 25]
 - HIGH PD CONTRASTS WITH TURBULENCE AND RECONNECTION
 - SPATIAL VARIATIONS AND TIME VARIABILITY DIFFERENT FROM MULTI-D MHD RESULTS [e.g. Olmi+16]



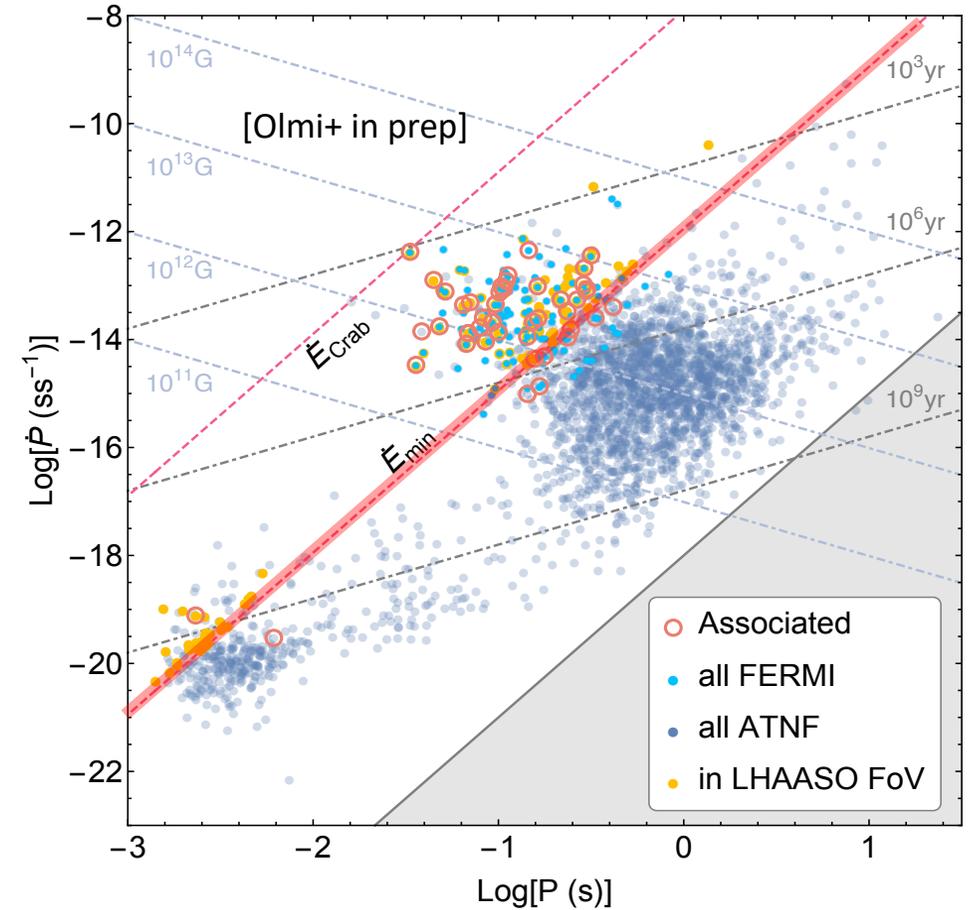
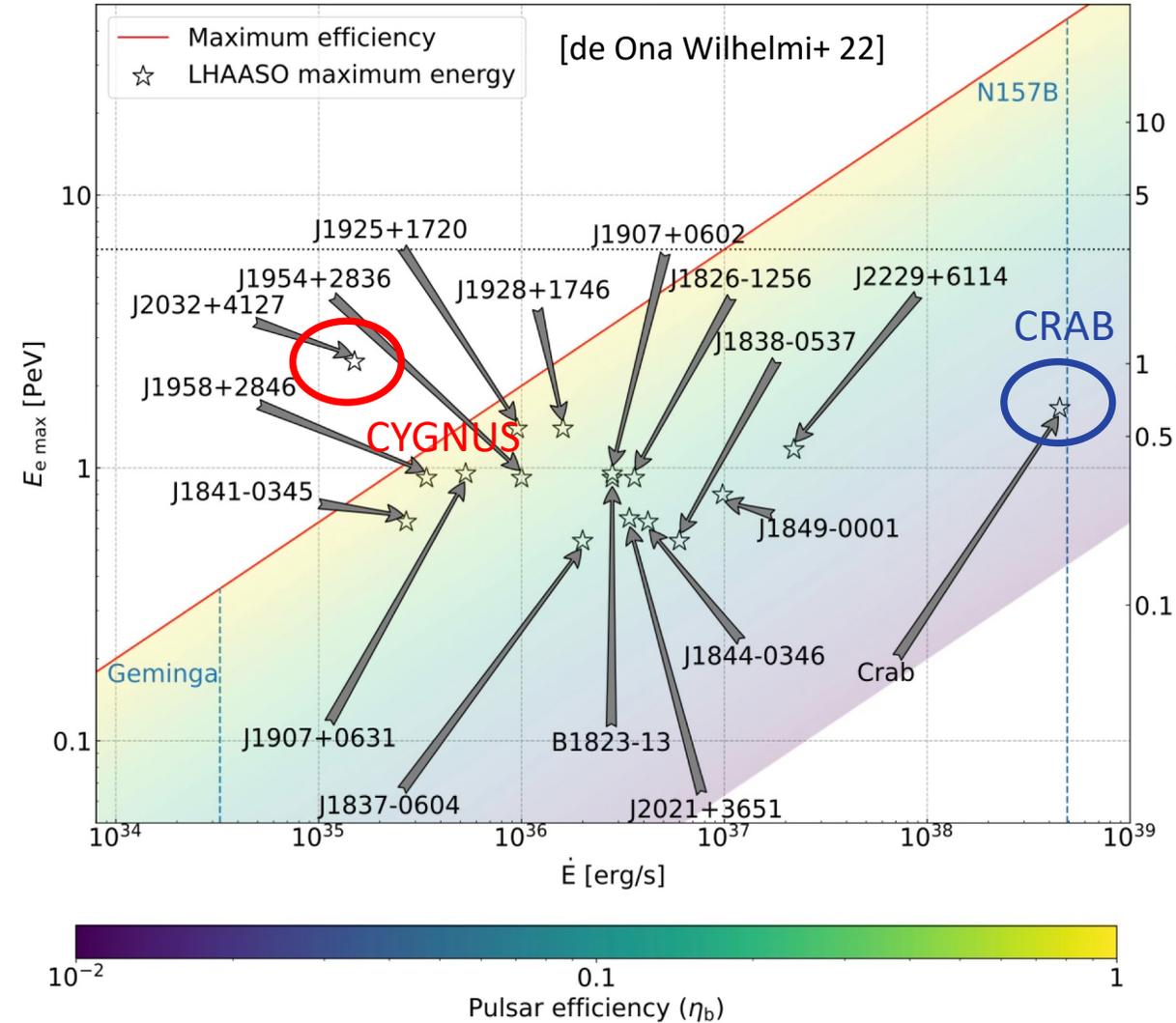
PSR PEVATRONS

$$E_{max,abs} = e\eta_E \eta_B^{1/2} \sqrt{\dot{E}/c} \approx 1.8 \text{ PeV } \eta_E \eta_B^{1/2} E_{36}^{1/2}$$

$$\epsilon_{\gamma,max,abs} \approx 0.9 \text{ PeV } \eta_E^{1.3} \eta_B^{0.65} E_{36}^{0.65}$$

$$E_{max,rad} \approx 6 \text{ PeV } \eta_E^{1/2} B_{-4}^{-1/2}$$

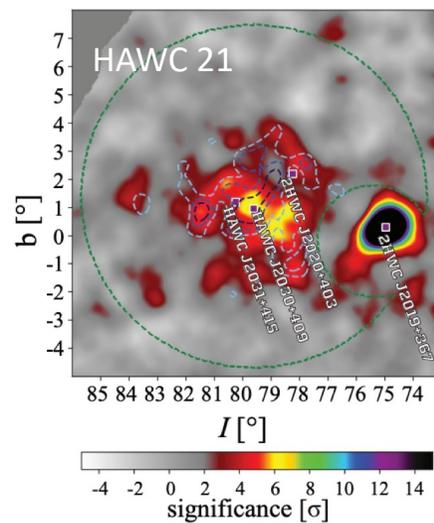
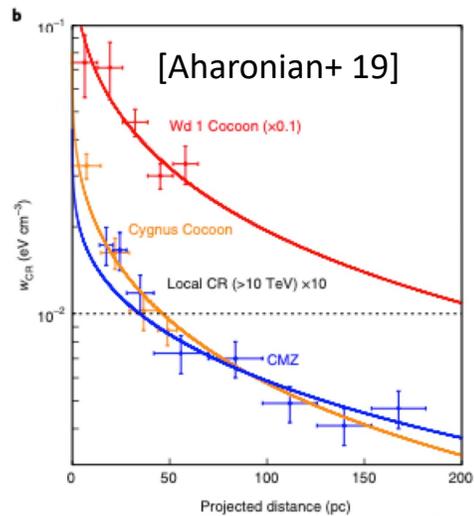
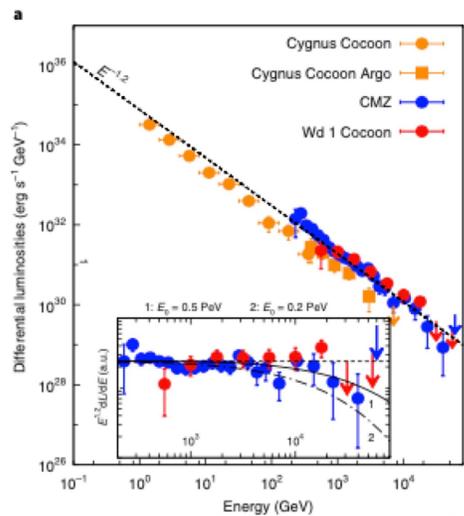
$$\epsilon_{\gamma,max,rad} \approx 1.1 \text{ PeV } \eta_E^{0.65} B_{-4}^{-0.65}$$



