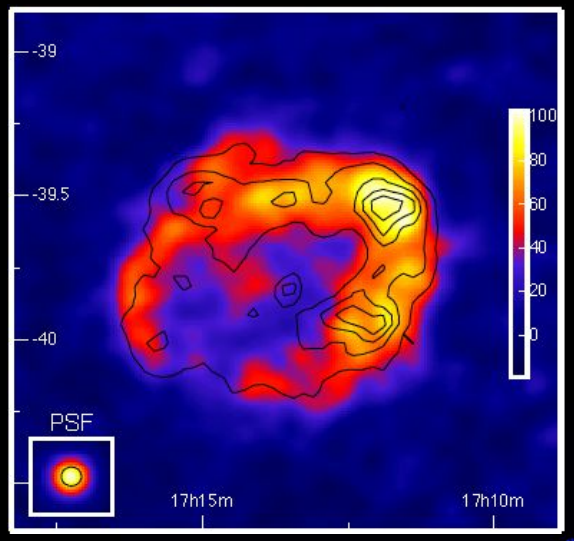
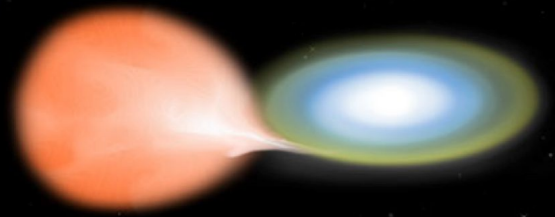


Galactic gamma-ray sources

Marianne Lemoine-Goumard
CENBG - Université de Bordeaux
CNRS-IN2P3

+ input from the Task force
(Fabio Acero, Pierrick Martin & Andreas Zech)



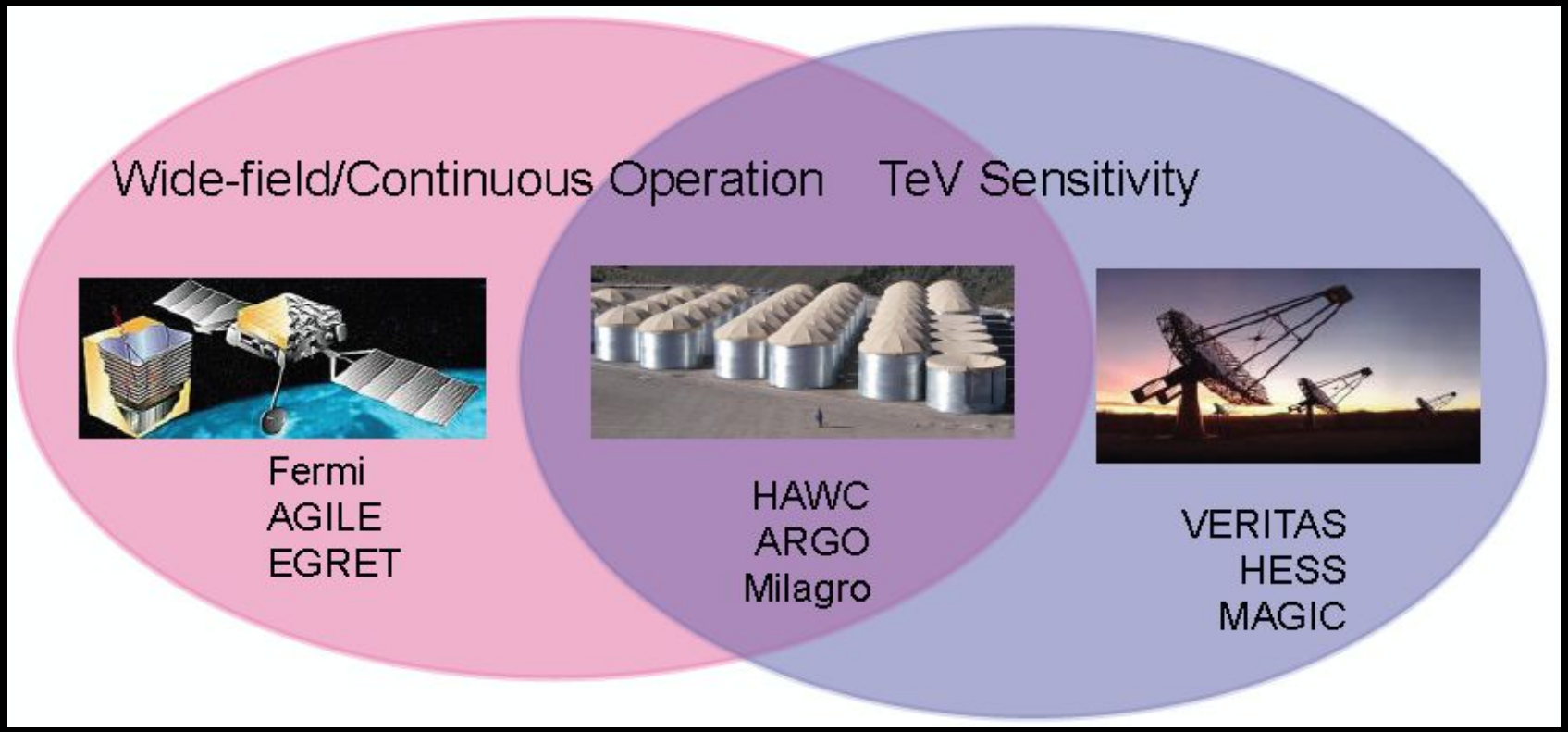
Outline

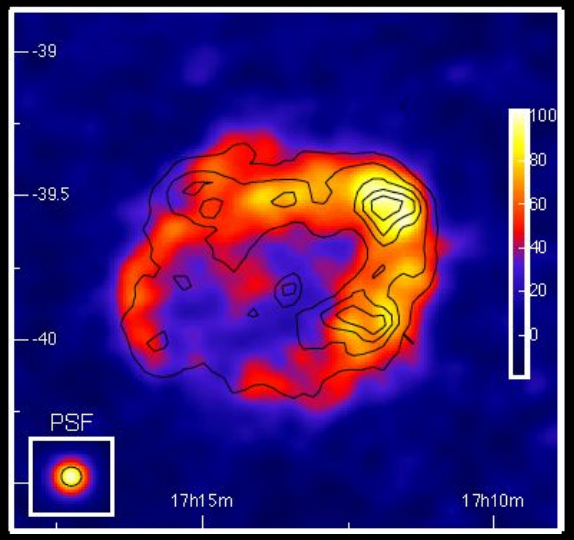
- What we have learnt and what we haven't learnt yet ?
  - Supernova remnants
  - Superbubbles & Star forming regions
  - Pulsar wind nebulae
  - Binaries
  - PeVatrons
  - Diffuse emissions
- What are still missing to improve our understanding
  - Models & Theory
  - Instruments : CTA, HAWC, LHAASO, e-ASTROGAM/AMEGO

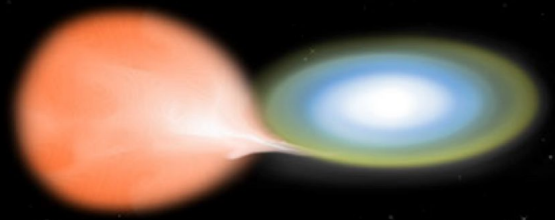
Complementarity of gamma-ray instruments

- Space-based detectors - continuous full-sky coverage from MeV to GeV

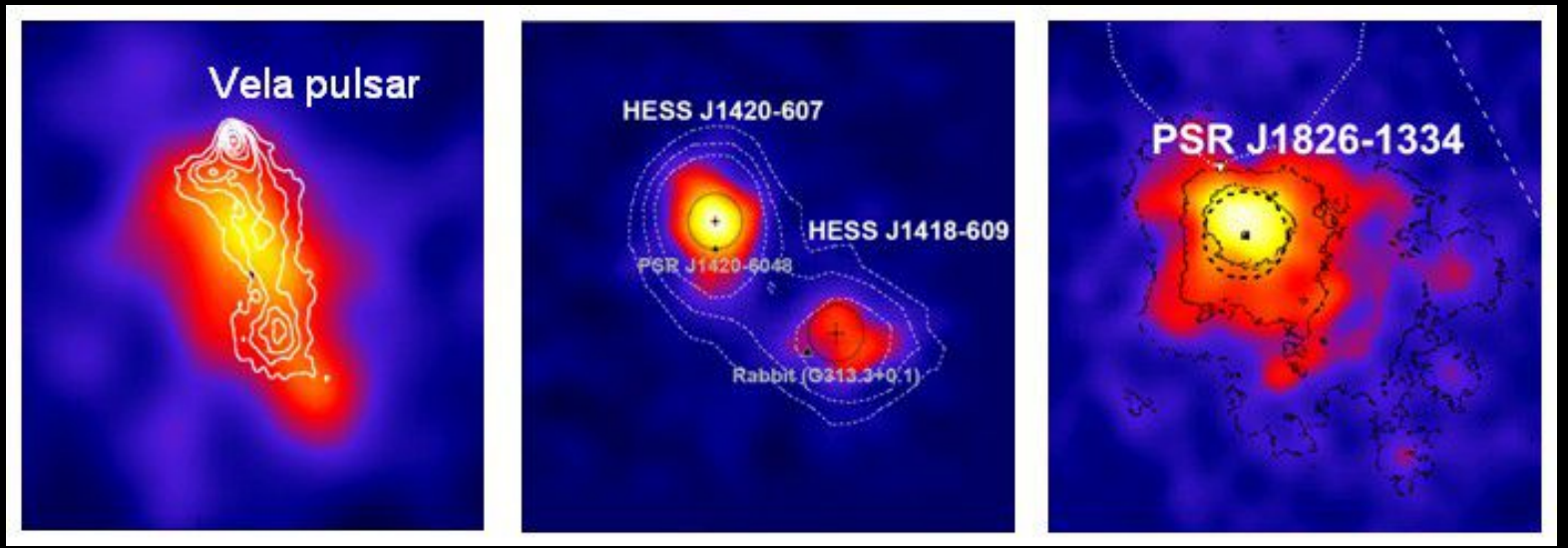
- Ground-based detectors have TeV sensitivity
  - Excellent energy and angle resolution, but FoV of 0.003 sr and duty cycle of 10%
  - Particle detectors have an aperture > 2 sr and duty cycle of 90% but angular resolution of ~0.6° (@ 1 TeV)





