Prospects for the astrophysics of galactic sources with the Cerenkov Telescope Array

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Summary

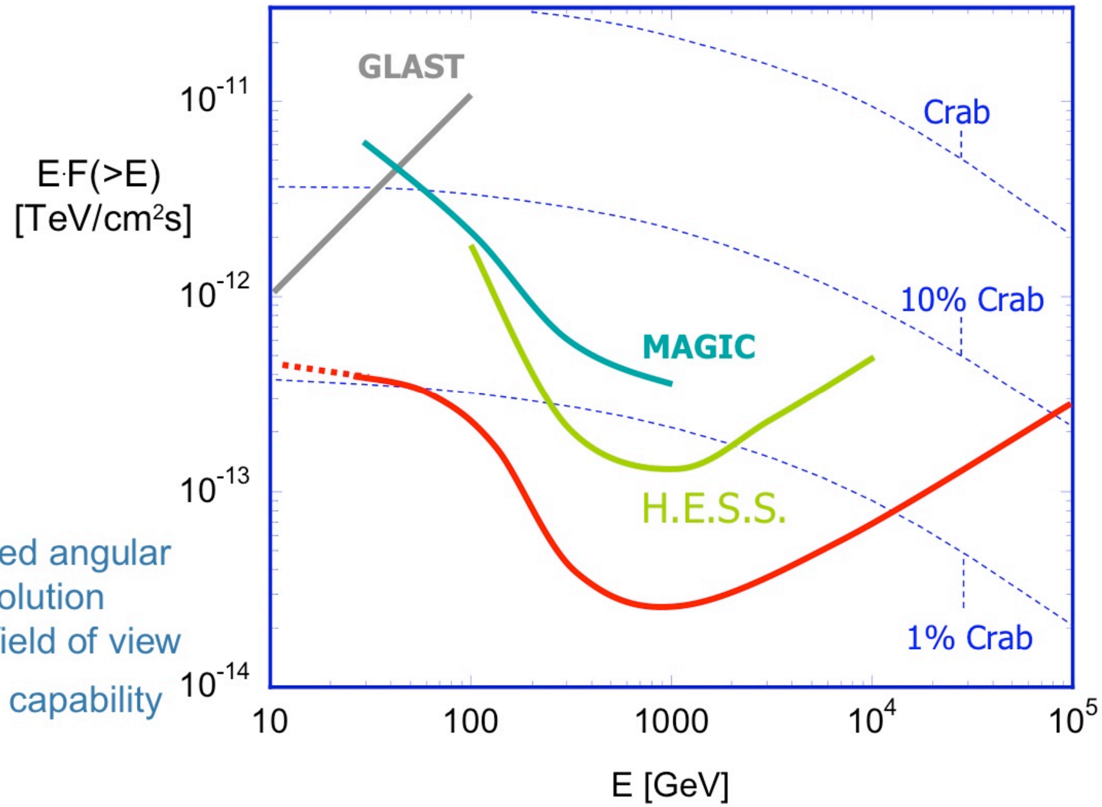
- Sensitivity
- Prospects for pulsars observations with CTA
- Prospects for SNRs/PWNe/cosmic-ray related observations with CTA
- Prospects for X-ray binaries and microquasars observations with CTA
- Prospects for clusters/stellar systems observations with CTA
- Prospects for Galactic Center observations with CTA (excluding Dark Matter studies)

Sensitivity

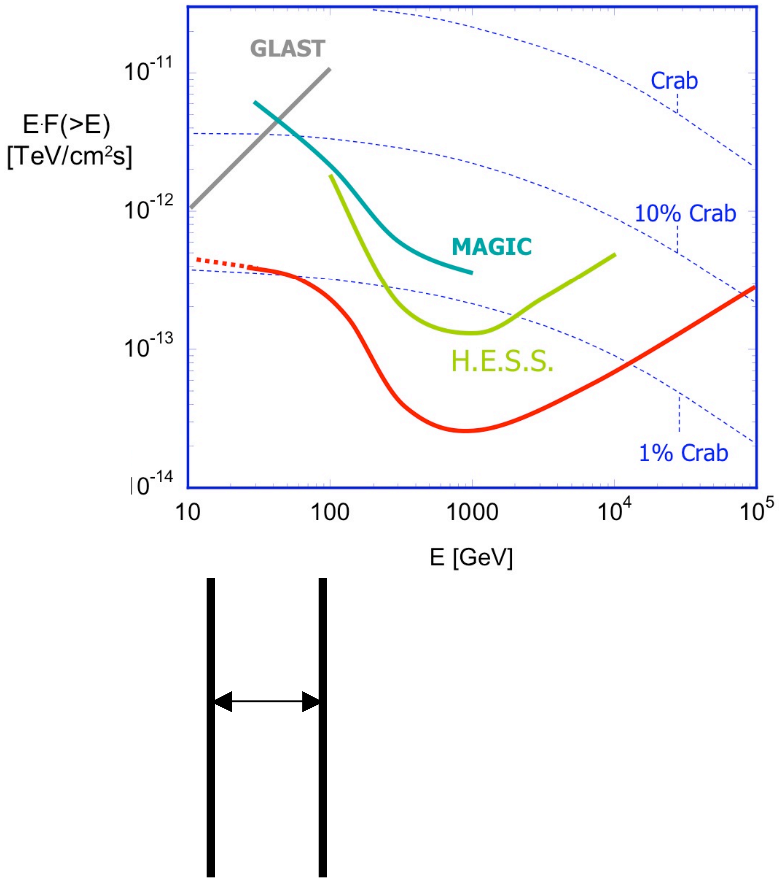
Sensitivity

- The devil is in the details
- Sensitivity assumptions for brainstorming

+ Improved angular resolution
+ Large field of view
+ all-sky capability



Sensitivity improve @ different energy ranges: first look



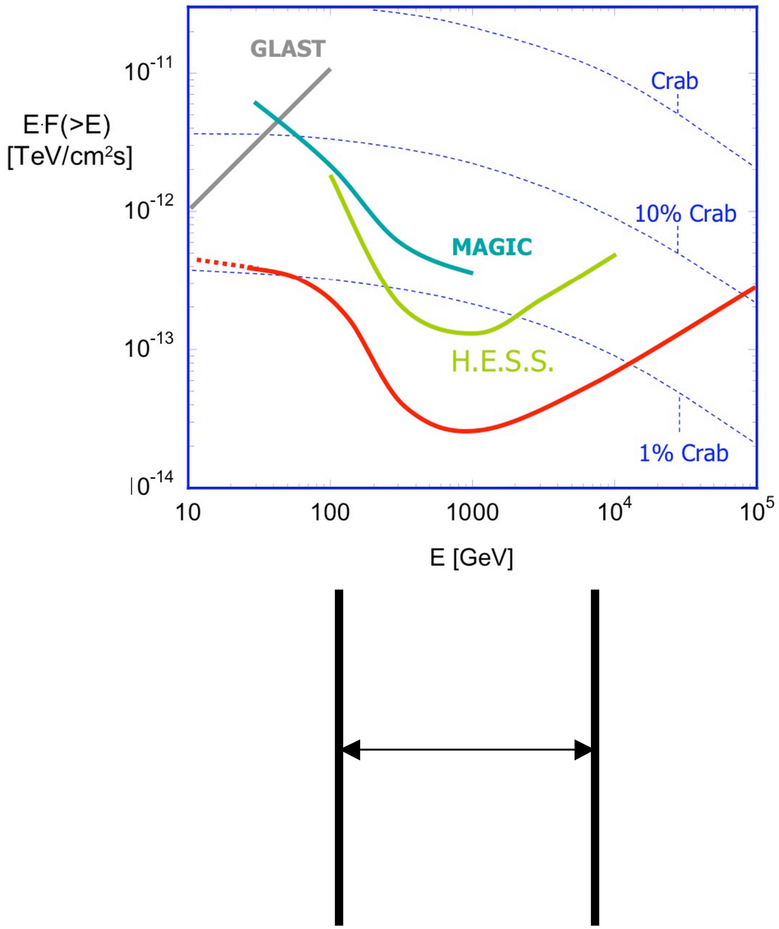
10-100 GeV:

low energy region for CTA, currently yet unexplored. New EM window.

GLAST to cover it, decreasing sensitivity with energy. Reminder: GLAST sensitivity curve is 1-year.

What does CTA specifically brings beyond GLAST?

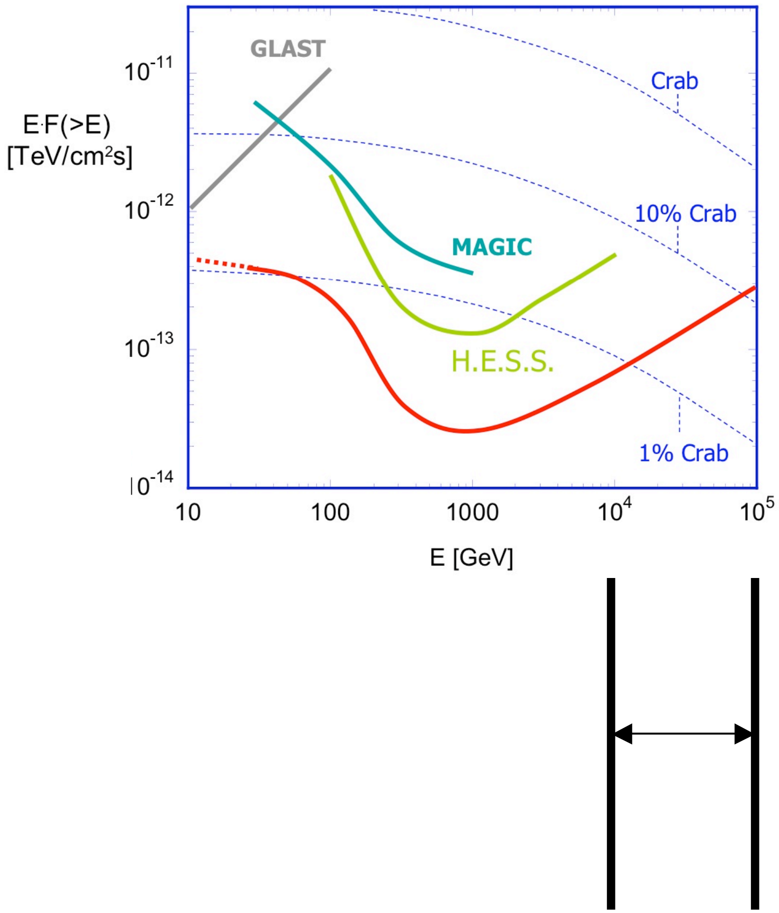
Sensitivity improve @ different energy ranges: first look



100 GeV - 10 TeV:

HESS and MAGIC success to be seen as pathfinder telescopes in this regime, with secure bread & butter astrophysics and feedback to detailed theory modelization

Sensitivity improve @ different energy ranges: first look



>10 TeV:

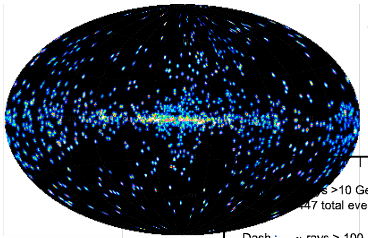
Predictably few new sources, but direct appeal to cosmic ray acceleration sites, possibilities for unexpected breakthrough, again mostly unexplored part of the EM

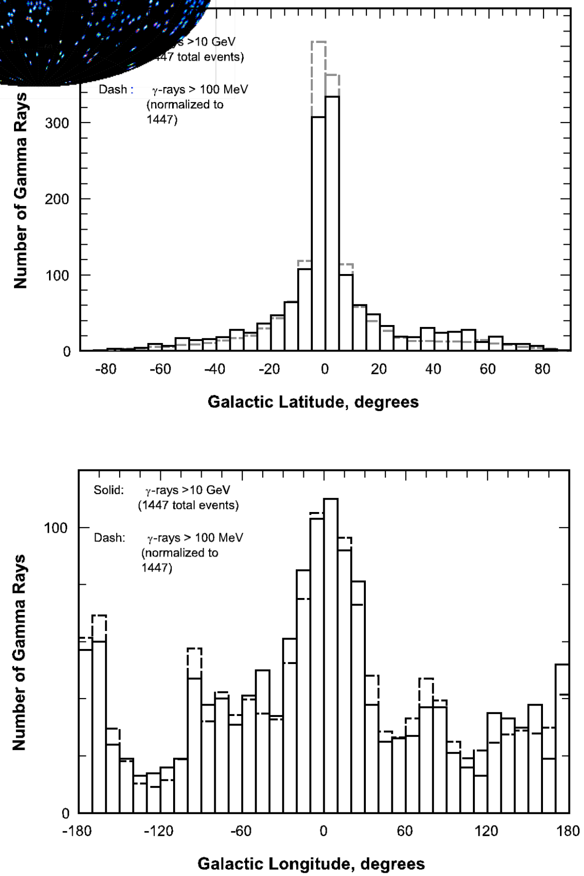
Pulsars

Low CTA energy regime - Pulsar physics: from EGRET to CTA

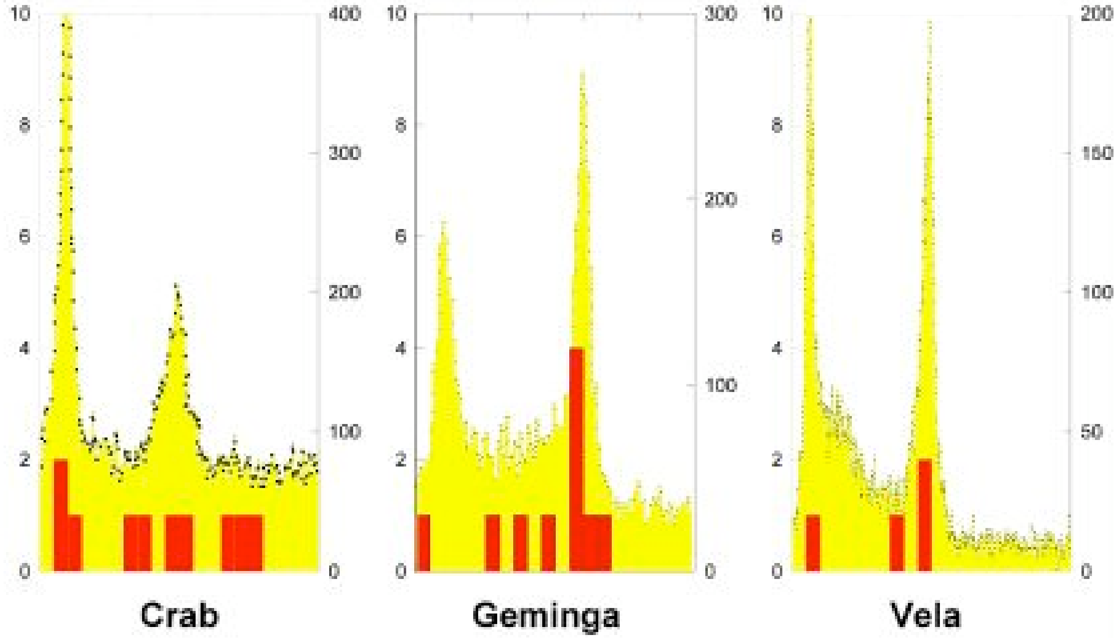
- EGRET (optimized for energies ~100 MeV)
- Number of high energy photons above 10 GeV: 1506 (out of 5M)

Energy Range (GeV)	Number
10 – 15	787
15 – 25	455
25 – 50	211
50 – 100	48
> 100	5





Thompson et al. (2006)



E > 10 GeV Galactic latitude and longitude distributions (solid) compared with the same distributions > 100 MeV (dashed)

Yellow (E>100 MeV), red (E>10 GeV), High energy emission consistent with being completely pulsed (except Crab), brightest EGRET sources above 10 GeV. No sharp cutoffs.

Other sources above 10 GeV in the Galaxy?

Seven unidentified 3EG sources, all in the high-intensity region of the inner Galaxy, were seen above 10 GeV:

J1410-6147 SNR G312.4-0.4?

J1627-2419

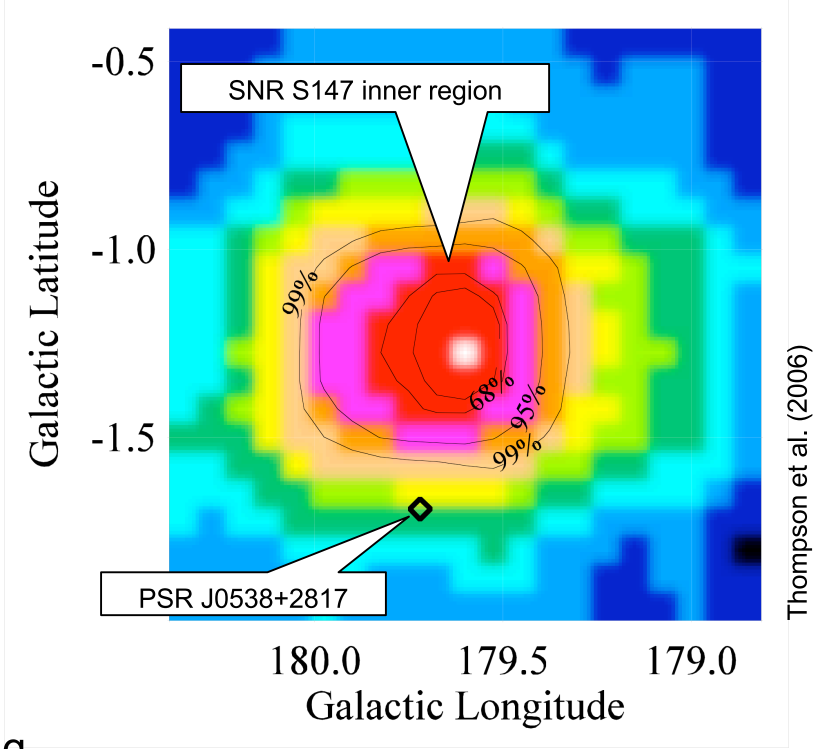
J1655-4554

J1714-3857

J1746-2851 Galactic Center?

J1837-0606

J1856+0114 SNR W44?

