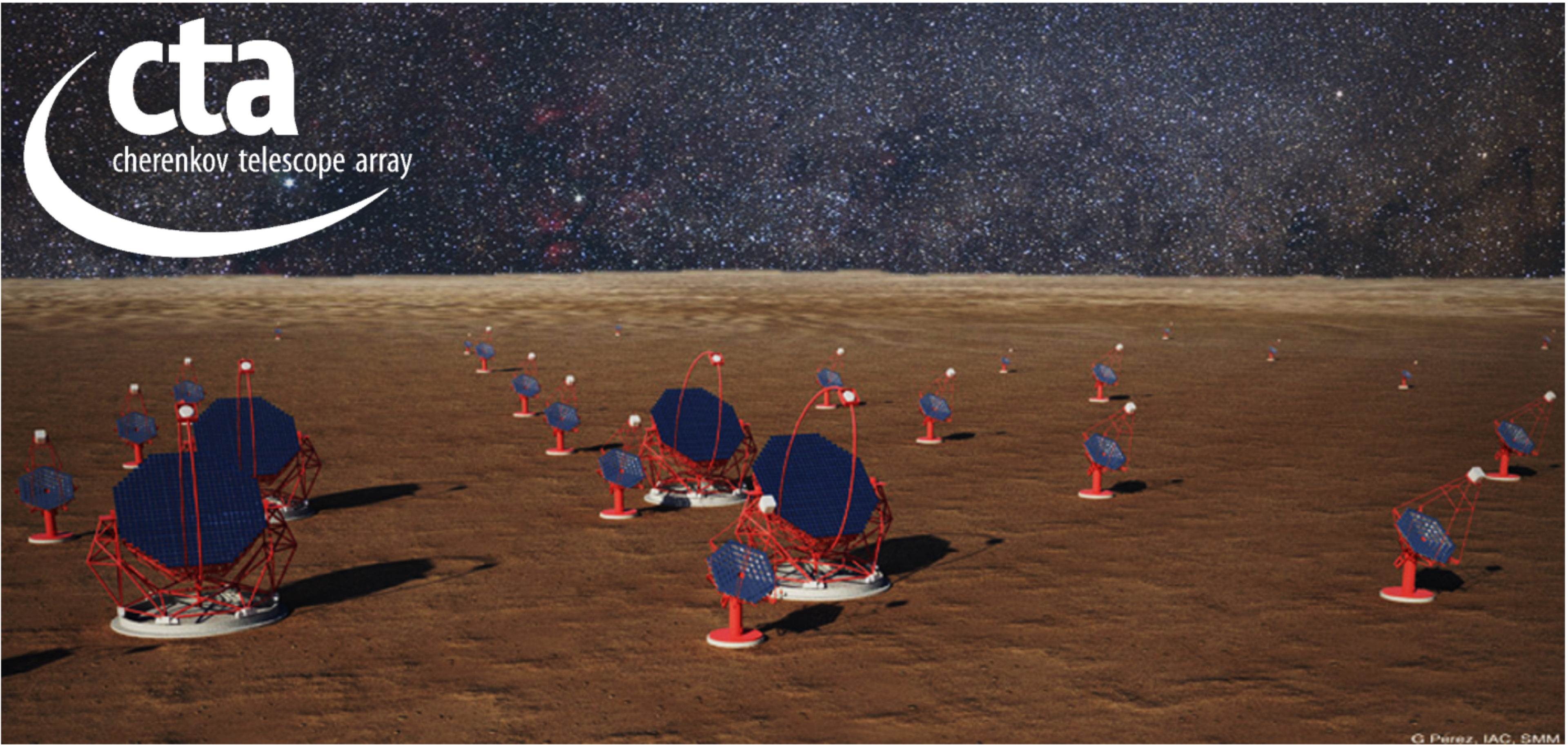
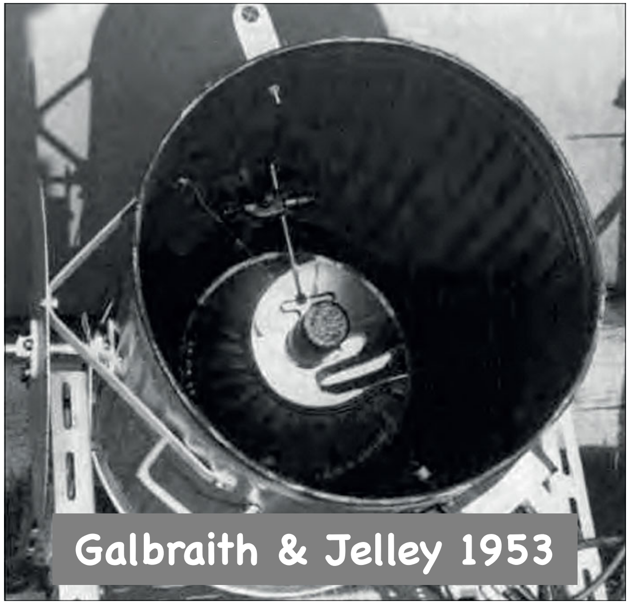
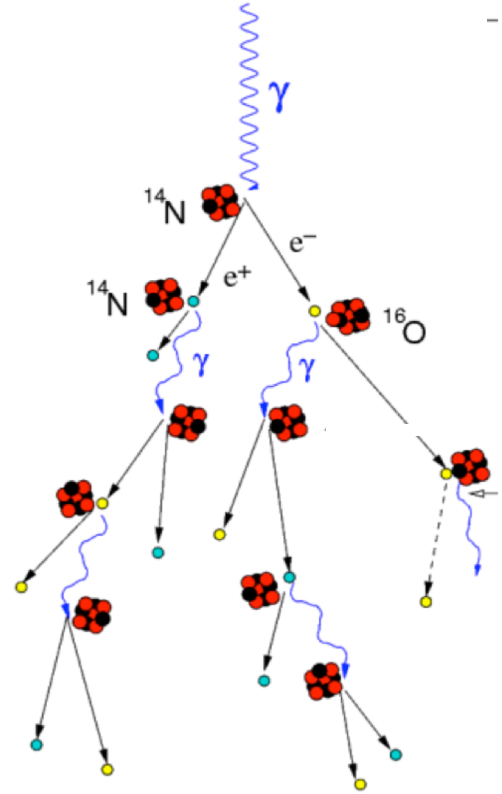
COSMIC RAY PHYSICS IN THE CTA ERA



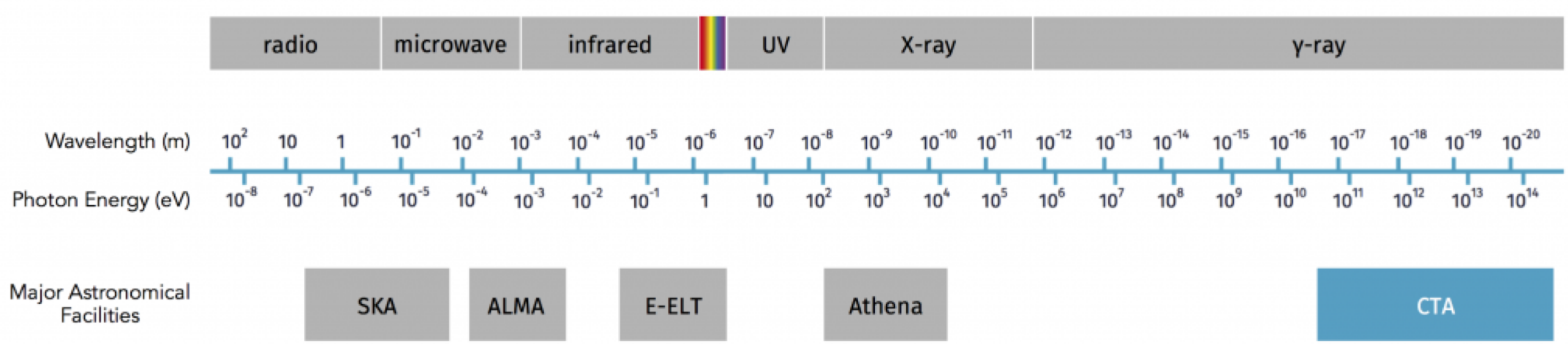
Elena Amato
INAF-Osservatorio Astrofisico di Arcetri

CHERENKOV ASTRONOMY


Galbraith & Jelley 1953



- ❑ VERY LOW FLUXES
- ❑ SPACE IS NOT AN OPTION
- ❑ NO ATMOSPHERIC PENETRATION
- ❑ ATMOSPHERIC SHOWERS

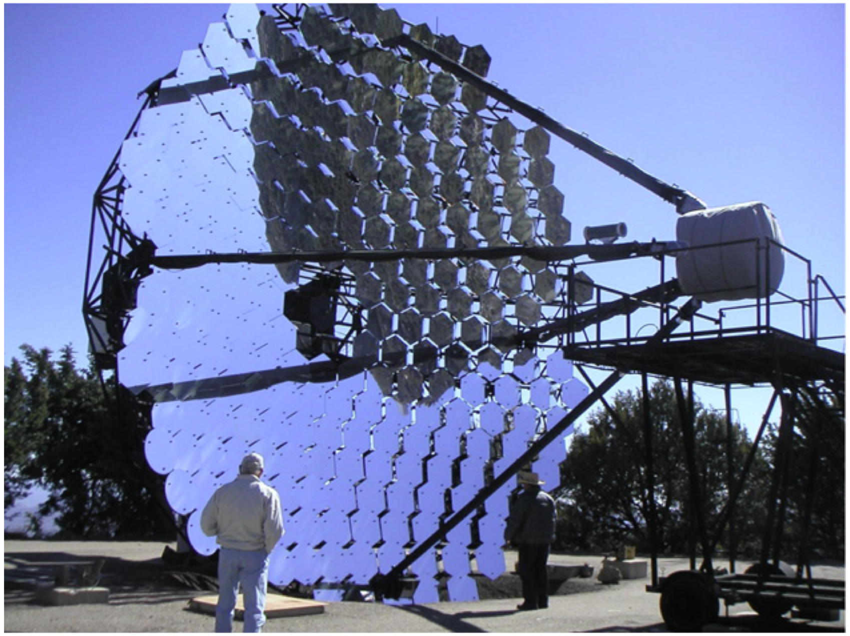


THE FIRST GAMMA-RAY SOURCE

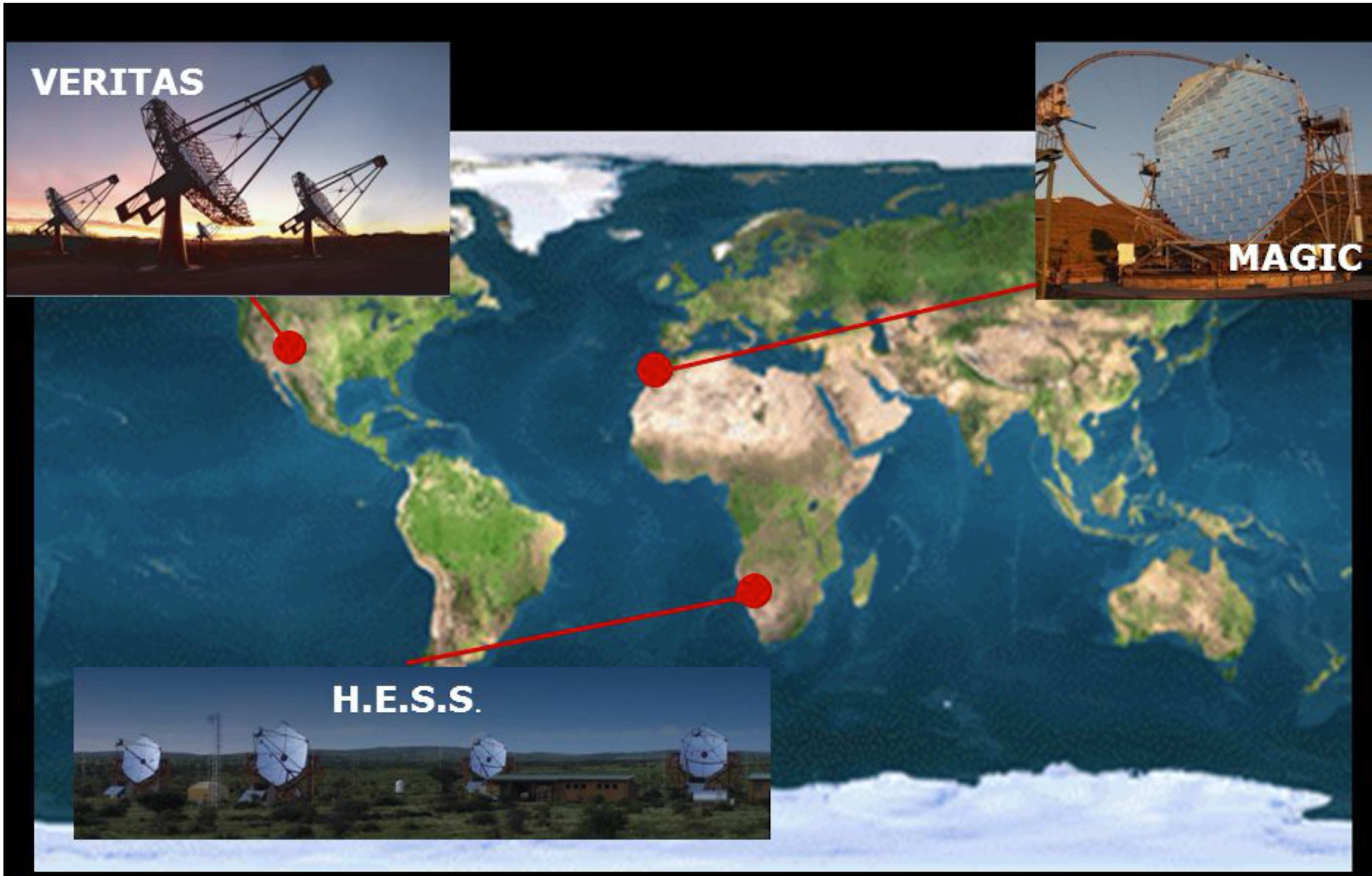
- 1960, COCCONI; THE CRAB NEBULA SHOULD EMIT GAMMA-RAY PHOTONS

- **1989: CRAB NEBULA** OBSERVED BY THE 10 M TELESCOPE WHIPPLE (Weekes+ 89)