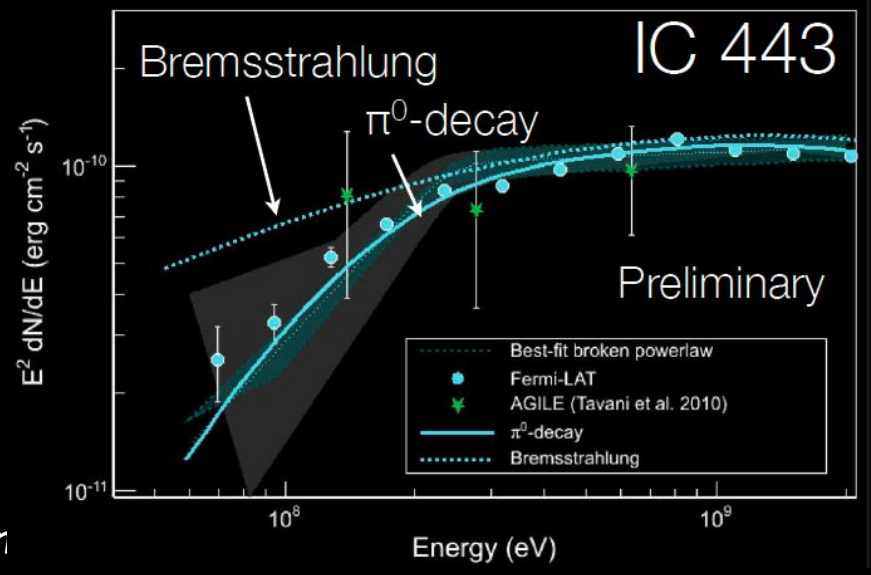


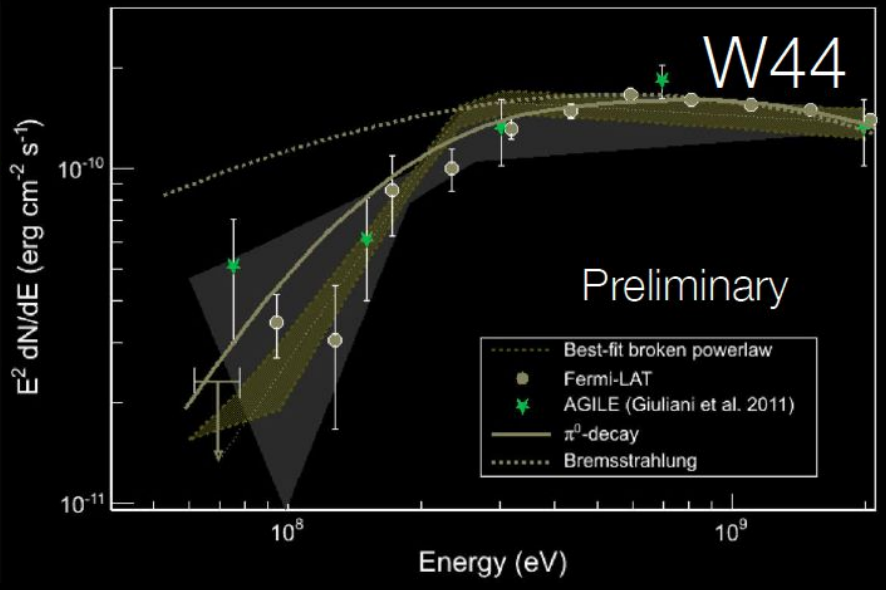
What we have learnt
&
what we haven't learnt yet



Supernova remnants : results

- Detection of the historical remnants Cassiopeia A & Tycho
- Detection of the 5 TeV shell-type SNRs with Fermi : RX J1713.7-3946, Vela Junior, SN 1006, RCW 86 & HESS J1731-347
- Detection of the « pion bump » feature in 4 different middle-aged remnants (W44, IC443, W49B & W51C) & in Cas A
- Detection of escaping cosmic-rays in W28 & W44; maybe also in the young remnants RX J1713.7-3946 & HESS J1731-347
- New shells detected at GeV and TeV energies : G150 detected with the FGES Catalog, & HESS J1534-571 associated with G323.7-1.0





Supernova remnants : open questions

- Non-detection of SN1987A by HESS implies that < 1% of E_{SN} is injected into CRs => when does the shock becomes efficient ?

- Detection of a cut-off at 12 TeV on Cas A by MAGIC => protons already left the system ? Or the maximum energy was reached in the past ?

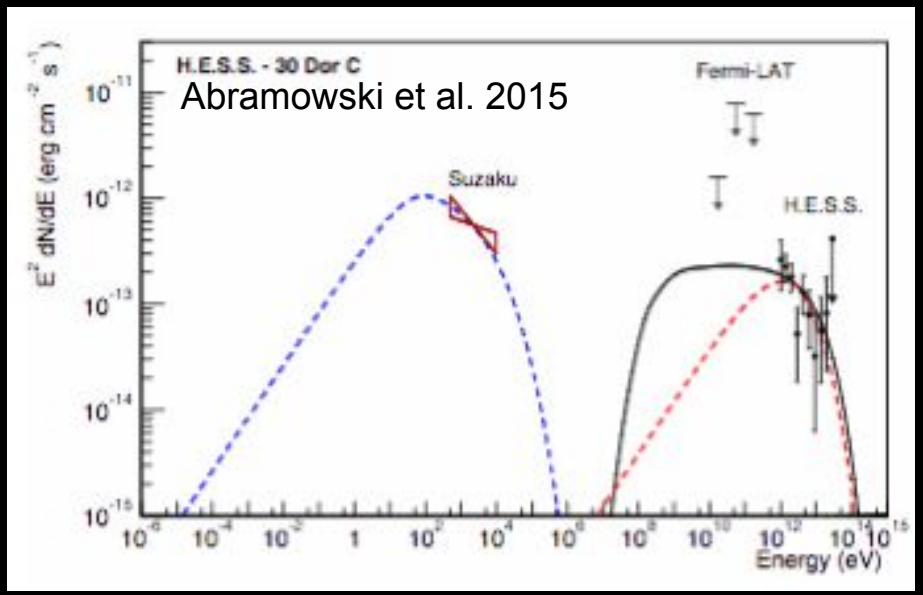
- Cas A and Tycho are well reproduced with proton index of ~2.3 : magnetic field amplification ? effect of neutrals at the acceleration region ?

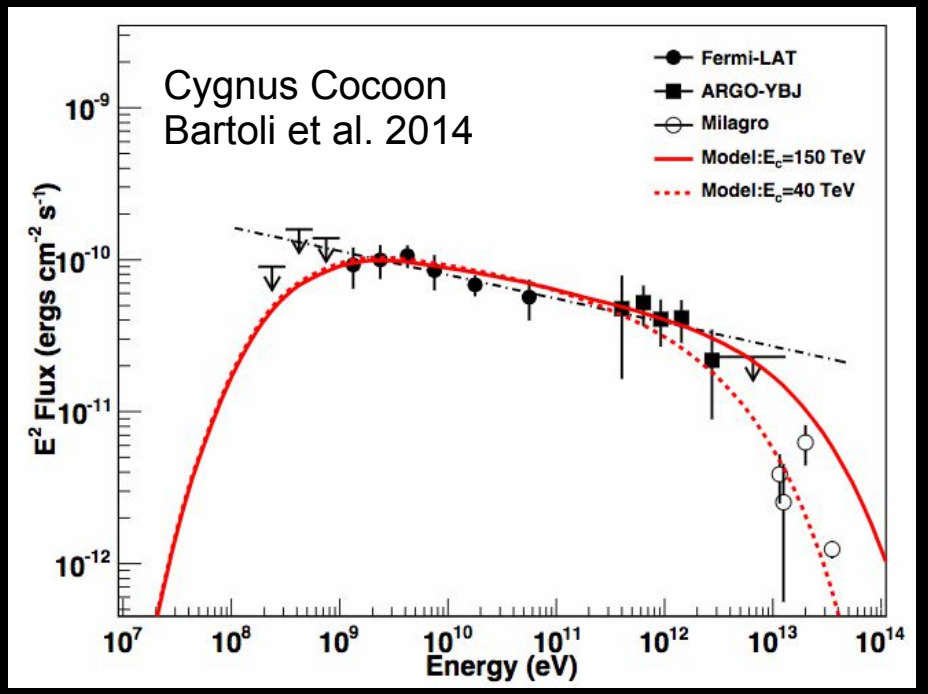
- Evidence of asymmetry in SN 1006 (SW region not detected) : effect of neutrals ?

