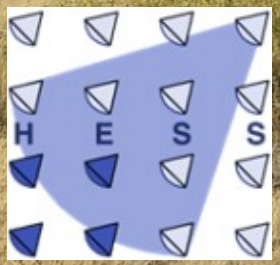
Results from **H.E.S.S.** observations of relativistic sources

Ulisses Barres de Almeida
University of Durham

For the **H.E.S.S.** collaboration



Durham University

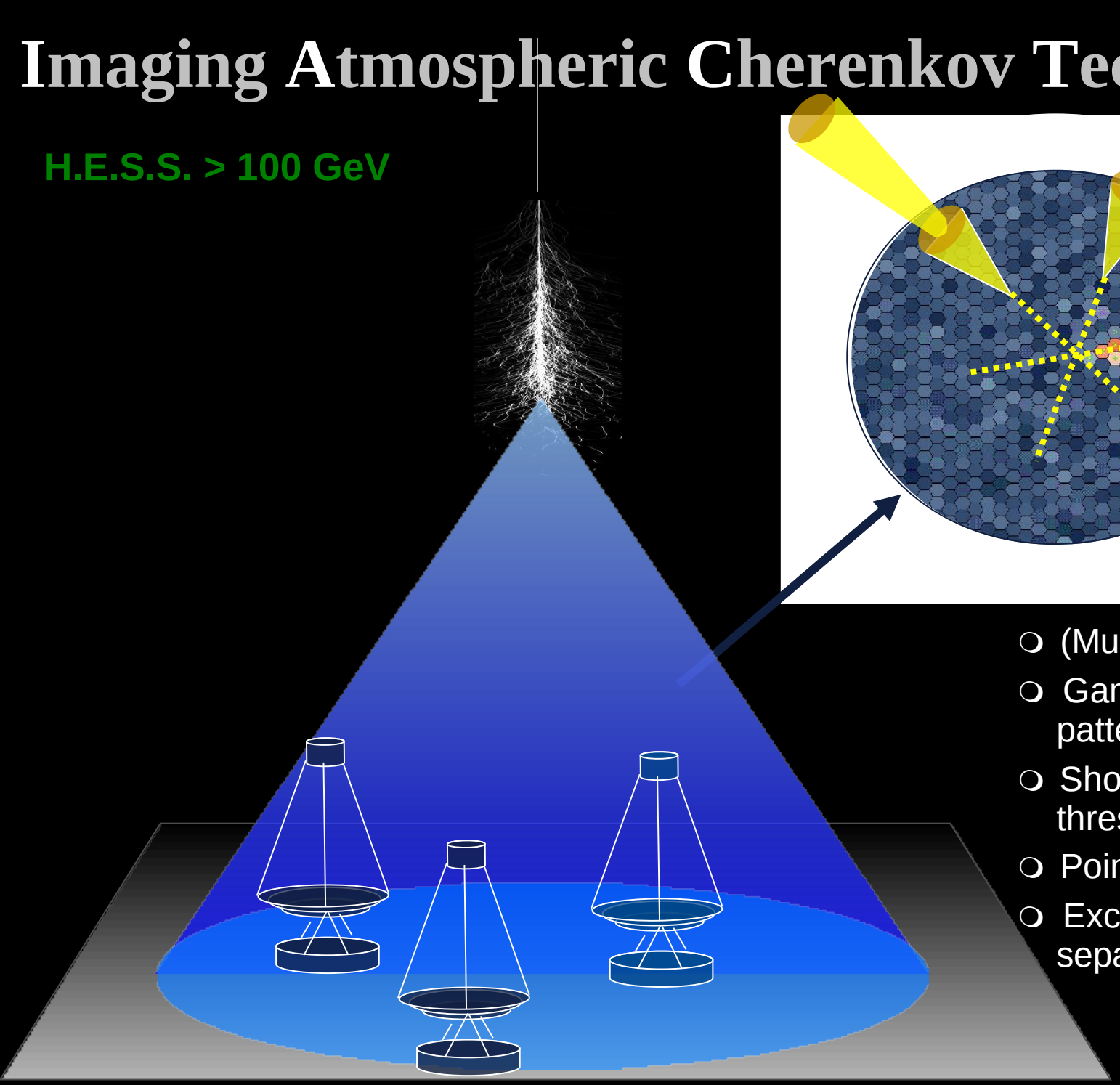
CAPES

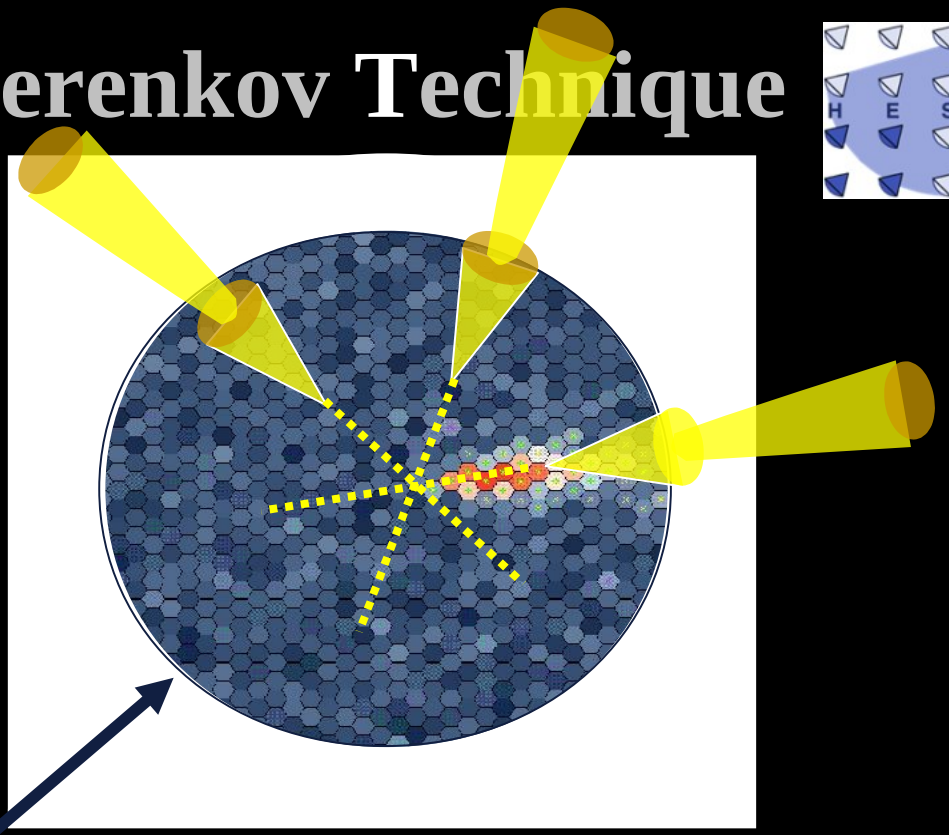
Overview

- **H.E.S.S.**
- **Active Galactic Nuclei**
  - PKS 2155-304
  - The Radio Galaxies M87 and CenA
- **Variable Galactic Sources**
  - LS 5039
- **GRBs with H.E.S.S.**
- **H.E.S.S.** phase-II

Imaging Atmospheric Cherenkov Technique

H.E.S.S. > 100 GeV





- (Multiple) Images of showers
- Gamma rays form consistent pattern