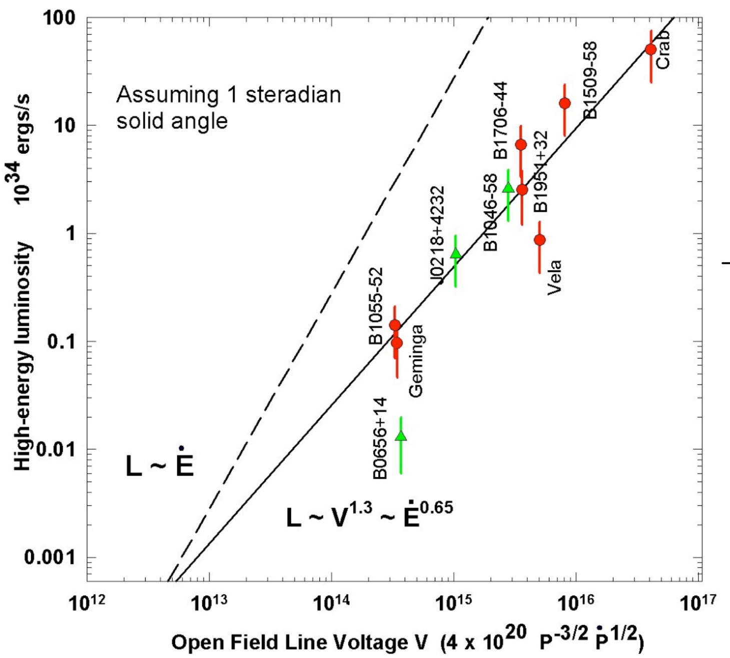


! Plus 1 new probable source (>4σ) (cluster of 5, E>10 GeV events) with no E>100 MeV emission

! Even with limited statistics, hints interesting astrophysics above 10 GeV is already there

EGRET to GLAST to CTA

- Essentially, to first order pulsed detection is limited by photon statistics
  - GLAST/LAT is more than 100 times more sensitive than EGRET above 10 GeV
  - detections >25 times fainter, or >5 times more distant (up to a few at galactic center distances)
- Extrapolate to CTA:
  - expected a factor of 10 (more?) better than LAT at ~50 GeV
  - difference at higher energy even larger, follow up of pulsar cutoffs @ HE
  - improvement in population studies, and feedback to theory



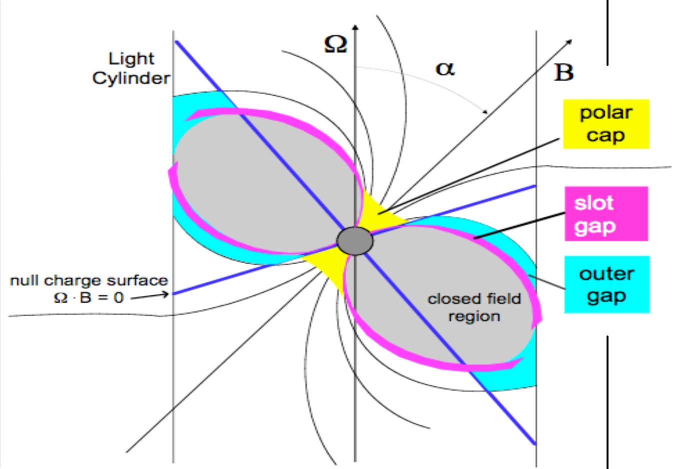
Example of questions requiring a larger sample:

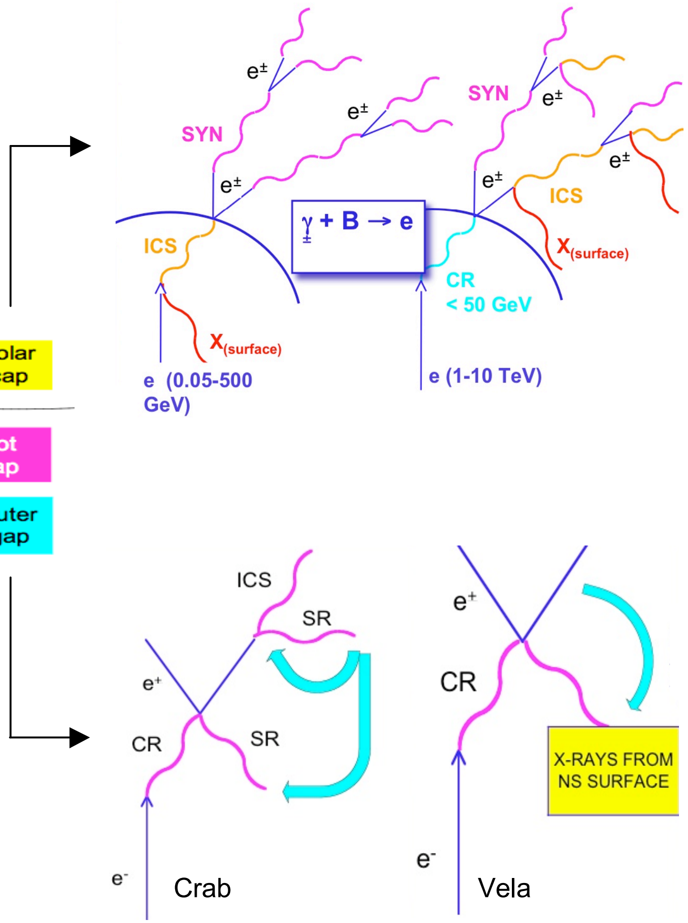
What happens as the observed luminosity approaches the total available spin-down luminosity?

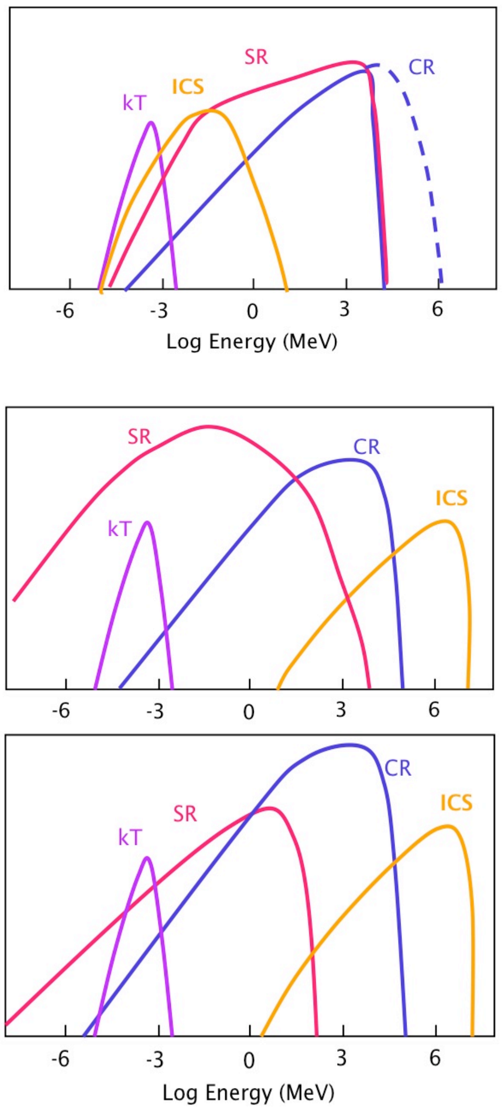
How much does the assumption of a 1 sr beaming solid angle distort the picture?

How does this correlation looks like above 10 GeV?

Polar cap - Outer gap: 1-slide concepts





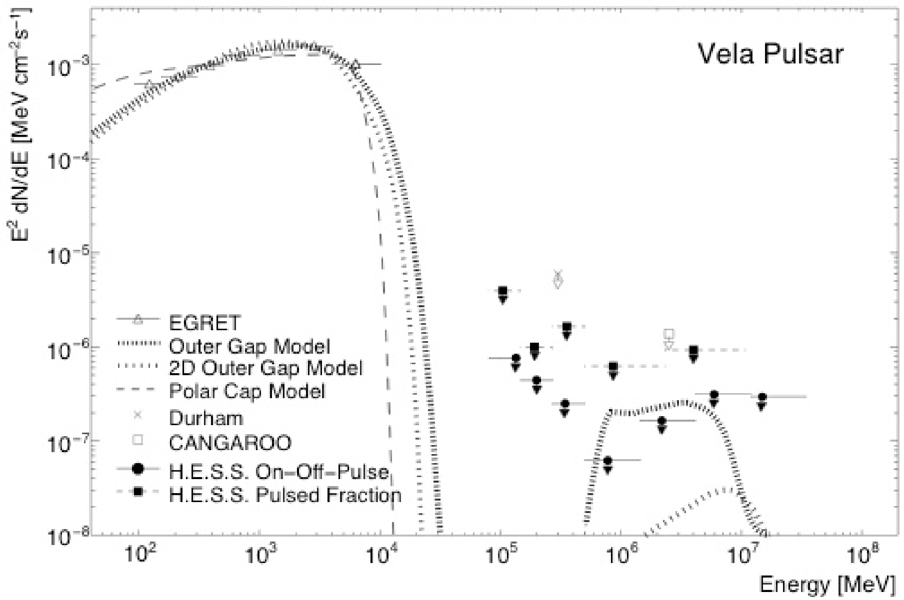


After Harding 2007

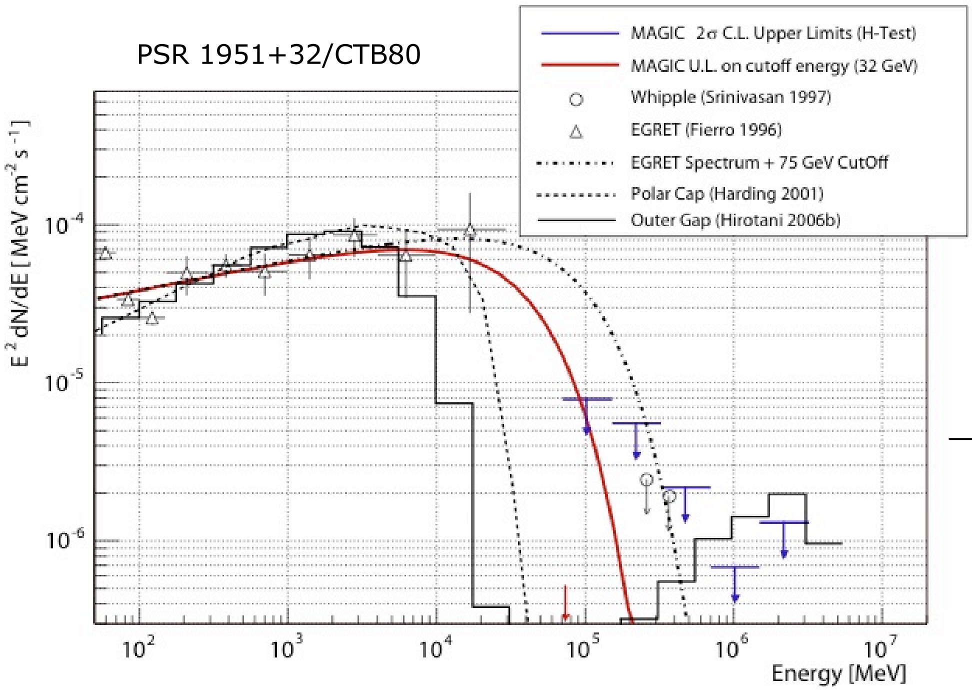
Polar Cap: Daugherty & Harding 82, Zhang & Hardng 00, Sturner & Dermer 94, etc
Ouer Gap: Cheng et al. 86, Cheng 94, Romani 96, Zhang & Cheng 97, 00, Hirotani 99, etc,

CTA to search for pulsar cutoffs, look at current results

Need to go below 100 GeV with good sensitivity to explore cutoff regime. Inverse Compton at TeV energies in outer gap models severely constrained, only the most detailed models survive. Polar cap models yet untested at these energy threshold.

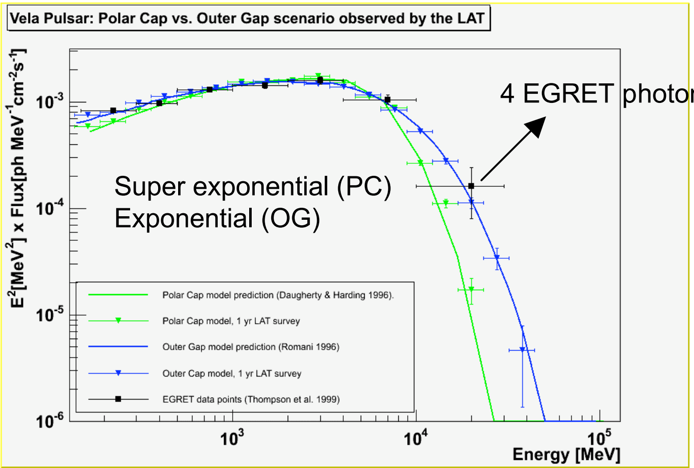


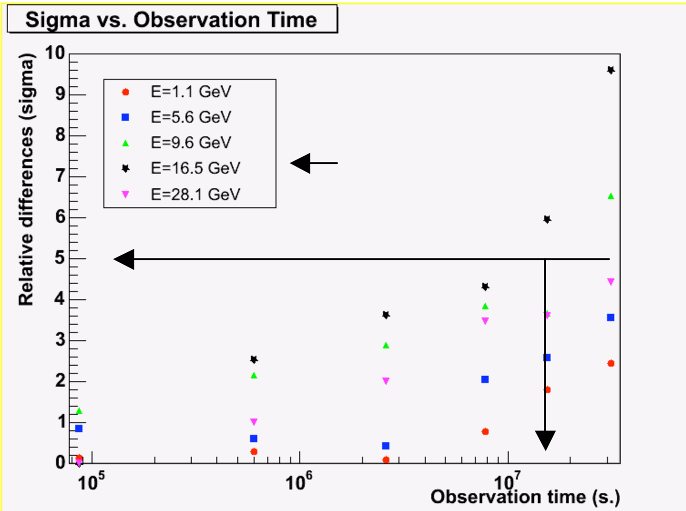
PSR 1951+32/CTB80



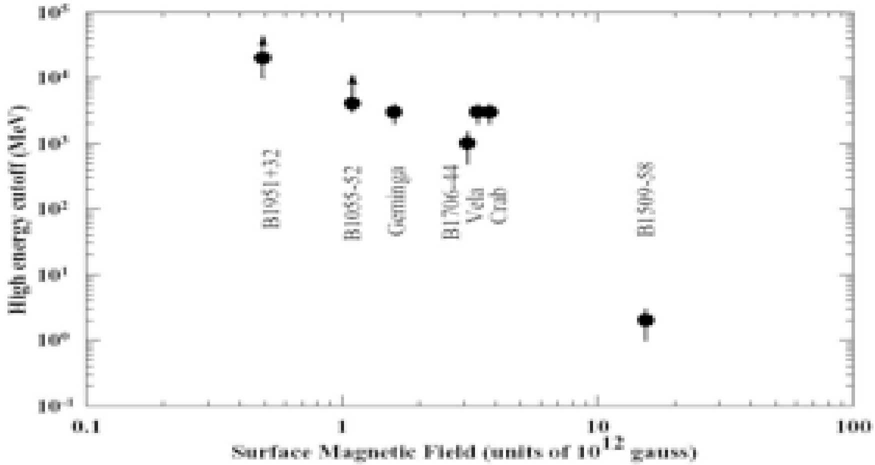
Upper limits to the pulsed emission imply a cutoff energy <32 GeV. Again, Inverse Compton at TeV energies in outer gap models severly constrained.

CTA to understand pulsar cutoffs with a large statistics





Razzano for the LAT collab., 1st GLAST Symp. 2007



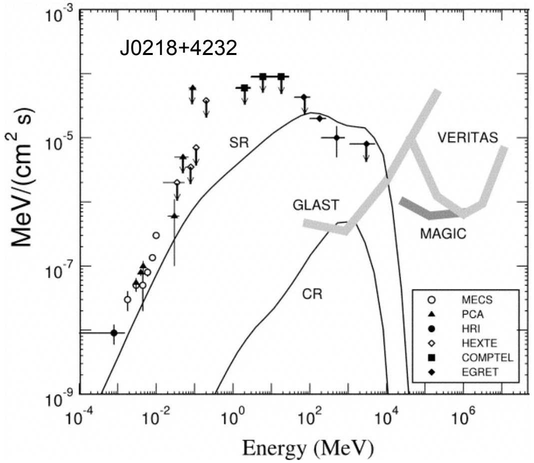
Example of question requiring a large sample:
correlation between Ec and surface magnetic field?

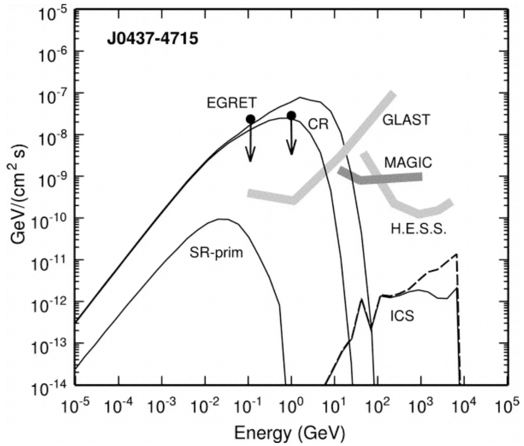
- Vela is an especial case for the LAT (brightest source above 100 MeV).
- The differentiation between models is best at E>10 GeV and requires 1 year statistics.
- It will be hard to achieve for many (a handful?) pulsars at this level of confidence.
- CTA can do this with a large sample

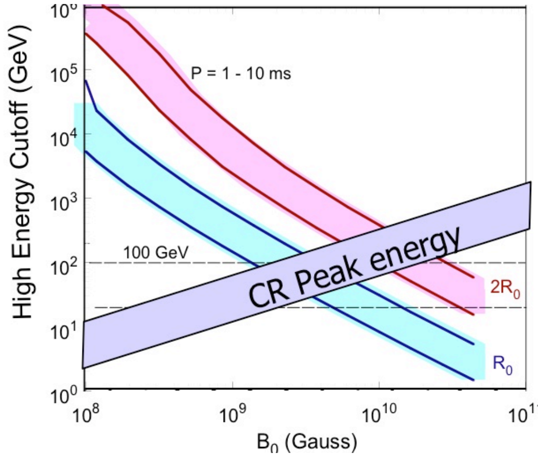
CTA to search for millisecond pulsar emission

Polar cap models

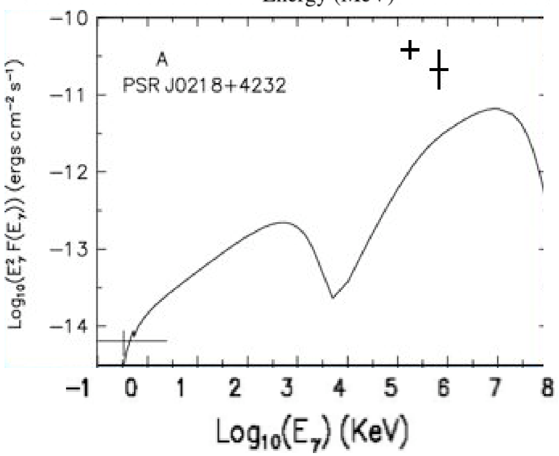
Harding et al. 2005

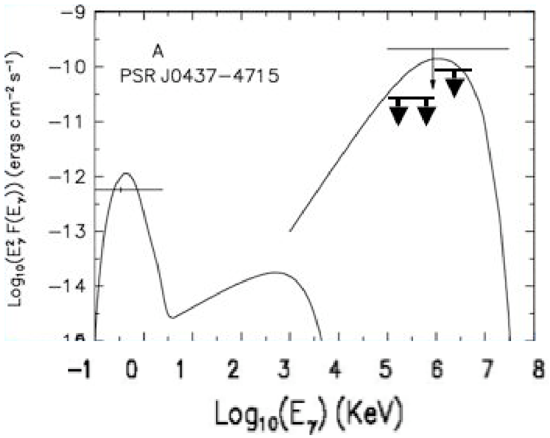






Zhang & Cheng 2003





Predictions for ms pulsars above 10 GeV favoured in polar cap models with low magnetic field.