- FLUX FROM CRAB: 6 PHOTONS/ m^2/yr



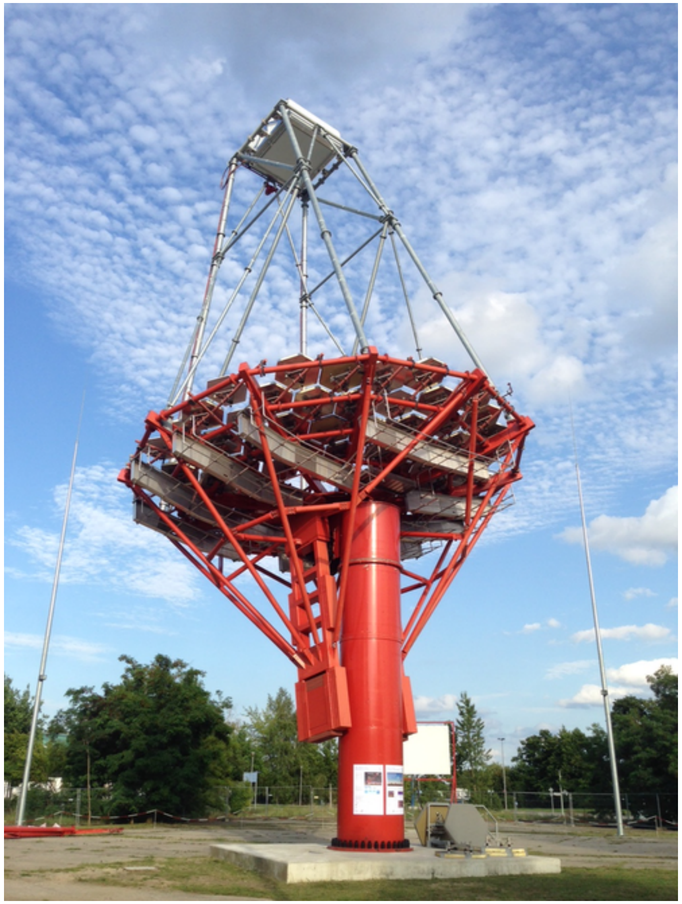
PRESENT DAY ATMOSPHERIC CHERENKOV TELESCOPES

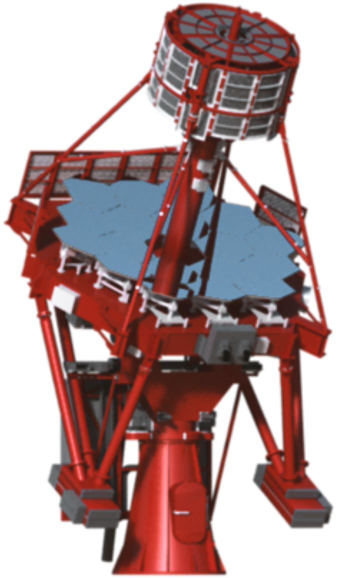


CTA


Heidelberg
MPIK
Zeuthen
DESY
Spain
La Palma
Bologna
INAF
northern hemisphere
southern hemisphere
Chile
Paranal
La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google
Array Sites
CTAO Offices
Science Data Management Centre

CTA TELESCOPES

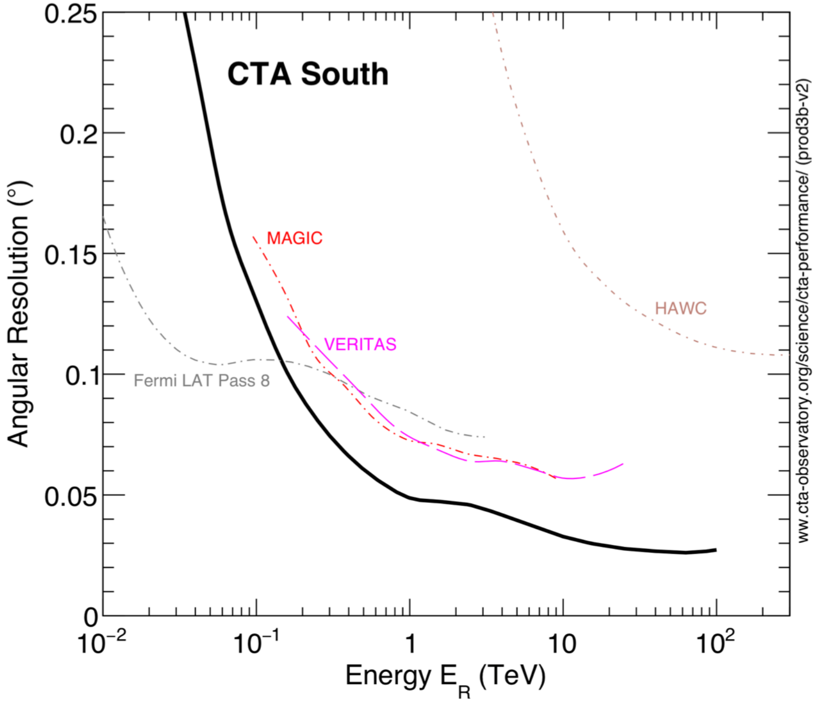


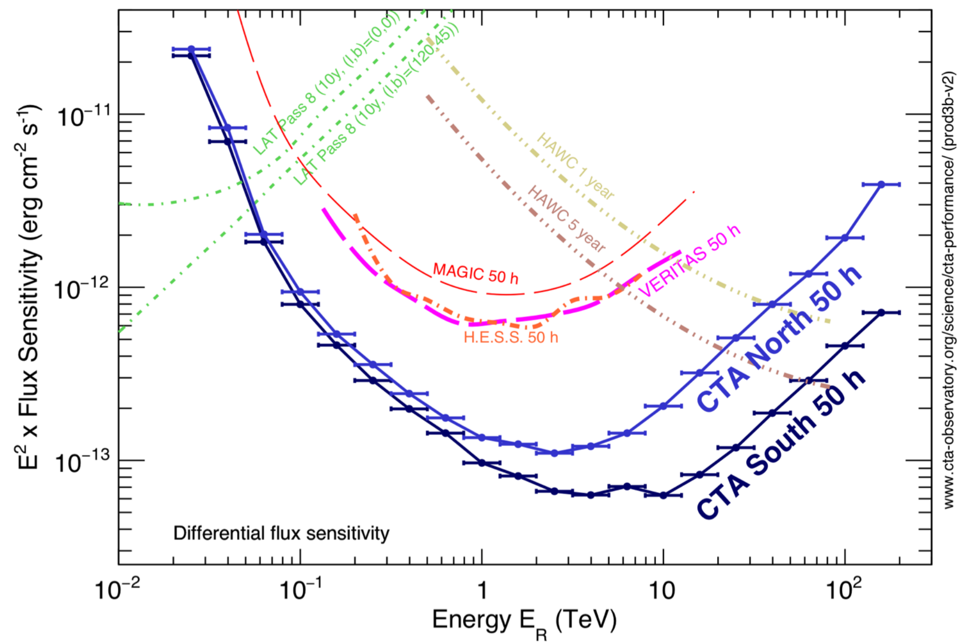


SST-2M ASTRI

- 4 LARGE (23 M) N/S
- 15/25 MEDIUM (12 M) N/S
- 70 SMALL (2M) S

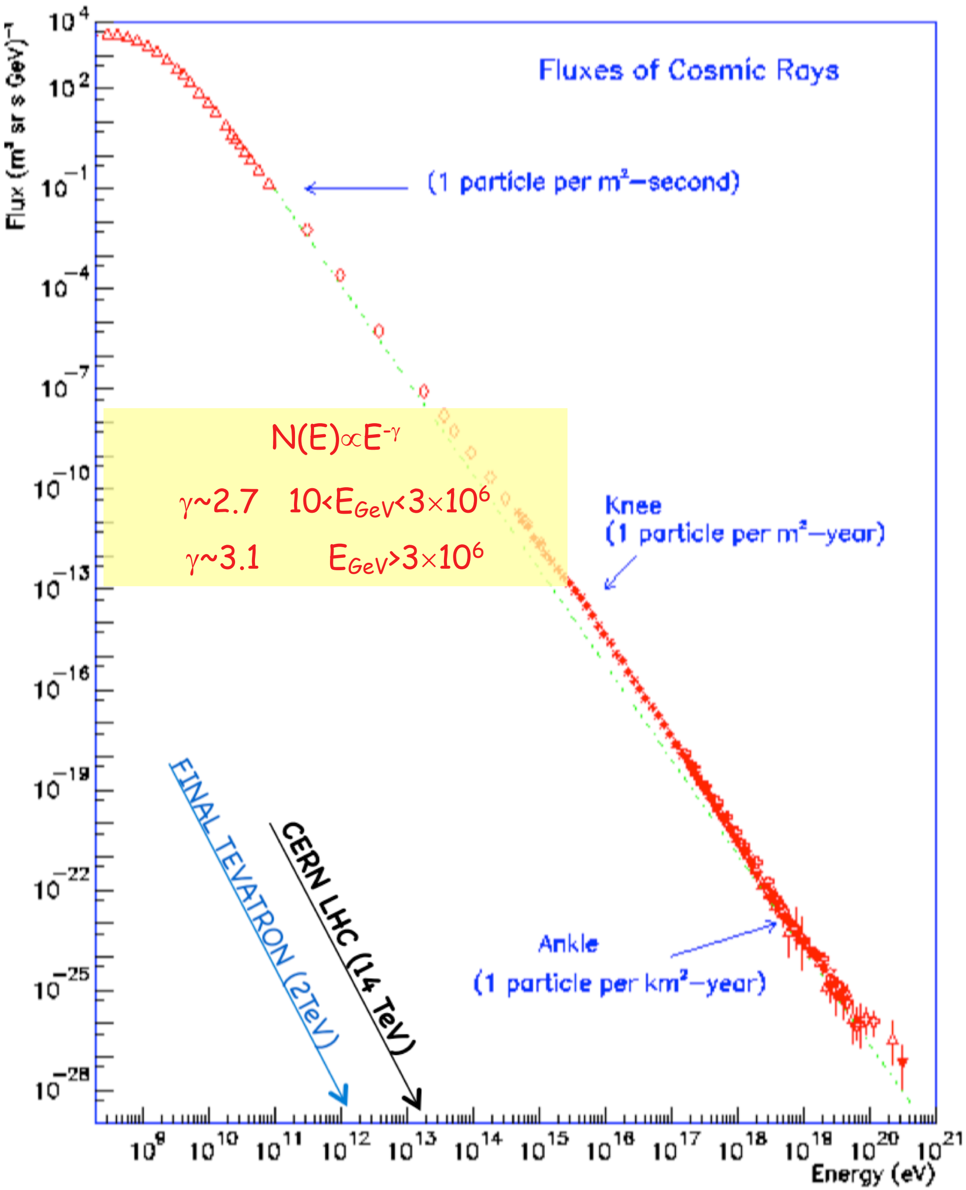
CTA PERFORMANCE





WHAT
CTA WILL DO FOR
COSMIC RAY PHYSICS

COSMIC RAYS



- ➢ 98% PROTONS AND NUCLEI
  - 87% PROTONS
  - 12% He
  - 1% HEAVIER NUCLEI
- ➢ 2% ELECTRONS
- ➢ 10^{-3} ANTIMATTER (POSITRONS AND ANTI-PROTONS)

$n \sim 10^{-9}$ cm^{-3}

VERY FEW PARTICLES BUT WITH AN ESSENTIAL ROLE FOR THE WORKINGS OF THE ENTIRE COSMOS

THE BIG QUESTIONS

- WHAT ARE THE MAIN SOURCES OF GALACTIC COSMIC RAYS?
- WHERE ARE THE GALACTIC PEVATRONS HIDING?

- WHAT IS THE END OF THE CR LEPTON SPECTRUM?
- CAN WE USE IT TO CONSTRAIN LOCAL TURBULENCE?
- PWNe?

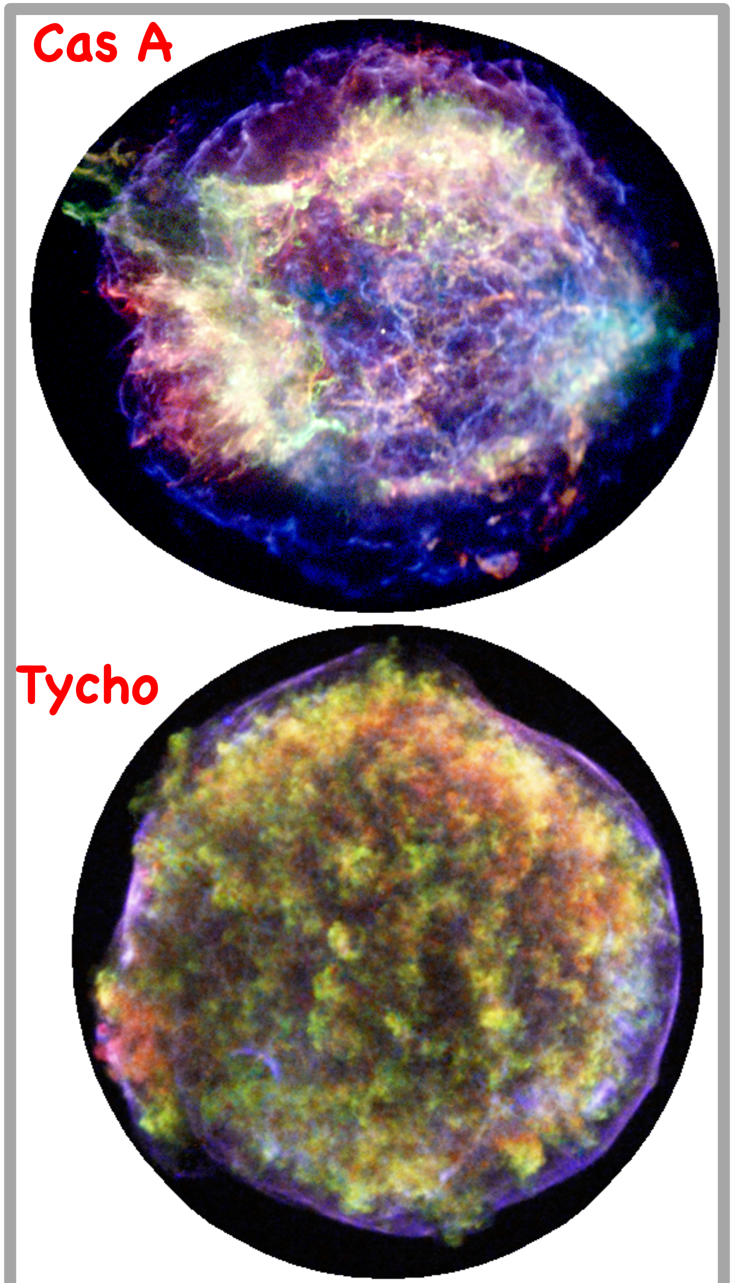
- IS THE CR SPECTRUM UNIVERSAL THROUGHOUT THE GALAXY?
- GALACTIC CENTRE PEVATRON AND ITS NATURE

- WHAT IS THE INTERPLAY BETWEEN CRS AND STAR FORMATION AT ALL SCALES
- IS THERE A UNIVERSAL GAMMA-RAY/IR RELATION?