- Breaks visible for all middle-aged remnants with energies between 1 and 100 GeV : what is the origin of this large interval ? The time since first interaction with the cloud ? A transition between fresh acceleration to re-acceleration (example : non-detection of W44) ?

Superbubbles & Star forming regions : results

- Detection of the Cygnus Cocoon with the LAT ; association proposed for the ARGO source J2031+4157
- Detection of the superbubble 30 Doradus C in the LMC with HESS (largest known X-ray synchrotron shell) : hadronic scenario implies high density and low diffusion coefficient
- Several candidates detected (to be confirmed) : Westerlund 1, Westerlund 2, G25, NGC3603





Superbubbles & Star forming regions : open questions

- Most core-collapse SNRs are located in star forming regions & superbubbles : how can we explain that very few are detected in gamma-rays ?

- What happens to CRs freshly escaping from their accelerators ? Are they confined for some time and potentially re-accelerated in the highly turbulent medium of star forming regions ? What impact do they have on the surrounding ISM ? Up to which energy are they re-accelerated ?

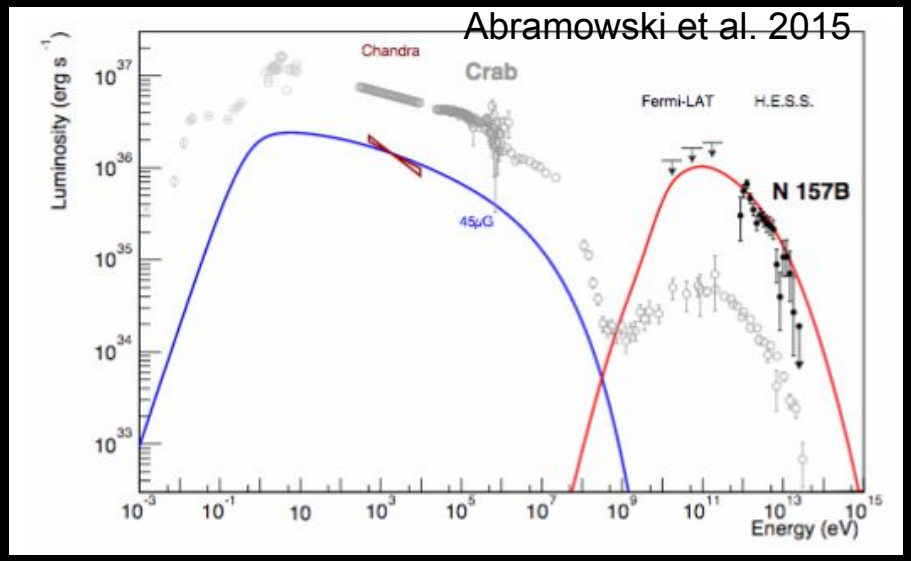
- Cygnus Cocoon : are we seeing a collective effect (superbubble) or a single SNR ?

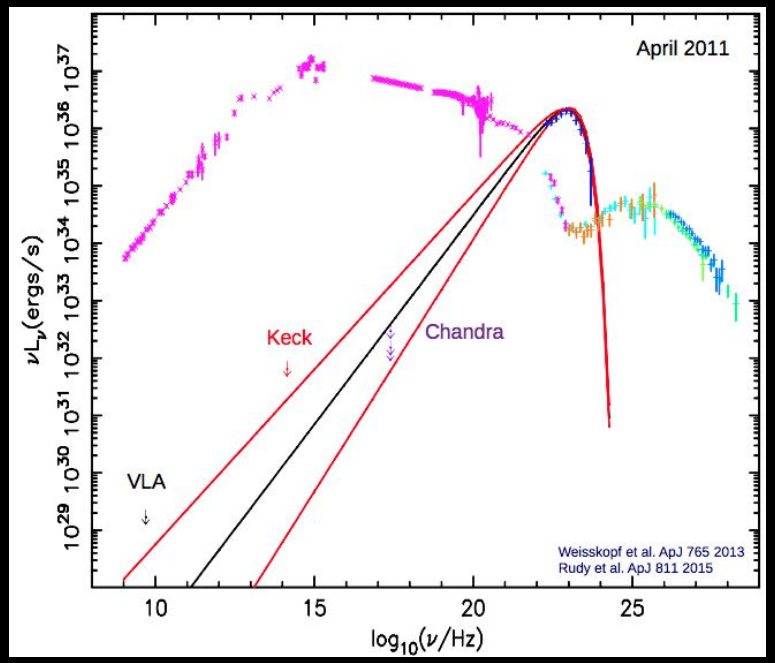
- If associated to Cygnus Cocoon, ARGO J2031+4157 sets a maximum energy of 150 TeV on the proton spectrum. Superbubble are not PeVatrons ? Or PeV particles already left ?

- Star forming region W49A not detected : shocks expected from interacting or collective stellar winds appear not very effective (in comparison to SNR W49B) ?

Pulsar wind nebulae : results

- Most numerous class of VHE galactic source (34 referenced in TeVCat => ~20% of all sources)
- Few young and energetic nebulae : e.g. N157B (associated to PSR J0537−6910 in the LMC) is the most luminous PWN to date (x 20 in comparison to the Crab)
- Detection of the Crab flares ; the most powerful (April 2011) implied a factor 30 in luminosity, B ~ few mG >> 200 µG, and PeV pairs
- A large fraction of the gamma-ray PWNe are relic nebulae very faint at other wavelengths (could explain part of the UNIDs)
- Detection of an extended TeV source spatially consistent with Geminga by HAWC





Pulsar wind nebulae : open questions

- Very extended emissions from HESS J1825-137 & Vela-X detected by the LAT : rapid diffusion of high-energy electrons ? > 1000 times faster than Bohm diffusion ?

- Geminga as seen by HAWC : diffusion much slower than usually assumed ?

- Crab flares : detection of synchrotron emission up to 375 MeV => magnetic reconnection ? Where does it operate exactly ?

- Vela-X cocoon : very hard LAT spectrum (~1.0) : is it also due to magnetic reconnection ?

Binaries : results

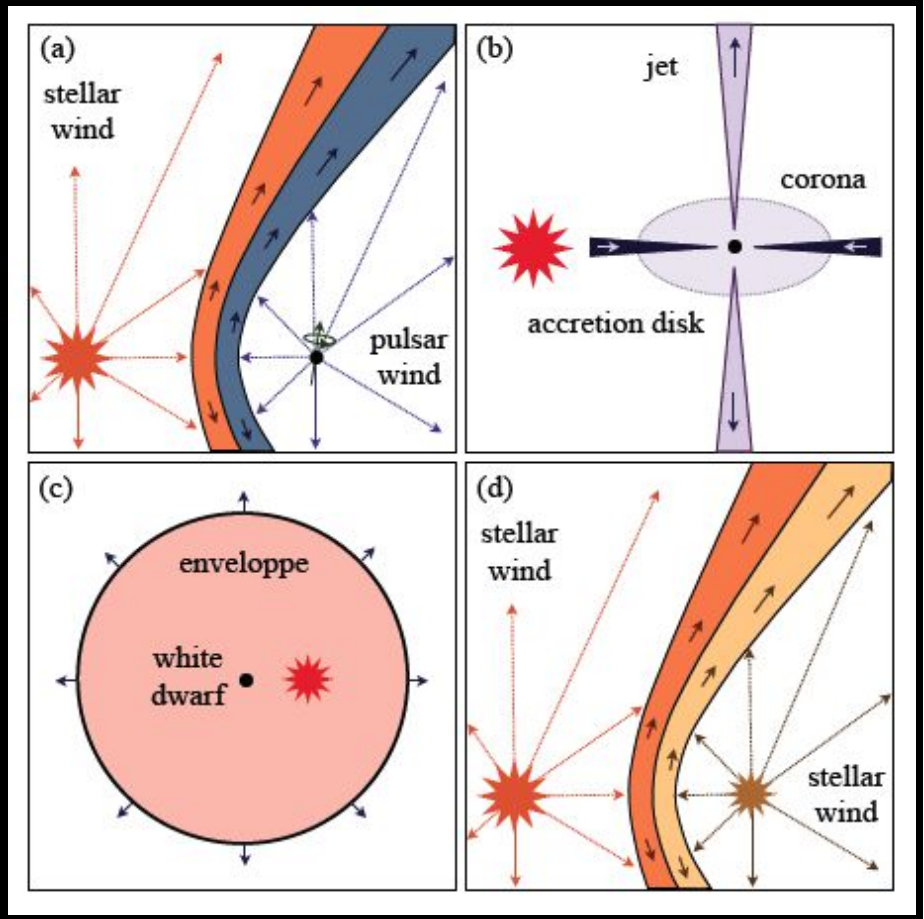
- Detection of high-mass gamma-ray binaries (e.g. LS 5039 detected at GeV and TeV energies) ; most luminous gamma-ray binary to date detected in the LMC

- Detection of microquasars (Cyg X-1 and Cyg X-3) with the LAT ; 4.9σ (pre-trial on Cyg X-1 with MAGIC

- Detection of novae with the LAT ; no TeV detections up to now

- Detection of the colliding-wind binary Eta Carinae with the LAT and H.E.S.S.