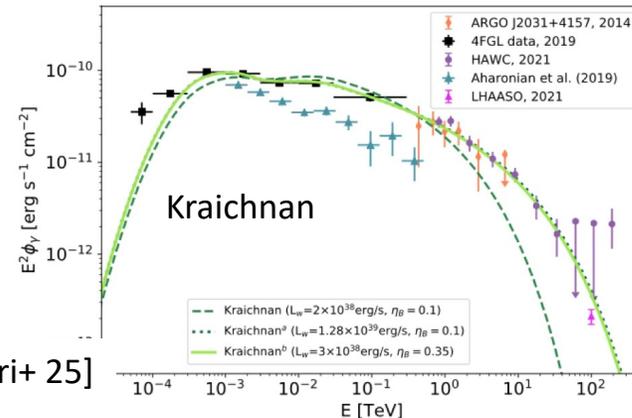
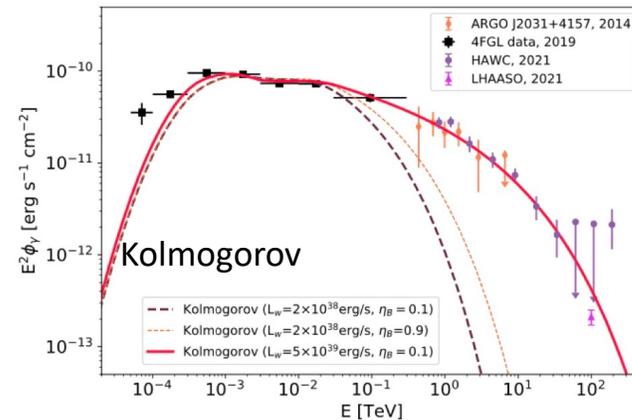
LEPTRONIC OR HADRONIC?

IN PRINCIPLE ALSO HADRONS IN PSR WINDS [eg EA & Arons 06] 15

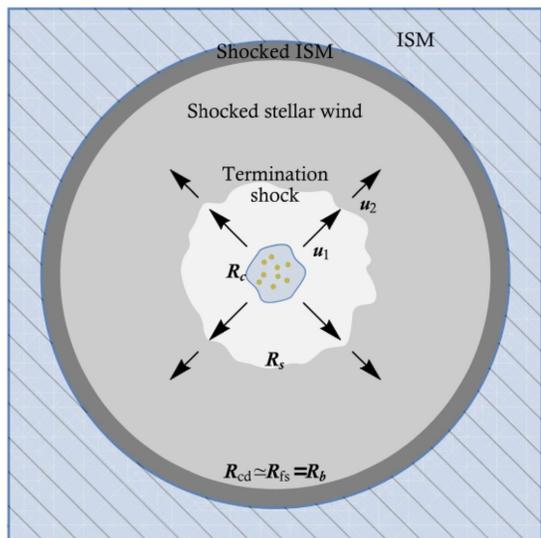
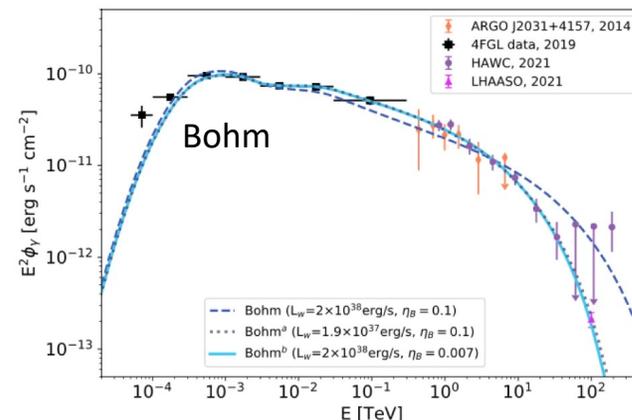
ALTERNATIVE PEVATRONS: STAR CLUSTERS



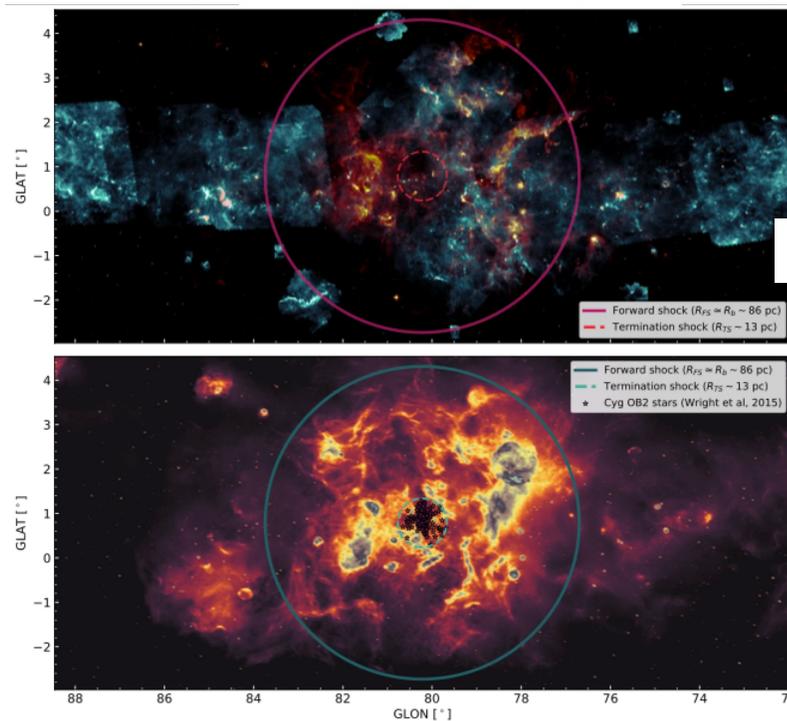
Cyg OB2



[Menchiari+ 25]

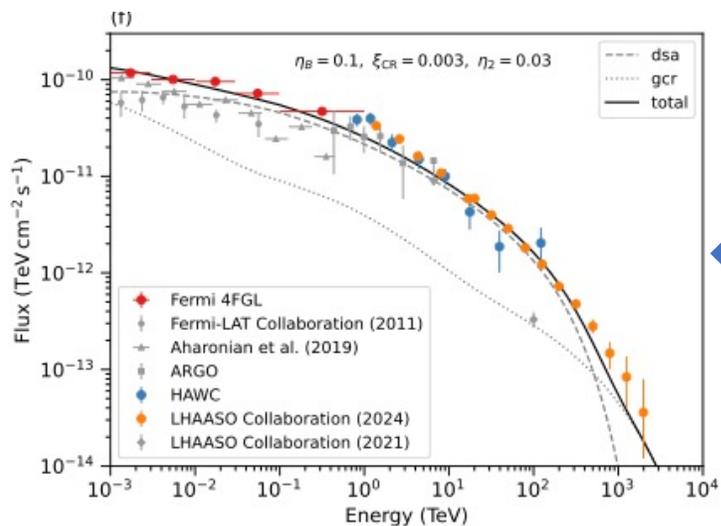


[Morlino+ 21]