- CRS AND IN OTHER GALAXIES: THE LMC

- WHAT IS THE ROLE OF CRS IN TERMS OF COSMOLOGICAL FEEDBACK?
- CR CONTRIBUTION TO GALAXY CLUSTER PHYSICS

GALACTIC COSMIC RAYS



- **ASSOCIATION WITH SNRS SUGGESTED SINCE THE '30S** (Baade&Zwicky 34)

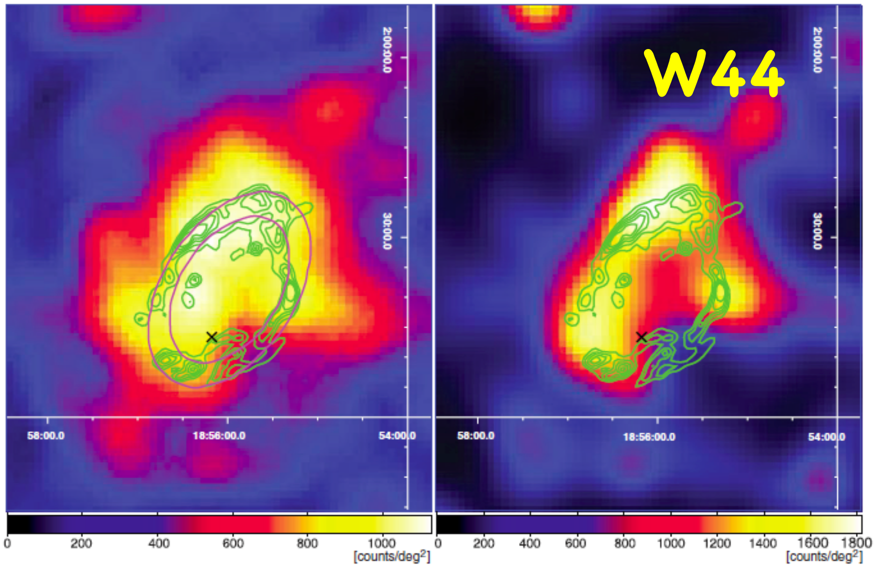
  $L_{CR} \sim 3 \times 10^{40}$ erg $s^{-1} \sim 10\%(10^{51}$erg/100yr)

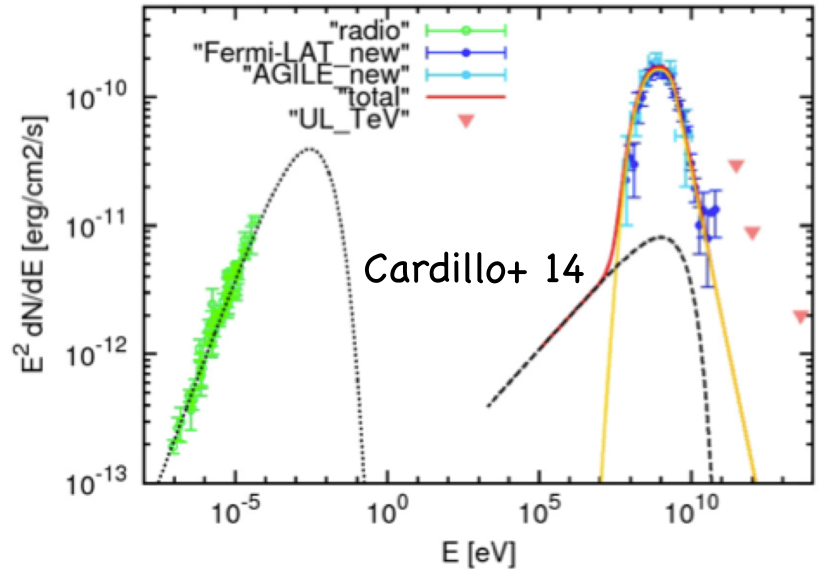
- **ACCELERATION MECHANISM SUGGESTED IN THE '70s**
  (Krymski 77, Bell 78, based on Fermi 49)

- **FIRST INDIRECT EVIDENCE: X-RAY OBSERVATIONS OF THIN SYNCHROTRON FILAMENTS IN YOUNG SNRs** (e.g. Ballet 06, Vink 12 for a review):
  MULTI-TeV ELECTRONS, AMPLIFIED B-FIELD

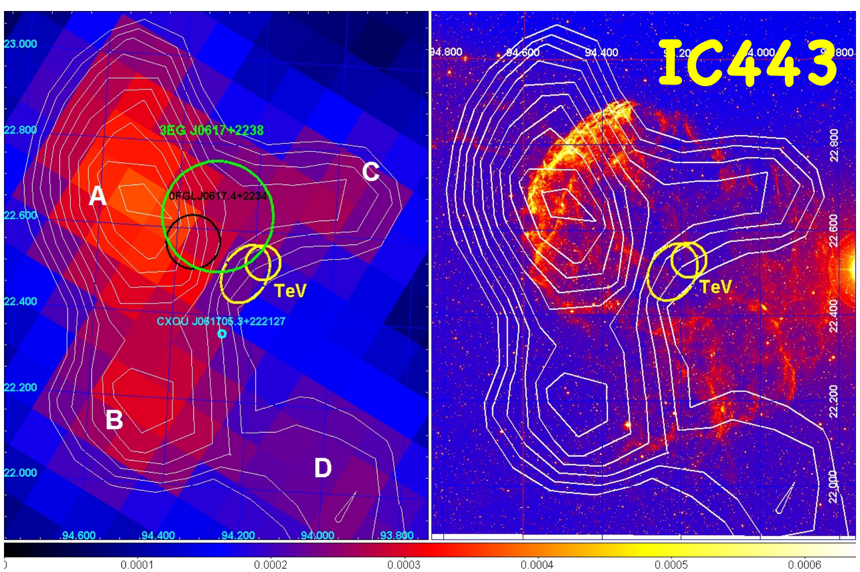
- **DIRECT EVIDENCE OF PROTON ACCELERATION IN MIDDLE-AGED SNRs: W44, IC443** (Agile, Fermi 09-10)

W44 & IC443

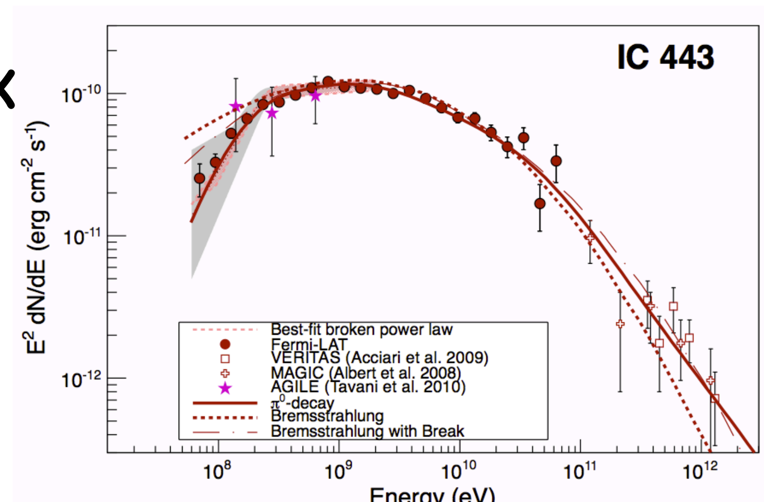




"PION BUMP" IN MIDDLE AGED SNRS INTERACTING WITH MOLECULAR CLOUDS *Fermi* (Abdo+ 09,10; Ackerman+ 13) & *Agile* (Giuliani+ 10,11; Cardillo+ 14)

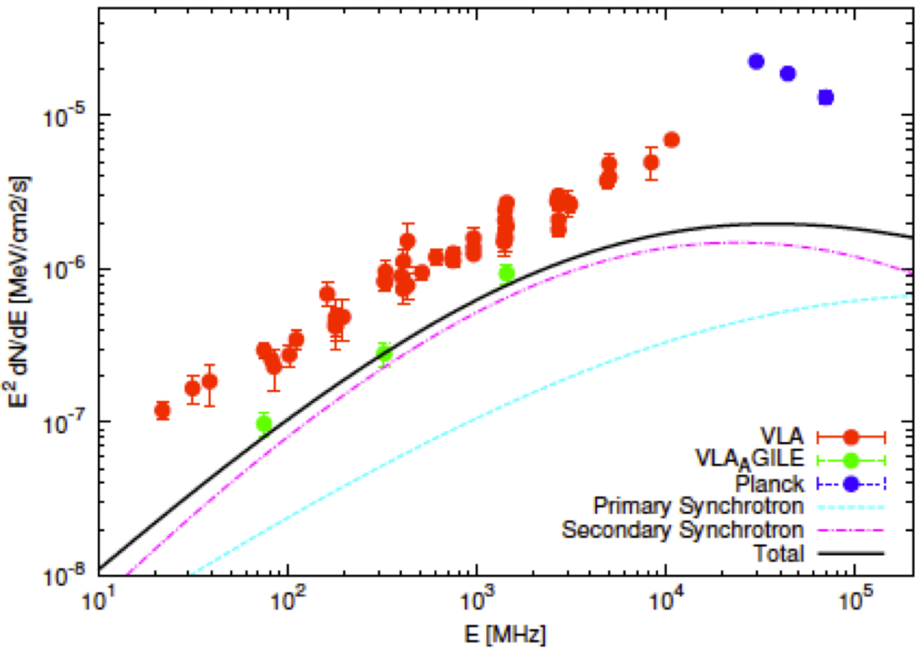


LOW MAX ENERGY

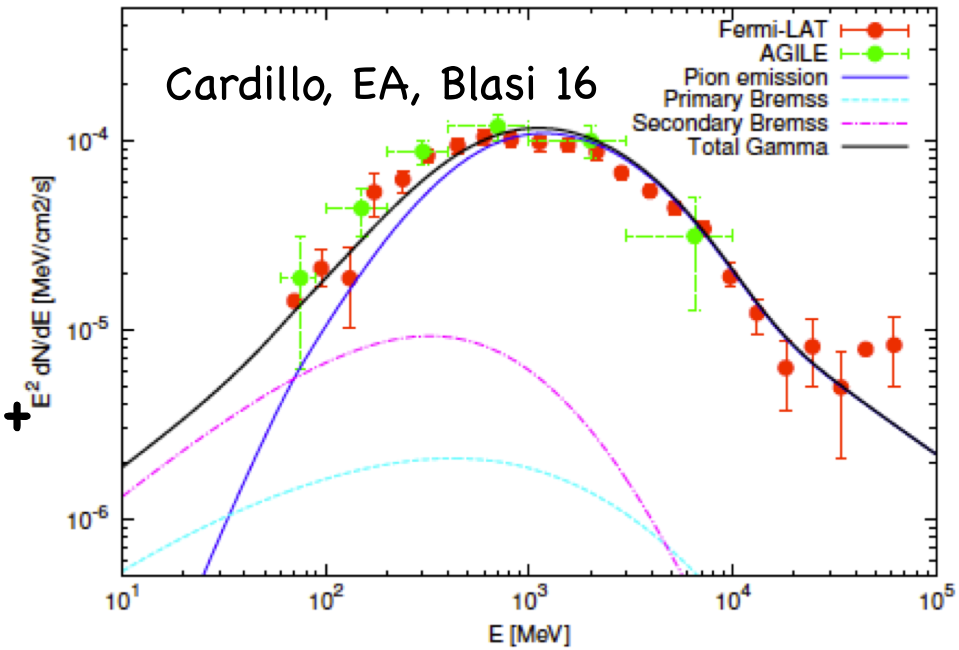


RE-ACCELERATION?