=> large variety of sources proves that particle acceleration is much more widespread than would have been considered a decade ago



Dubus et al. 2015

Binaries : open questions

- Why do some binaries emit high-energy emission and others do not ?

- Does that mean that the conditions are special in detected systems (because a strong shock is present, or because particle acceleration is somehow stunted in the others ?)

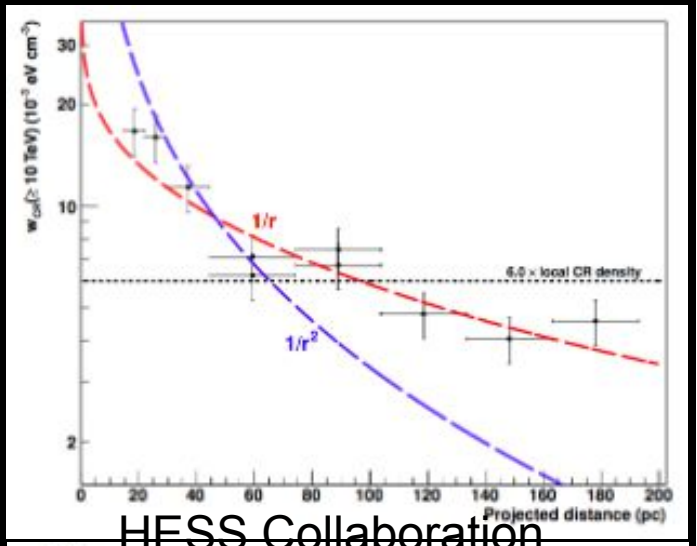
- How much do these different source types contribute to the CR spectrum ? If so, up to which energy ?

- Are they all mostly electron accelerators ?

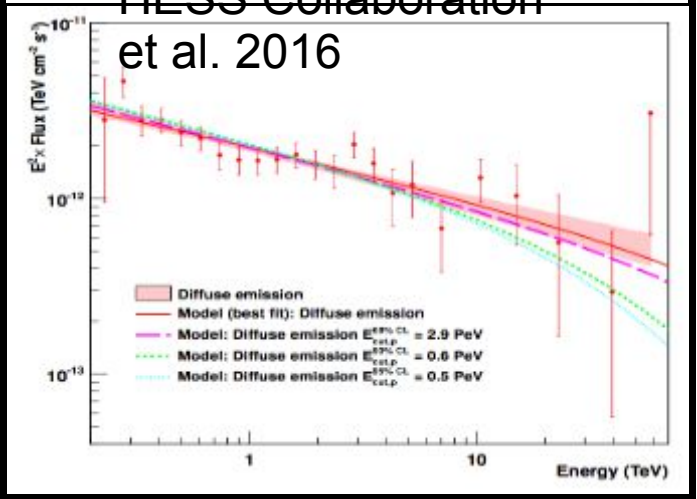
- What is the maximum energy reached at these shocks ?

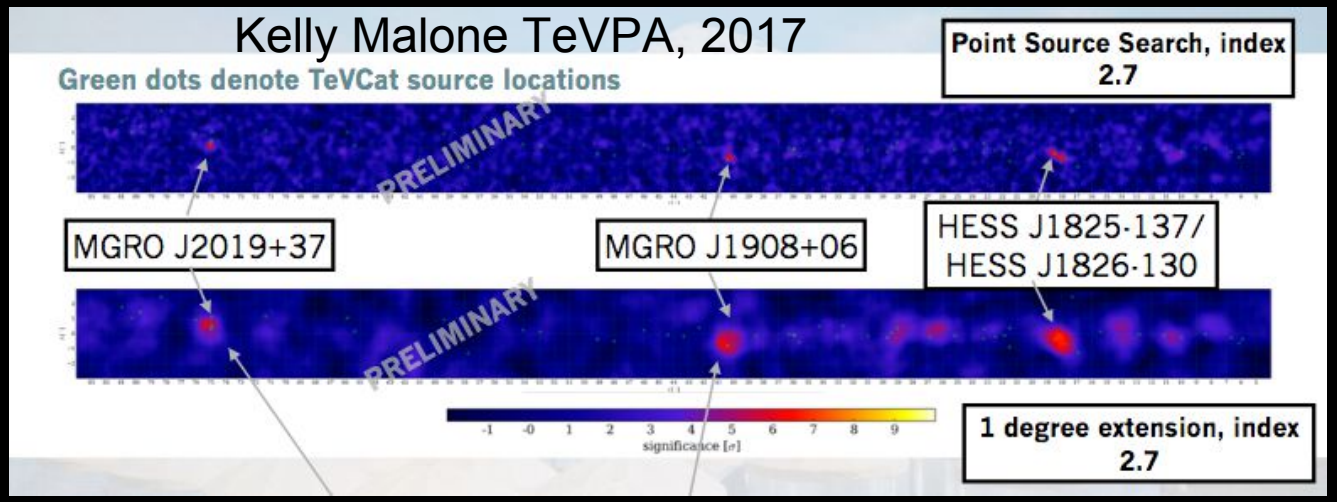
PeVatrons : results

- No SNRs detected as PeVatron up to now
- Detection of a PeVatron at the Galactic center with H.E.S.S.
- Several PeVatron candidates detected by H.E.S.S. : unidentified sources HESS J1641-463, HESS J1741-302, HESS J1826-130
- First release by HAWC of sources detected above 50 TeV : MGRO J2019+37, MGRO J1908+06, HESSJ1825/HESSJ1826



HESS Collaboration et al. 2016





PeVatrons : open questions

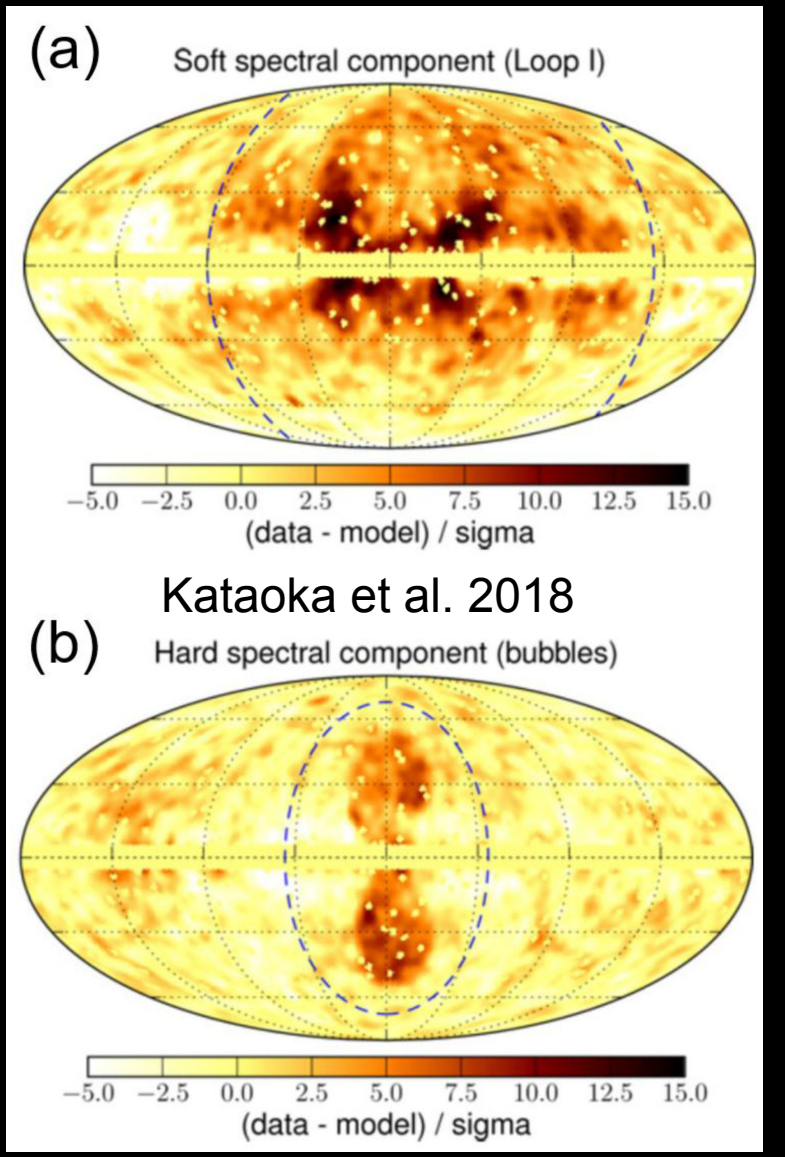
- Do young shell-type SNRs accelerate hadronic cosmic rays up to PeV energies ? If so, up to which energies and how effective is this acceleration ?