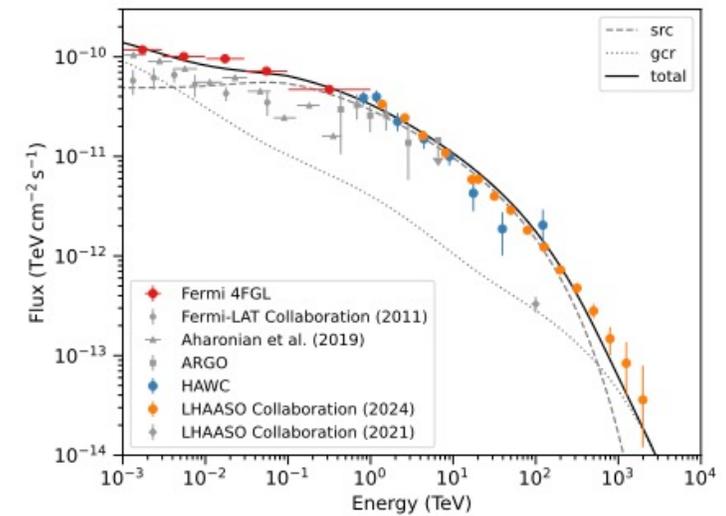
ALTERNATIVE PEVATRONS: STAR CLUSTERS

Cyg OB2

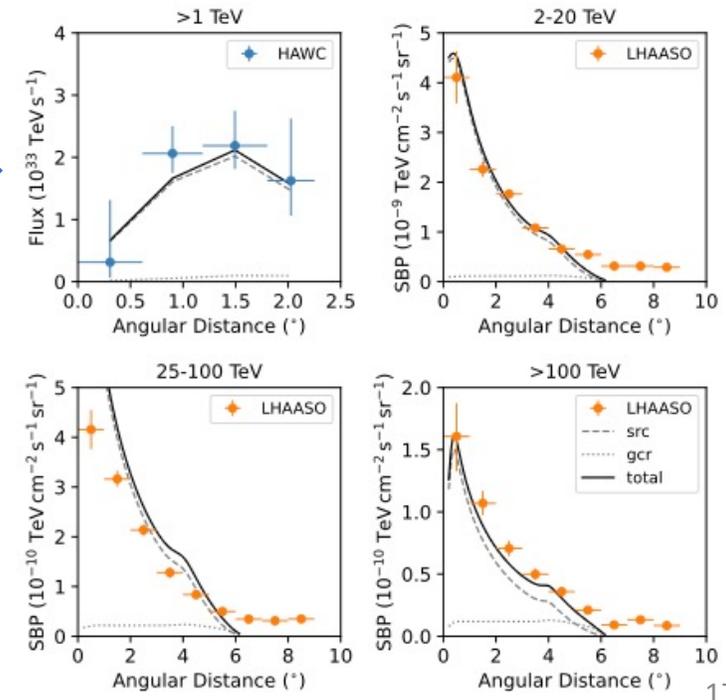
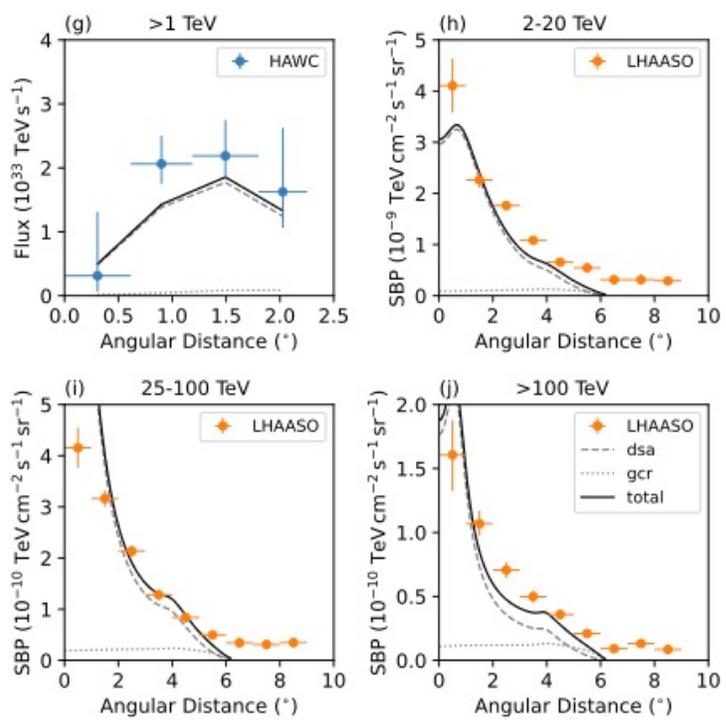


COLLECTIVE WIND TERMINATION SHOCK

BUT MAYBE NO TERMINATION SHOCK
[Harer+ 25]



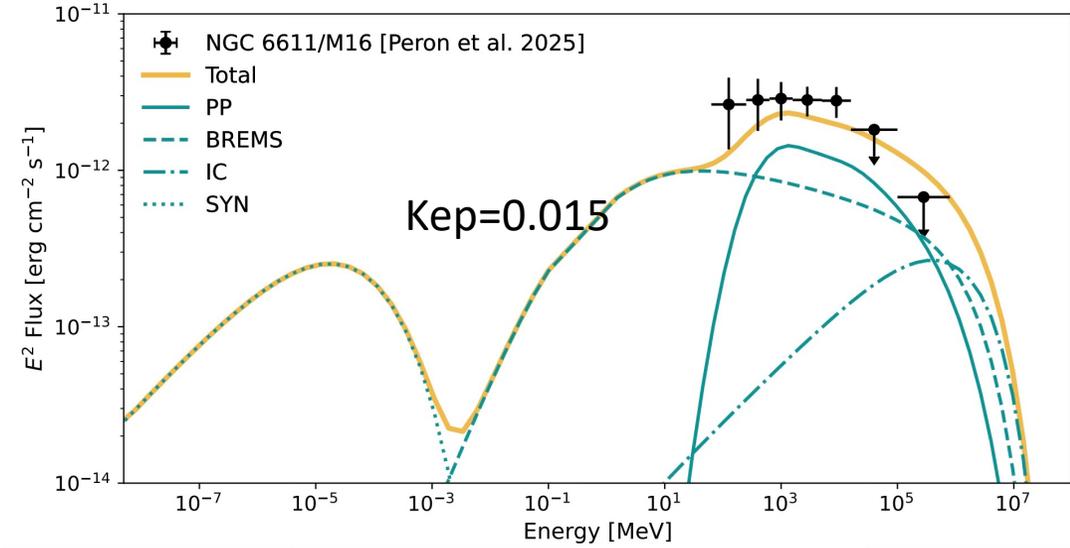
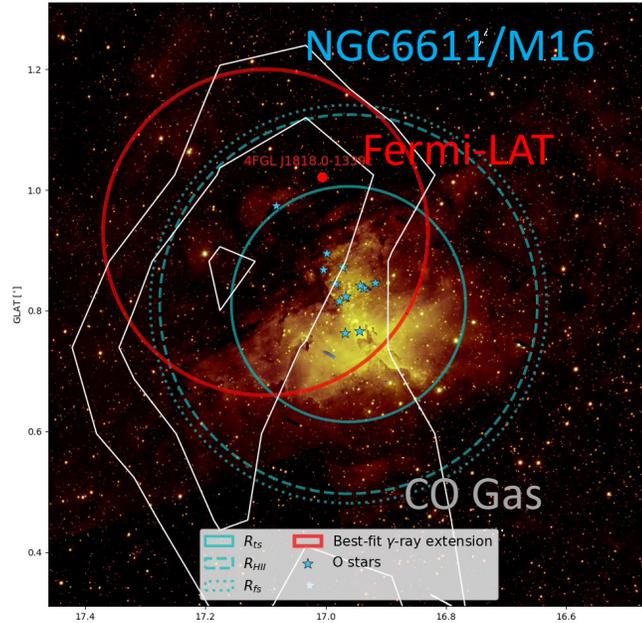
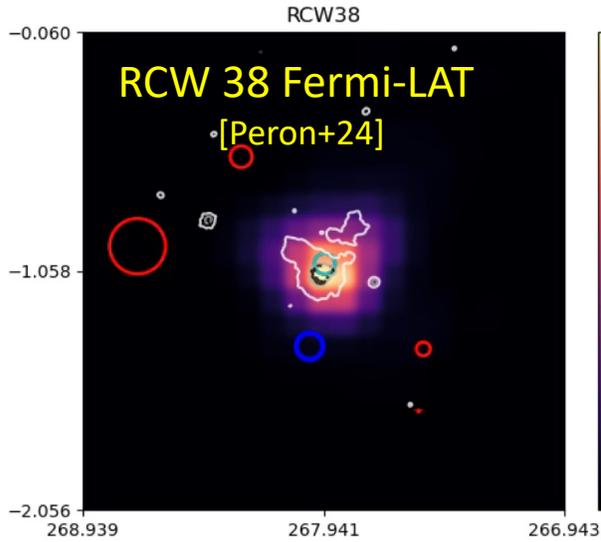
CONTINUOUS INJECTION BY CENTRAL POINT SOURCE