Outer gap models

CTA for blind searches, quantified, radio quiet fraction measured

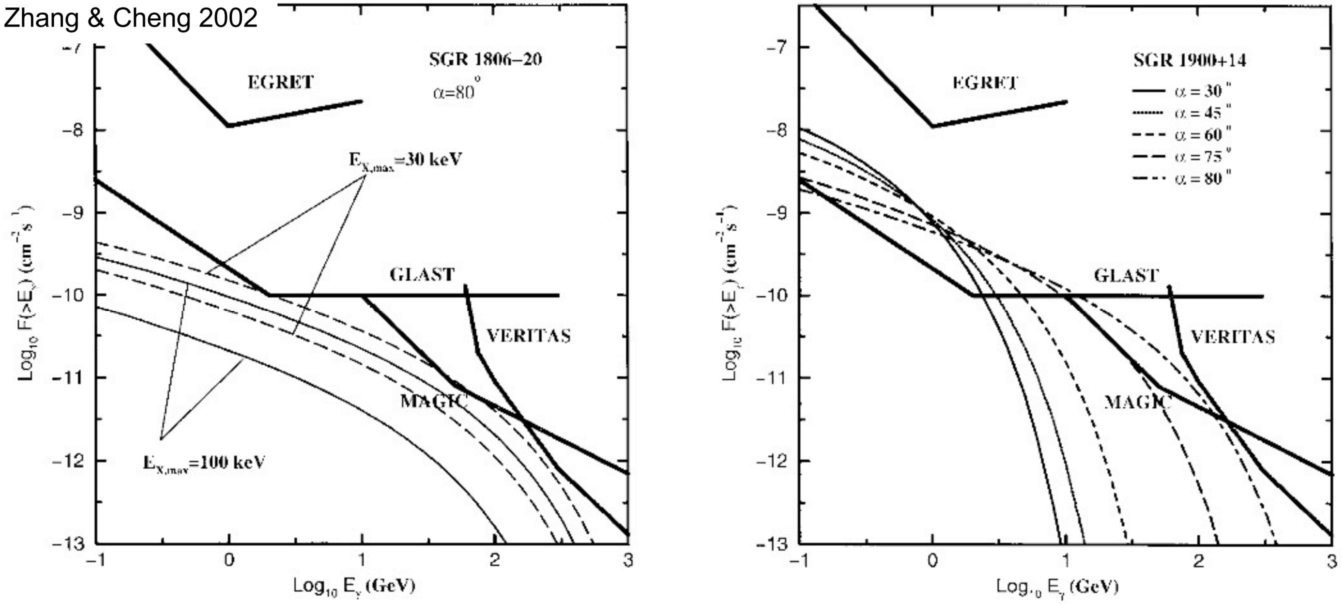
- Many GLAST and CTA sources will be unidentified
  - are they pulsars?
  - Need to search blindly for the pulsar period
  - Problem: pulsars are not perfect clocks!
  - $\phi=2\pi\,(t\,\nu + t^2\, d\nu/dt)$, t=time $\nu=1/P$
    - variation of phase due to change in the period can be neglected if its phase contribution is at most, less than half cycle

      $t^2\, d\nu/dt < 1/2$
    - thus the duration of the time for the search in absence of a priori information about P and dP/dt should satisfy $T_{obs} < (1/\,2\, d\nu/dt)^{0.5}$
    - during this time enough photons should be collected to determine P
    - e.g., with P and dotP of Crab, useful blind observation time is 10 hours
    - GLAST can only deal with the brightest
- CTA will know positions of all GLAST unidentifieds around 50 GeV, and all will be bright sources for it: pulsar ids, fraction of radio quiet measured directly

CTA to test outer gap model for magnetars

- Soft gamma-ray repeaters and anomalous X-ray pulsars are magnetars
  - P = 6 - 12 s
  - persistent X-ray sources (much beyond spin down): 10^{34} - 10^{36} erg s^{-1}
  - dipole fields 10^{14} - 10^{15} G in neutron stars
  - AXPs would be the first class of astrophysical objects the emission of which is mainly driven by magnetic field decay (Thomson & Duncan 1996)
- No significant emission expected from polar caps

Zhang & Cheng 2002



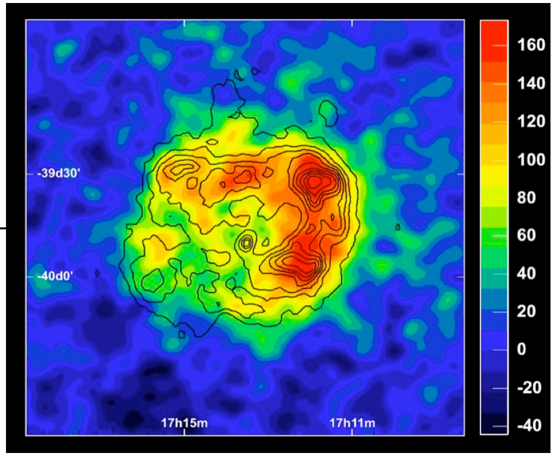
Some questions for CTA

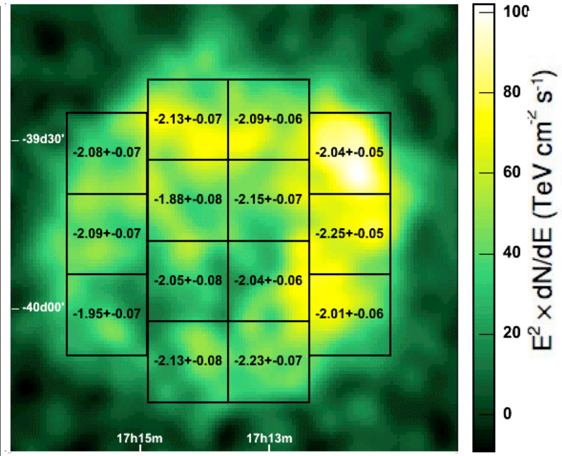
- How and where are particles accelerated in the pulsar magnetosphere? What are the high-energy radiation mechanisms?
  - CTA mission: study of pulsar profiles (geometry), and cutoffs (acceleration)
- Are processes the same for all pulsars?
  - CTA mission: broad band spectra with high number statistics (many pulsars wtith well measured spectrum)
- Are there gamma-ray millisecond pulsars? Are there gamma-ray magnetars?
  - CTA mission: accesibility to large number of ‘in principle’ observable ms pulsars, large sensitivity above 10 GeV
- What are the population trends: Spectrum index vs age, L(gamma) vs L(SP), Ec vs B0, limit to gamma-ray radiation efficiency as function of E, radio-loud to radio-quiet fraction?
  - CTA mission: almost all radio pulsars in the P-Pdot diagram accesible, large number for population studies, answers directly measured, blind searches
- Serendipity
  - CTA mission: high confidence detection in seconds timescales may open the window for new high energy phenomena yet unhidden in the folding or in the low number statistics for the photon regime (e.g., timing noise? Glitches?)

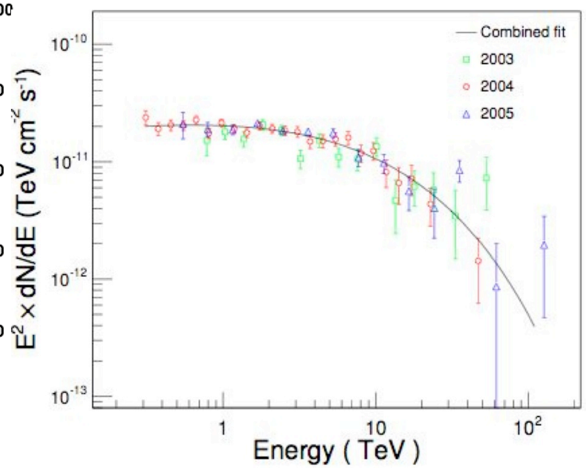
SNRs - PWNe - Cosmic rays (I)

Observations of SNRs: quick look @ current status

HESS Collab.

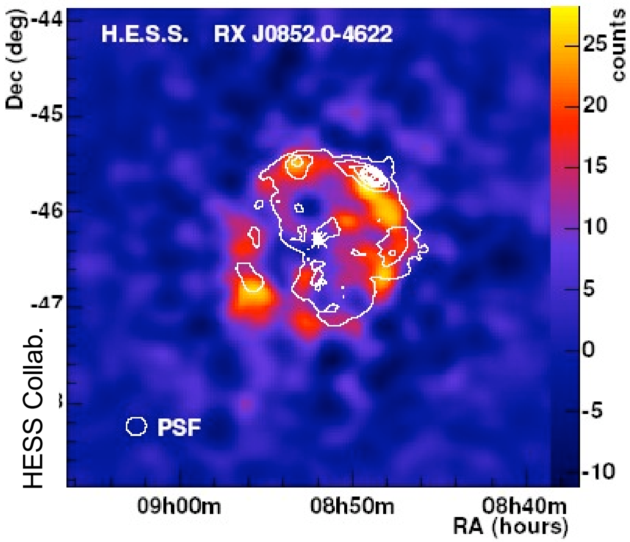


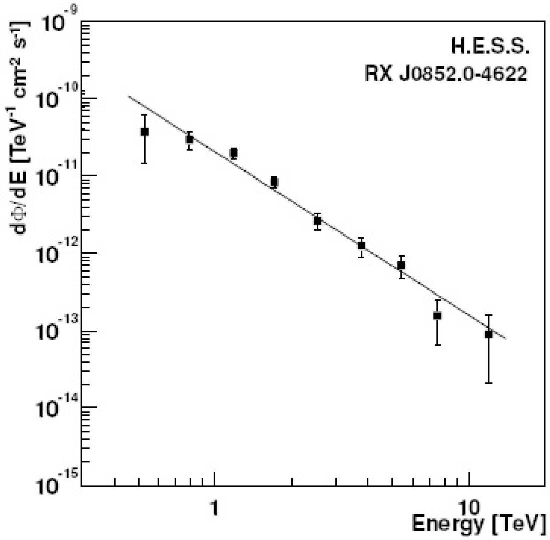




RX J 1713
Vela Jr.

HESS Collab.



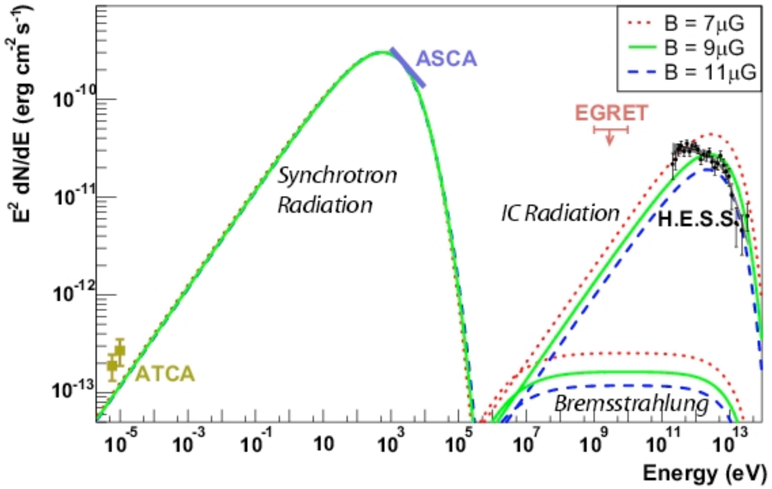


RX J1713 has E>40 TeV gammas: 1st model independent proof of particle acceleration to E>100 TeV

if hadrons: primary energy ~ 30 TeV/0.15 = 200 TeV

if leptons: primary energy ~100 TeV (KN effects)

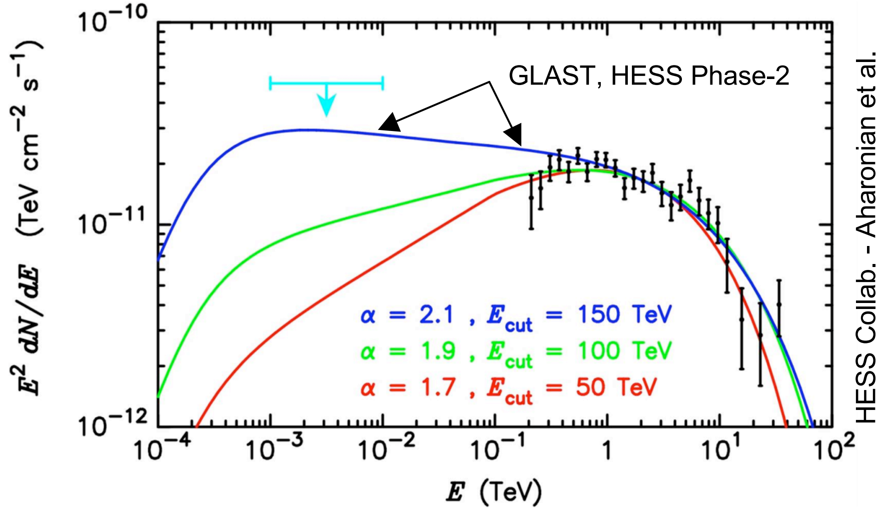
Hadronic Origin of gamma-rays: the case of RX J1713



IC not ruled out.. but B<10 μG, and Emax>100 Tev

Two assumptions going in opposite directions within DSA models (field amplification in shocks)

Does not provide a good fit.



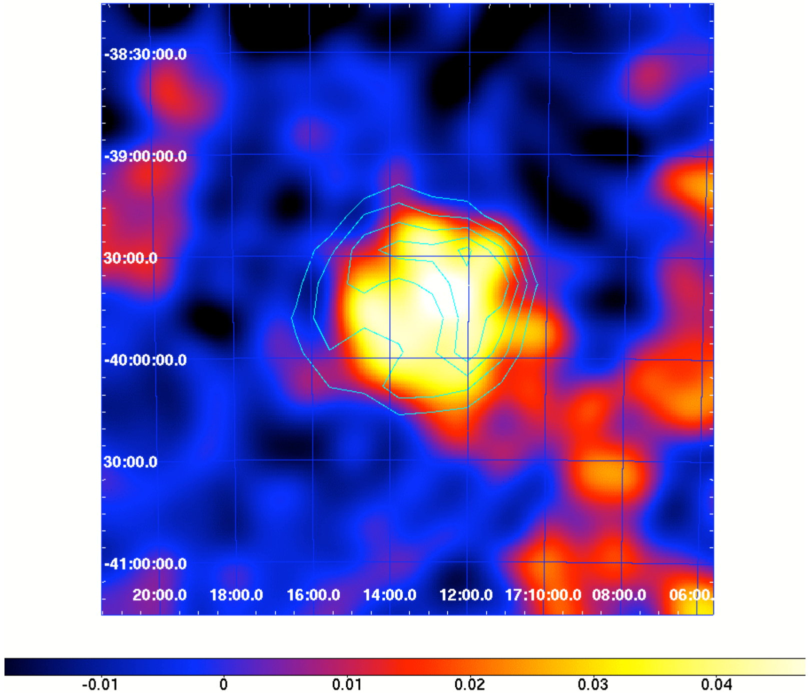
HESS Collab. - Aharonian et al.

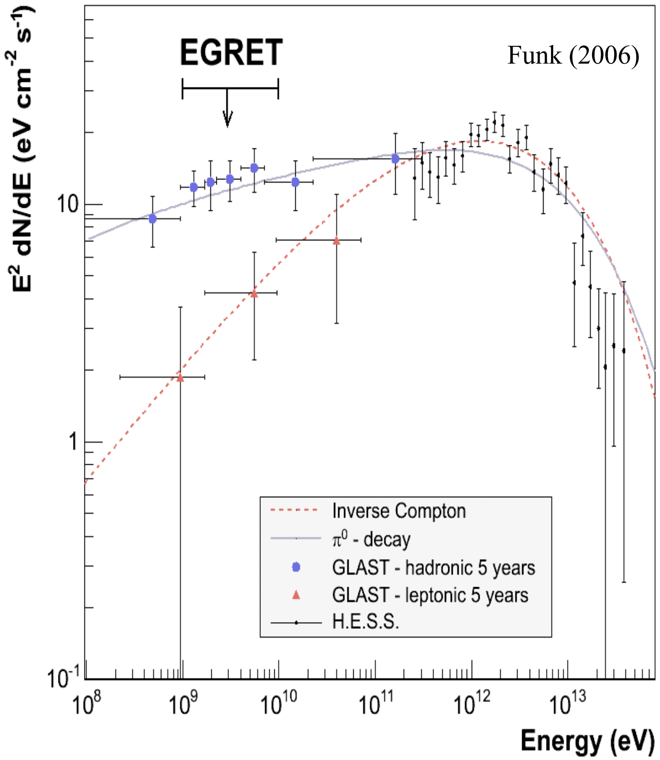
Hadronic models comfortably fitting the spectrum, with reasonably energetics (10^{50} erg in n=1 cm^{-3} medium)

Possibility of differentiating the cutoff energy.

CTA to sensibly distinguish hadronic from leptonic origin

- Couldn't that be done before?
  - Certainly GLAST plus HESS/MAGIC/VERITAS will have/are having a say on this
  - probably yes only for particular cases, not for a large sample
  - e.g., RX J1713: need 5 years of GLAST data for a sensible distinction above 1 GeV
    - particularly difficult for GLAST, an EGRET source 5x more luminous nearby
- Spatial resolution, CTA is to improve on HESS, much beyond GLAST

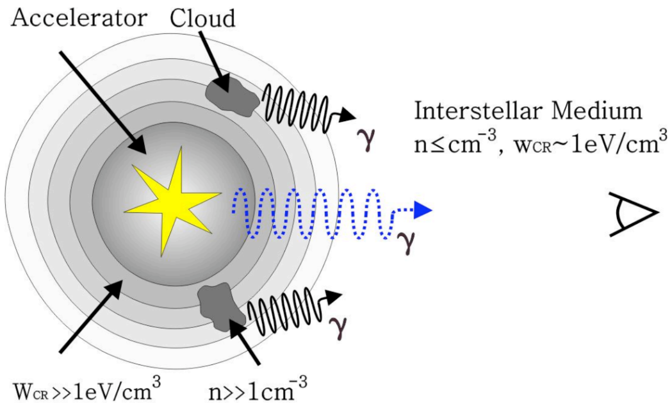




CTA begins to address a more sensible question: how much?