- Does the PeVatron at the Galactic center contribute significantly to the CR spectrum or to the populations of massive stars/SNRs there ? If so, in which energy interval ?

- PeVatron candidates detected by H.E.S.S. or HAWC are electron or proton accelerators ?

Diffuse emissions : results

- Detection of the Fermi Bubbles with the LAT : two large structures in gamma-rays up to 50° above and below the Galactic center
- Detection of Loop I, a radio continuum loop spanning across 100° on the sky
- Precise view of the Galactic Diffuse background with the LAT
- Detection of the Galactic diffuse background with H.E.S.S.
- Detection of a gamma-ray excess at the Galactic center
- Detection of diffuse emission from external galaxies (LMC, SMC, M31,...)



Kataoka et al. 2018

Diffuse emissions : open questions

- What is the origin of the gamma-ray excess in the inner galaxy ?

- Why is the LMC diffuse emission apparently so different from that of the Milky Way ?

- Is there a link between the Fermi bubbles and Loop I ? If so, do they both originate from past activity in the GC ?

A: conclusions

Very large variety of sources proves that particle acceleration is much more widespread than would have been considered a decade ago

Only one robust detection of a Galactic PeVatron but several candidates still need to be identified : sources confusion is a real issue

CR transport still not under control (diffusion coefficient not constrained)

Several electron PeVatrons detected associated to PWNe : remain one of the best acceleration site (for electrons). What about gamma-ray binaries ?

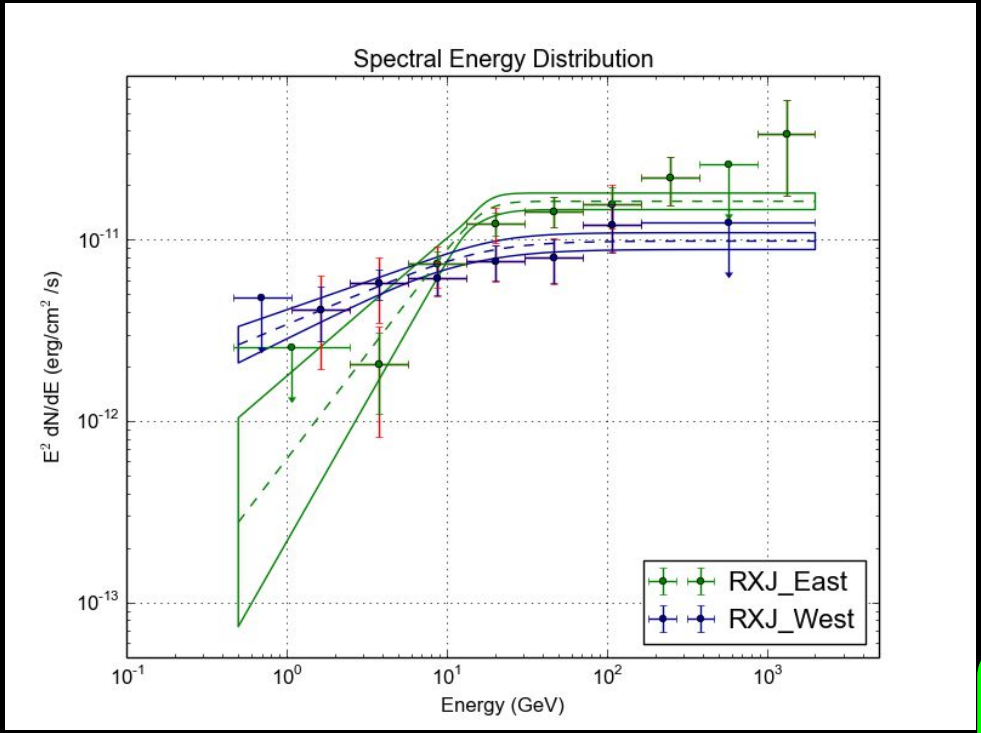
What is still missing to improve our understanding : Models, Theory & Instruments

Models & Theory (I)

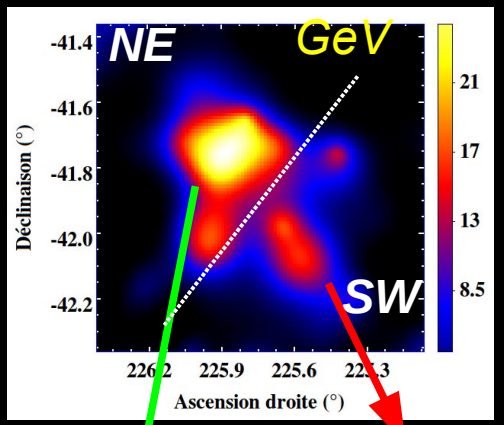
One-zone models are not sufficient to reproduce MWL data

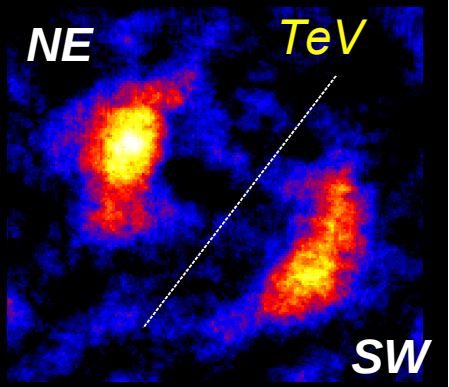
=> Models on sub-regions with associated MWL data are crucial

RX J1713.7-3946 : 4σ in favour of different spectra East vs West



SN 1006 :





SW region
TS = 12.9 => no detection
Γ = 2.60 ± 0.80

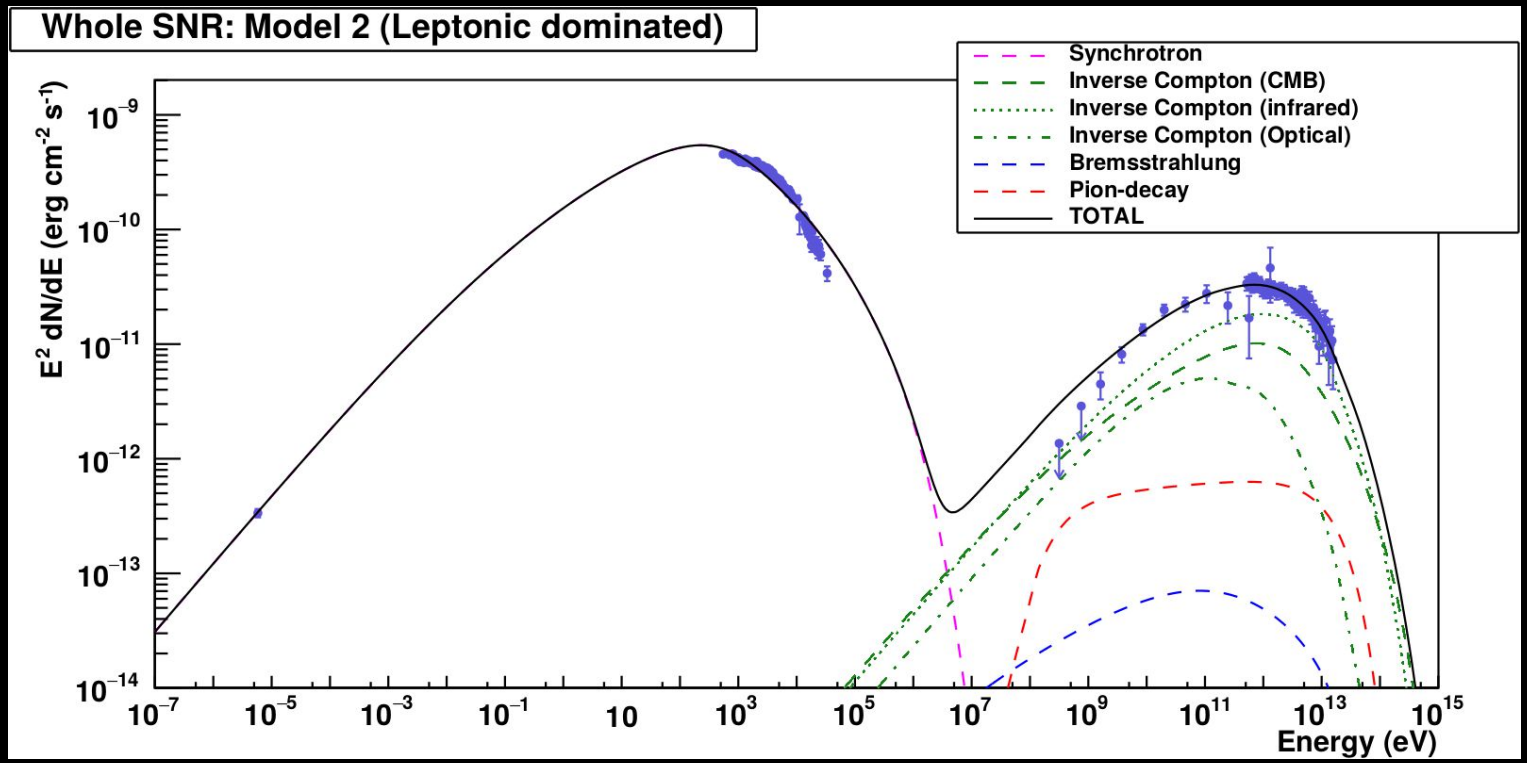
NE region
TS = 28.3 => **detection**
Γ = 1.47 ± 0.26

Models & Theory (II)

One also need to take into account the whole history of the SNR shock via CR-hydro-NEI codes for instance

=> example of RX J1713.7-3946 that needs a break at 17 GeV in the electron population. Due to a higher B field at earlier times ?