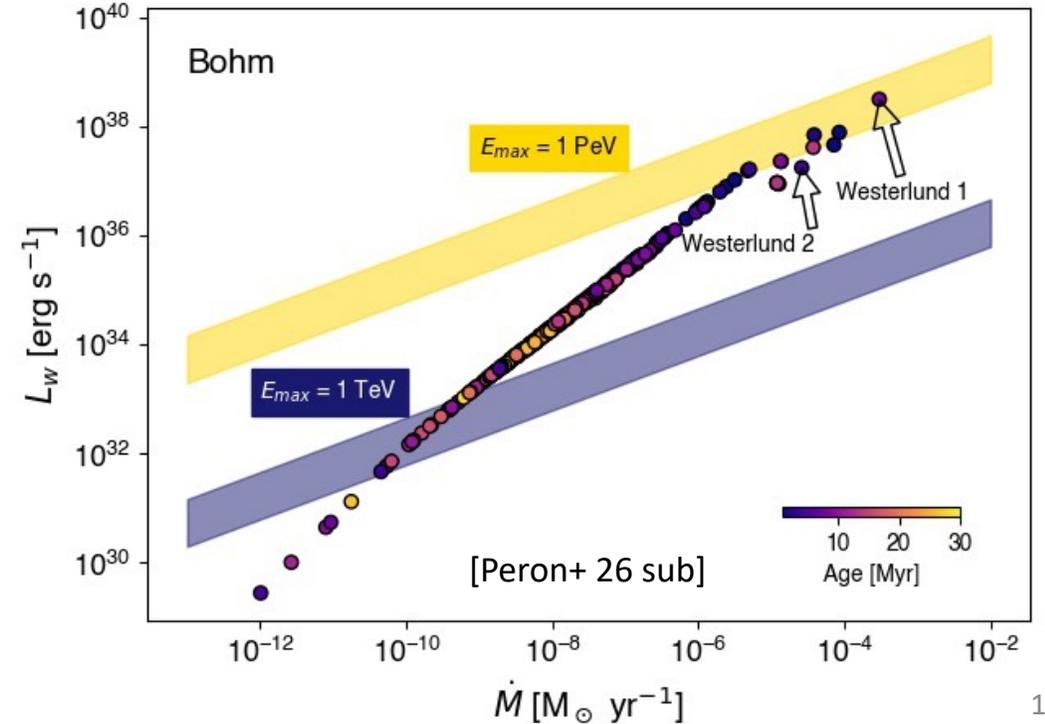
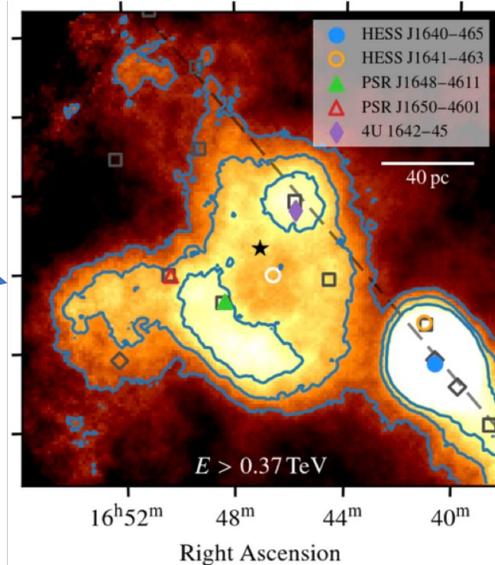
- BOTH SCENARIOS ALLOW TO FIT SPECTRUM AND MORPHOLOGY, BUT EXTREME PARAMETERS
- NO FIT WITH BURSTY POINT SOURCE

[Li, Blasi, EA submitted]

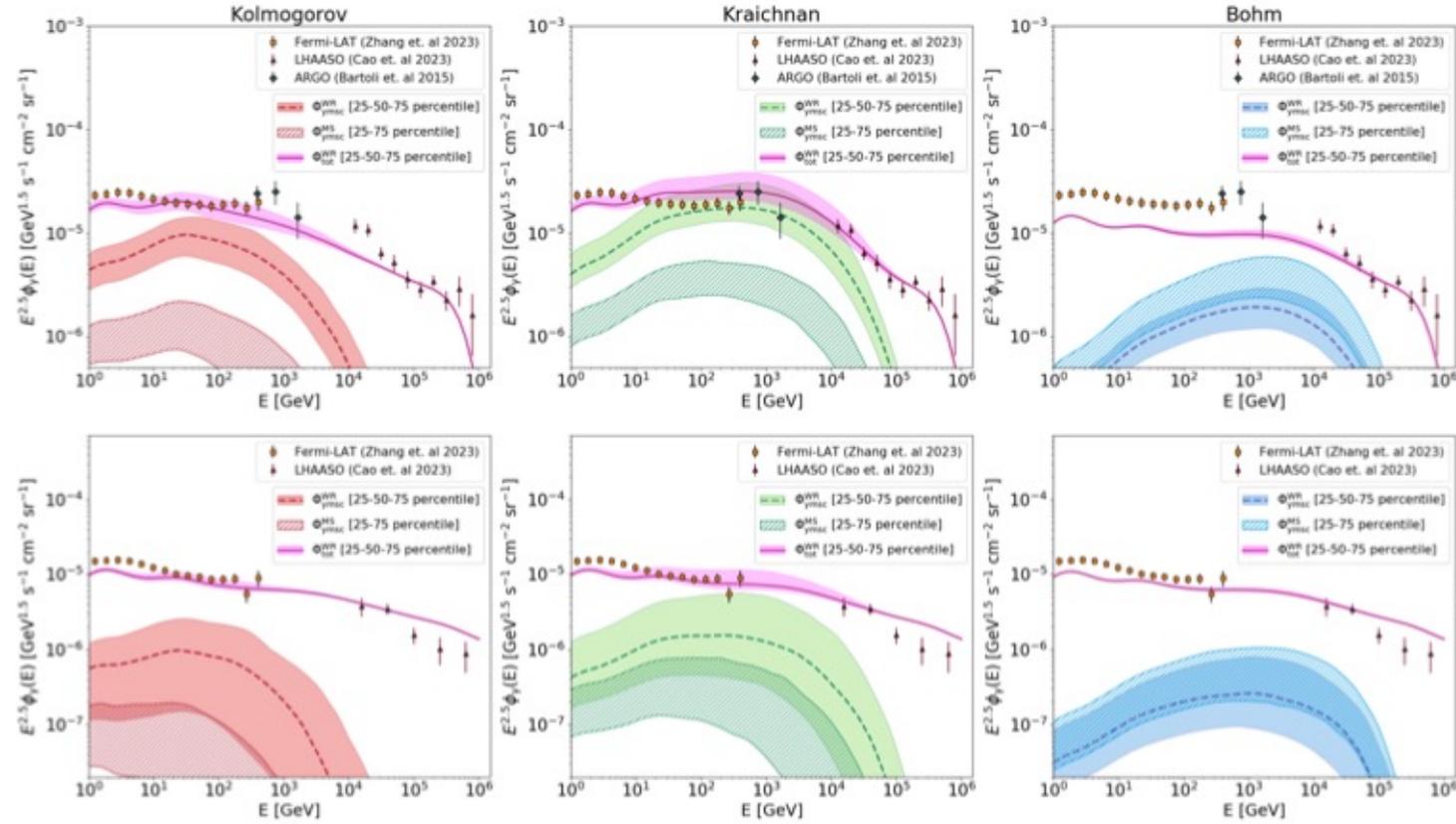
ALTERNATIVE PEVATRONS: STAR CLUSTERS



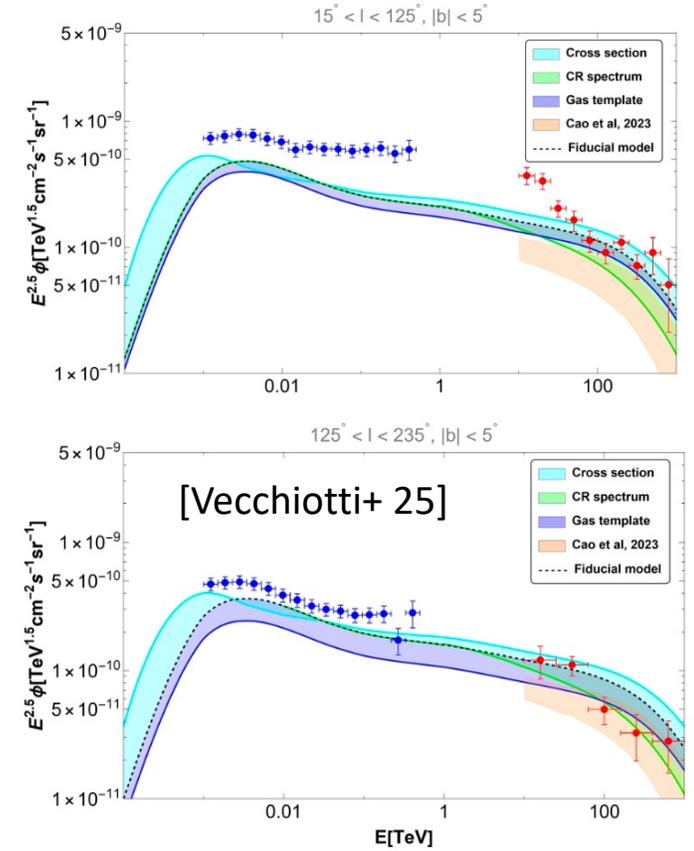
- NECESSARY AT SOME LEVEL TO EXPLAIN CR COMPOSITION [Tatischeff & Gabici 21]
- SOME MIGHT BE POWERFUL ENOUGH TO PRODUCE PEV