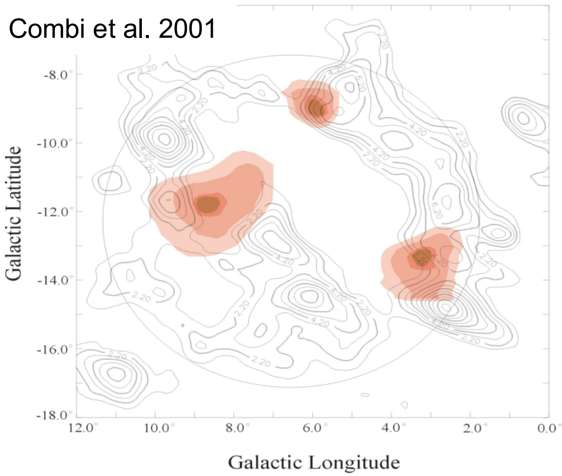
- Yodh 2007 at the 1st GLAST Symposium:
  - "But... you know, the real question is how much of hadronic and how much of leptonic origin is there for the same source."
  - Hybrid model comparison for sources 'in between'
  - Field in its infancy, again driven by observations

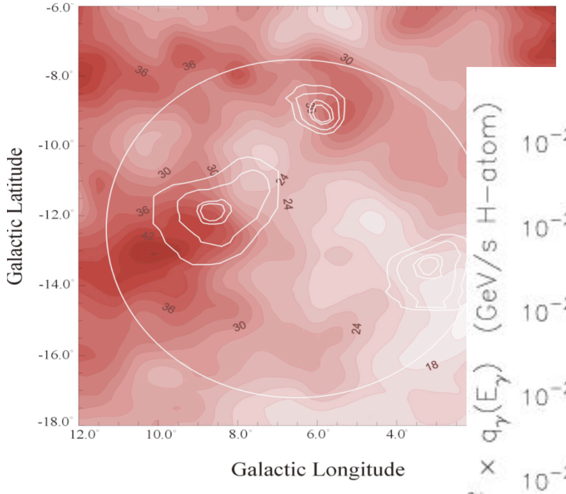
CTA to study gamma-rays as tracers of cosmic rays

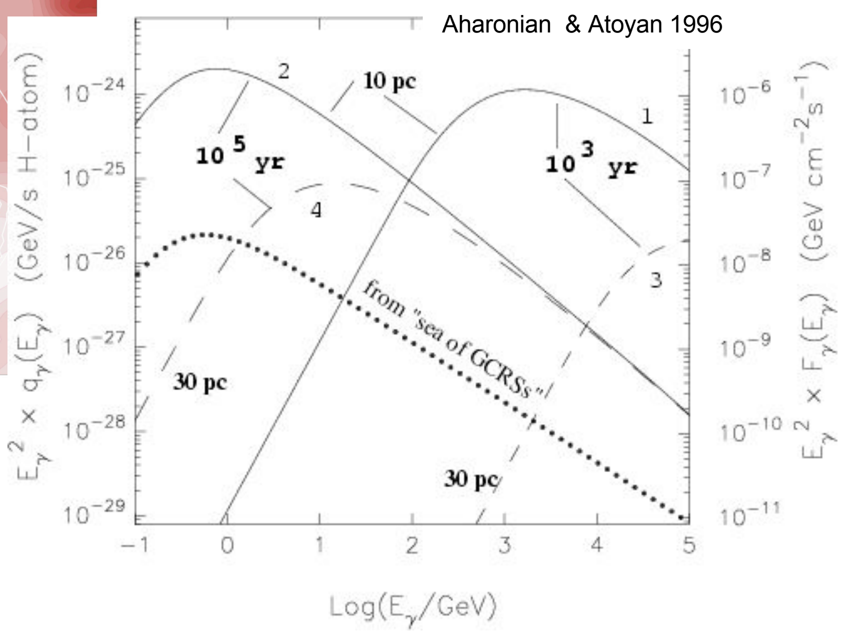


While travelling from the accelerator to the cloud the spectrum of CRs is a strong function of time t, distance to the source R, and the (energy-dependent) Diffusion Coefficient D(E)

Depending on t, R, D(E) one may expect any proton, and therefore gamma-ray spectrum: hard/soft/with & without TeV tail/with & without GeV counterpart, ... even worse if the target is moving, like a stellar wind (convection)

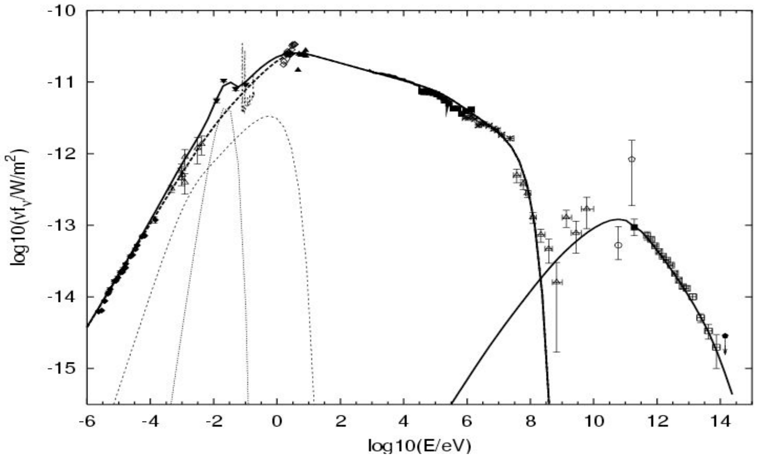


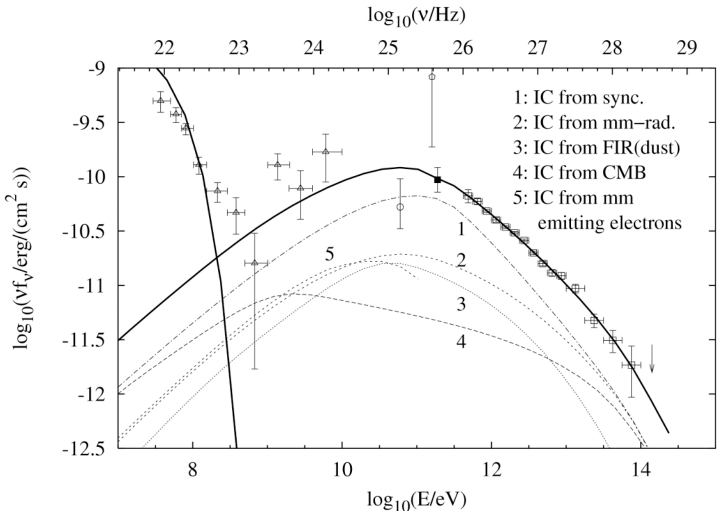




large range of parameter space observable by CTA

From Crab to the PWN zoo



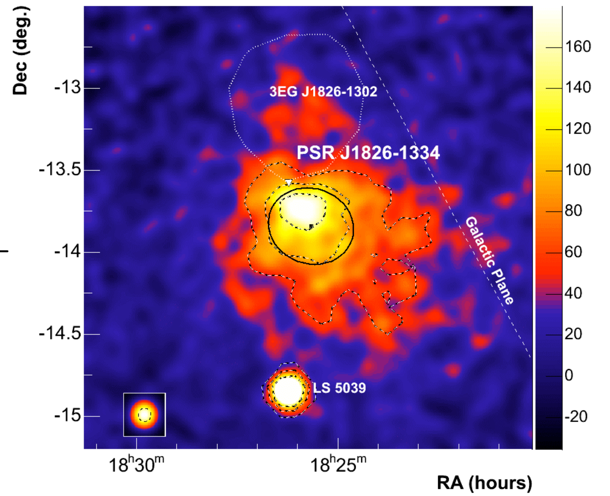


Crab Nebula is a very effective accelerator but not an effective IC gamma-ray emitter.
We see gamma-rays from Crab because of its large spin-down reservoir (~10^{38} erg s),
but gamma-ray lum. << spin-down power, because of a large magnetic field,
whose strength also depends on spin-down.

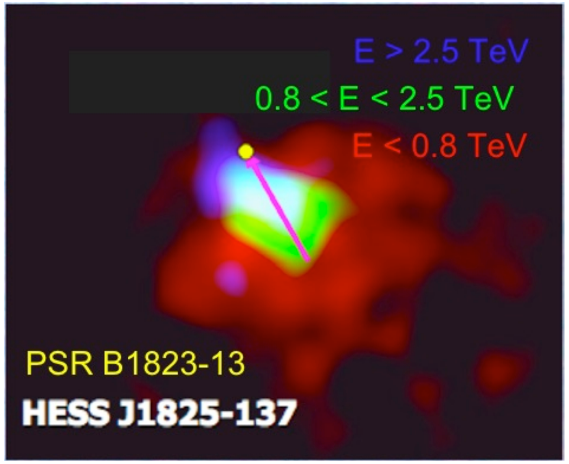
A large zoo is awaiting for CTA (building upon the results from HESS):
less powerful pulsar --> weaker magnetic field --> higher gamma-ray efficiency

(i.e., even when there is less spin-down power available,
there is a more efficient sharing between synchrotron and IC losses).

CTA to build upon discoveries of HESS PWNe



HESS J1825

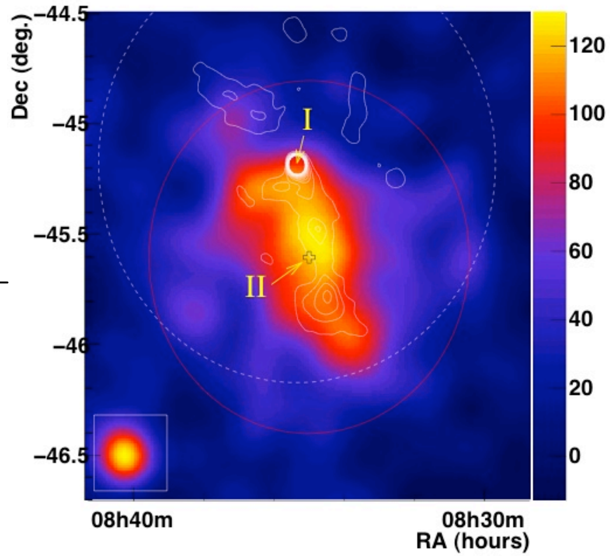


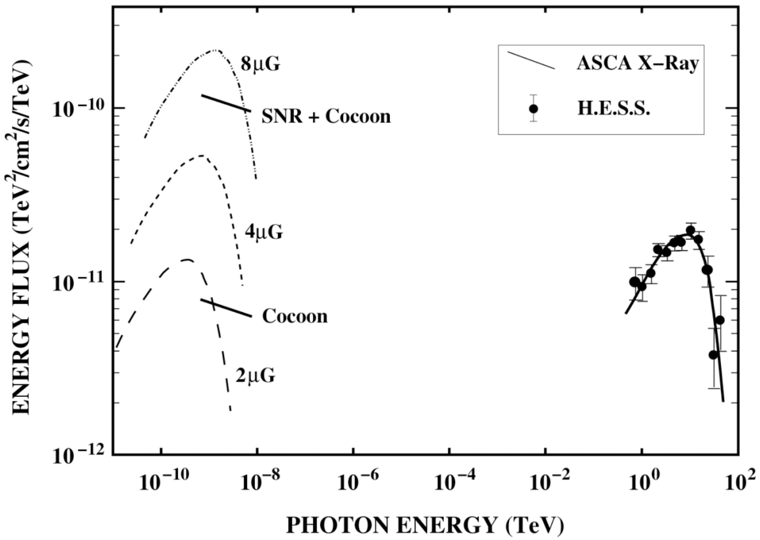
Above 0.2 TeV, similar luminosity to Crab, but 2 order of magnitude less spin down. Magnetic field few μG, instead of hundreds.

Decrease in source size with increasing energy (softening of the spectra with distance).

Relic electrons from an earlier phase with more spin down power?

Vela X





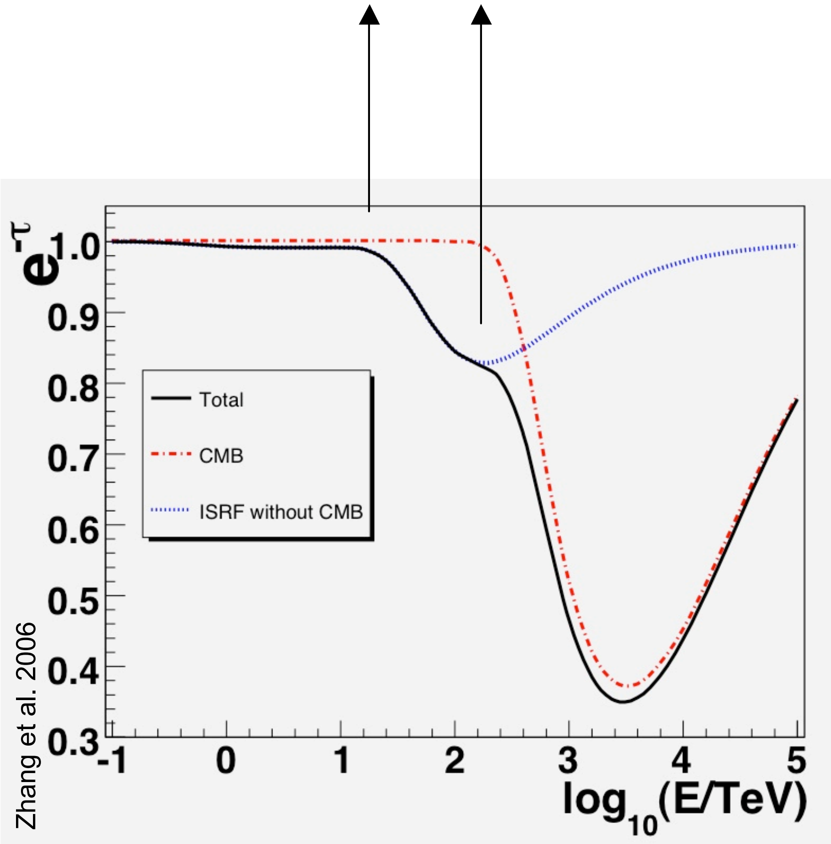
1st obs. of peak in VHE source?

Compton peak? Magnetic field too low?

Hadronic wind? (Horns et al. 2006)

CTA to measure VHE absorption in interstellar radiation field

- Higher infra-red background near the galactic center (Porter and Strong 2006)
  - The attenuation due to the CMB is at only 10 Kpc if E>500 TeV (opaque universe)
- The attenuation due to the ISRF (with a comparable number density at longitudes 20µm to 300µm, can produce absorption at about 50 TeV (Zhang et al. 2006)



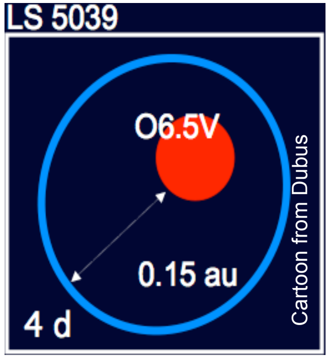
Observation on the cutoff energy will provide independent information to test and constrain the ISRF model (similar to EBL).

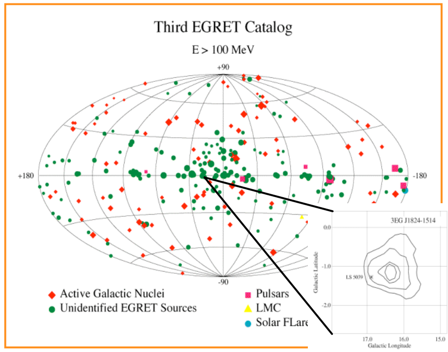
CTA to discover sources at different distances to independently test/measure the absorption model/ISRF.

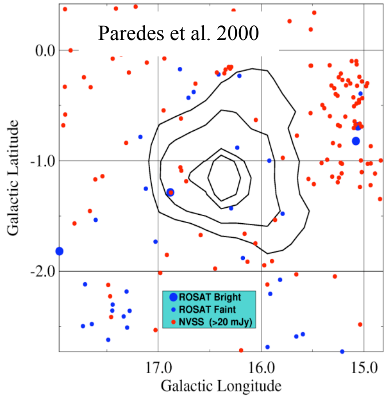
Less uncertainty between intrinsic/extrinsic features in the spectrum than for EBL studies.

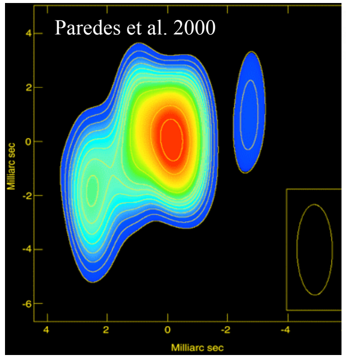
Microquasars - X-ray binaries

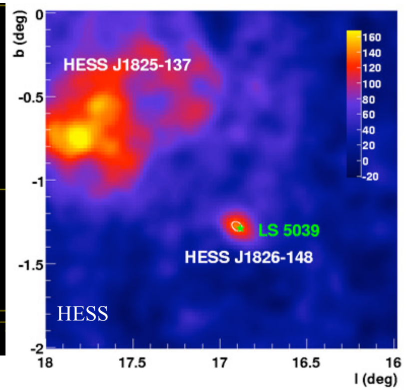
Current observational status of gamma-ray binaries @ HE

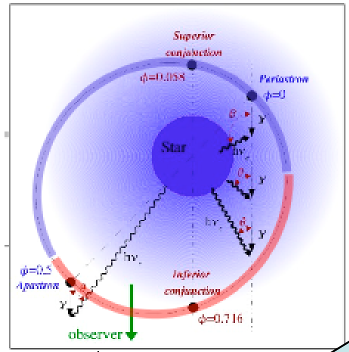


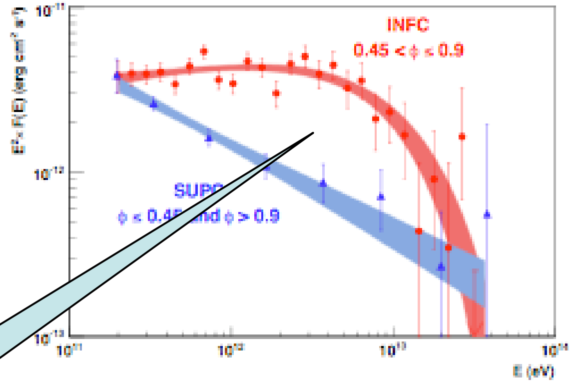


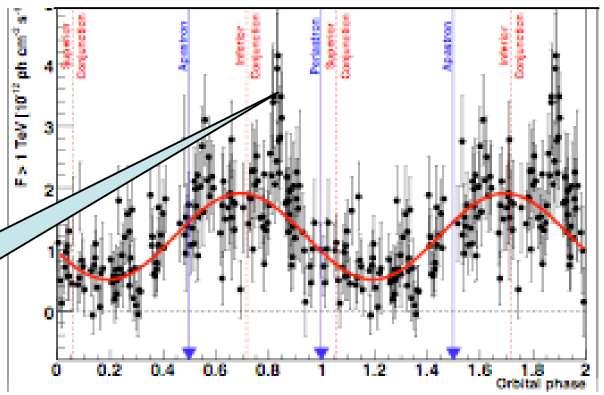


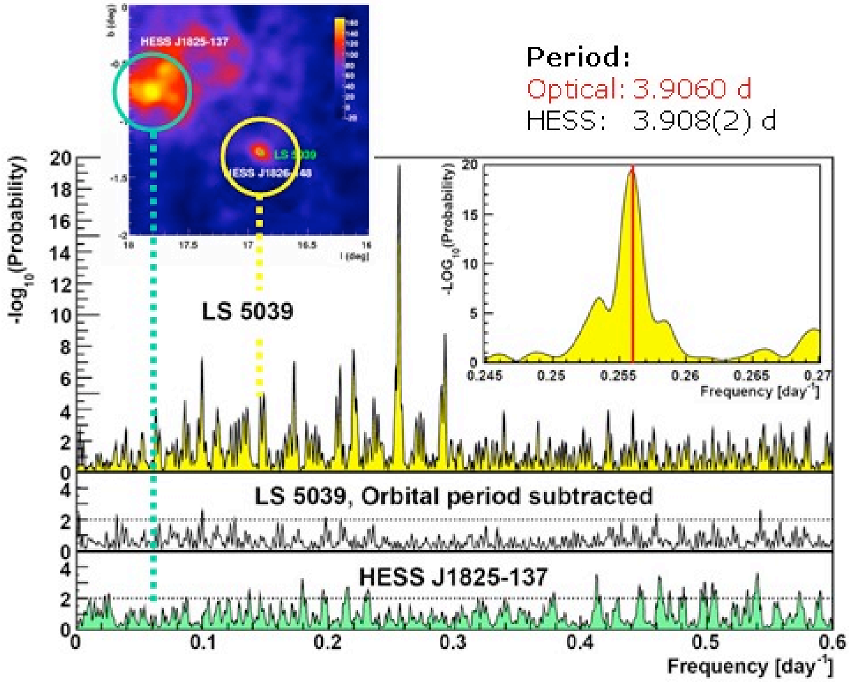








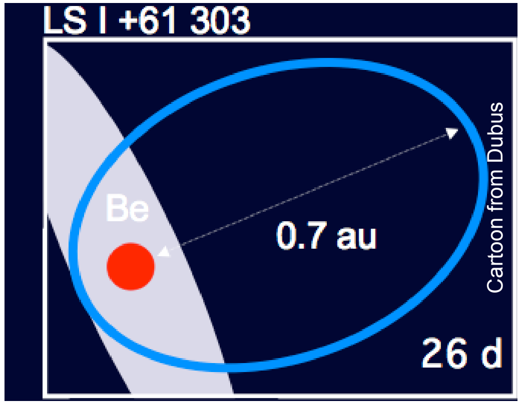


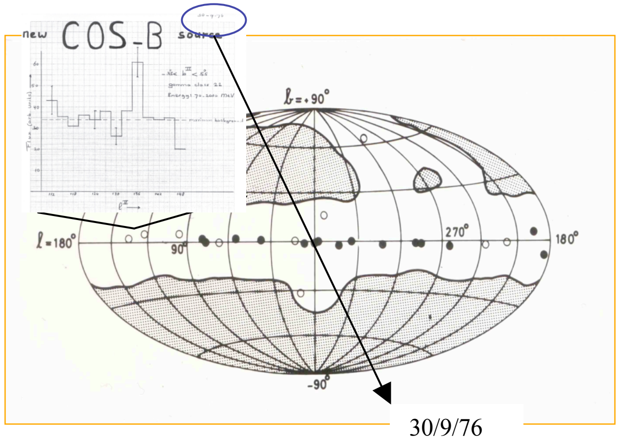


CTA fills in:
Need variations in
acceleration
and absorption to
explain spectra

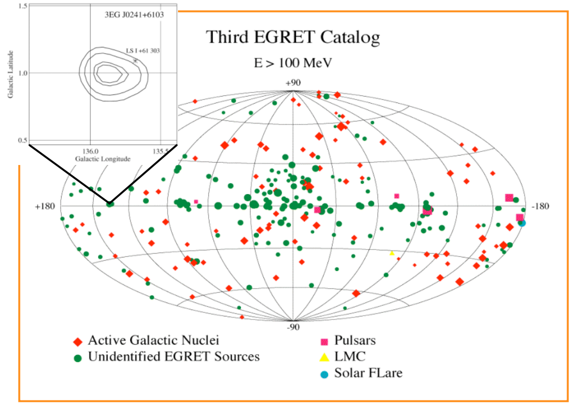
CTA: What is this?