=> see Slane et al. 2014 for Tycho which estimates an energy of 16% E_{SN} (instead of ~3% for simple one zone models)



Models & Theory (III)

Two main scenarios for middle-aged remnants : escape or direct interaction

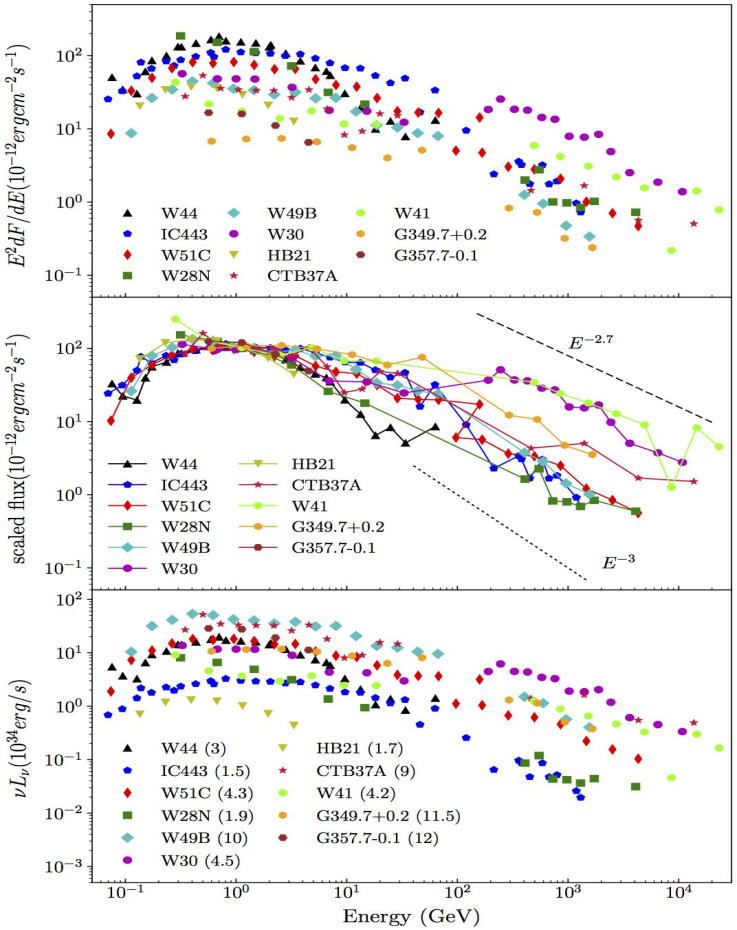
How much relic particles are still left in middle-aged remnants ?

How would they affect the primary CR spectrum and the corresponding gamma-ray emission ?

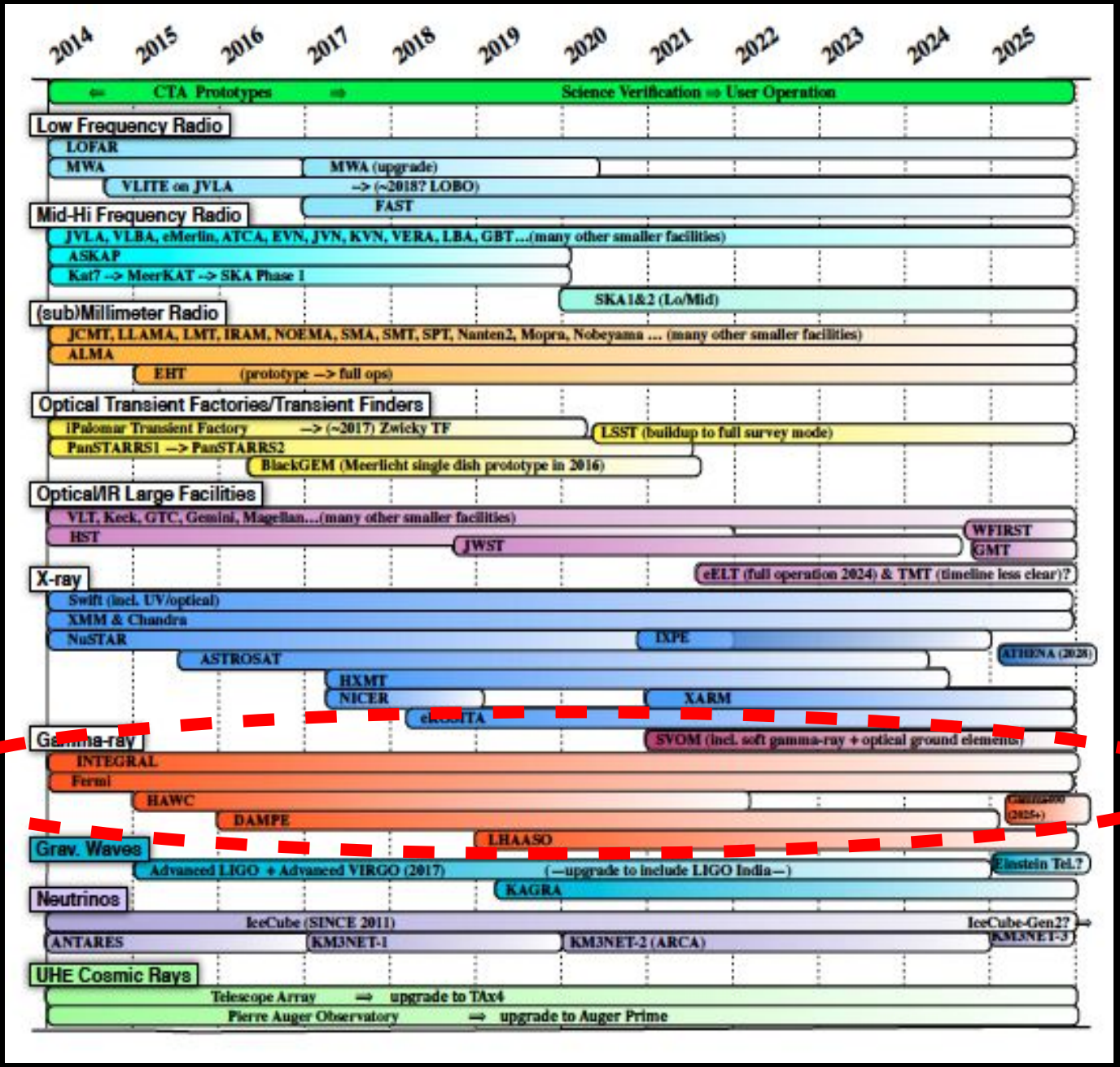
Need to take into account both the particles escaped from the remnant and those being confined at the SNR