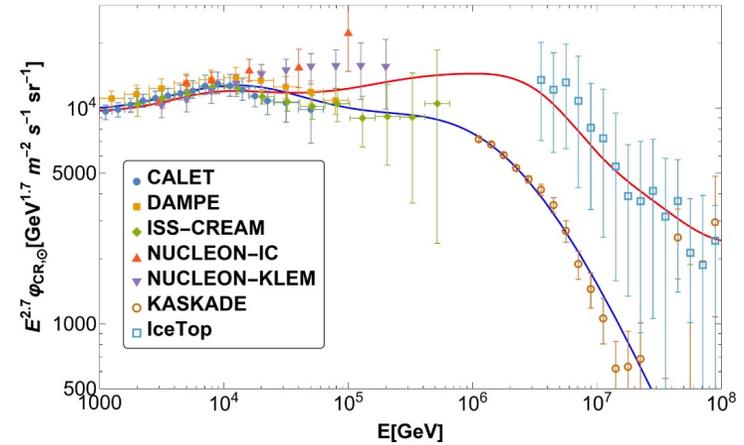
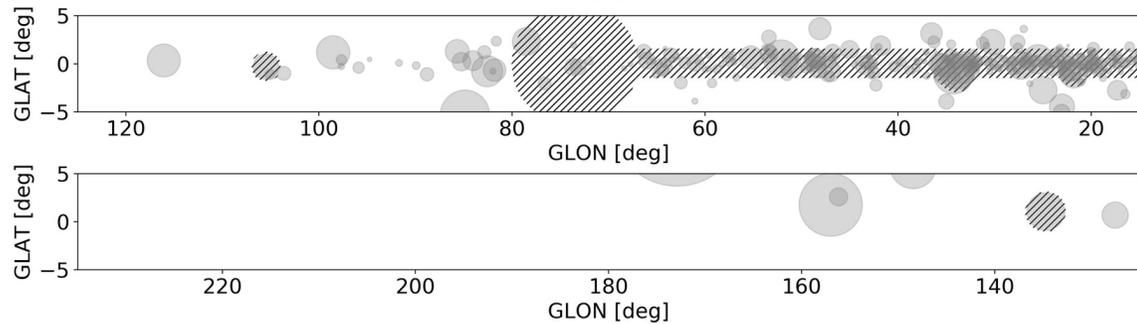
DIFFUSE GAMMAS FROM SCs



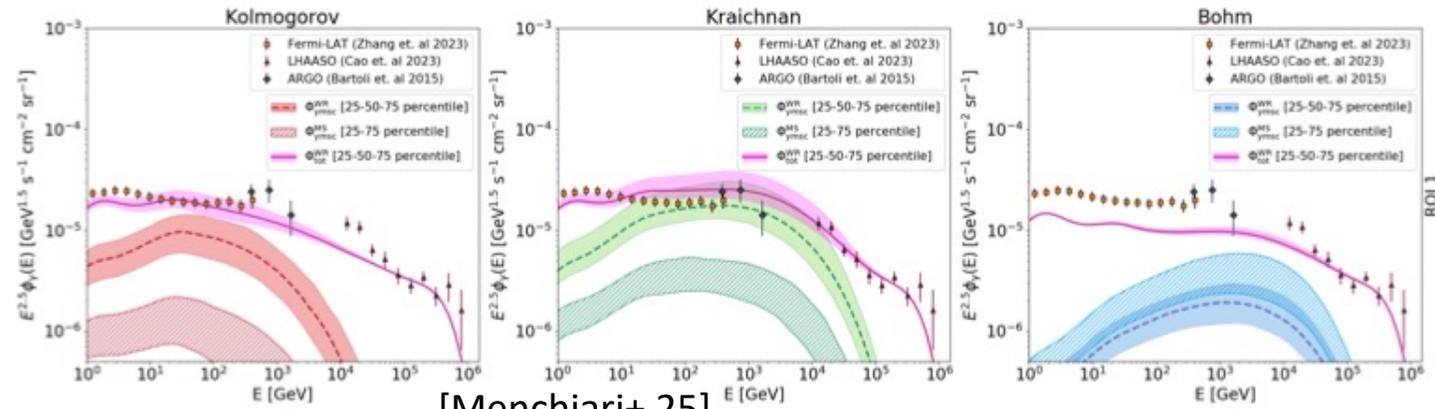
IDEAL UNRESOLVED SOURCES



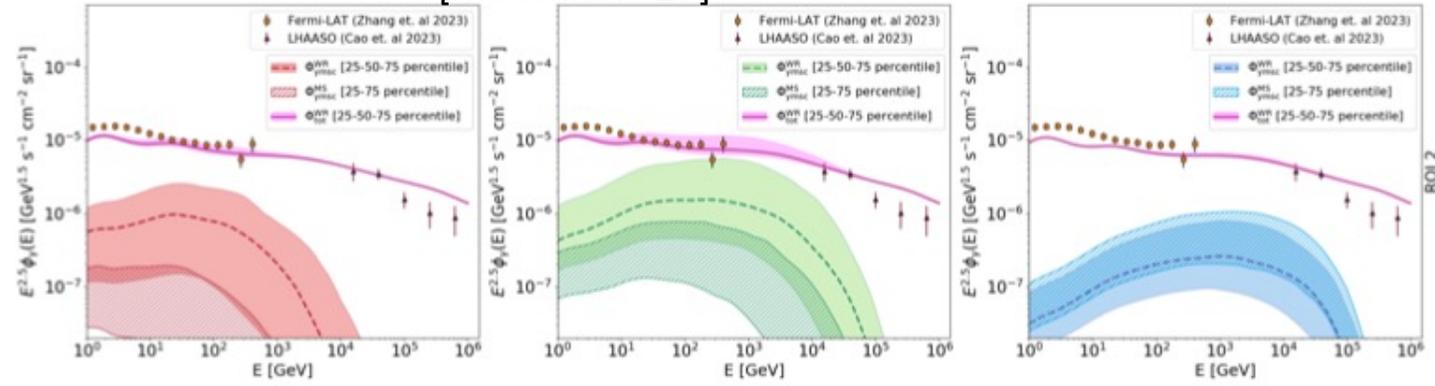
[Menchiari+ 25]



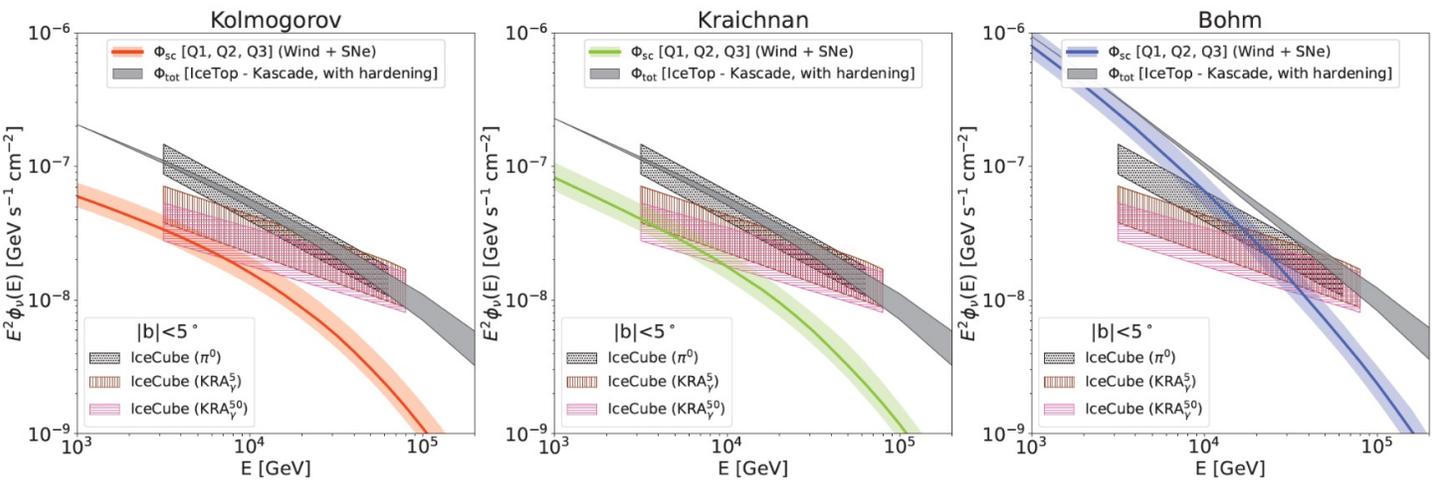
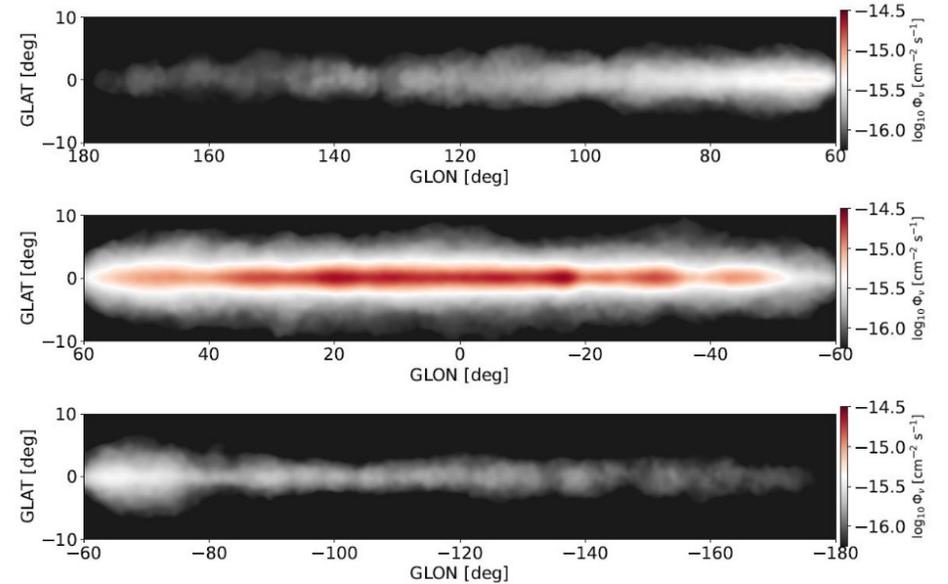
DIFFUSE GAMMAS AND NEUTRINOS FROM SCs