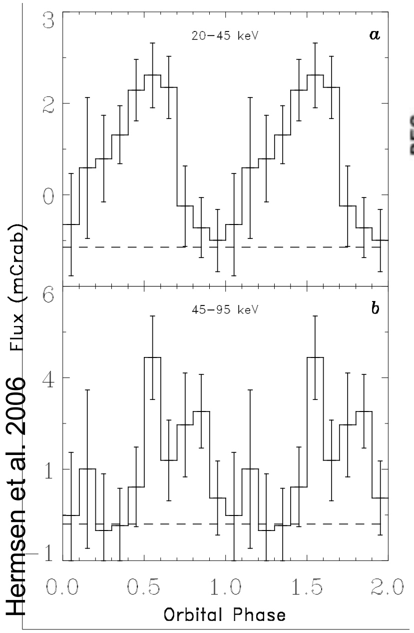
Current observational status of gamma-ray binaries @ HE

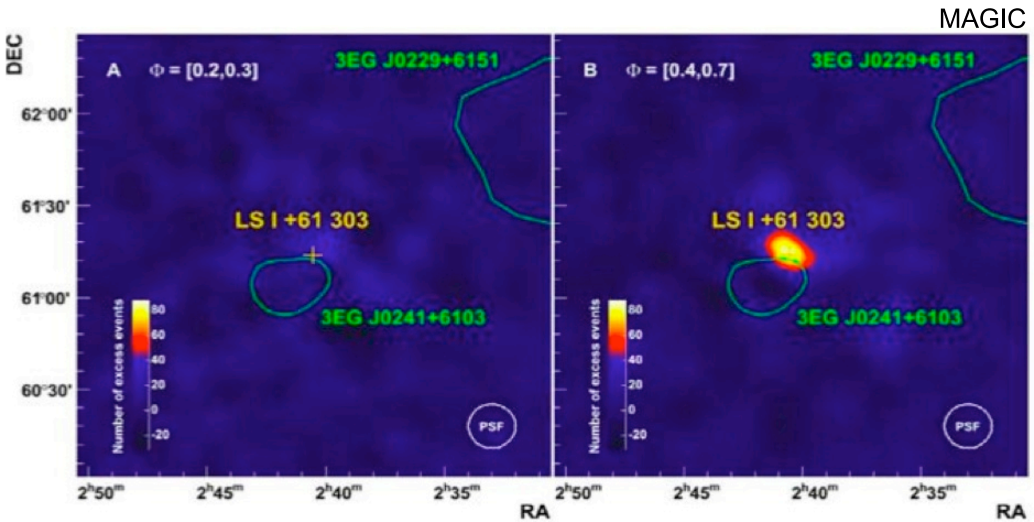


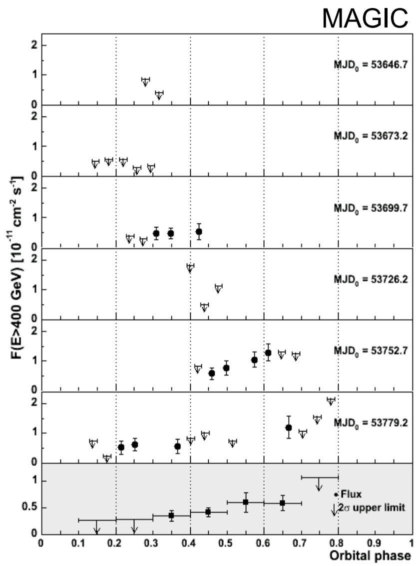


30/9/76
Hermsen

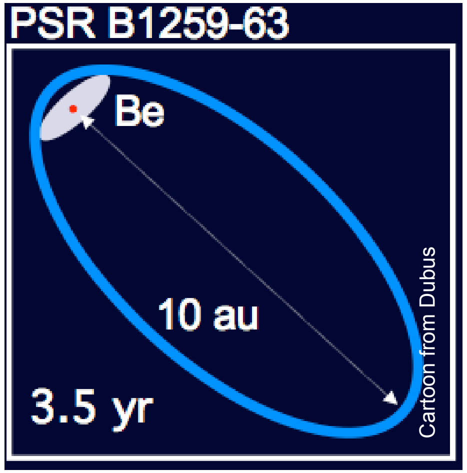


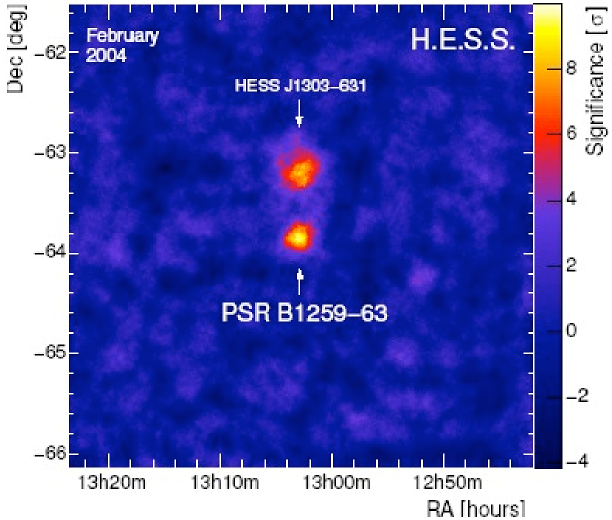


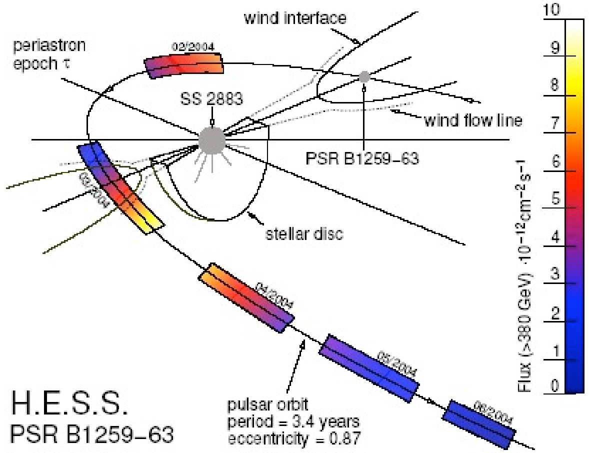


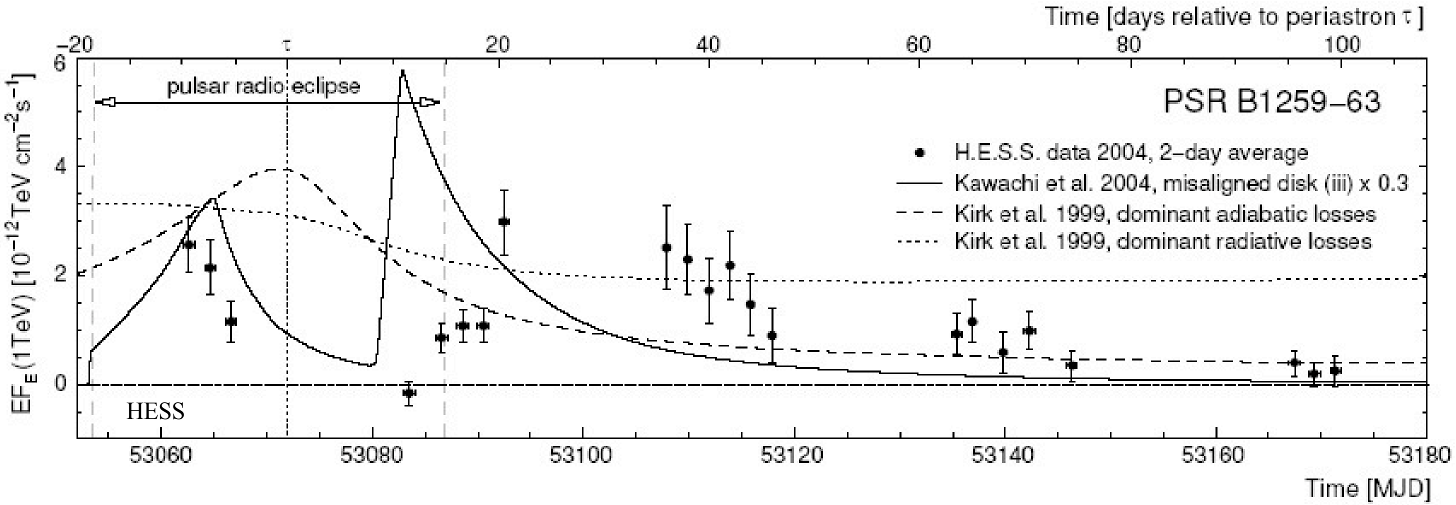


Current observational status of gamma-ray binaries @ HE



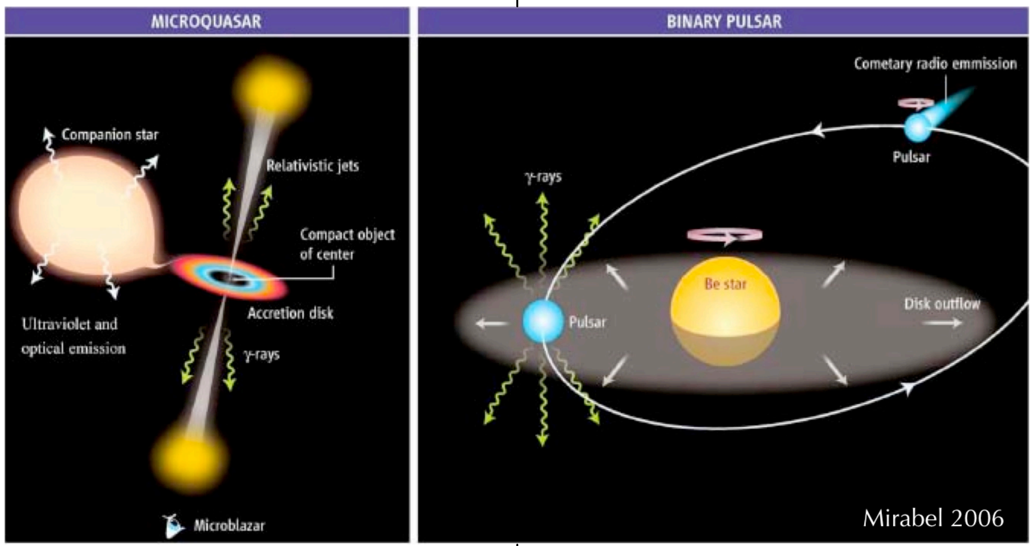


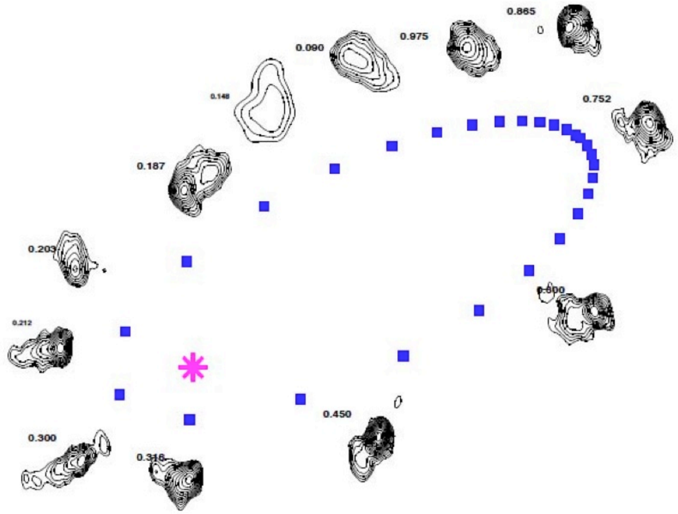


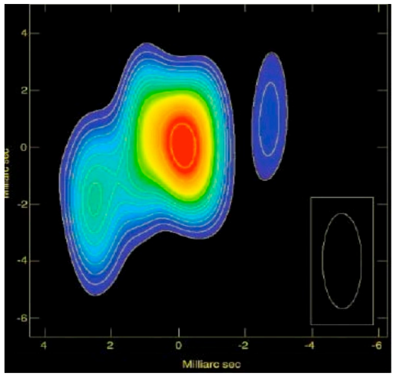


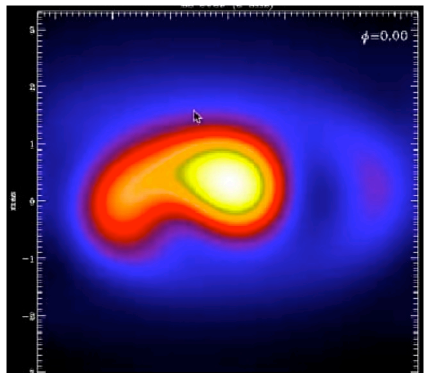
CTA: Explore this dichotomy beyond just a few single cases

LSI appears not a jet source, Dhawan et al. 2006



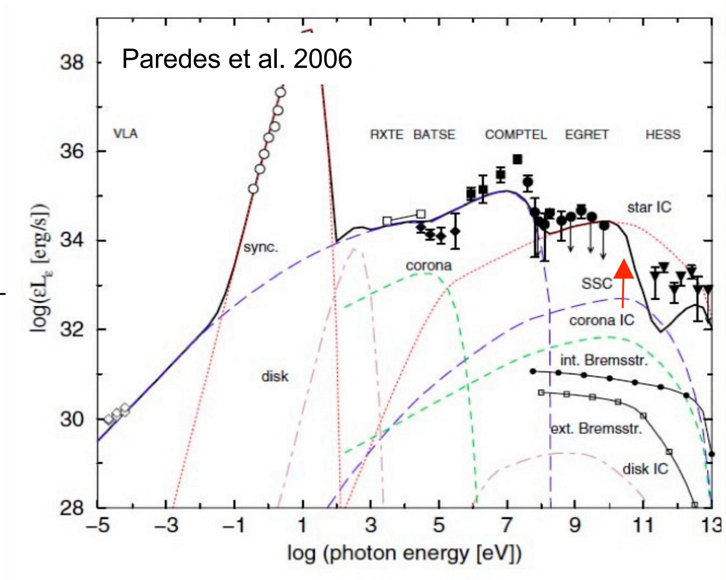


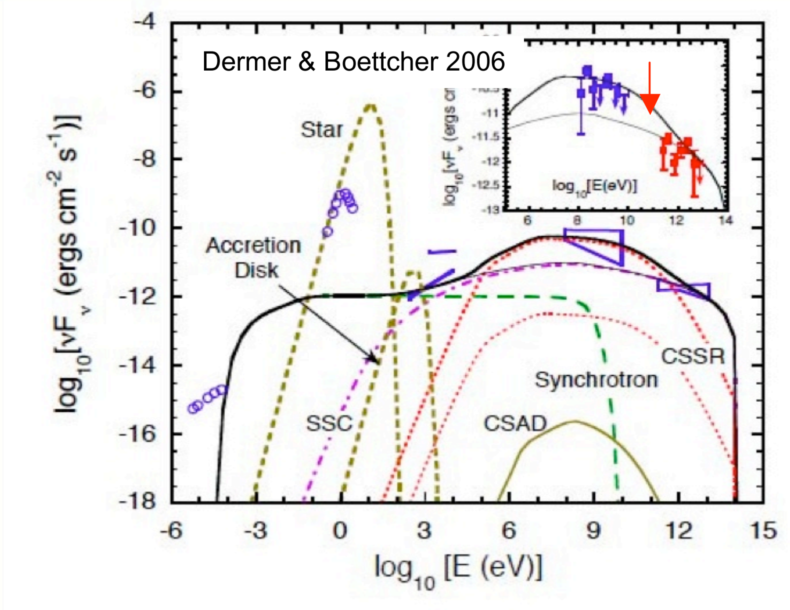




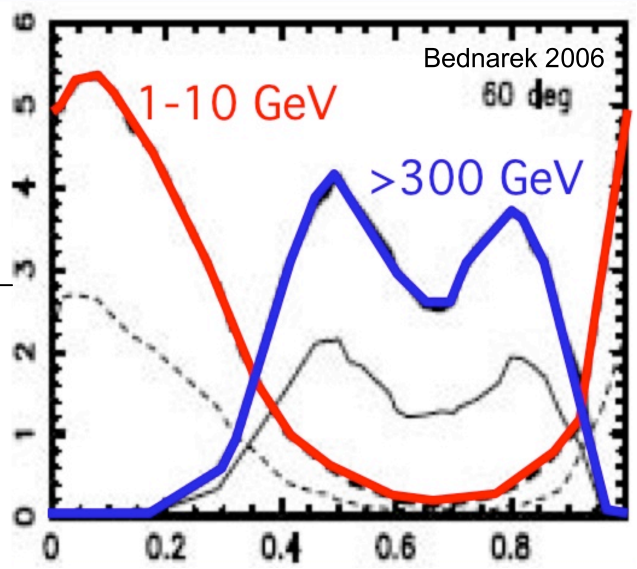
LS 5039 could not entirely surprinsingly be similar, Dubus 2006

CTA observations crucial to feedback theoretical models





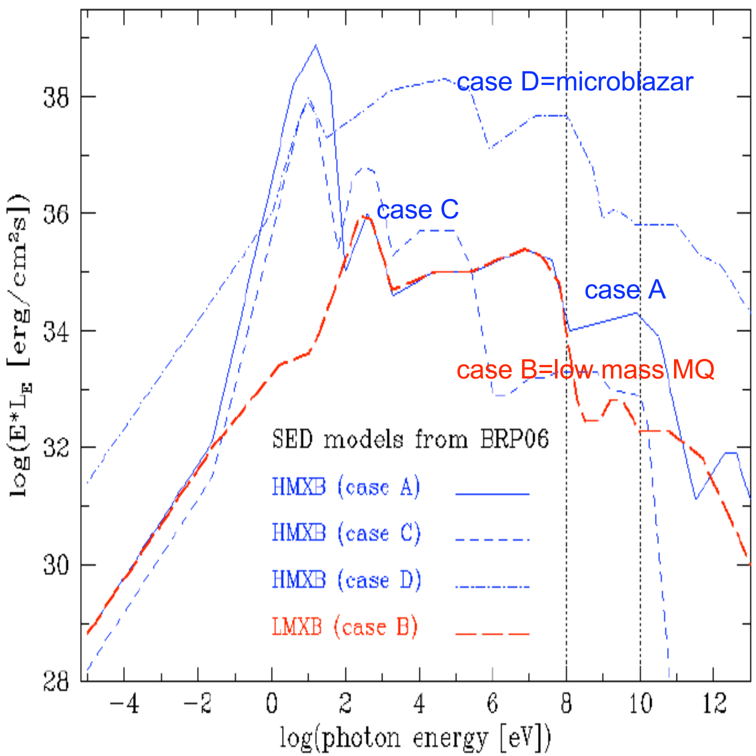
Leptonic models (e.g., LS 5039)