W44: MOSTLY REACCELERATION



+



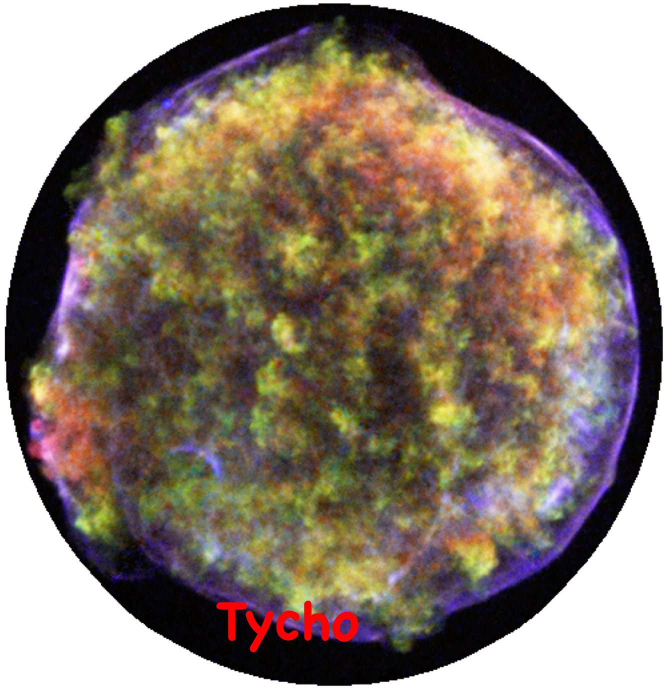
$$\boxed{p_{\rm MAX} = 20{\rm GeV/c}\left(\frac{B_0}{3\mu G}\right)\left(\frac{t_{\rm int}}{2\times 10^4{\rm yr}}\right)\left(\frac{L_c}{0.1pc}\right)^{-1}\left(\frac{v_S}{100{\rm km/s}}\right)^4}$$

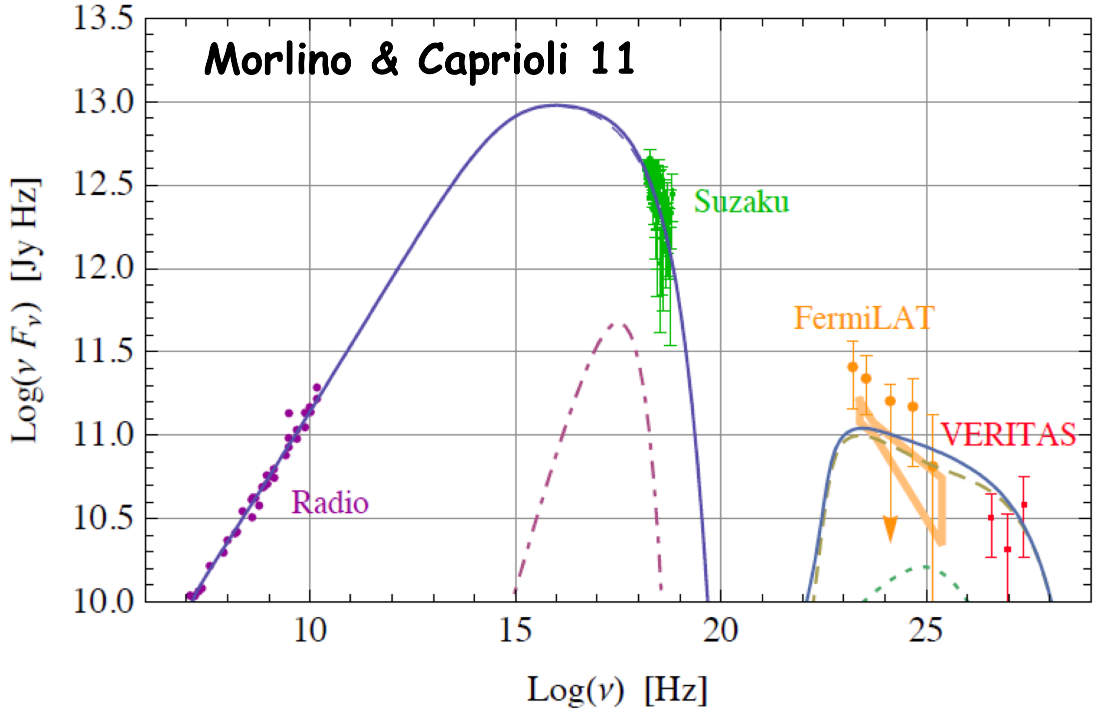
$\xi_{CR} \approx 2 \times 10^{-5}$

- **OLD, SLOW SHOCK, LOW EFFICIENCY**
- **BRIGHT THANKS TO WEALTH OF TARGET**

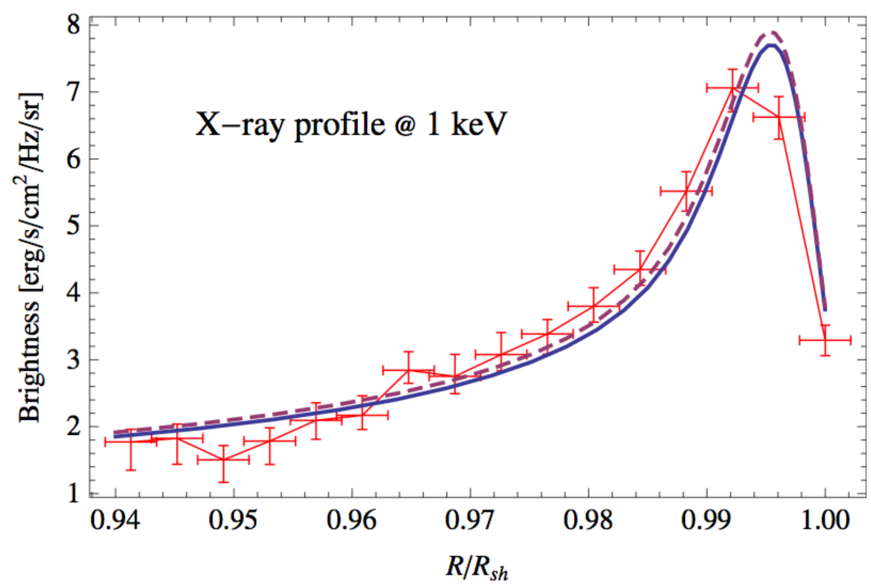
LOOK FOR EFFICIENT ACCELERATION ELSEWHERE, e.g. TYCHO (Morlino&Caprioli 12)

YOUNG SNRs





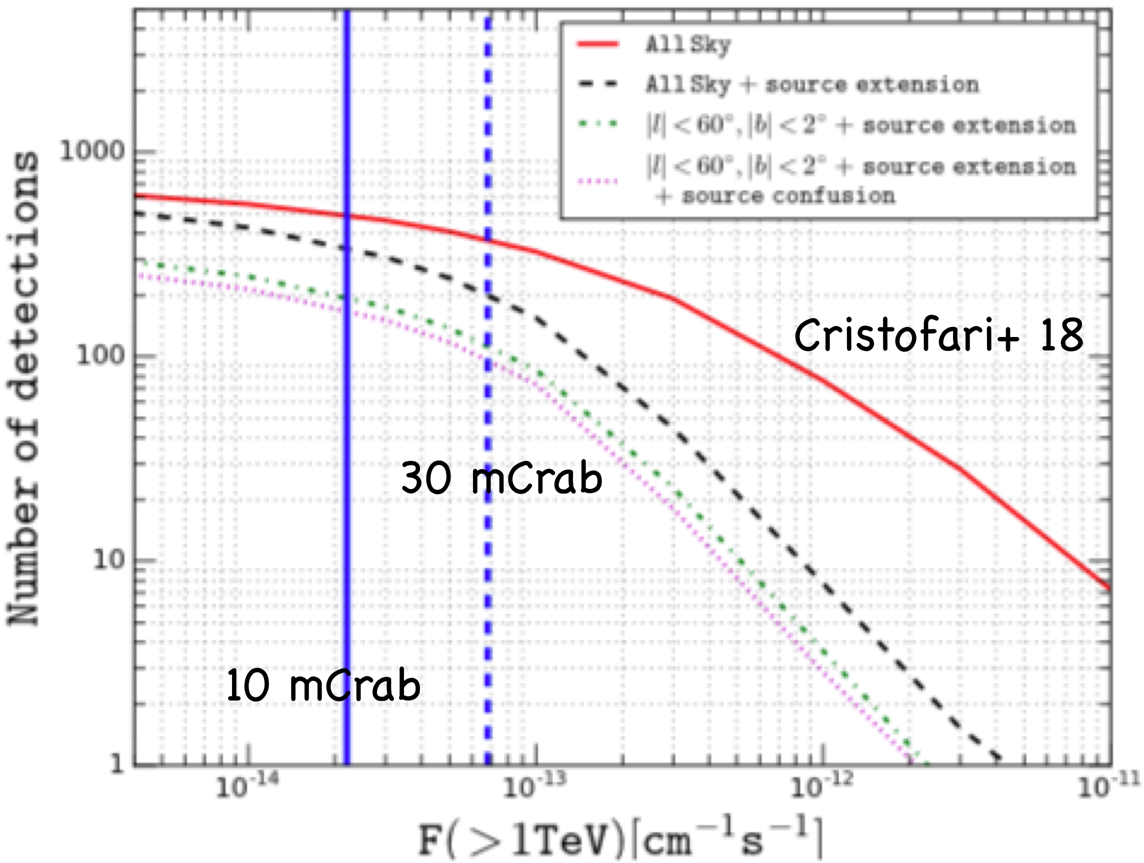
- E_{MAX} ≈500 TEV
- ξ_{CR} ≈10%



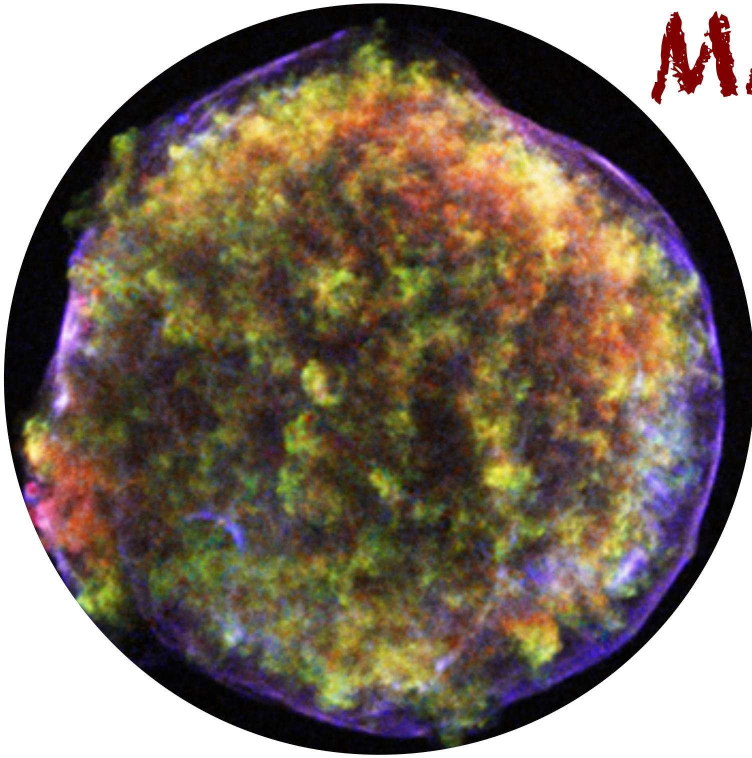
TeV GAMMA-RAYS DETECTED FROM >10 SNRs:

- MOST SHOW STEEP SPECTRA
- CUTOFF/BREAK E_γ<10 TEV

DETECTING PEVATRON SNRS WITH CTA



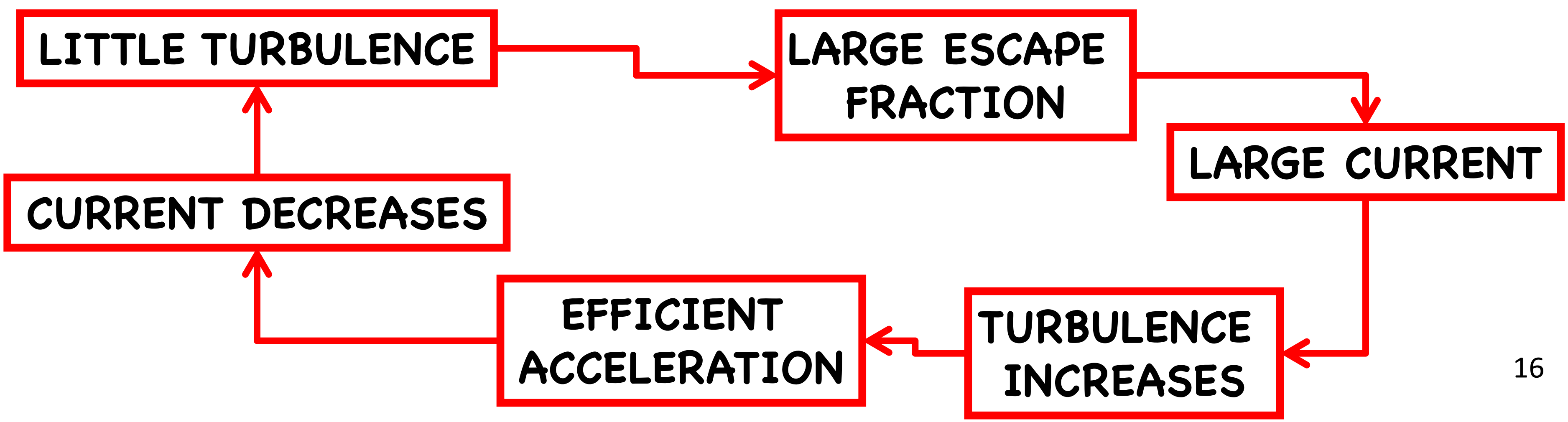
- 100s OF NEW DETECTIONS OF SNRS
- COMPETING WITH RADIO WAVELENGTH DETECTIONS



MAXIMUM ENERGY IN SNRs

- MFA (Bell 04) DUE TO CURRENT OF ESCAPING PARTICLES
- GROWTH RATE PROPTO J_{CR} WHICH DEPENDS ON SPECTRUM AT THE SHOCK, P_{MAX} AND V_S (Schure & Bell 13, Cardillo, EA, Blasi 15)