[Menchiari+ 25]

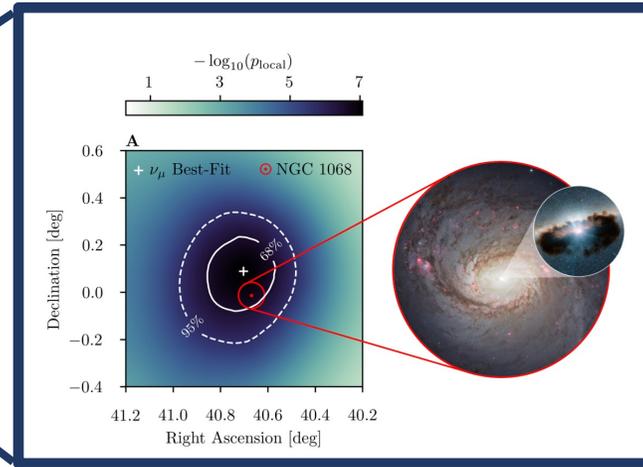
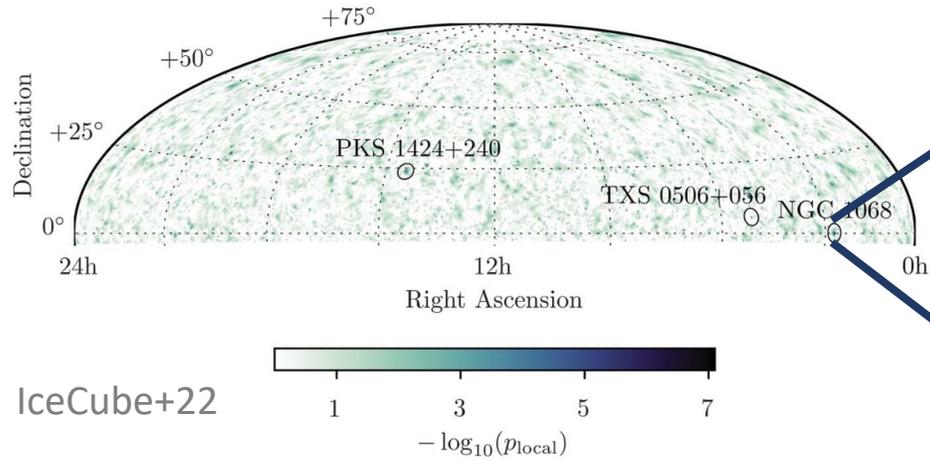


Integrated median SCs neutrino emission (E>1 TeV)



[Menchiari+ in prep]

NEW NEUTRINO SOURCES

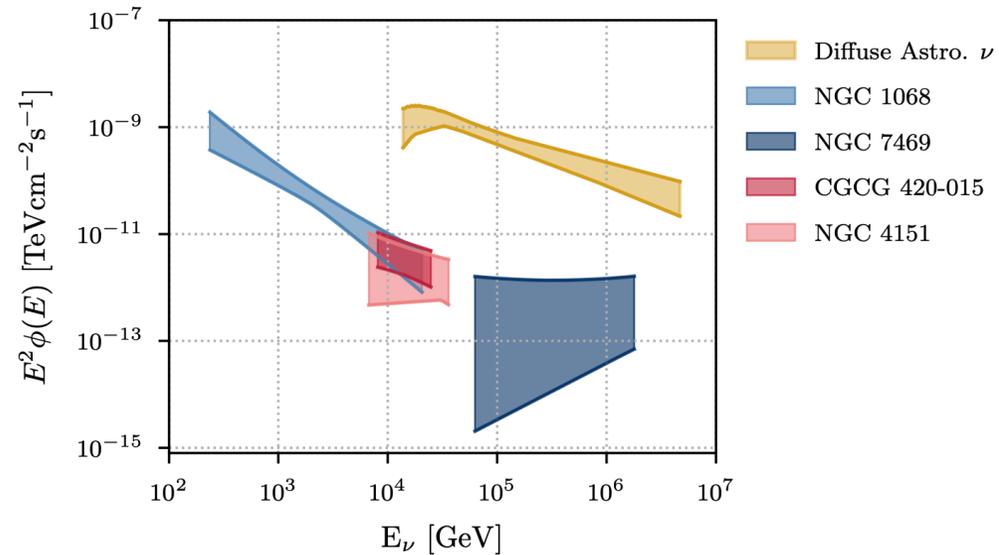


**IceCube hottest spot
coincident with NGC 1068
(significance 4.2σ)**

*Spectra of the four most significant X-ray-bright sources
together with the diffuse flux measurement*

**Cumulative neutrino excess
from X-ray bright Seyferts:
post-trial significance 3.3σ**

IceCube+25



Activities & Highlights

Institutes / Collaboration Involved: INAF–OAR, INAF –OAA / MAGIC, LST-1, CTAO

Key Activities

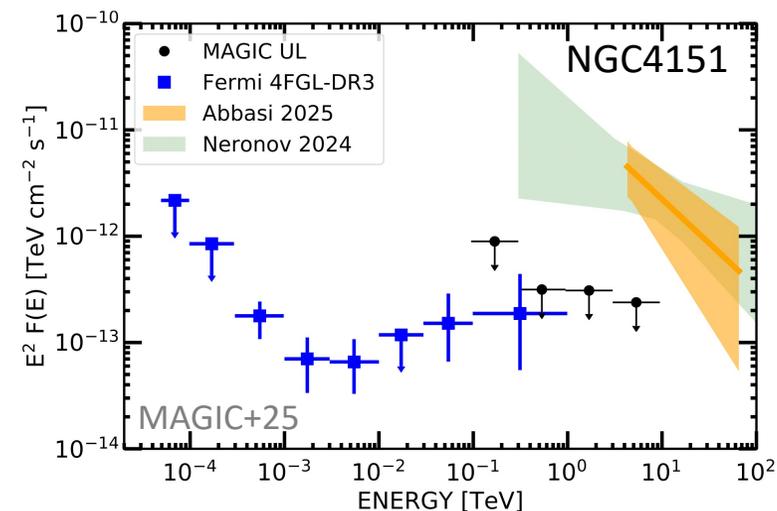
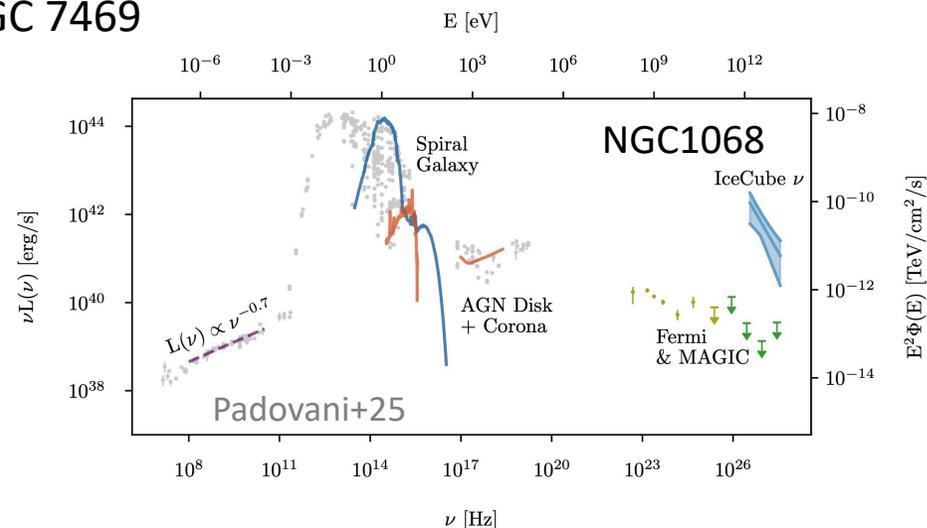
- Identification of **top candidates**: NGC 1068, NGC 4151, CGCG 420-015, NGC 7469
- **VHE gamma-ray searches & ULs**: constrain neutrino production region
- **Theoretical modeling**: AGN outflows, corona, starburst
- **Simulations**: prospects for observing Seyfert galaxies with CTAO