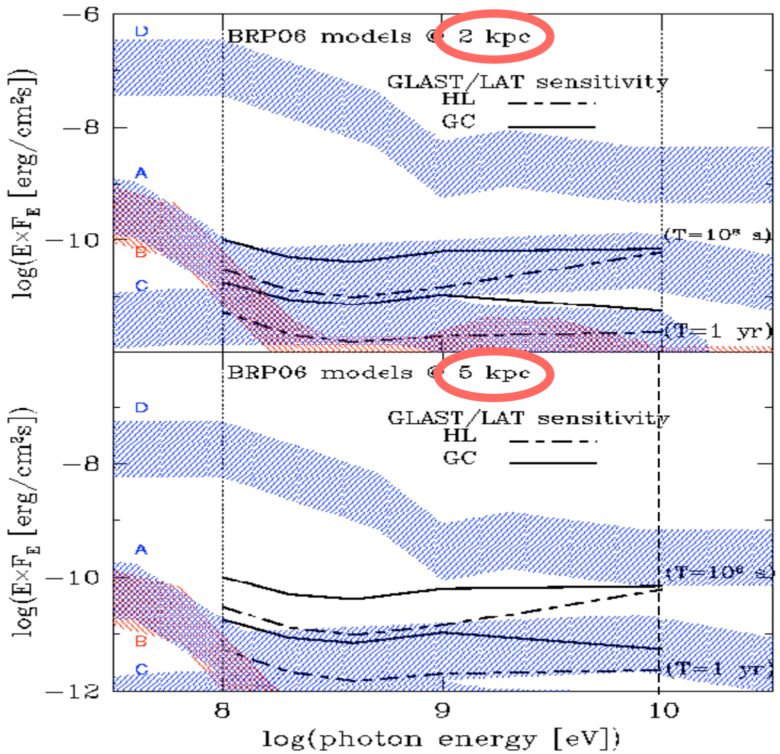


If cascades: expect anti-correlation of signal @ HE (e.g., LS 5039)

GLAST pathfinds the brightests MQs, CTA to make population

- Look at LAT yield from assumption of leptonic jets in MQs
  - viewing angle dependence + sky location
  - not many detectable candidates, and need long exposures, small distances





Santolomazza et al. 2006

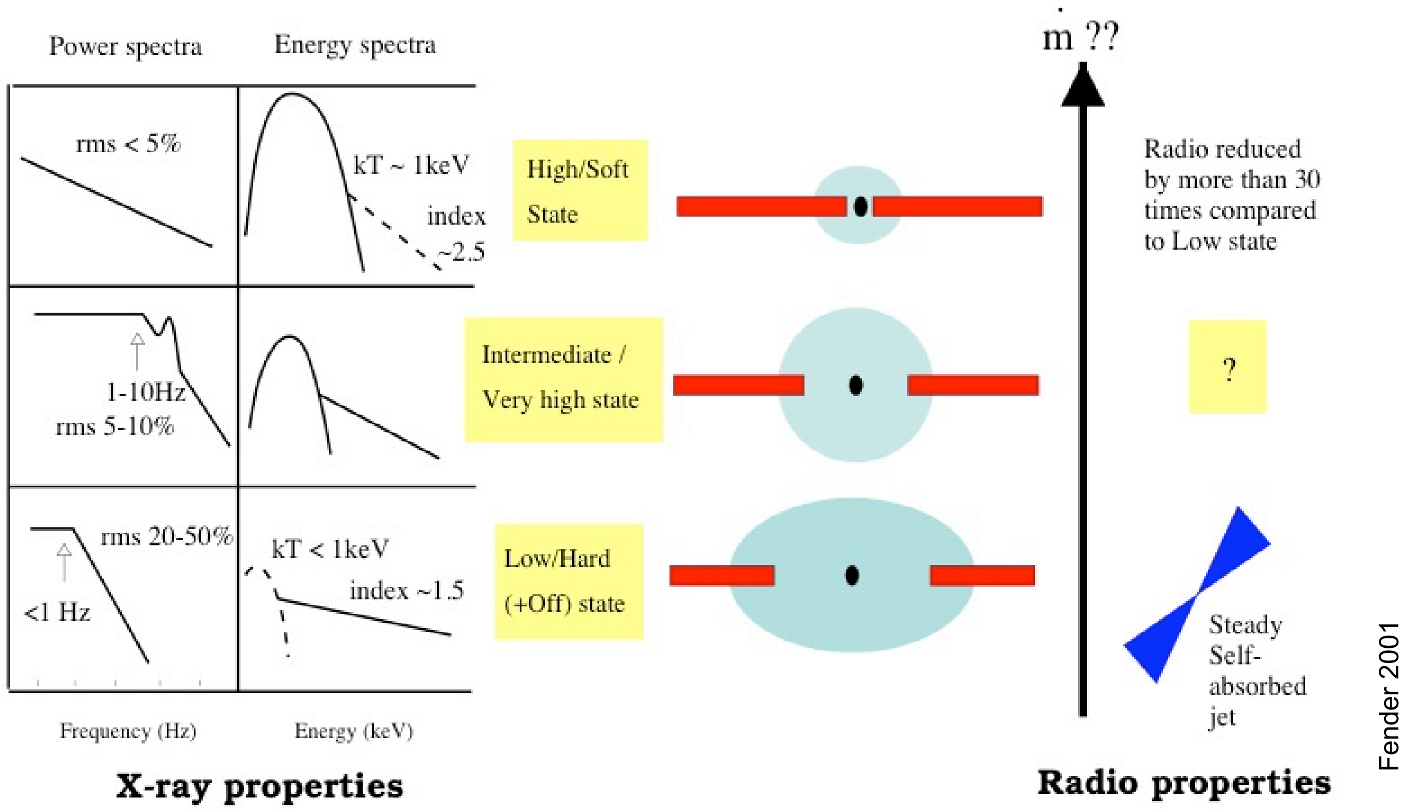
CTA: short timescale variability studies are possible

- Transient behavior in XRBs
  - To detect a source @ 10^{-13} erg/(cm^2 s) GLAST would need months, against hours at CTA: Below GLAST dectectability
  - above 10 GeV detection is barely possible
  - Phenomenology simple not accesible by other instruments, but CTA

Black holes display different X-ray spectral states:
- Low/hard state (a.k.a. power-law state). Compact radio jet.

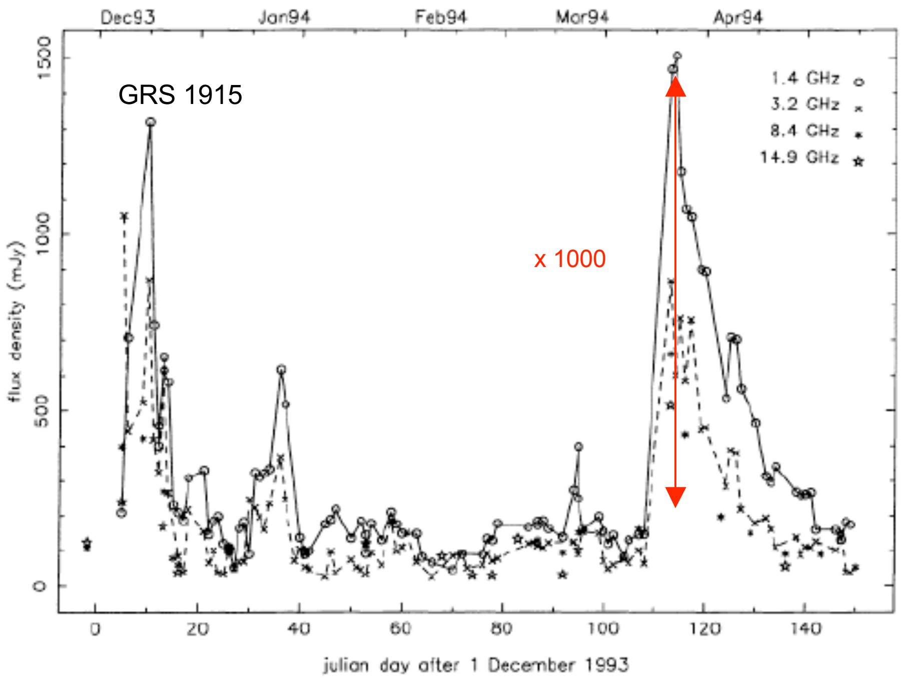
- High/soft state (a.k.a. steep power-law state). No radio emission.

- Intermediate and very high states → transitions. Transient radio emission.



CTA observations crucial to feedback theoretical models

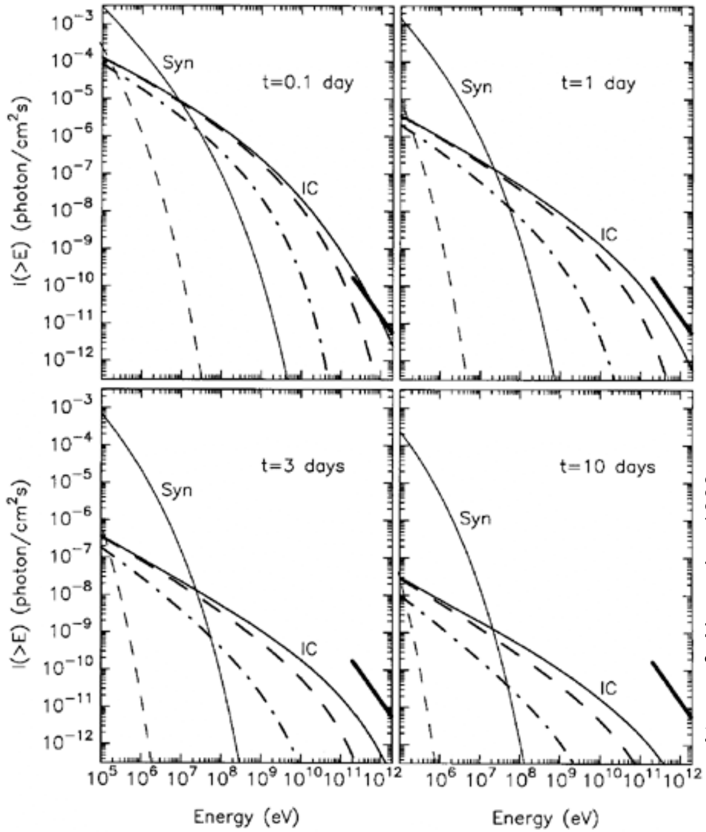
Emission during non-thermal radio flares?



Rodrifuez et al. 1995

Modeled as synchrotron radiation of relativistic e⁻ suffering radiative, adiabatic and energy-dependent escape losses in fast-expanding plasmoids (radio clouds) [SSC model]

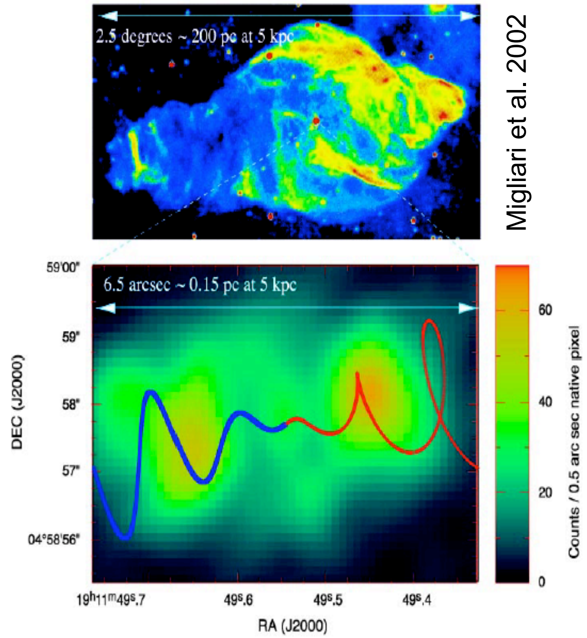
Exponential cutoff energies:
20 TeV _____
1 TeV _ _ _ _
30 GeV _ . _ . _

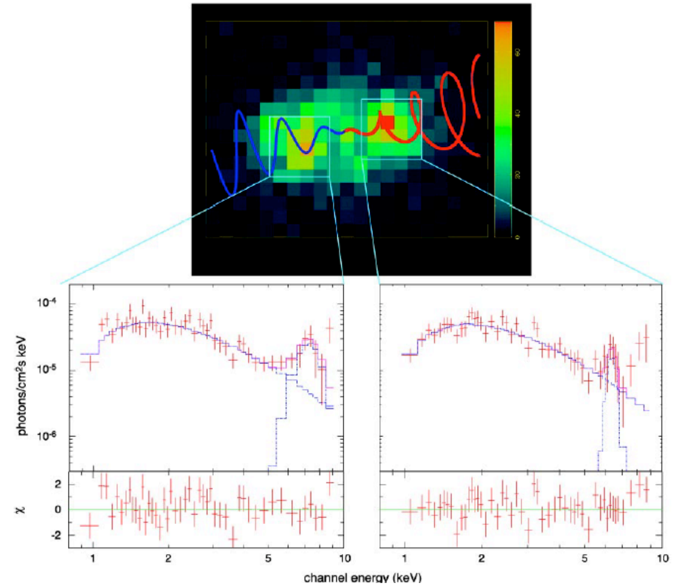


Atoyan & Aharonian 1999

Below GLAST dectectability, only CTA in the E> 10 GeV regime.

What about protons? Emphasizing neutrino connections

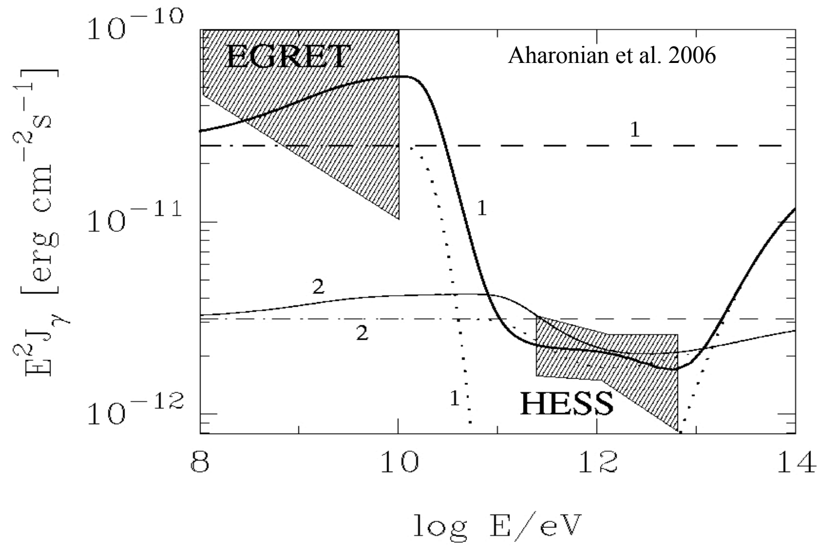


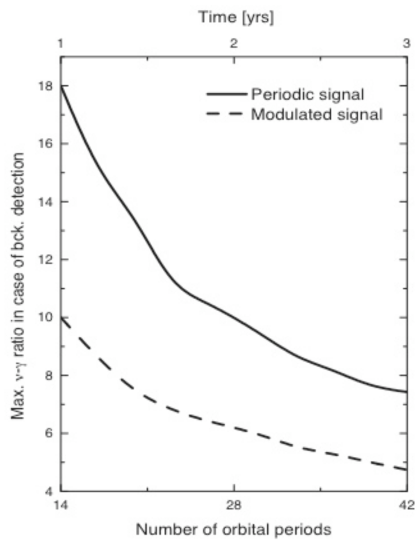


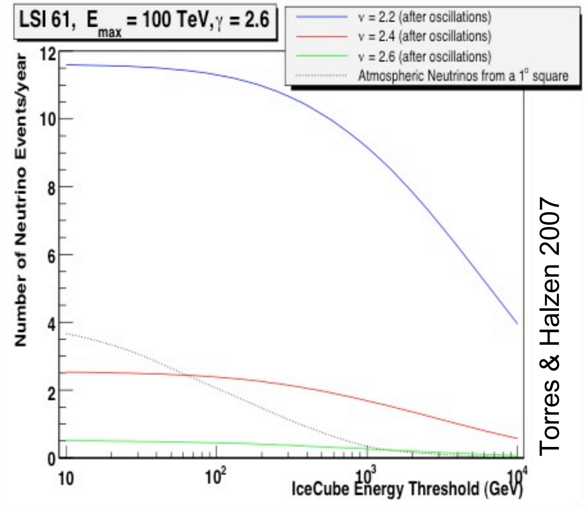
Relativistic ions in the jet of SS443 discovered by Fe Ka line observations

If protons populate the jet, gammas come from pion decay, and neutrinos come from charged pions

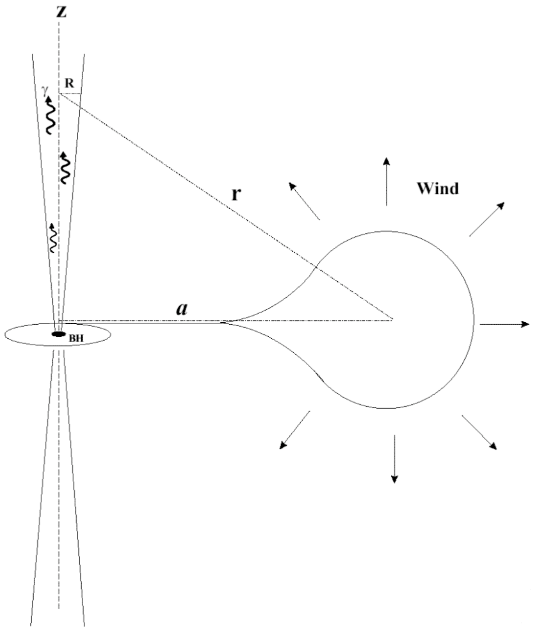
CTA + Neutrino facilities
BUT: CTA much more sensitive!

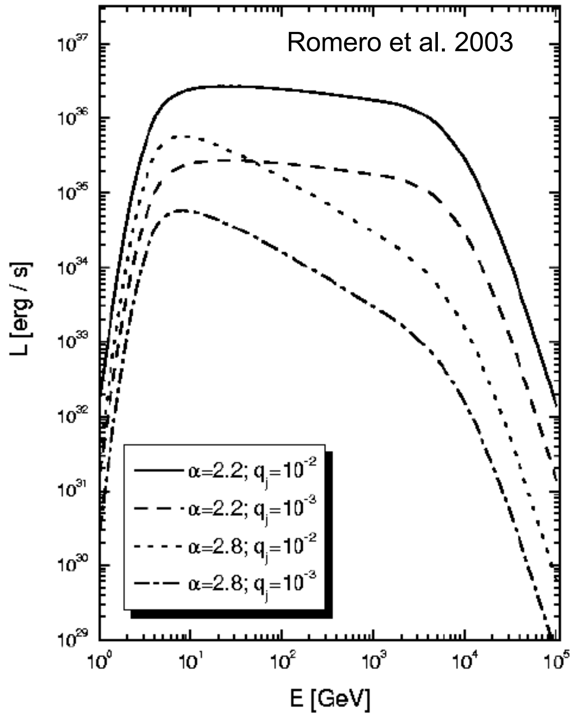






CTA observations crucial to feedback theoretical models... again





Hadronic models

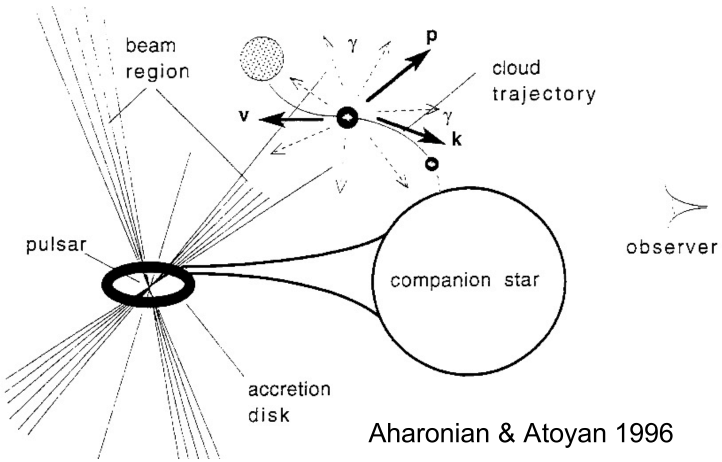
Conical jet 10^{14} eV protons interacting with stellar wind protons, assuming efficient wind proton diffusion inside the jet.