- Showers located to ~0.1° at threshold
- Point source location to ~ 30”
- Excellent gamma-hadron separation (~ 99%)

High Energy Stereoscopic System

- Located in Namibia @ 1800 m a.s.l.
- Four 13 m ACTs

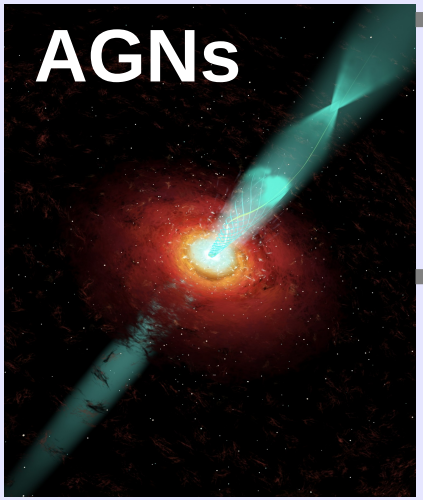
- Energy Threshold 100 GeV
- Energy Resolution 15%
- Camera Field of View ~ 5º
- Angular Resolution 0.05º - 0.1º
- Pointing Accuracy ~ 10 arcsec

Sensitivity:

- 1 Crab in 30 sec
- 0.01 Crab in 50h

(All at zenith)

Source Categories seen with HESS



blazars

PKS 2155-304, Mkn 421, H2356-300,
1ES 1101-232, 1ES 0347-121,
PG 1553+113, RGB J0152+017...