=> Hybrid model involving both scenarios

X. Tang, 2018

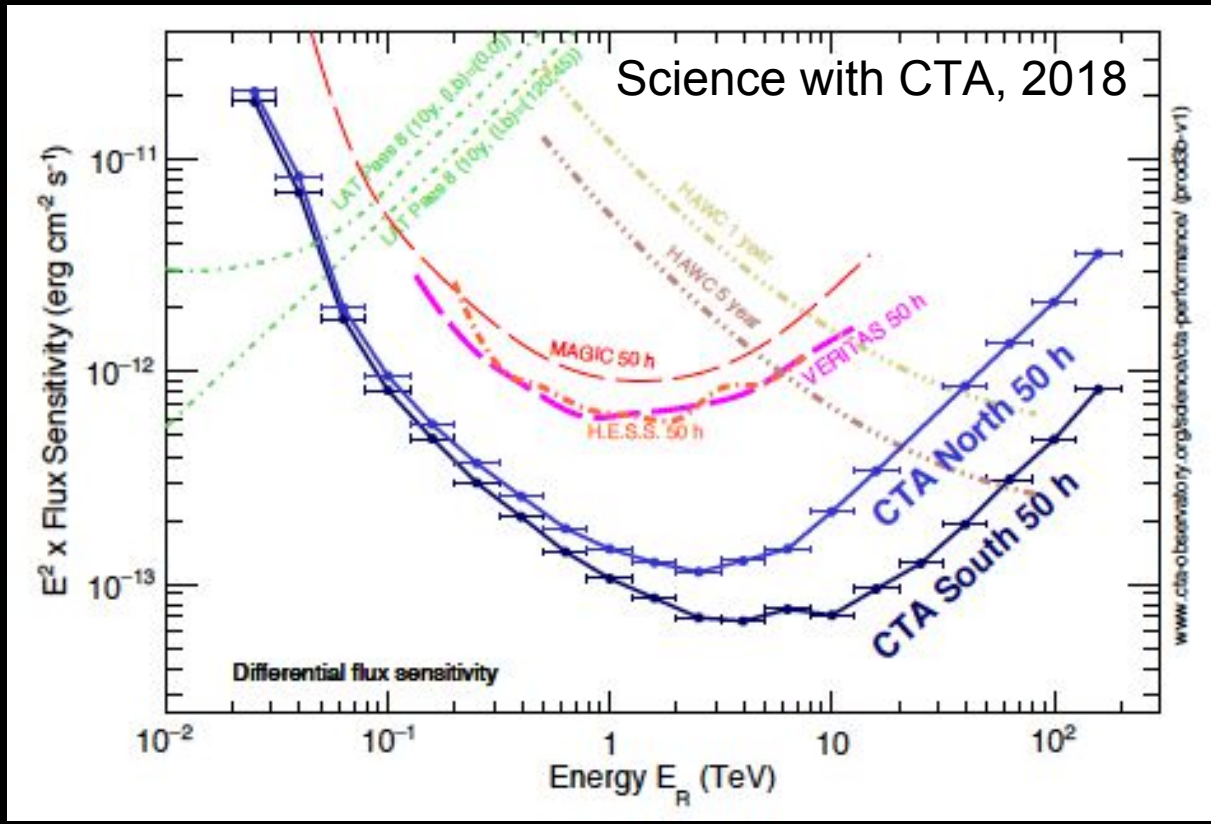


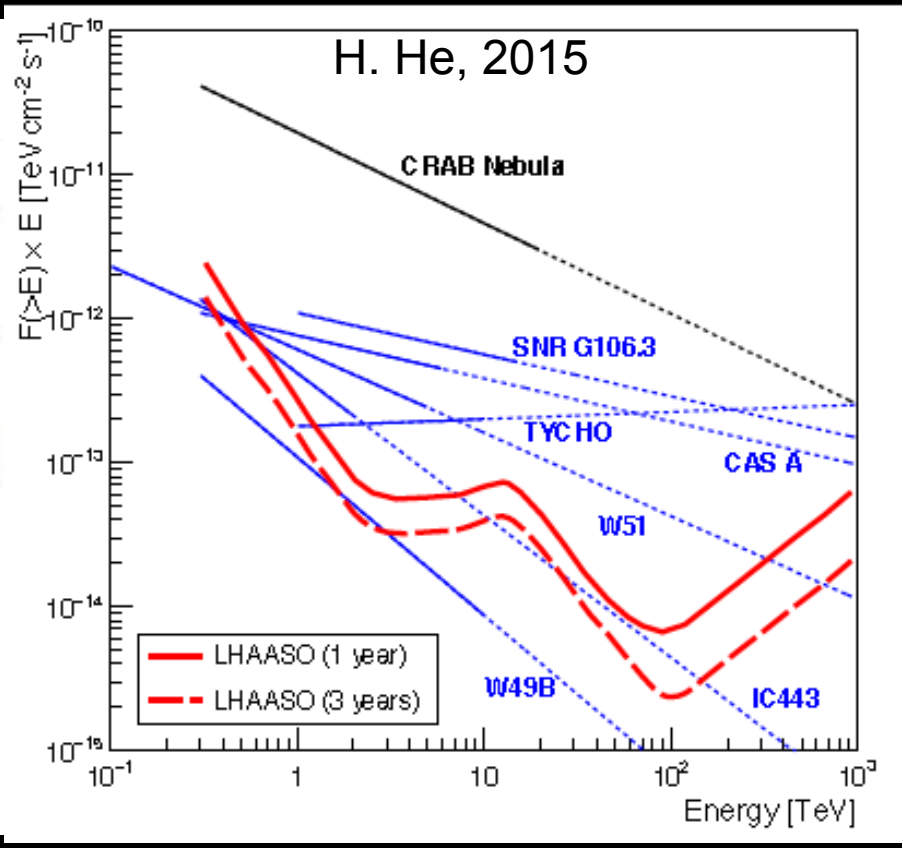
Future instruments



M. Lemoine-Goumard, CFRCOS, March 26, 2018

Sensitivy comparisons





Instruments : CTA

2 sites selected: North (La Palma, Spain) ; South (Paranal, Chile)

3 Telescope sizes

Increased sensitivity : detection of new supernova remnants, star forming regions, superbubbles and binaries. Young remnant such as SN1987A and G1.9 is a key science topic

Excellent angular resolution : perfect for morphologically-resolved spectral analysis of extended sources such as SNRs or the diffuse emission of the Galactic Center or star forming regions

Energies up to 100 TeV in South Site : PeVatron search and constraints on Emax for different source types

Increased FoV and Survey capabilities : ideal for new source detections and PeVatrons search

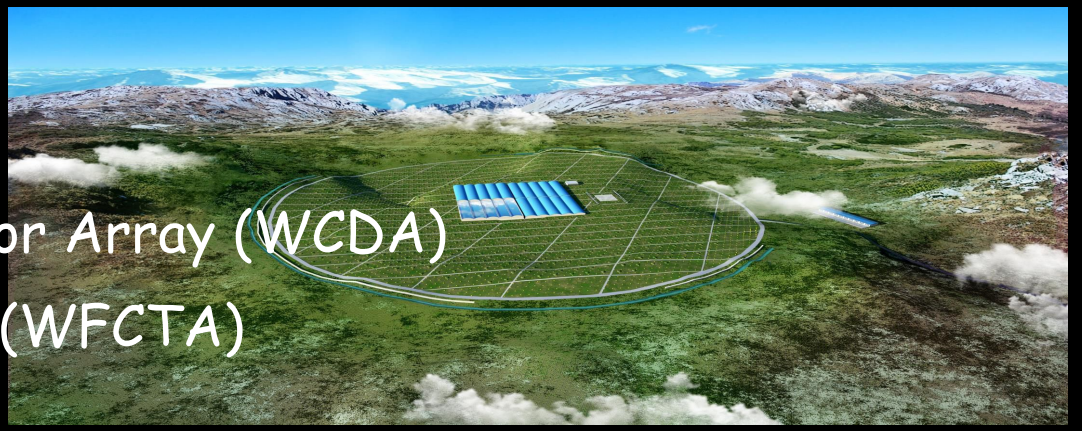
Instruments : HAWC & LHAASO (I)

LHAASO detectors:

- air shower array of 1 km2

. 75 000 m2 Water Cherenkov Detector Array (WCDA)

- 12 Wide-field Cherenkov telescopes (WFCTA)
- Infilled shower core detectors



HAWC :

300 water tanks on an era of 20 000 m2 at 4100 m

Completed since March 2015 but taking data since August 2013

Instruments : HAWC & LHAASO (II)

HAWC :

ideal for large scale structures and extended sources such as the Cygnus cocoon, the Westerlund sources or extended remnants

Ideally suited for transients due to its large field of view and 100% duty cycle : first detection of a nova at TeV energies ? First detection of the Crab nebula flares at TeV energies ?

Access to very high energy photons for Northern sources

LHAASO :

will complement CTA at higher energies in a similar way to HAWC

access to the highest gamma-ray photon energies => PeVatron search, Constraints on Emax via ULs on selected objects might prove useful