Protons are injected in the base of the jet and evolve adiabaticaly.

Emission arises from the decay of neutral pions created in the inelastic collisions between relativistic protons ejected by the compact object and the ions in the stellar wind.

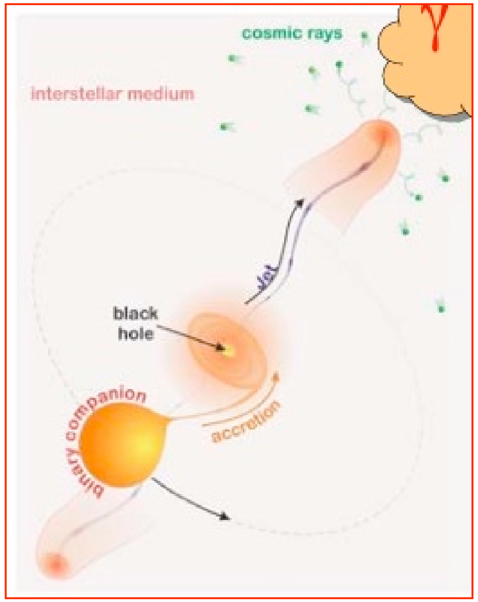
Interactions of hadronic beams with moving clouds in the context of accreting pulsars

Timescales and fluxes beyond reach of satellites

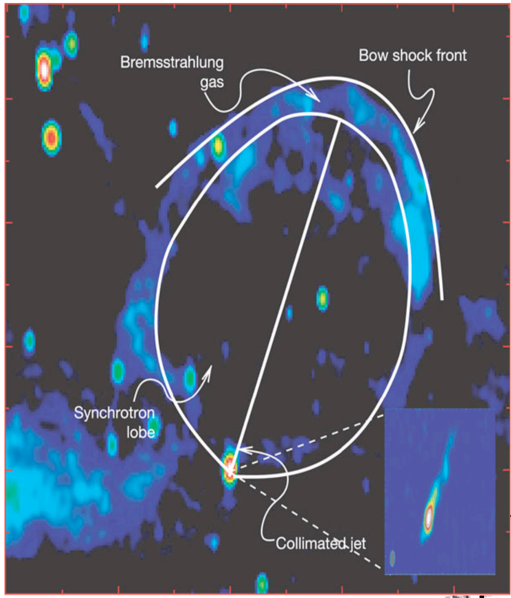


Aharonian & Atoyan 1996

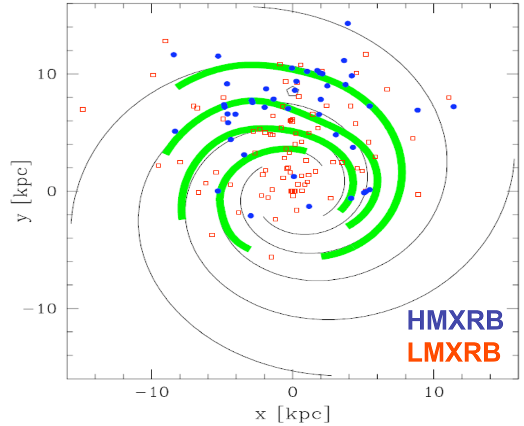
Just the tip of the iceberg is known: Jet - ISM interaction



[Heinz & Sunayer 2003]

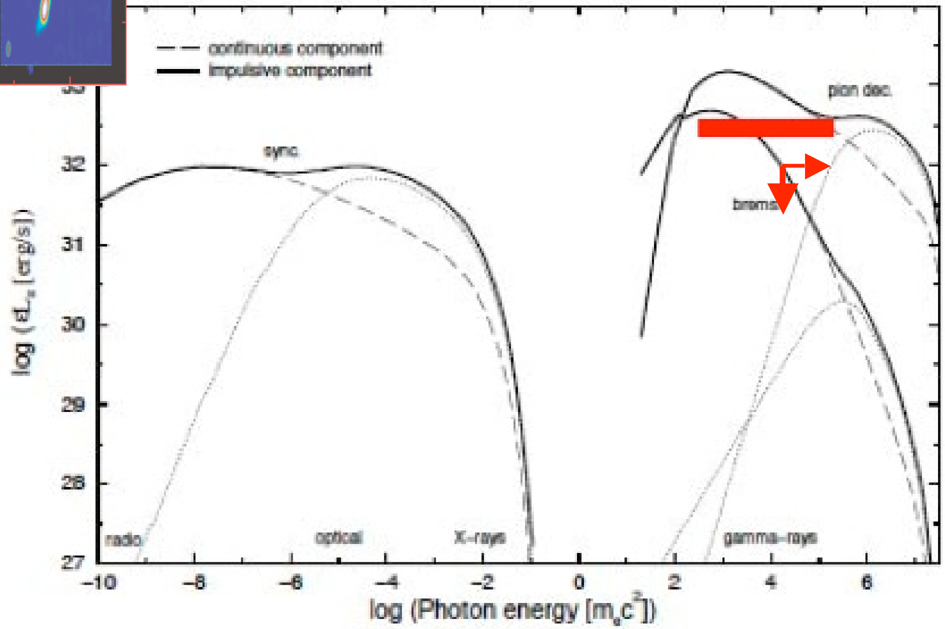


[Gallo et al. 2005]



[Grimm et al. 2002]

Bosch-Ramnon et al. 2005



Gamma-ray emission and its energy range depend on a large number of parameters:

from jet composition, to target material, from impulsive
or continuous injection, to duty cycle, distance, etc.

CTA to open parameter space for model testing
CTA wide field of view to allow serendipity discoveries of source (pairs?)

Some questions for CTA

- Significantly enlarge the population of XRBs/MQs observed
  - CTA mission: understand dichotomy between pulsar/star interactions and jets, detailed log N - log S

- Feedback to models
  - CTA mission: understand the emission process, the emitting region, absorption/cascading, magnetic fields, composition, primaries

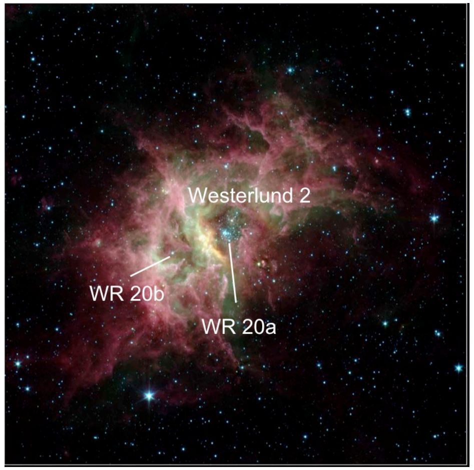
- Short term variability
  - CTA mission: follow up radio and/or X-ray flares
  - CTA mission: GeV to TeV emission in state changes?
  - CTA mission: Radio - X - Gamma correlation?

- Explore the jet - ISM interaction
  - CTA mission: steady + periodic source components, keys to CR acceleration in Galactic jets

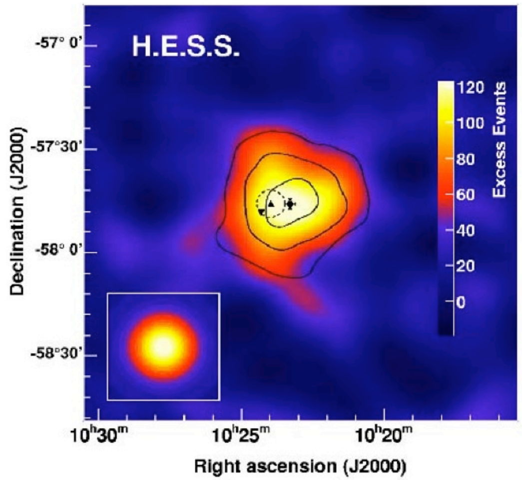
Clusters - Stellar systems

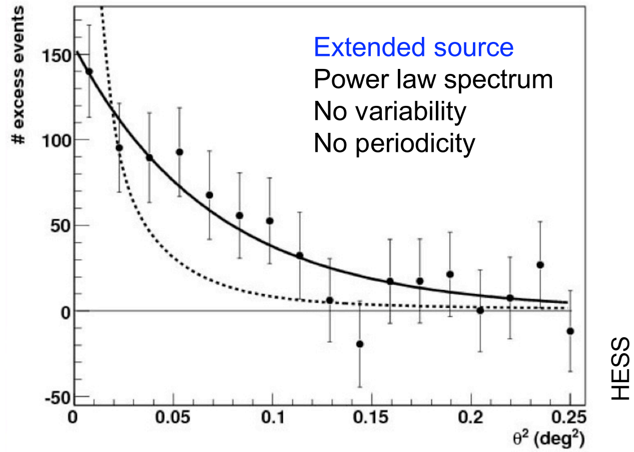
CTA to study star formation sites, already a detected source

8 stars earlier then O7, 2 WRs, and in particular WR20a, the most massive measured star (81 solar masses) in our Galaxy (WN6+WN6 binary)



Theoretical summary by O. Reimer





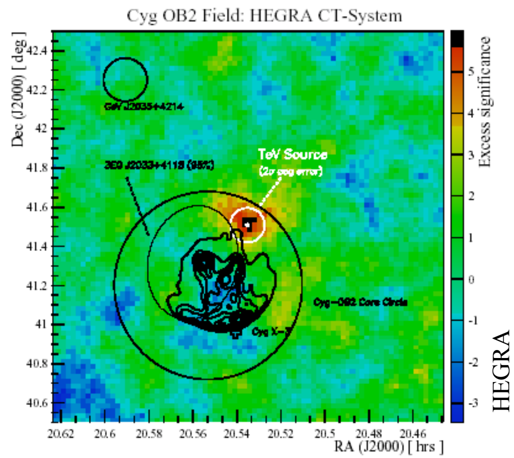
Colliding Wind Scenarios (leptonic)
Gamma production (optically-thin := no casc) IC of relativistic electrons with the dense photospheric stellar radiation fields in the wind-wind collision zone [Eichler & Usov 93, White & Chen 95, Benaglia & Romero 03, A. Reimer et al. 06]

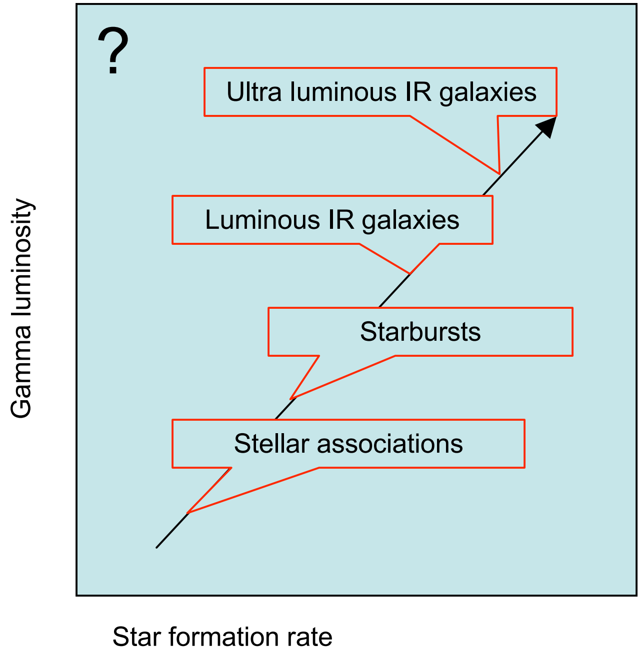
Colliding Wind Scenarios (hadronic)
neutral pion decay products, where mesons produced by inelastic interactions of relativistic nucleons with the wind material [White & Chen 92, Benaglia et al. 01, Benaglia & Romero 03, A. Reimer et al. 06]

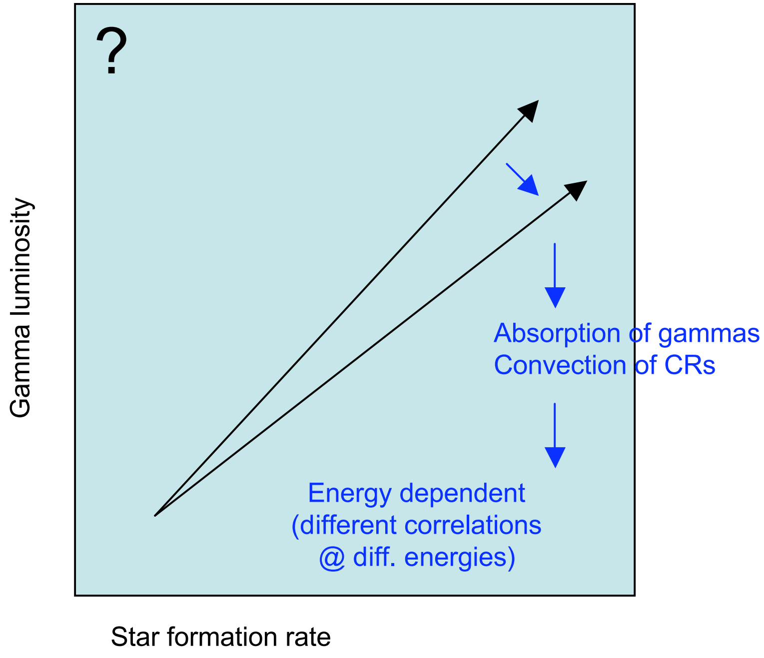
IC pair cascades
initiated by high-energy neutral pion decay photons (from nucleon-nucleon interactions in the stellar winds) [Bednarek 2005]

Collective Wind Scenario in young stellar cluster or OB-association
diffusive shock acceleration by encountering multiple shocks [Klepach et al. 2000]
pp interactions with collective winds - convection of primaries [Torres et al. 04, Domingo & Torres 06]

MHD particle acceleration
Magnetized plasma produced by supersonic flows, which then penetrate into a dense medium (-> bubbles), usually known in context with SNR [e.g. Bykov et al. 87, 01]







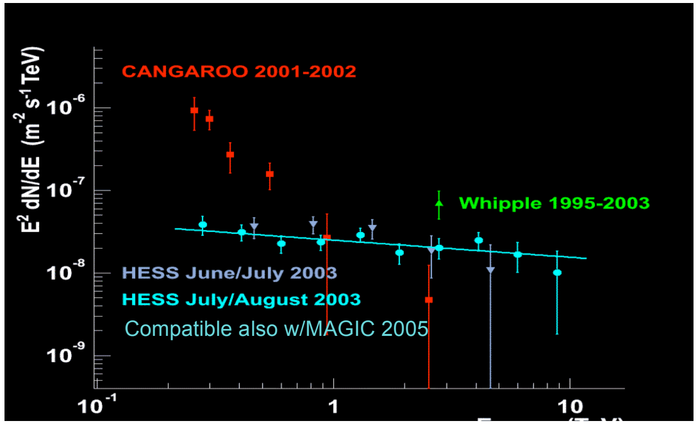
Aim: Understand collective vs single contributions with stellar associations in the Galaxy

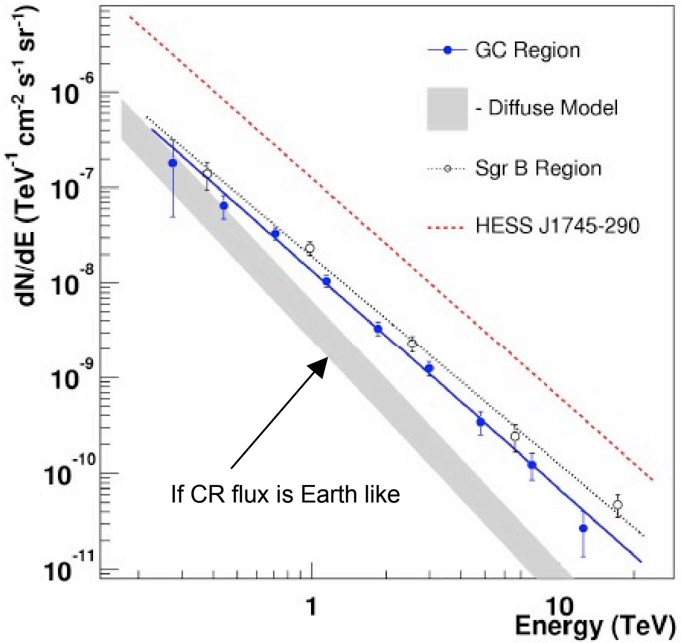
Early 2007
Upper limits for galactic stellar systems (open clusters, HEGRA)
Upper limits only for ULIRGs, and starbursts (MAGIC - HESS)
Clear detection of Wd2 (HESS), and displaced (unrelated?) detection in Cyg OB2 (HEGRA), important clusters still pending to report (with instruments @ current sensitivity)

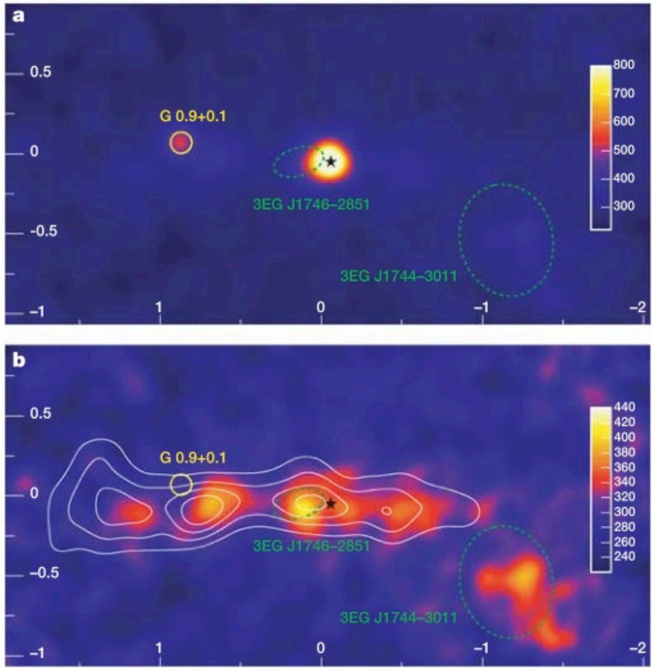
Galactic Center & Cosmic rays (II)

Cosmic ray population and sources in the Galactic Center

Steady state 0.05 % (E> 165 GeV)
Power-law with α = 2.2 ± 0.09 ± 0.15







Galactic Center Region (HESS)

a) sources
b) source subtracted with molecular clouds contours as measured in CS line

Compelling case for CR interaction with target matter.