radio-galaxies

M87,
Centaurus A

Starburst

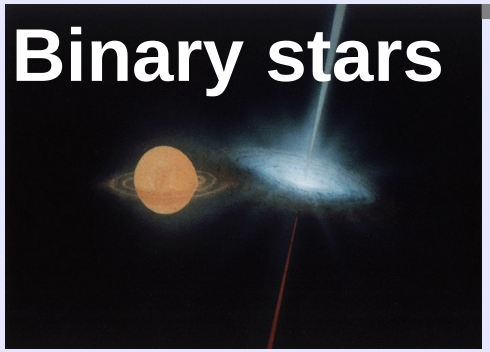
NGC 253

PWNs ← *Ask me!*

HESS J1708-443, IGR J18490-0
HESS J1912+101, HESS J1809-193...

SNRs

W 28, CTB 37A, RCW 86,
CTB 37 B, SN 1006...



Binary systems

LS 5039, PSR B1259-03,
HESS J0632+057

Ask me!

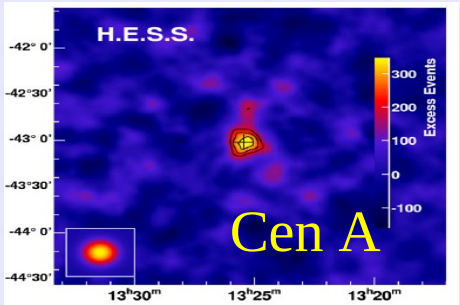
WRs?

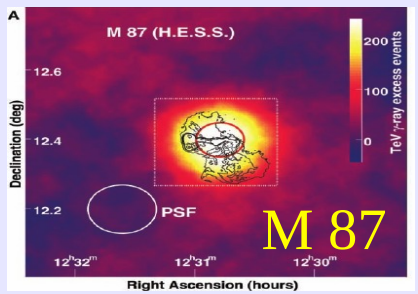
Westerlund 1, HESS J1848-018,
Westerlund 2

The Xgal sky as seen with HESS

- ~~All~~ *most* sources are AGNs (HBLs + 2 radio gals + Starbust Galaxy NGC 253; Science '09)
- Total of 13 Xgal sources; 10 first detections
- Only HESS ULs available for other classes (LBLs, FSRQs, etc.)

Object name	Redshift	Type	First VHE detection	Flux level	Photon index	Shortest var. time scale
Centaurus A	0.0018	FRI	2008 (H.E.S.S.) [18]	0.8	2.7±0.5	–
M 87	0.004	FRI	2003 (HEGRA) [19]	0.5 - 3.3	2.2±0.15	~1 day
Mrk 421	0.031	HBL	1992 (Whipple) [20]	15 - 1300	2.56±0.07	~15 min
PKS 0548-322	0.069	HBL	2007 (H.E.S.S.) [21]	1.4	2.8±0.3	-
PKS 2005-489	0.071	HBL	2005 (H.E.S.S.) [22]	2.8	4.0±0.4	~1 month
RGB J0152+017	0.080	HBL	2007 (H.E.S.S.) [23]	2	2.95±0.36	~1 month
PKS 2155-304	0.116	HBL	1999 (Mark VI) [24]	15 - 1500	3.32±0.06 (low state)	~3 min
1ES 0229+200	0.139	HBL	2006 (H.E.S.S.) [25]	1.8	2.5±0.19	-
H 2356-309	0.165	HBL	2006 (H.E.S.S.) [26]	2.3	3.09±0.24	~1 month
1ES 1101-232	0.186	HBL	2006 (H.E.S.S.) [27]	2.3	2.94±0.20	~1 year
1ES 0347-121	0.188	HBL	2007 (H.E.S.S.) [28]	2	3.10±0.23	~1 year
PG 1553+113	>0.250	HBL	2006 (H.E.S.S.) [29], [30]	3.4	4.5±0.3	-





- All TeV extraglactic objects are point sources

H.E.S.S. PSF ~ 10 arcmin

The Xgal sky as seen with HESS

- ~~All~~ *most* sources are AGNs (HBLs + 2 radio gals + **Starbust Galaxy NGC 253; Science '09**)
- Total of 13 Xgal sources;
- Only HESS ULs available