SELF-REGULATION MECHANISM



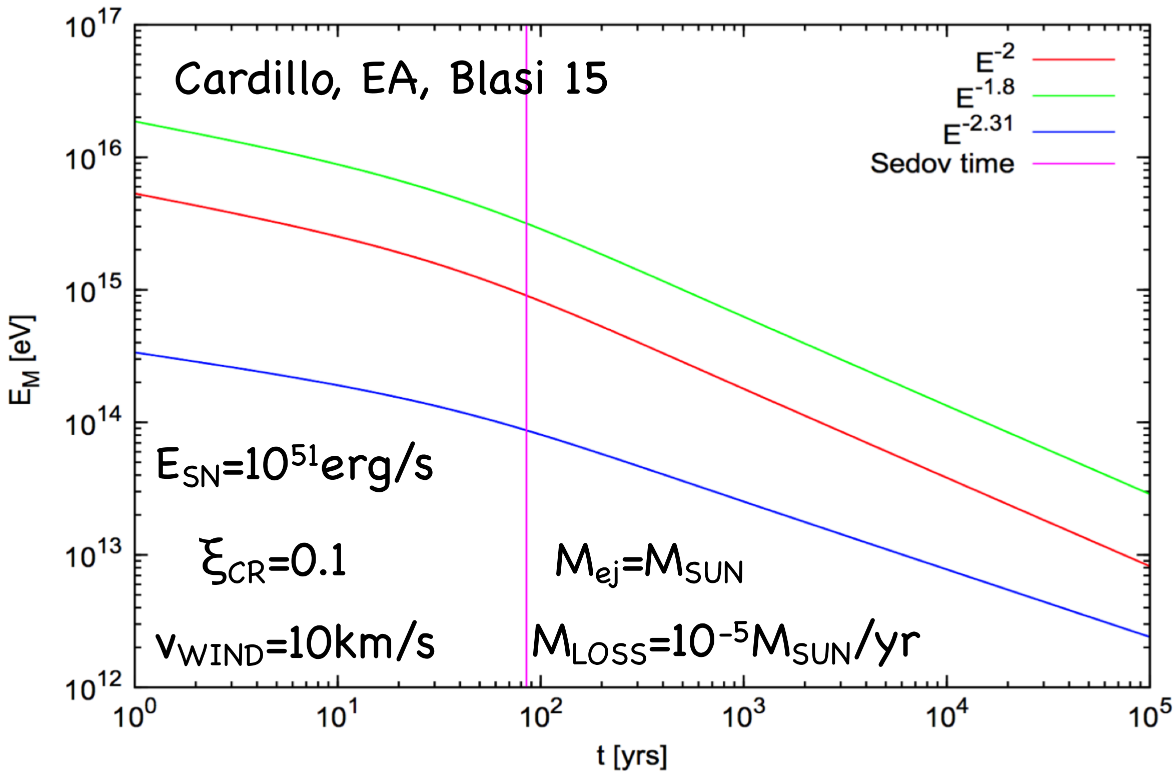
PEVATRONS

TYPE I

$$E_M \approx 130 \left(\frac{\xi_{\rm CR}}{0.1}\right)\left(\frac{M_{\rm ej}}{M_\odot}\right)^{-\frac{2}{3}}\left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)\left(\frac{n_{\rm ISM}}{\rm cm^{-3}}\right)^{\frac{1}{6}} {\rm TeV}$$

TYPE II

$$E_M \approx 1 \left(\frac{\xi_{\rm CR}}{0.1}\right)\left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1}\left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)\left(\frac{\dot{M}}{10^{-5}M_\odot{\rm yr}^{-1}}\right)^{\frac{1}{2}}\left(\frac{v_w}{10{\rm km/s}}\right)^{-\frac{1}{2}} {\rm PeV}$$

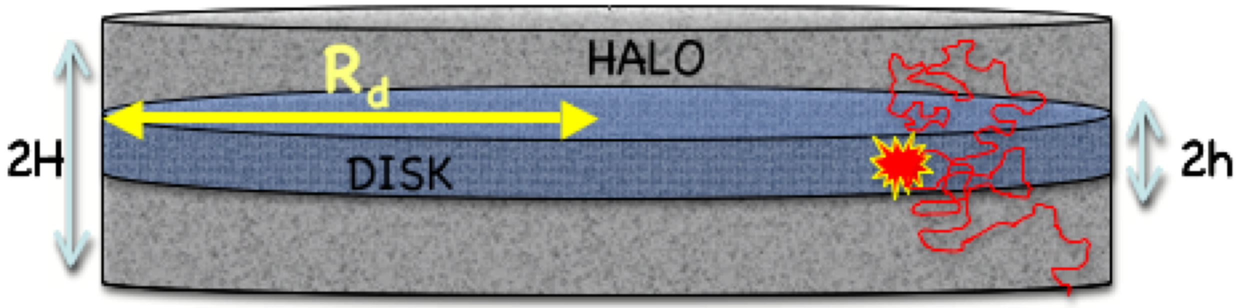


RECENT B/C BY AMS-02 INDICATES STEEP CR INJECTION SPECTRA:

$$N(E) \propto \frac{Q(E)}{D(E)} \propto E^{-\gamma-\delta}$$

$$\frac{N_{\rm sec}(E)}{N_{\rm prim}(E)} \propto \frac{1}{D(E)} \propto E^{-\delta}$$

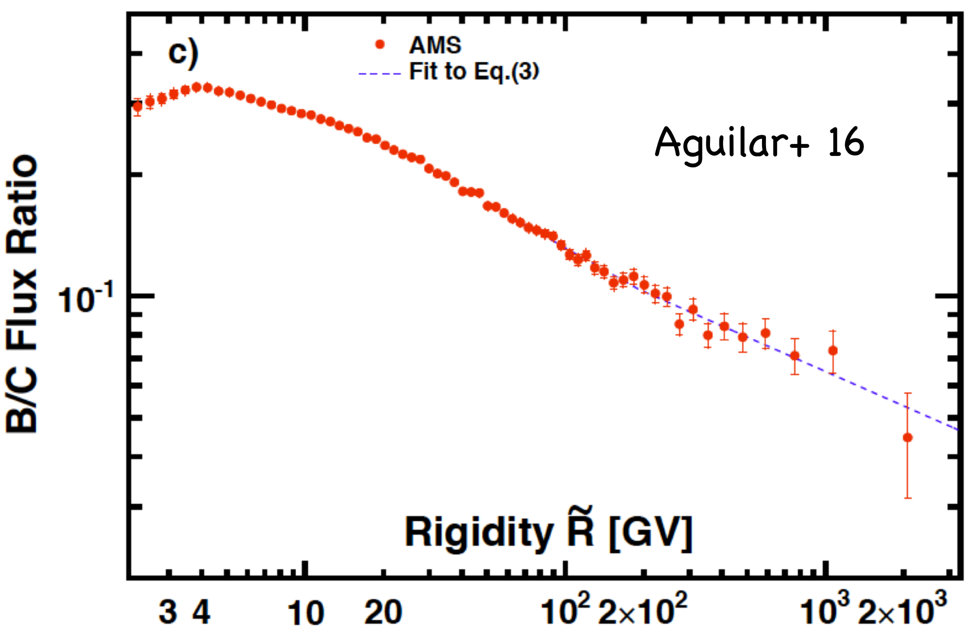
WORSENING THE PROBLEM



$$N(E) = Q(E)\tau_{ESC}$$

$$\tau_{ESC}(E) \approx \frac{H^2}{D(E)} \propto E^{-\delta_e}$$

$$N_{\rm prim}(E) \propto \frac{Q(E)}{D(E)} \propto E^{-\gamma-\delta_e}$$

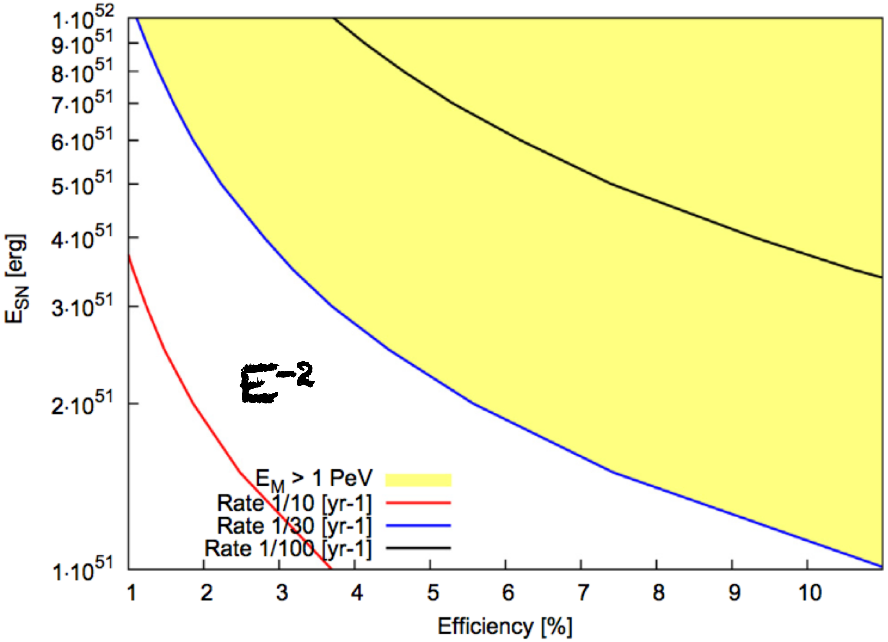


$$N_{\rm sec}(E) \propto N_{\rm prim}(E)\tau_{\rm esc}$$

AMS02 DATA POINT TO $\delta_e \sim 0.4$

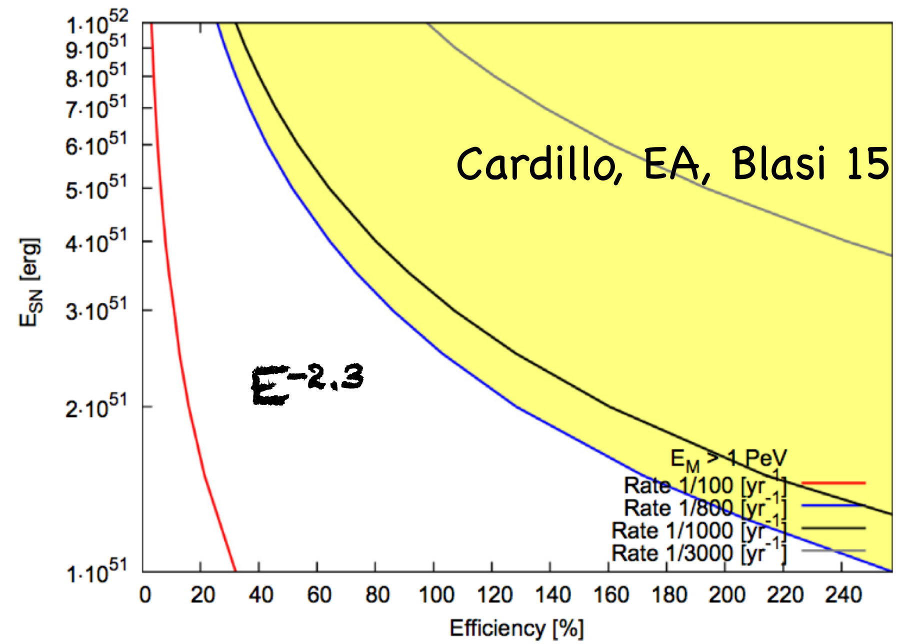
$\gamma \sim 2.3$

MAXIMUM ENERGY AND SOURCE SPECTRUM



$$E_{\rm MAX} \propto \xi_{\rm CR} E_{\rm SN}$$

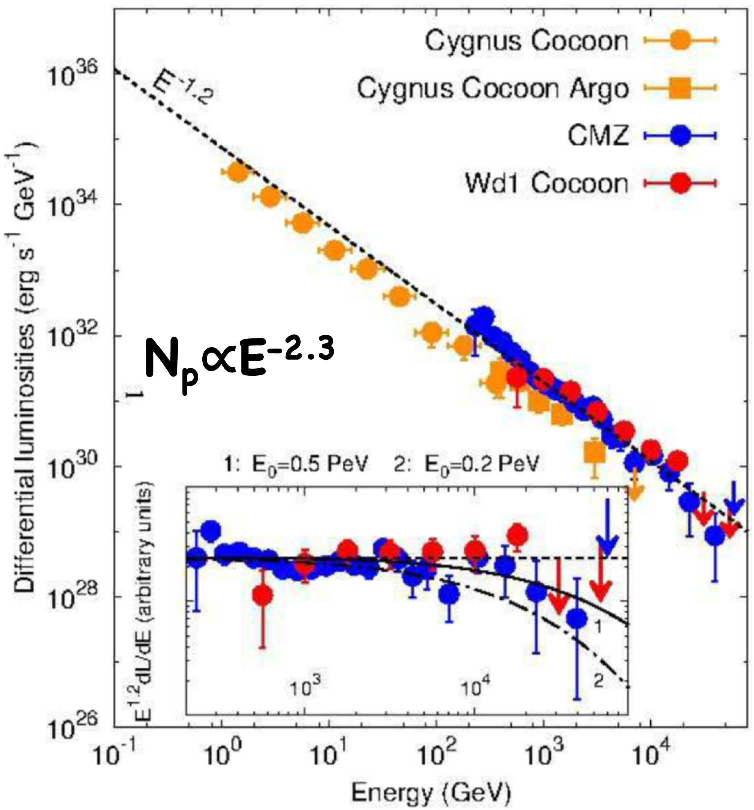
$$Flux \propto \xi_{\rm CR} E_{\rm SN} \mathcal{R}$$

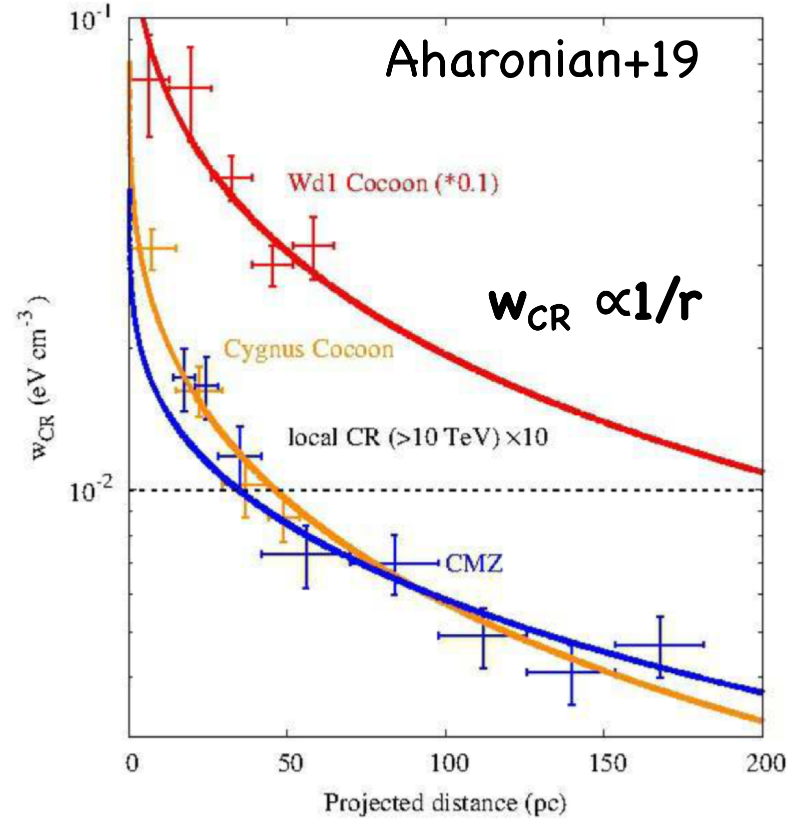


WITH Γ_{CR} >2,
P_{max}=PeV REQUIRES:

- **RARE** (<1/1000 yr^{-1})
- **EXTREME EVENTS** (E_{SN}>10^{52}erg)
- **EXTREME EFFICIENCY** (ξ_{CR}>30%)

MASSIVE STAR WINDS?