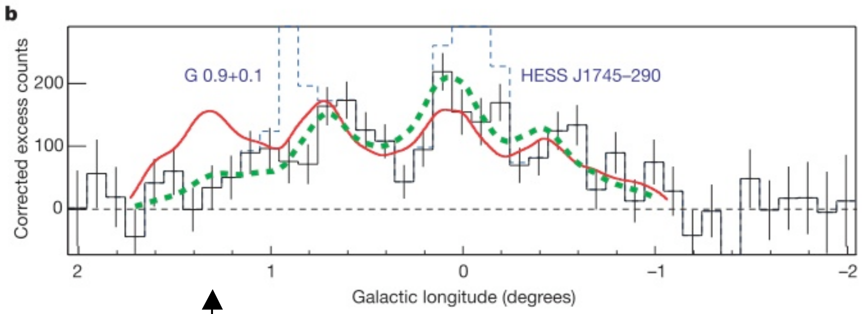
Dark Matter (specific talk)

CTA Larger sensitivity and angular resolution to provide:

- -Analysis of CR diffusion in the region
- -Distinguish between one or multiple originators of the primary CR population
- -Rule out of the possibility for a number of smaller IC sources to be behind the emission
- -Allow for similar studies in other regions, less intense

CTA to measure the CR diffusion coefficient in the GC region

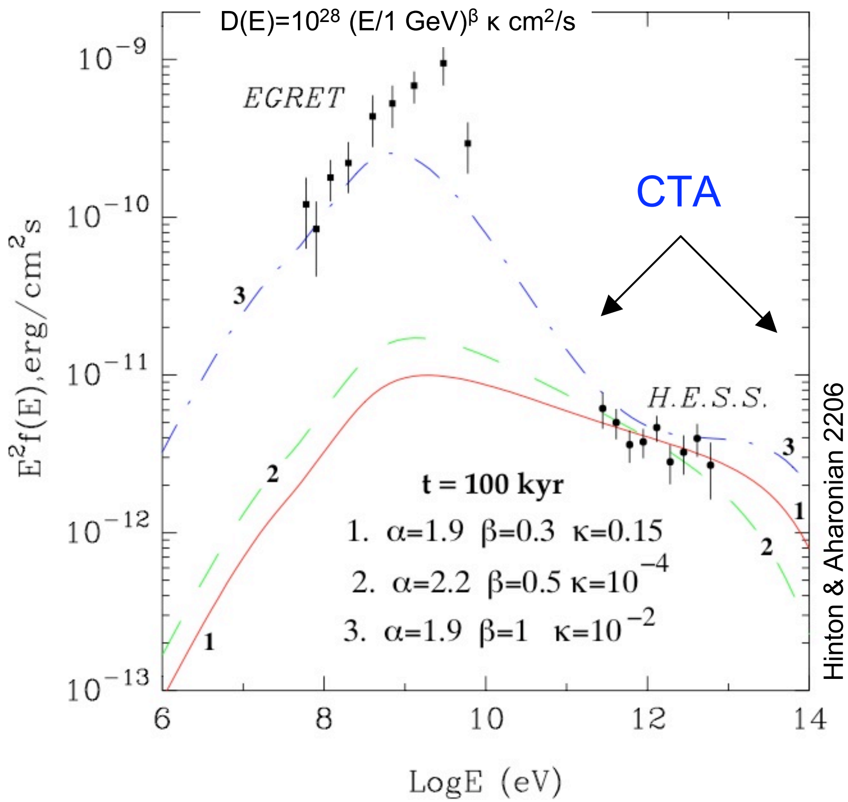
Hess Collab.



Red: molecular target
Green: TeV emission

At -1.3 there is a deficit of TeV emission. Why?
Difussion!

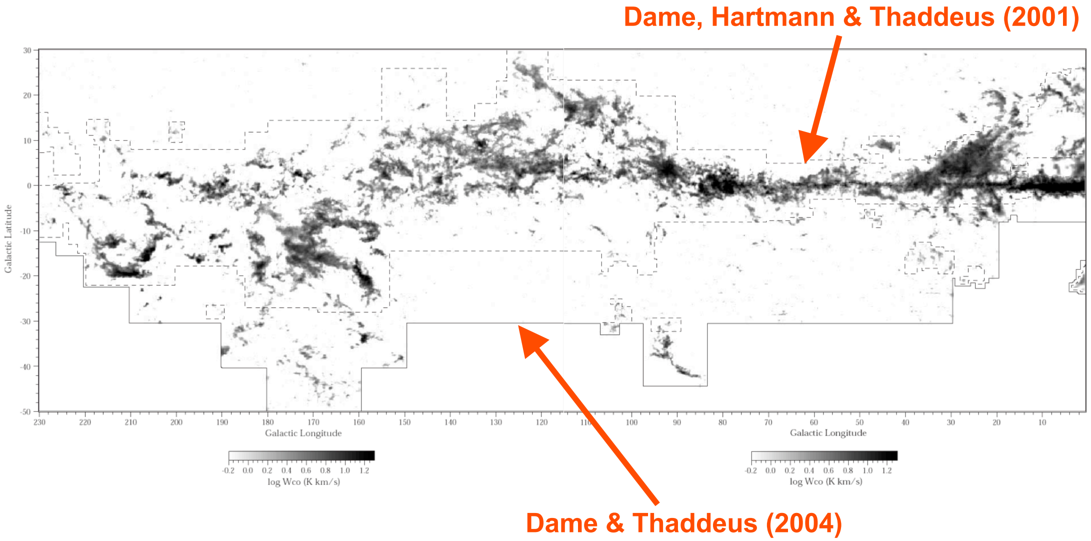
CTA could measure the diffuse gamma-ray distribution in smaller bins for different energy, to determine the difussion coefficient experimentally

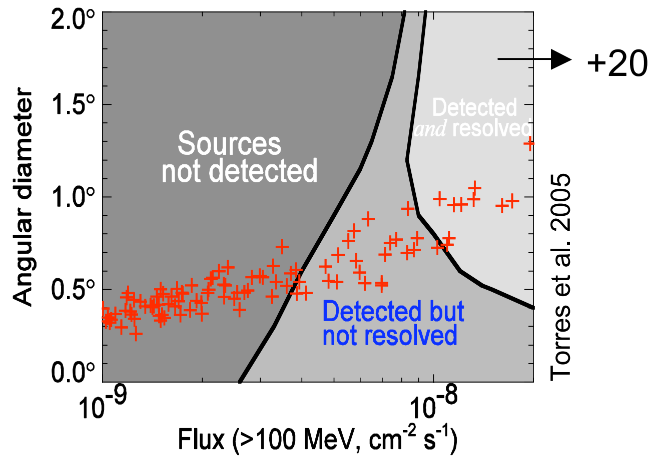


Hinton & Aharonian 2206

CTA to map the CRs in the local ISM

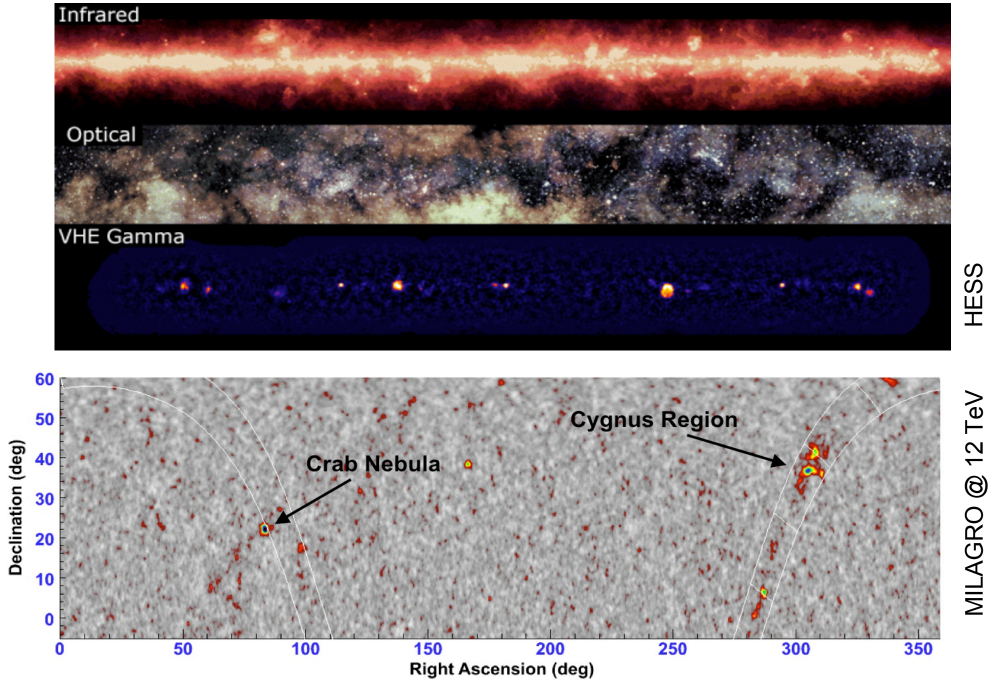
- New sensitive CO surveys, e.g., cover |b| < 30° and $\delta > -17°$ (l < 230°) with a sampling interval of 1/4° or better (Dame & Thaddeus 2004).
- >200 relatively small and isolated molecular clouds, |b|>10°
- Mostly likely at ~100 pc, masses 1-100 solar
- Assuming no CR enhancement: many detectable by CTA sources: feedback upon the mass estimation and the CR spectrum





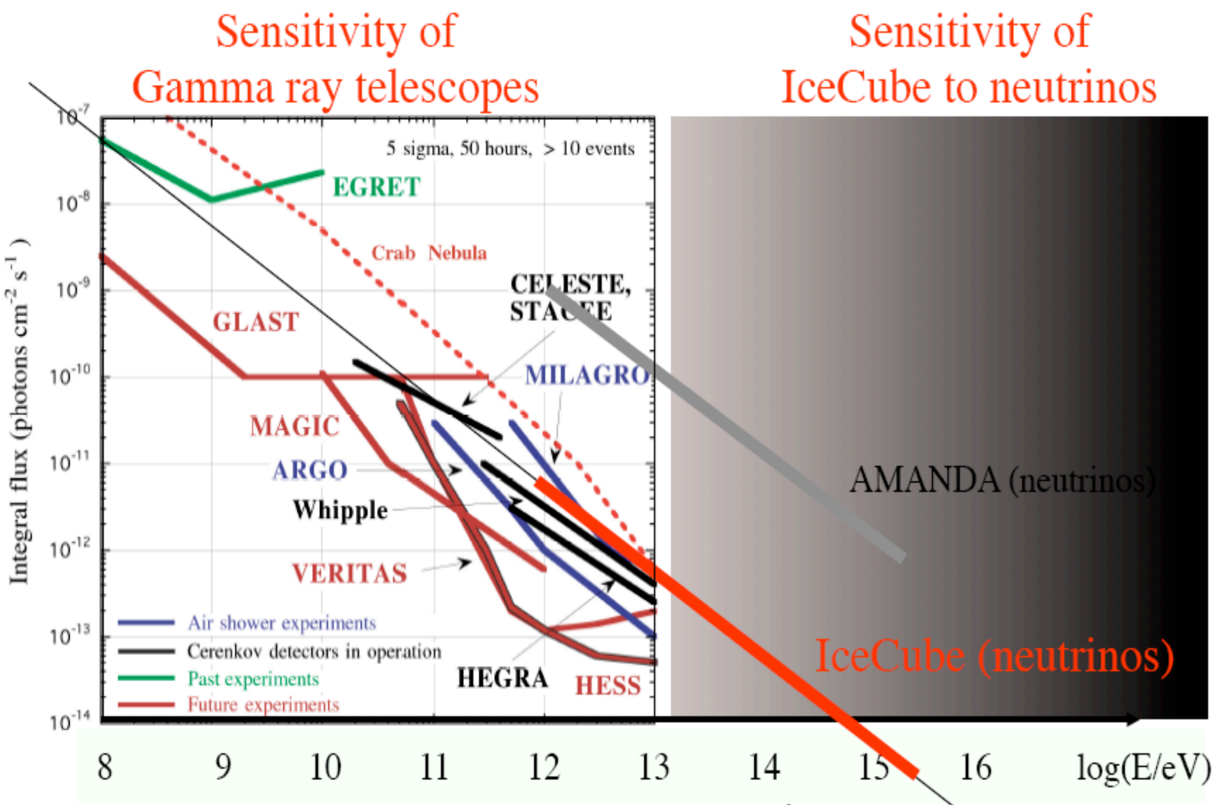
Emphasizing general key points as concluding remarks

- Importance of surveys for unbiased studies and unexpected discoveries
- Importance of number statistics for population studies (both @ sub TeV – and TeV) that can feedback theory
- Importance of observations in unexplored energy regimes (particularly above 10 TeV: e.g., particle acceleration sites + absorption @ ISRF)
- Importance of sensitivity for unifying concepts (emission of classes of systems, e.g. pulsars, x-ray binaries, star forming sites)
- Importance of sensitivity for accessing phenomenology at timescales never before tested
- Importance of both the angular resolution + sensitivity, e.g. for diffusion studies of cosmic rays



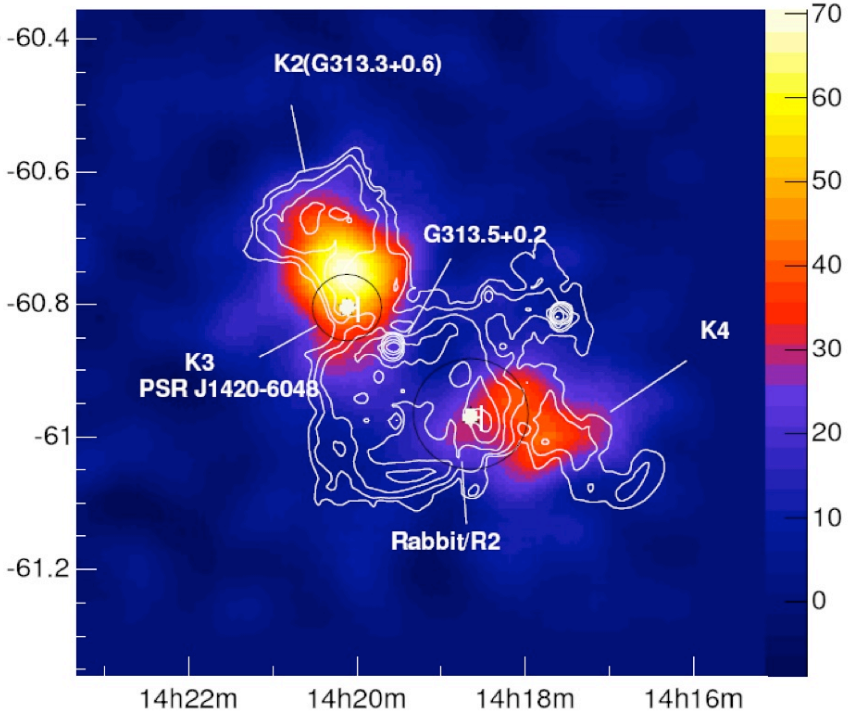
Thank you

CTA to go deep, neutrino obs. to find brightest hadronic sources



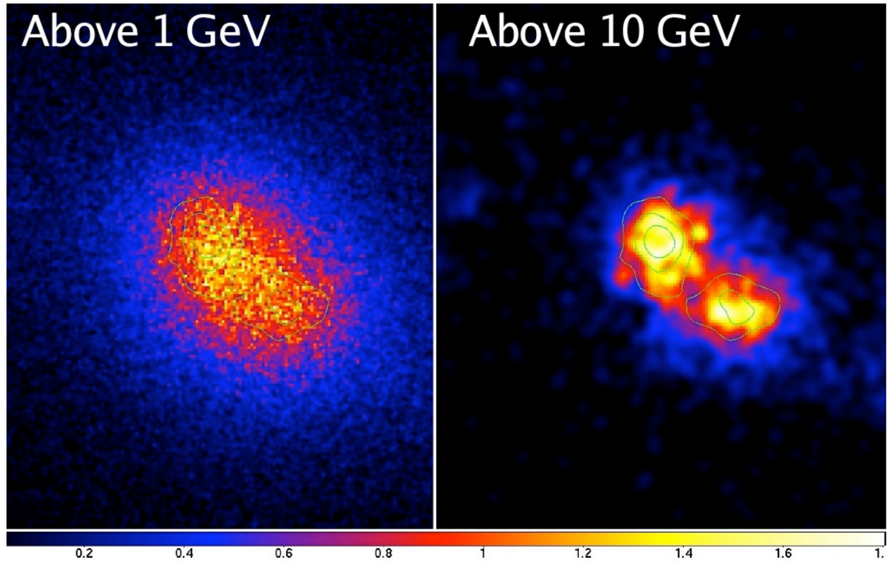
CTA to distinguish components across the energy domain

HESS, Kookaburra, above ~300 GeV



GLAST simulation, Funk 2006

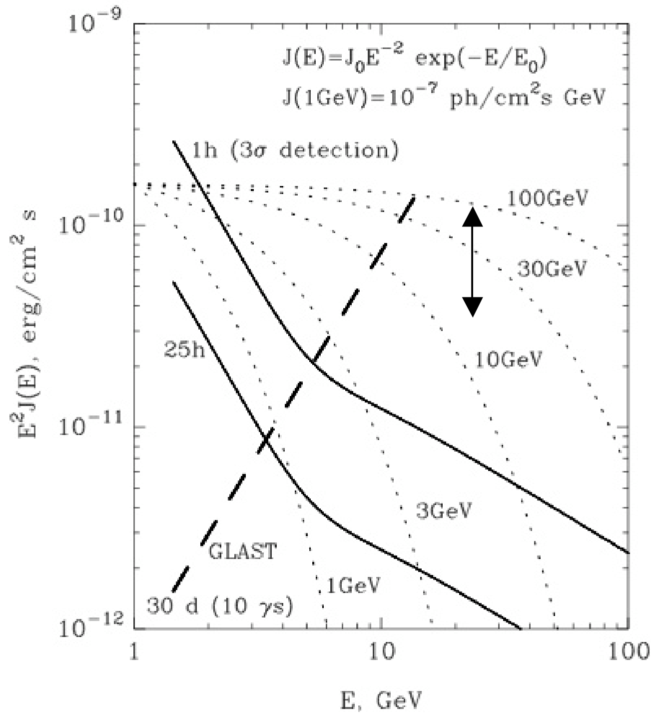
3EG J1420-6038/GeV J1417-6100

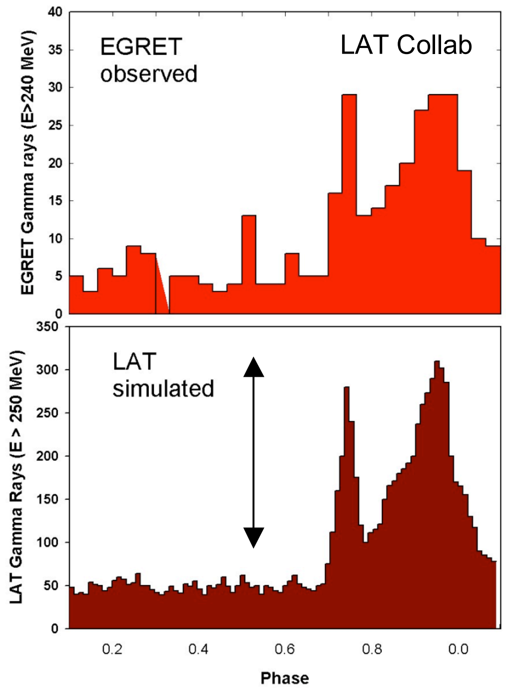


GLAST as pathfinder mission for the CTA array at low energy

- GLAST will have simultaneous coverage of 20% of the sky, diffuse bkgs.
  - But collecting area is small, and short time variability studies are compromised
  - Also, blind searches only possible for brightest sources, with high counts
- The Vela pulsar could appear in an instrument with CTA sensitivity in matter of min or less: even when folding is still required for pulses, + detailed analysis of profiles and their evolution from 10 GeV up (almost all *seem* to disappear)

Aharnonian et al. 2001.





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Is the emission away from the pulse associated with the source (as predicted by the slot gap) or not (predicted by outer gap)?

How are the pulse shapes, separation, and relationship to pulses seen at other wavelengths explained in different models?