Highlights

- **NGC 1068 & NGC 4151**: VHE ULs → emission region must opaque to gamma-rays
- **CGCG 420-015 & NGC 7469**: promising IceCube-associated candidates → follow-up in preparation
- **Theoretical work**: Ultra fast outflows (UFO), starburst, corona models

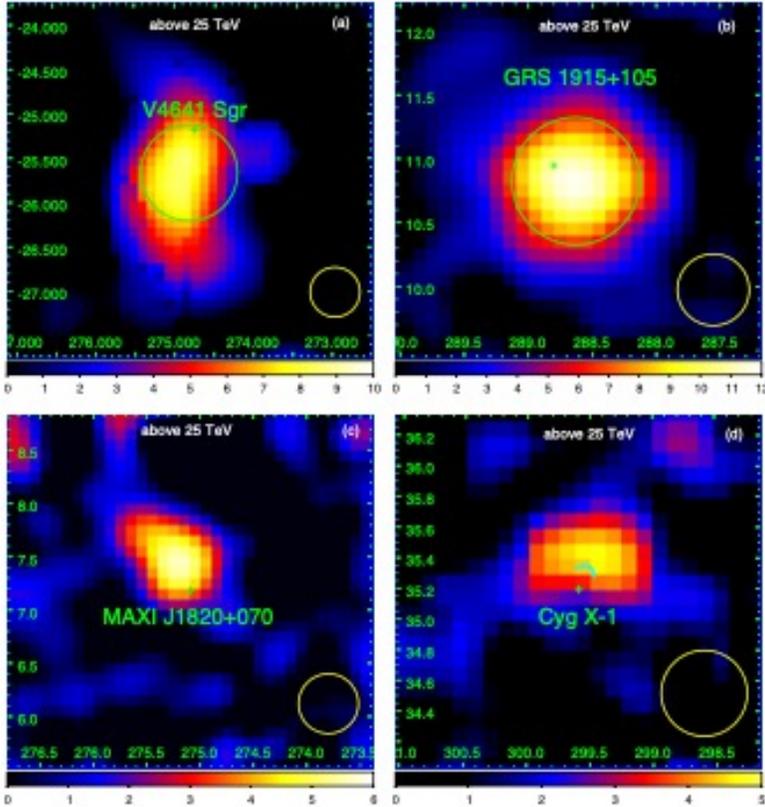
Open Questions

- Where are neutrinos produced?
- Which mechanism dominates?
- Are Seyfert galaxies the main contributors to the diffuse neutrino flux observed by IceCube?

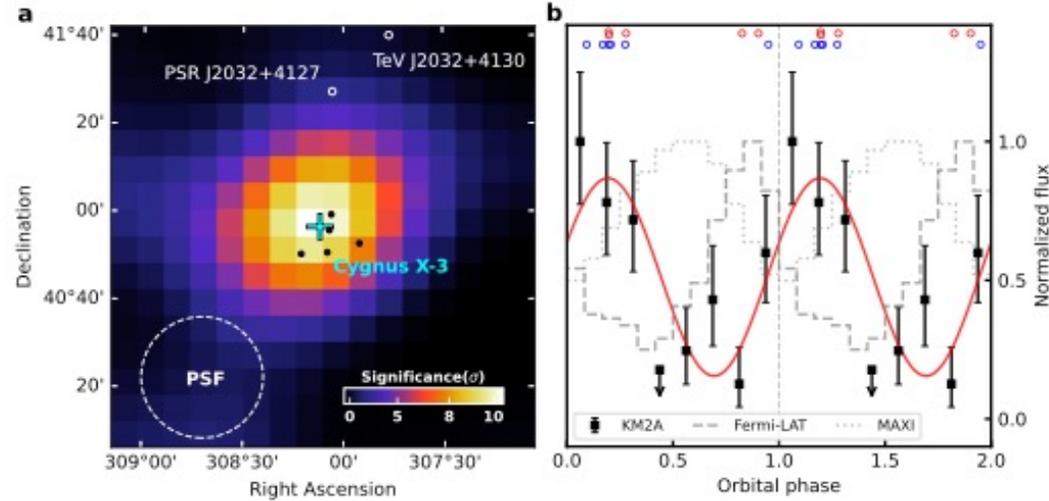


ALTERNATIVE PEVATRONS: MICROQUASARS

LHAASO [Cao+ 25] DETECTS 6 MQs at E>25 TEV

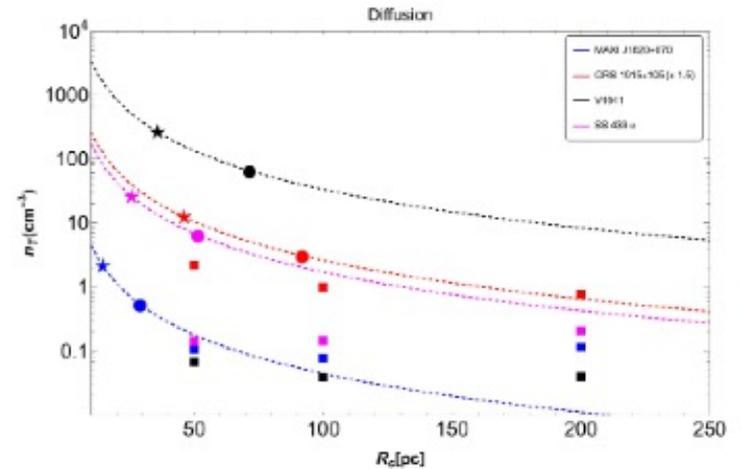
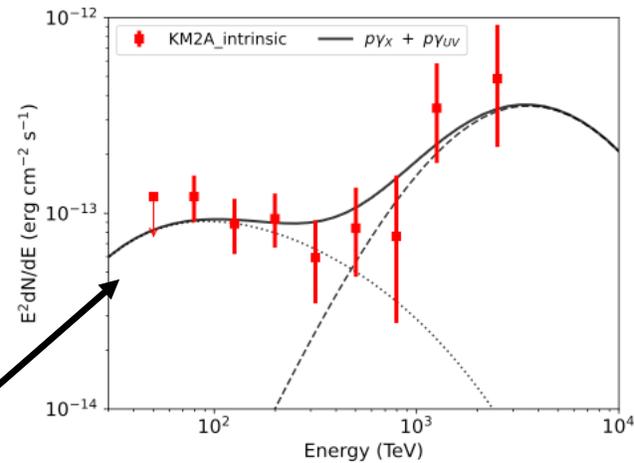


AND EVEN VARIABILITY FROM CYG X-3



QUESTIONS:
LEPTONIC OR HADRONIC?
ACCELERATION EFFICIENCY?

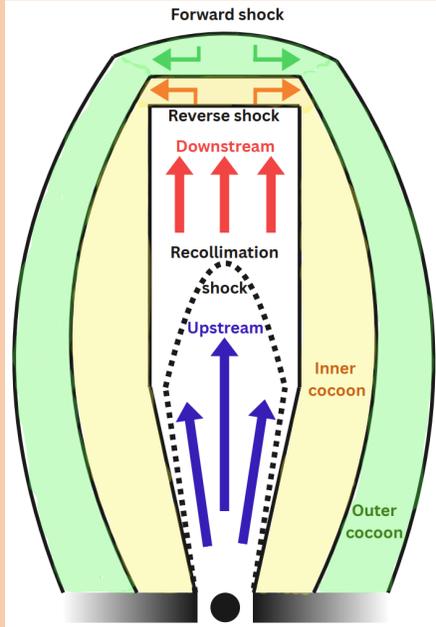
CONSTRAINING TRANSPORT
AND GAS DENSITY
[Vecchiotti+ in prep]



INTRIGUING LOW ENERGY CUT-OFF:
PARTICLE ACCELERATION
OR EMISSION MECHANISM?