CR SPECTRUM AND ENERGETICS OK
WITH CONTINUOUS INJECTION OVER FEW X 10^6 YR

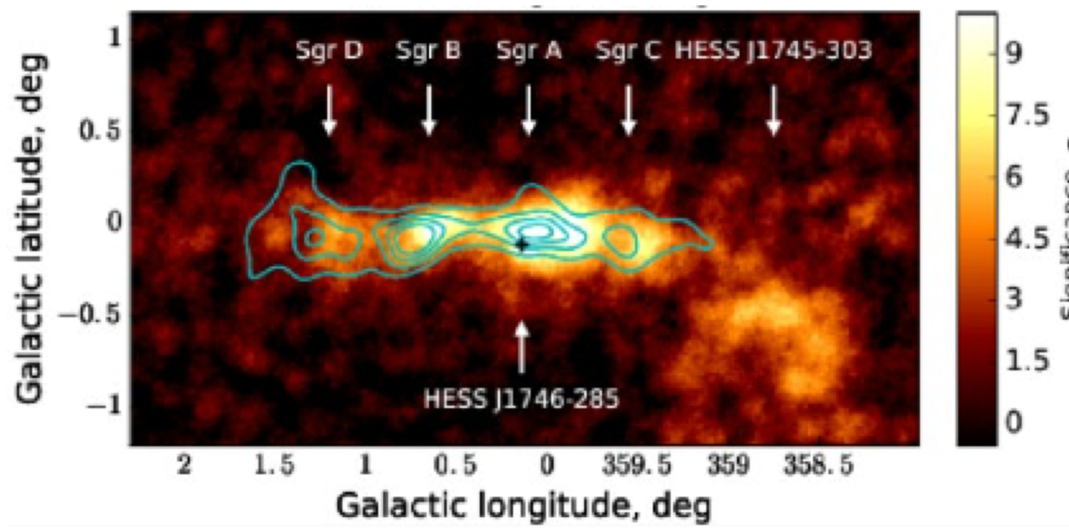
STRIKING SIMILARITY WITH GALACTIC CENTRE

WITH CTA:

- LOOK FOR CUTOFF
- CONSTRAIN SIZE OF EMITTING REGION (ENERGETICS)

THE GALACTIC CENTRE

- ➢ CLOSEST SUPERMASSIVE BH
- ➢ DENSE MOLECULAR CLOUDS
- ➢ MANY SNRs AND PWNe
- ➢ STAR FORMING ACTIVITY
- ➢ BASE OF LARGE-SCALE OUFLOW

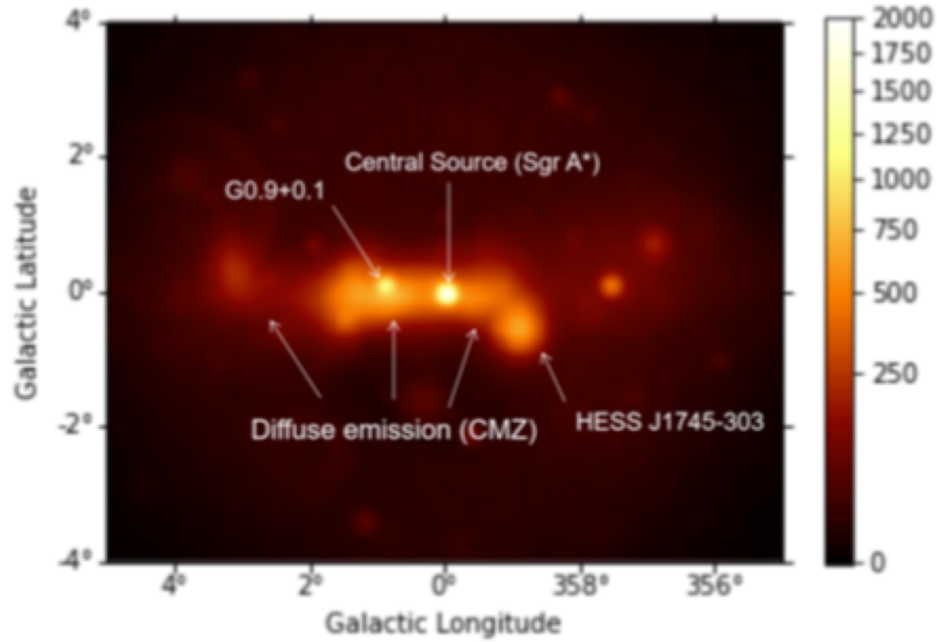


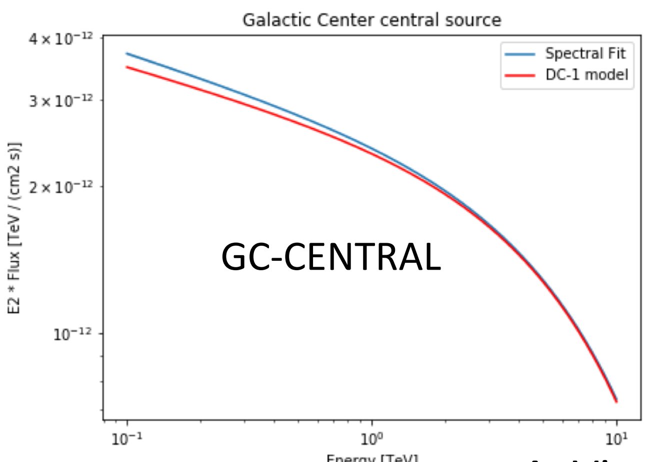
WITH CTA

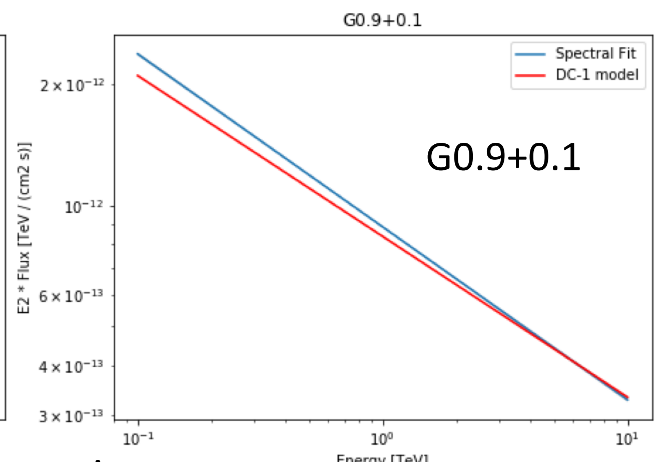
- NATURE OF POINT-LIKE CENTRAL GAMMA-RAY SOURCE
  - HIGH SPATIAL RESOLUTION, SENSITIVITY TO VARIABILITY
- PARTICLE ACCELERATION HISTORY
  - DISTINGUISH CLOUDS FROM INDIVIDUAL POINT SOURCES, LOOK FOR CUT-OFF
- NATURE OF LARGE-SCALE OUTFLOWS
  - DETECT FBs AT 3 SIGMA IN 50 HR
- STUDY SNRs, PWNe, MCs

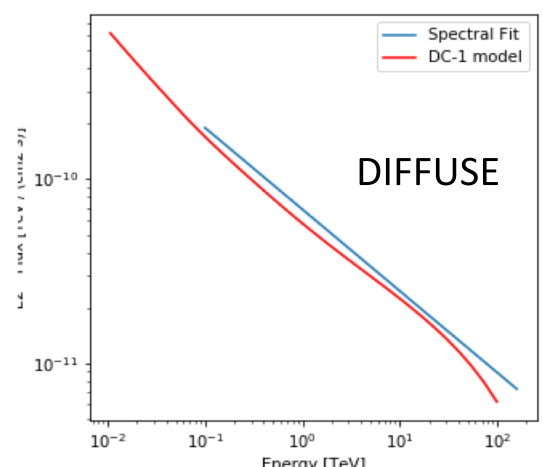
INDIVIDUAL SOURCES AND DIFFUSE EMISSION

SIMULATED CTA VIEW OF INNER 4^0







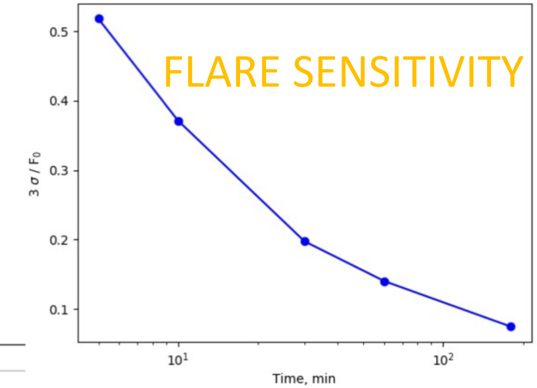


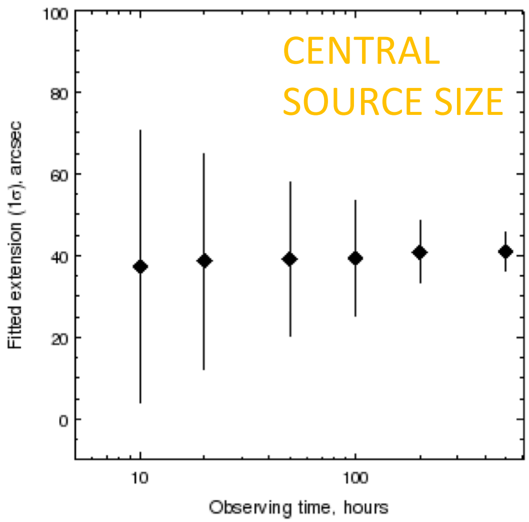
A. Viana + in prep.

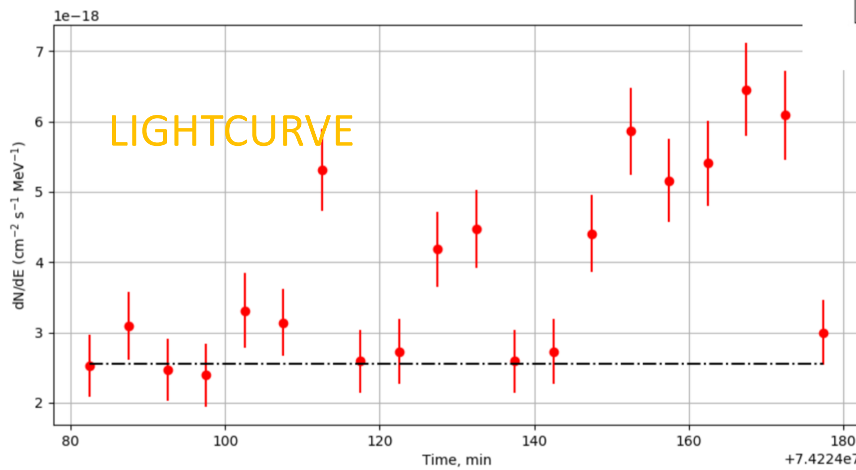
CENTRAL SOURCE AND J1741-302

CTA CAN UNCOVER:

- **CENTRAL SOURCE EXTENSION**
- **CENTRAL SOURCE VARIABILITY**
- **SPECTRAL VARIABILITY WITH T<30 MIN**



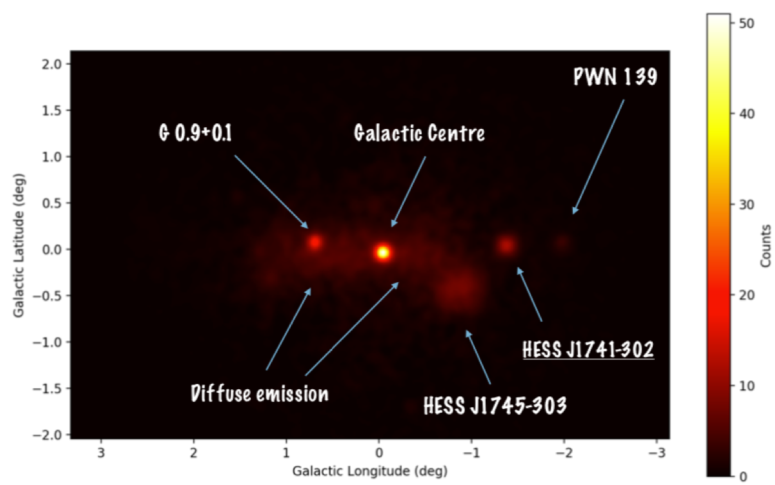




A. Viana + in prep.

CTA CAN DETERMINE:

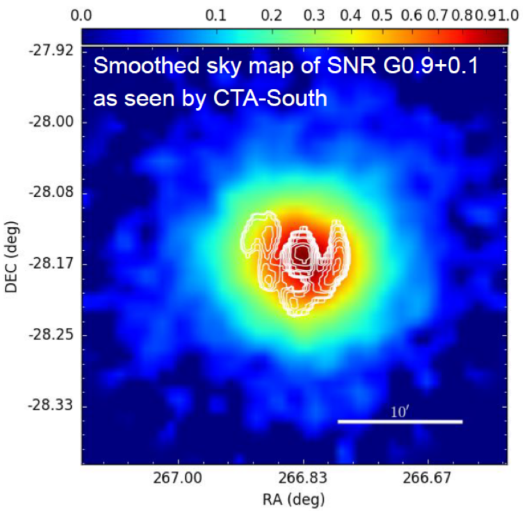
- **J1741-302 CUTOFF**
  (CURRENTLY UNDETECTED TO 10 TeV)
- **NATURE OF EMISSION**
  (LEPTONIC VS HADRONIC)



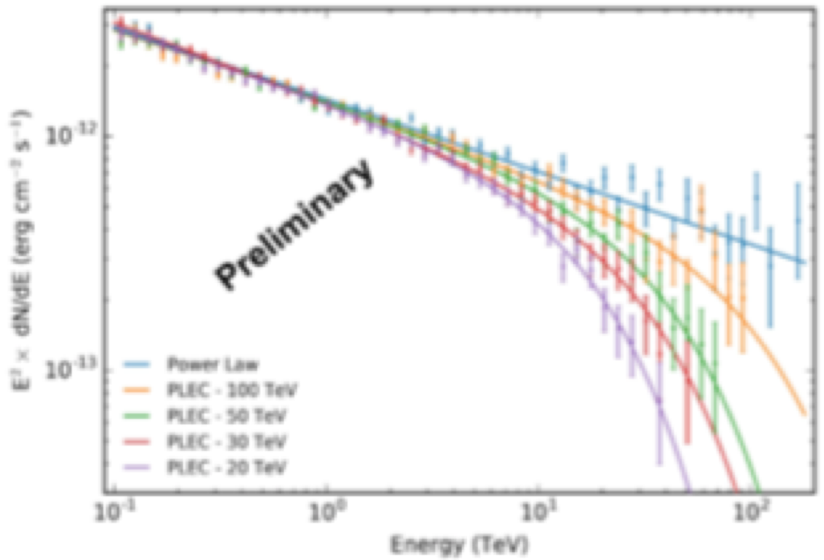
CTA CAN UNCOVER:

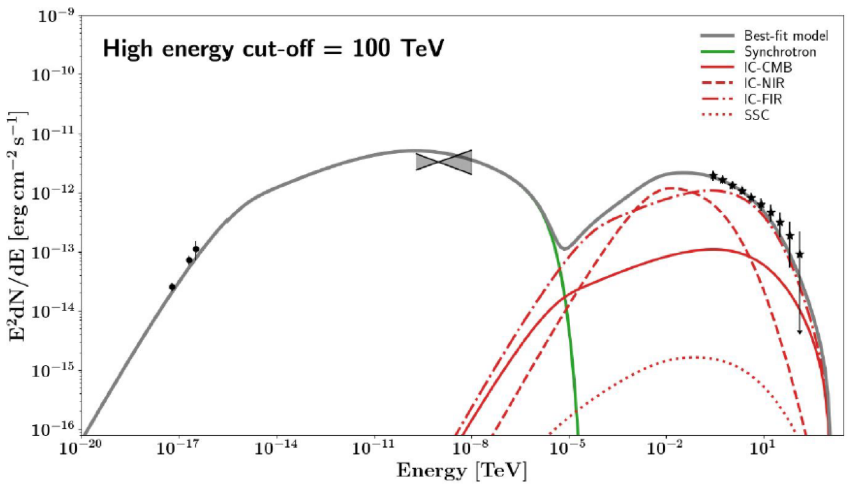
G0.9+0.1

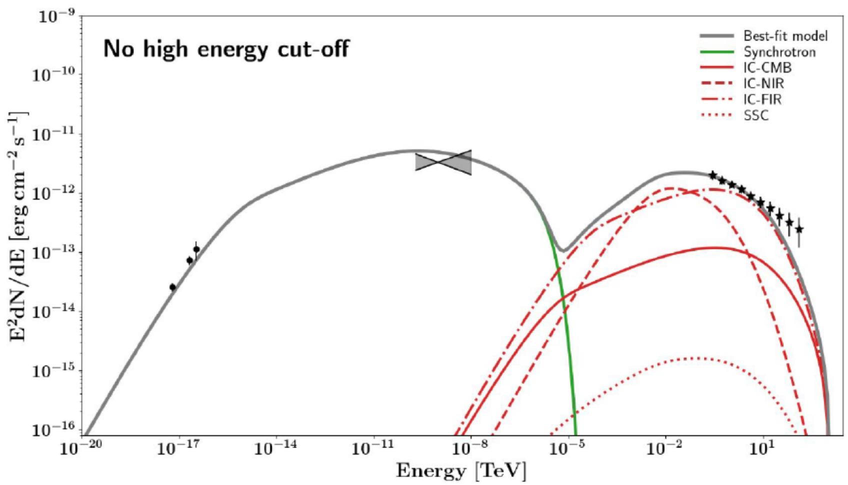
- MORPHOLOGY
- SPECTRAL CUT-OFF UP TO 100 TeV
  (200 h observation)



SIMULATED OBSERVATIONS

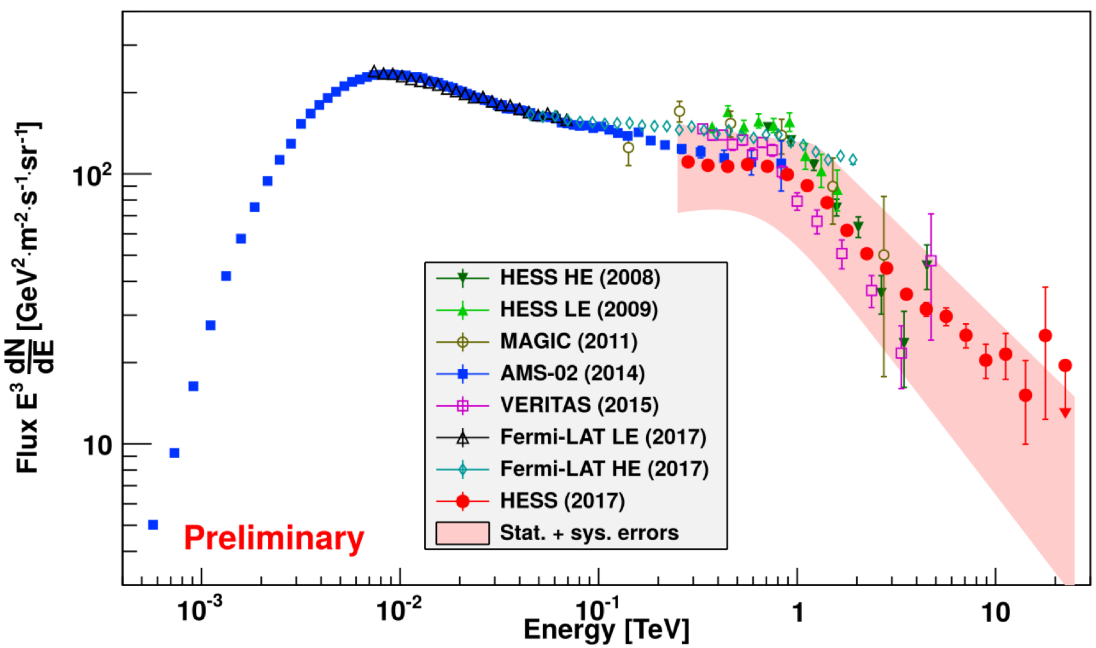






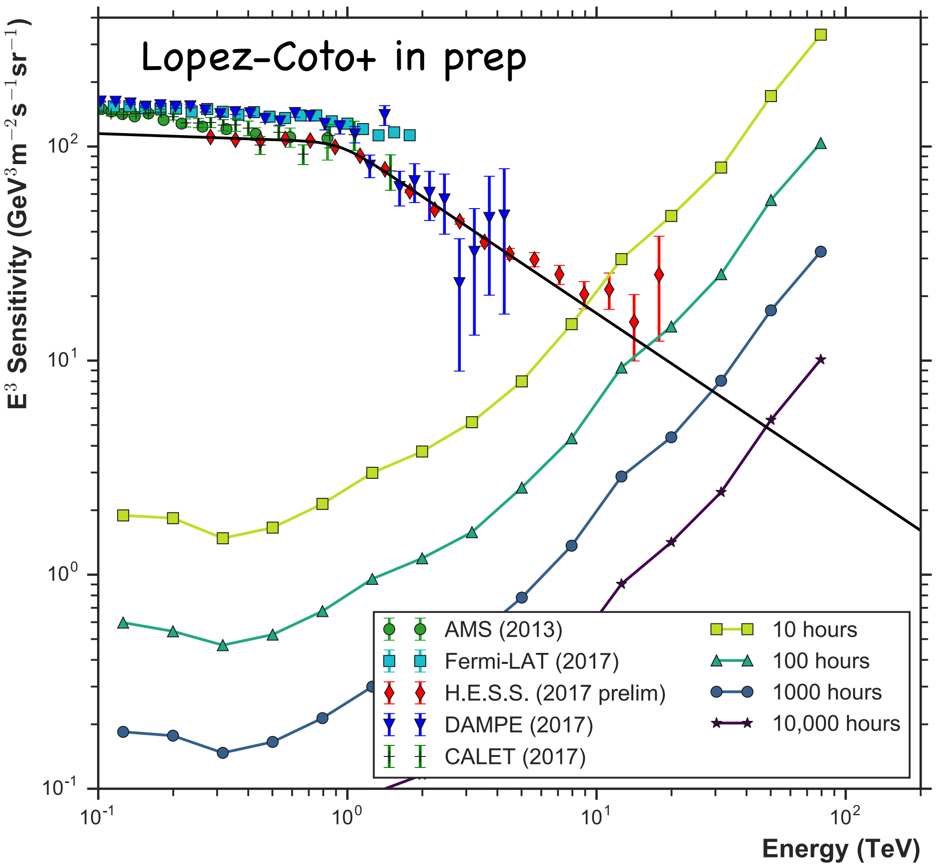
COSMIC RAY ELECTRONS

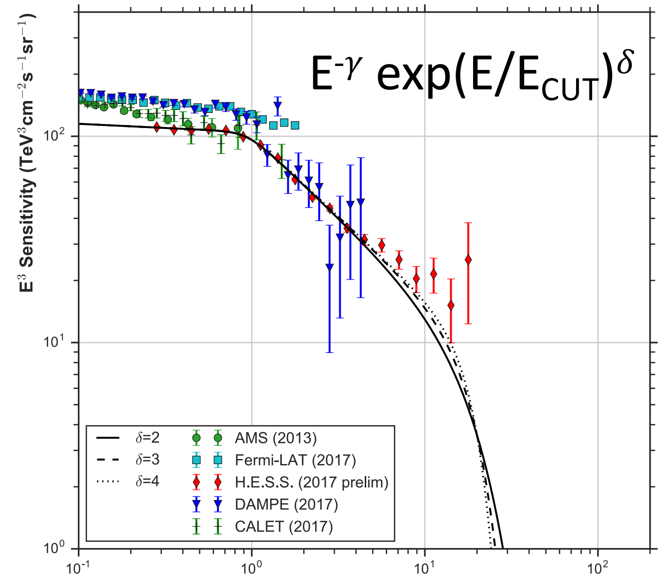
- CR ELECTRONS AT E>10 TeV PROBE THE LOCAL CR ACCELERATION ENVIRONMENT (LOSS LENGTH ~100 pc)
- IACT SUITABLE FOR MEASUREMENTS (SEE H.E.S.S.)
- BROKEN POWER-LAW [SLOPE -3(-3.8) BELOW (ABOVE) 1TeV] DIFFICULT TO INTERPRET
- FINDING A CUT-OFF

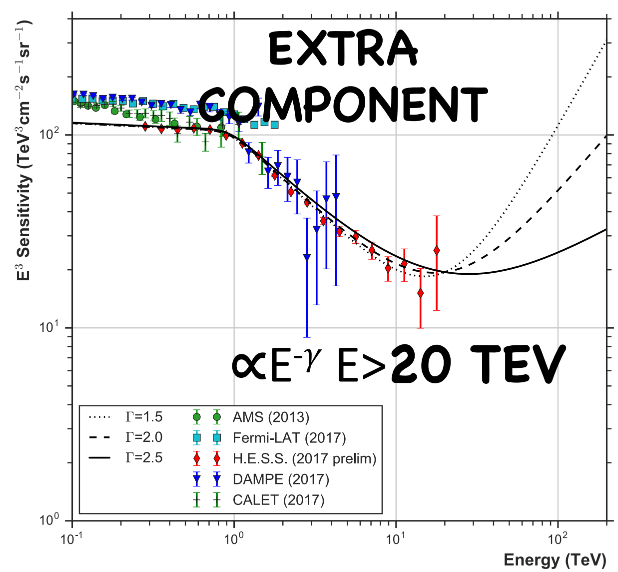


ELECTRONS WITH CTA

3-SIGMA MEASUREMENT







CLUSTERS OF GALAXIES

LARGEST GRAVITATIONAL STRUCTURES IN THE UNIVERSE:

30-300 GALAXIES, R ~FEW Mpc, M~10^{14}-$10^{15}M_{\odot}$

30% BARYONS (10% STARS, 15-20% HOT DIFFUSE GAS)