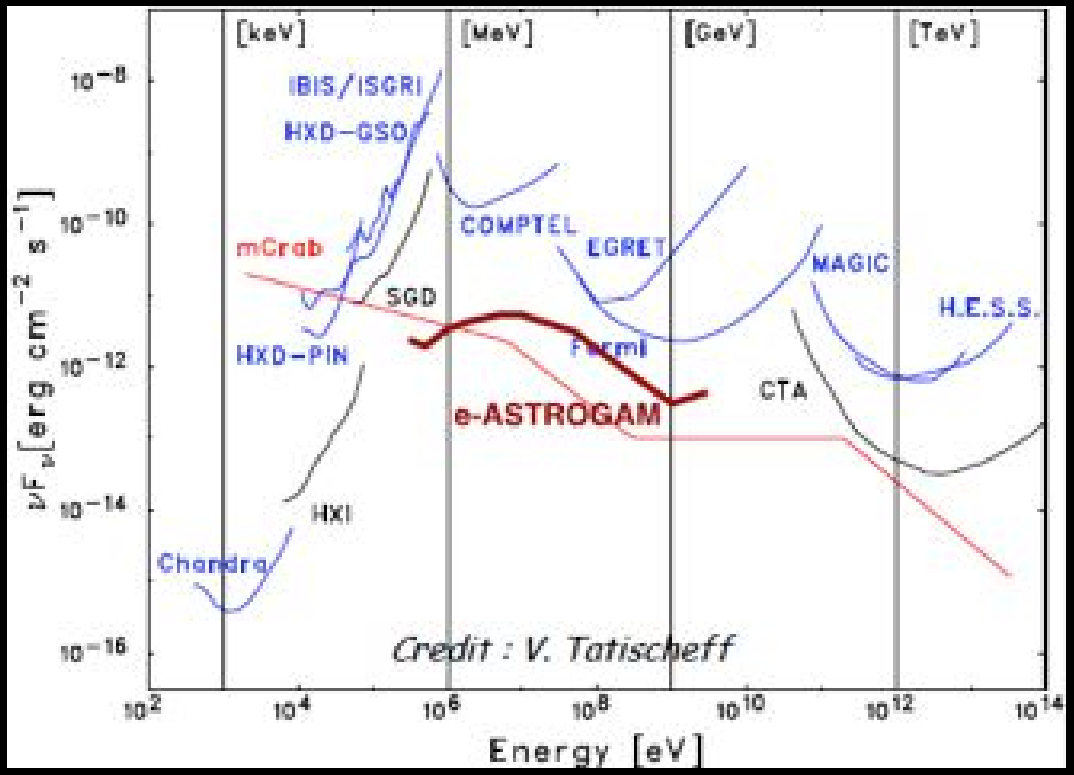
example with the case of Cas A : if PeV protons already escaped, a gamma-ray halo should be visible around the source

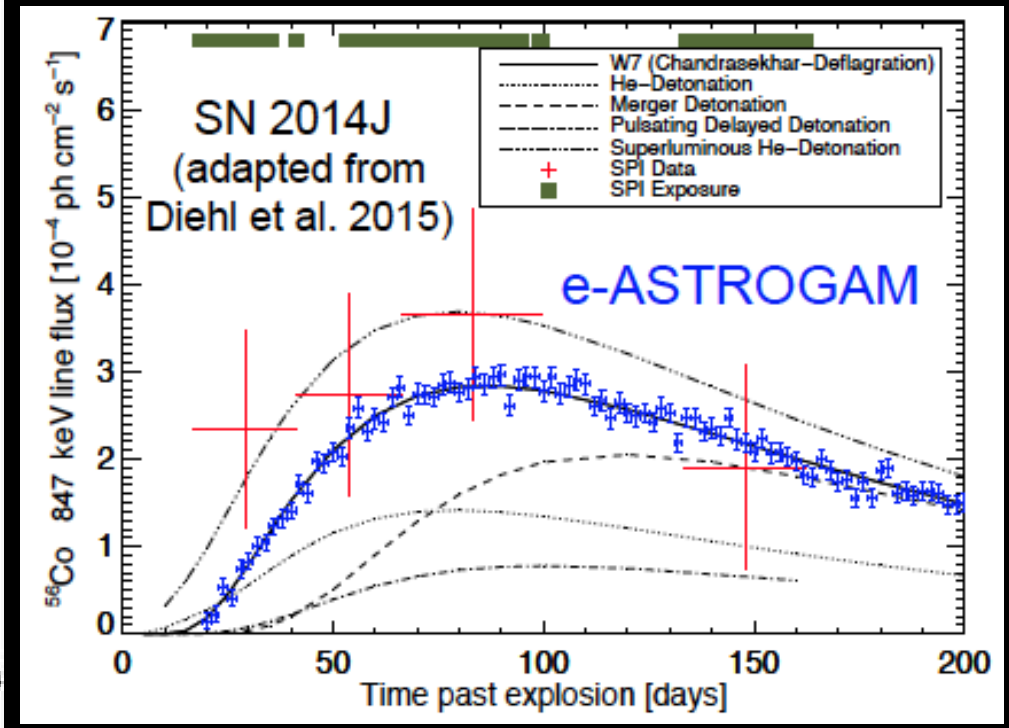
Instruments : e-ASTROGAM/AMEGO (I)

Objective : Improve sensitivity by a factor of about 50 in the **mostly unexplored energy range 0.3 - 100 MeV** (continuum and line detection)

- ideal for « pion-bump » search, looking for proton-proton interaction in supernovae or novae

- Gamma-ray lines : important for nucleosynthesis studies in SNRs but also for the study of LECRs in the Galaxy

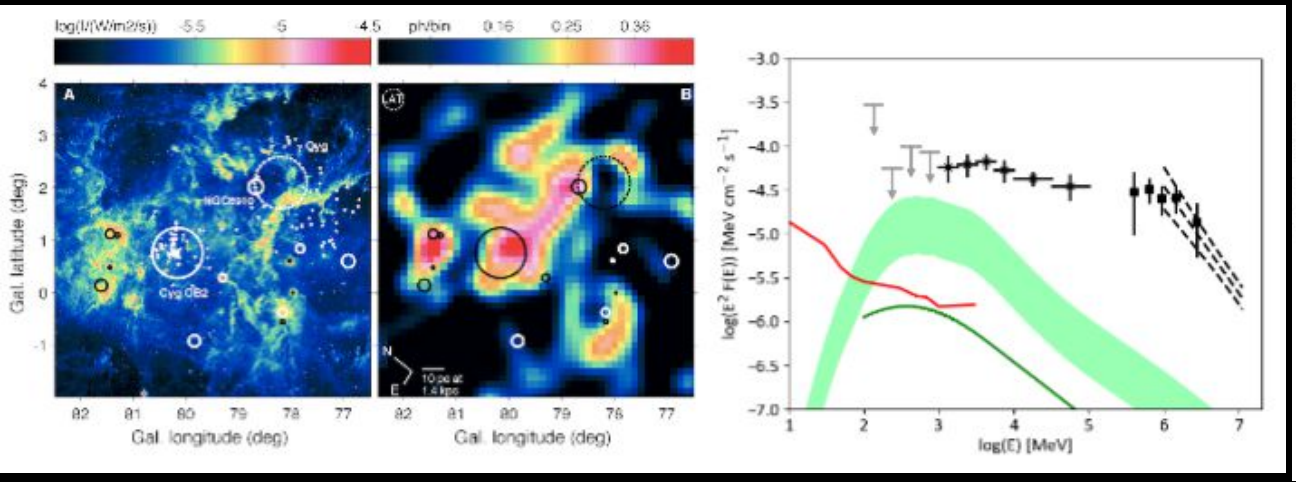


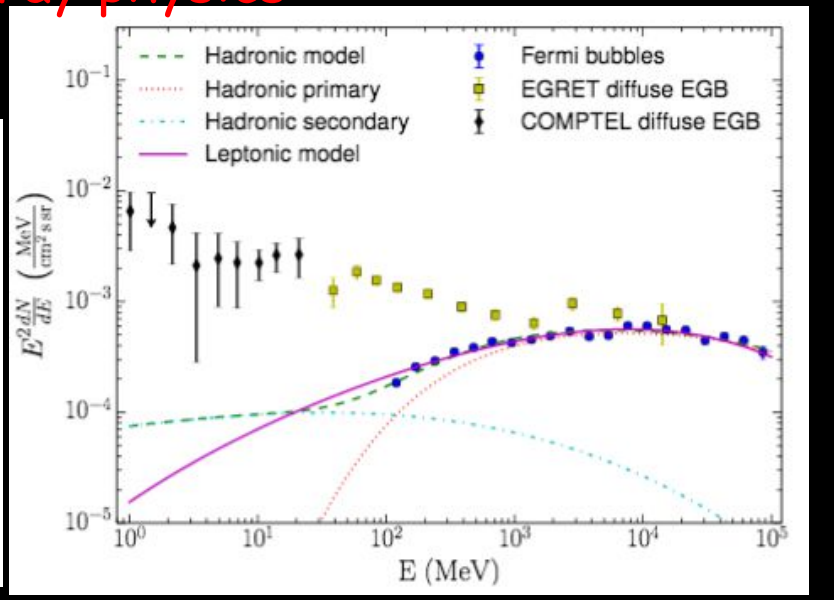


Instruments : e-ASTROGAM/AMEGO (II)

- constraints on leptonic/hadronic models from the low energy end of the spectrum ; especially useful in the case of Eta Carinae
- star forming regions, especially Cygnus cocoon is easily detectable : improved angular resolution : helps to separate the diffuse cocoon emission from the sources in this region ; lower energy threshold : extend the cocoon spectrum below 1 GeV, look at spectral variations through the cocoon....and detect OB associations such as the Orion nebula
- Origin of the Fermi bubbles
- pulsar wind nebulae : constraints on the maximum energy reached....

=> These instruments will be crucial for cosmic-ray physics





Summary

- There is an incredible diversity in the Galactic gamma-ray sky : many sources, many source classes => particle acceleration is much more widespread than would have been considered a decade ago

- Increased sensitivity and angular resolution require more sophisticated models : taking into account the evolution of the shock and the environment

- A MWL synergy is crucial ; MeV sky is still barely known while a large number of CR topics can be treated in this energy band

« It's a great time for gamma-rays.
In terms of mapping gamma rays,
we have barely opened our eyes. »
E. Hays