ALTERNATIVE PEVATRONS: MICROQUASARS

Diffusive shock acceleration



Jet head → forward-reverse shocks

Recollimation shock

Modeling

- Jet structure

$$\begin{cases} \rho_j(u_j - v_h)^2 + P_j \approx \rho_a v_h^2 \\ P_c \approx \rho u^2 \sin^2 \psi \end{cases}$$

Pressure balance at the jet head and at the recollimation shock

- Acceleration of particles

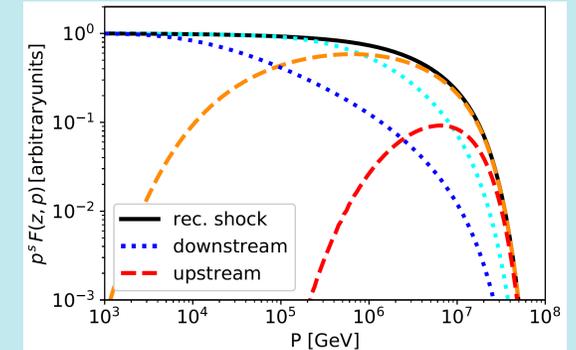
$$u \nabla f = \nabla D \nabla f + \frac{p}{3} \partial_p f \nabla u + Q$$

Transport along the jet

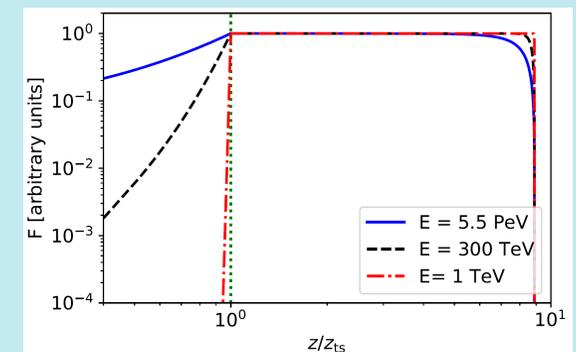
[Peretti+ in prep]

Results

- Particle spectra

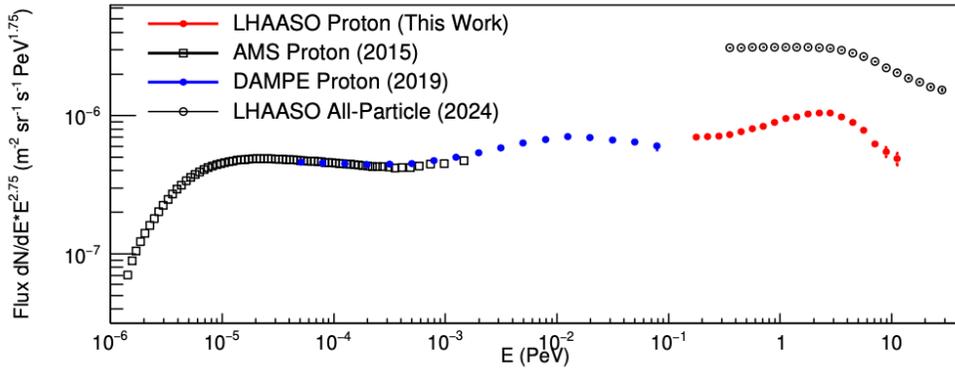


- Spatial distribution



UHE DIFFUSE EMISSION AND CRs THROUGH THE GALAXY

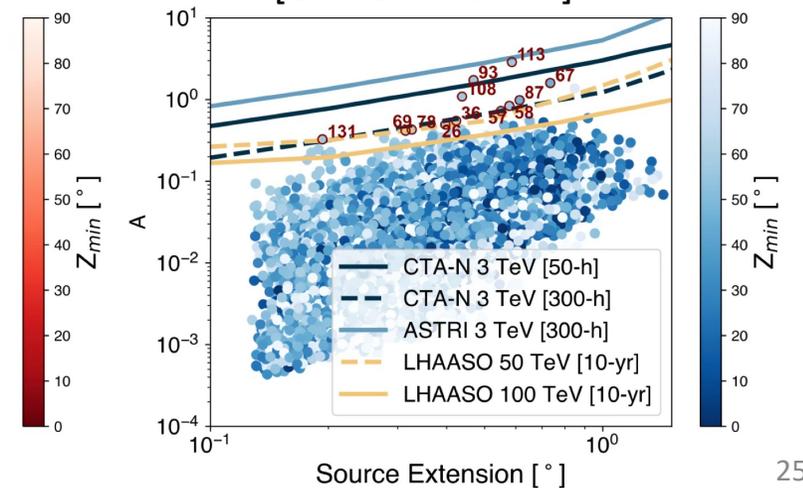
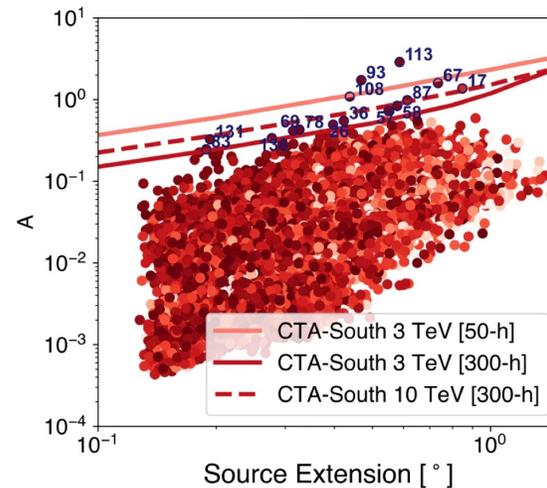
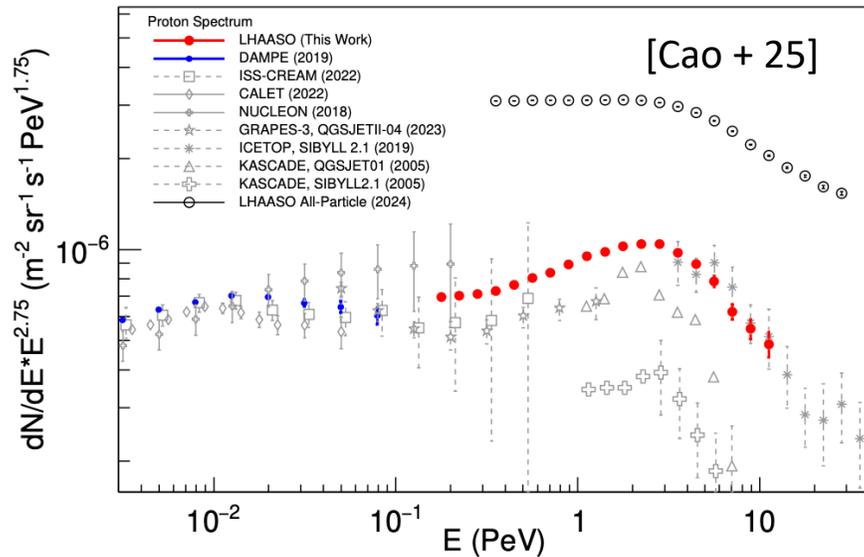
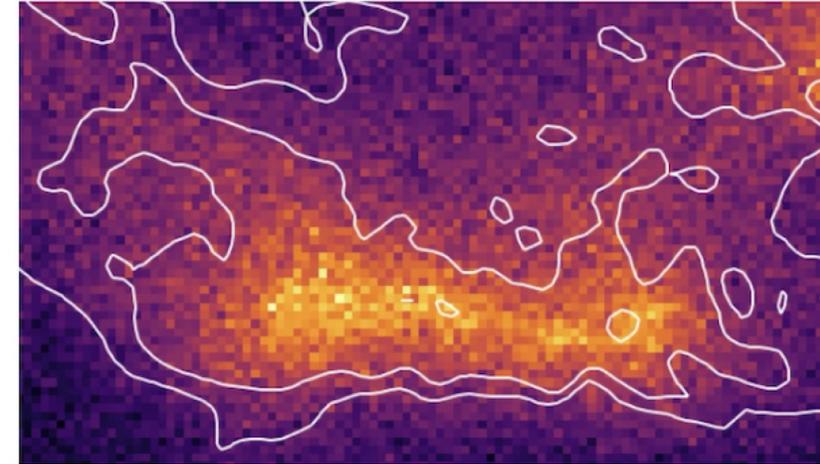
LHAASO PROTON SPECTRUM INCONSISTENT WITH LHAASO DIFFUSE EMISSION!!!!



CLOUDS AS IDEAL PROBES OF THE CR SPECTRUM THROUGH THE GALAXY

$$F_{\gamma} \propto N_H J_p(E_p) = \frac{M}{d^2} J_p(E_p)$$

Orion A [Fermi-LAT > 1 GeV]



CONCLUSION

- VERY DYNAMIC TIME FOR CR AND NEUTRINO SCIENCE: RECENT DETECTION OF FIRST PEVATRONS FIRST NEUTRINO SOURCES, DETAILED MAPPING OF THE SKY IN ALL MESSENGERS.... UPCOMING GAME-CHANGER FACILITIES!!!!
- INAF COMMUNITY HOLDS EXPERTISE THAT HAS ALLOWED FIRST CLASS WORK ON MANY ASPECTS OF COSMIC RAY PHYSICS, WITH INNOVATIVE OBSERVATIONAL, PHENOMENOLOGICAL AND THEORETICAL EFFORTS
- NOW IT IS TIME TO BRING TOGETHER OUR EXPERTISE AND MAKE A COMMON PLAN TO USE OUR MANY TOOLS TO MAKE THE MOST OF UPCOMING WORLD CLASS INFRASTRUCTURES THAT WE HAVE LONG BEEN WORKING FOR AND THAT HOLD REAL PROMISE TO ANSWER MANY OF THE OPEN QUESTIONS