70% DARK MATTER

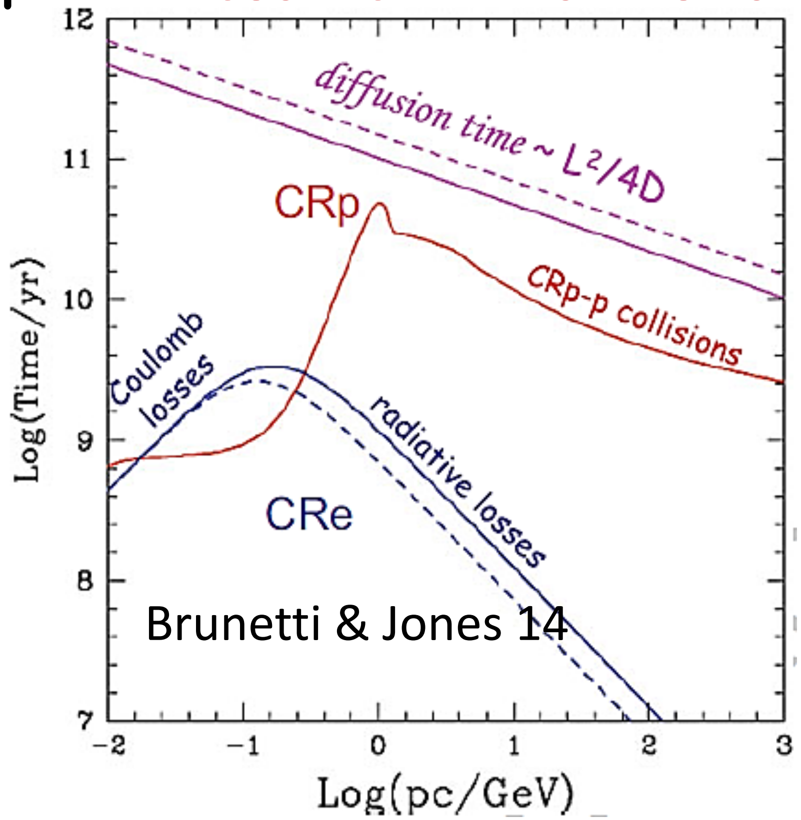
ENERGY INPUT (MERGERS): 10^{64} erg/Gyr

CLUSTER SCALE RADIO EMISSION

OPEN QUESTIONS FOR CTA

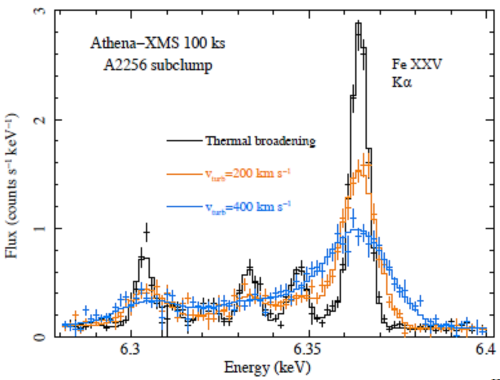
- DETECT GAMMA-RAY EMISSION FOR FIRST TIME
- DETERMINE CR PROTON CONTENT AND DYNAMICAL IMPACT
- CR ACCELERATION, PROPAGATION, CONFINEMENT
- ELECTRON ACCELERATION
- MAGNETIC FIELD DISTRIBUTION

COSMIC RAY RESERVOIRS

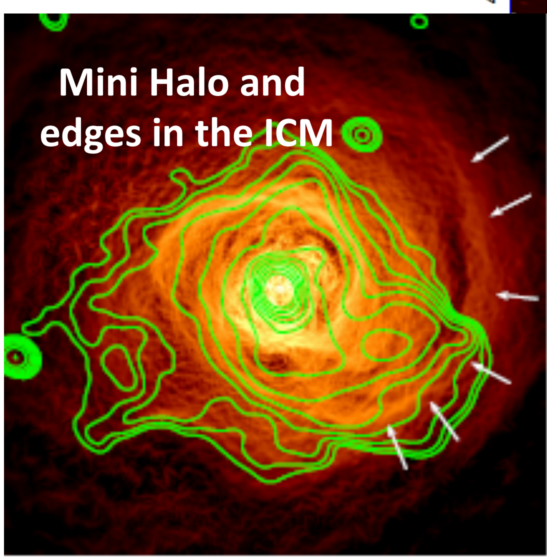


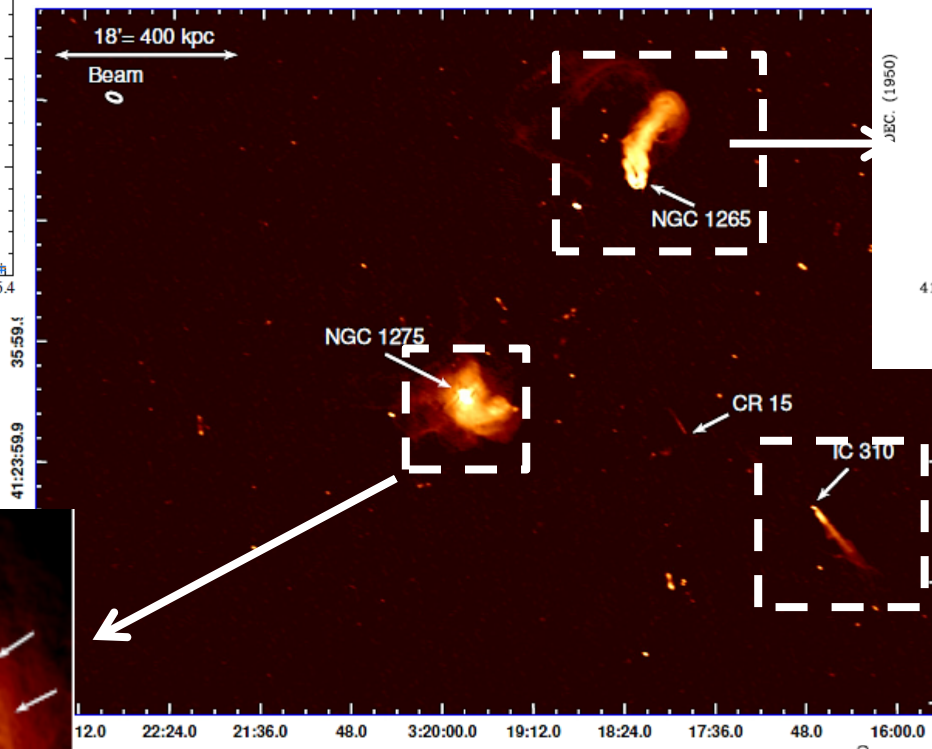
CTA KSP ON PERSEUS

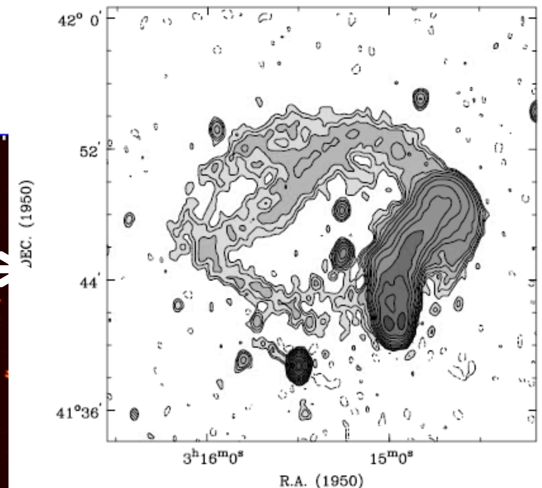
Hitomi Coll, 16

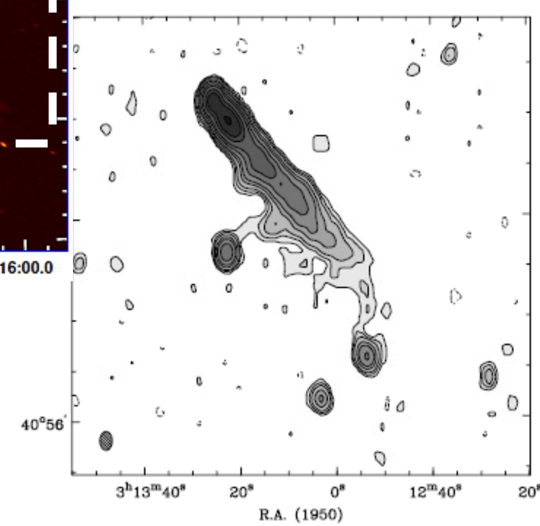


turbulence



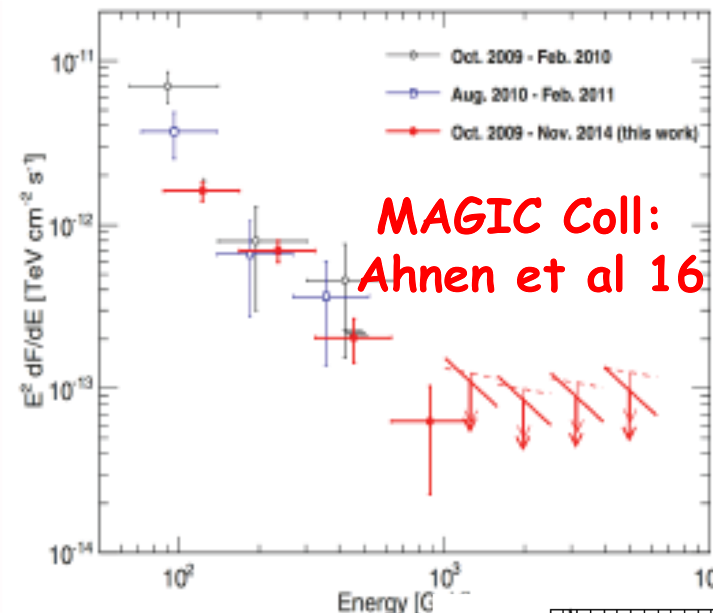


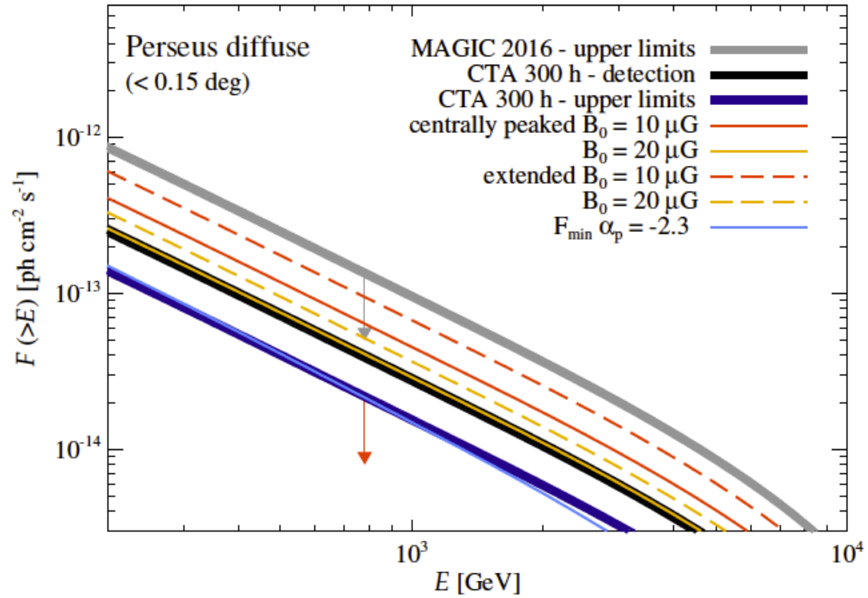


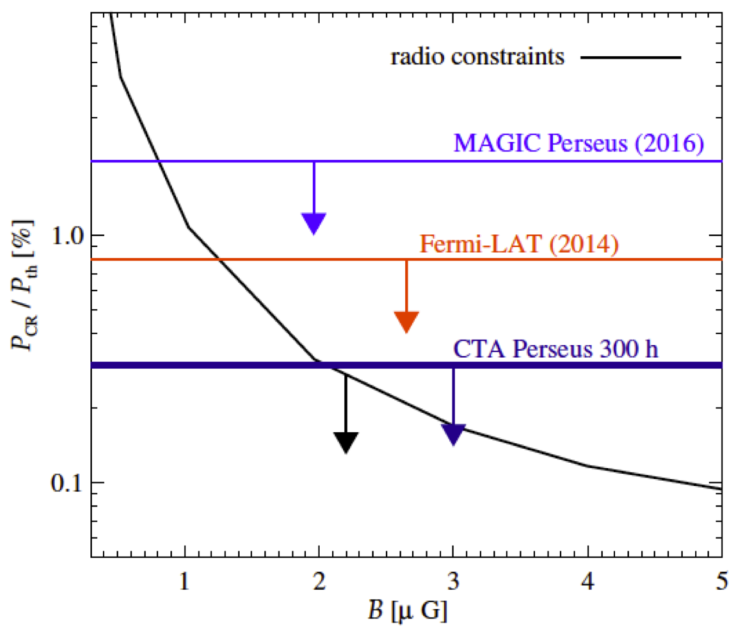


- ❑ +Nearby massive
- ❑ Brightest (ICM targets)
- ❑ AGNs sources of CRs
- ❑ Turbulence : CR transport

LIMITS ON CRs IN PERSEUS







SUMMARY AND CONCLUSIONS

- ✓ MANY OPEN QUESTIONS IN CR PHYSICS
- ✓ CTA WILL GREATLY CONTRIBUTE TO CLARIFY SOME OF THEM
  - ❑ THE NATURE OF GALACTIC PEVATRONS
  - ❑ PHYSICS IN THE GALACTIC CENTRE REGION
  - ❑ HELP CONSTRAIN GALACTIC PROPAGATION IN OUR NEIGHBOURHOOD THROUGH MEASUREMENYS OF MUTI-TEV ELECTRONS
    - AT THE SAME TIME CLARIFY ORIGIN OF POSITRON EXCESS
  - ❑ CR CONTENT OF GALAXY CLUSTERS
    - COSMOLOGICAL IMPACT OF CRs
- ✓ EXCITING TIMES AHEAD