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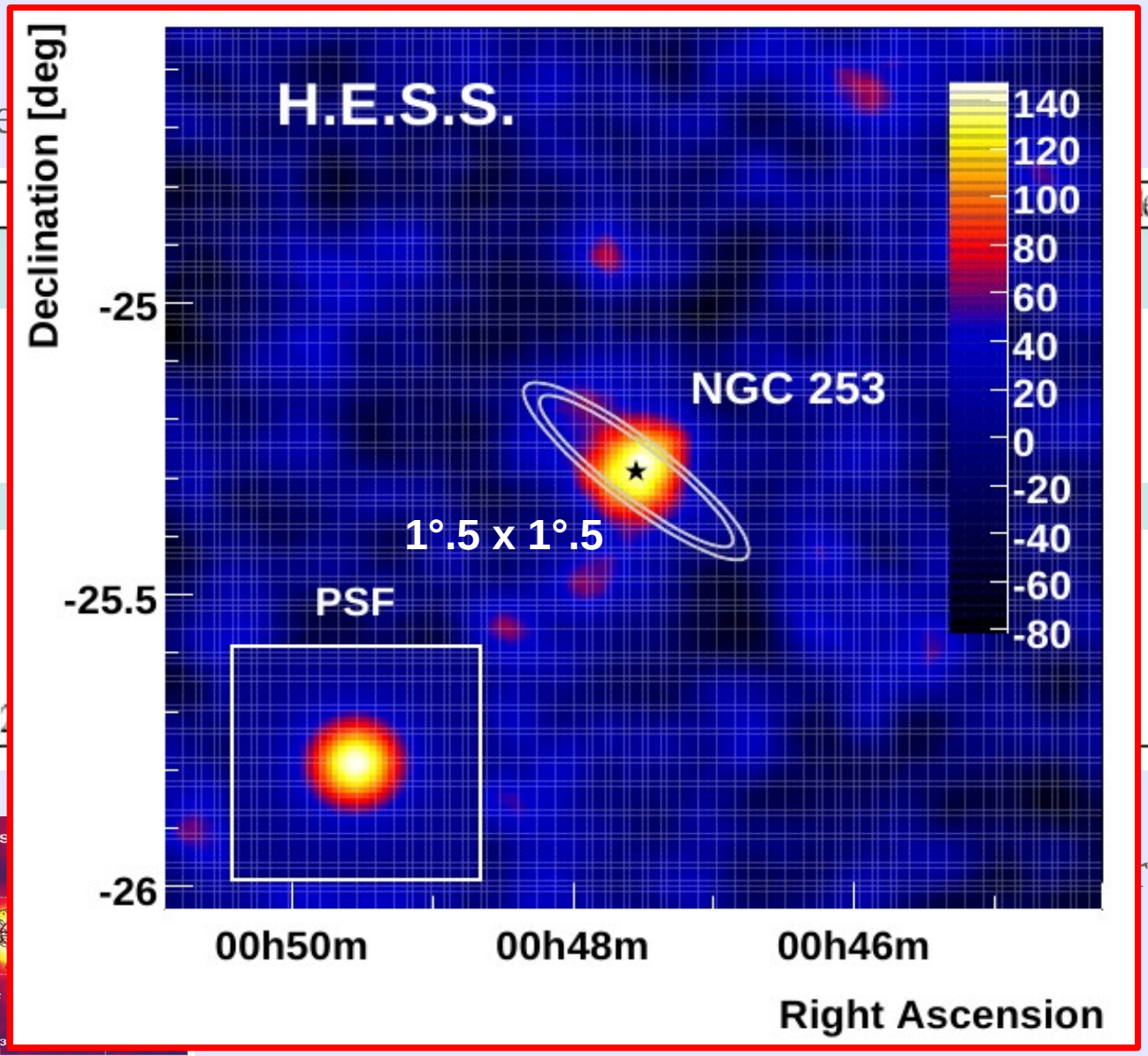
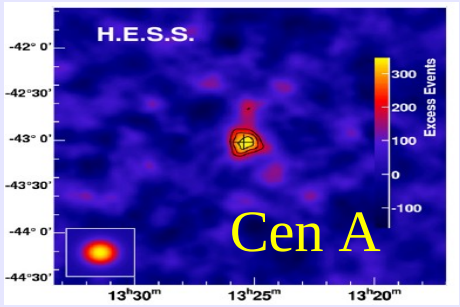
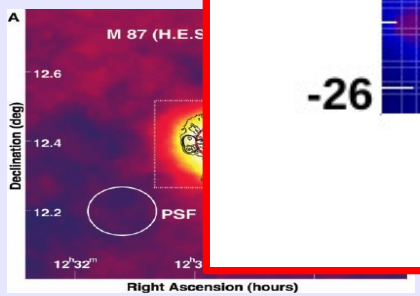
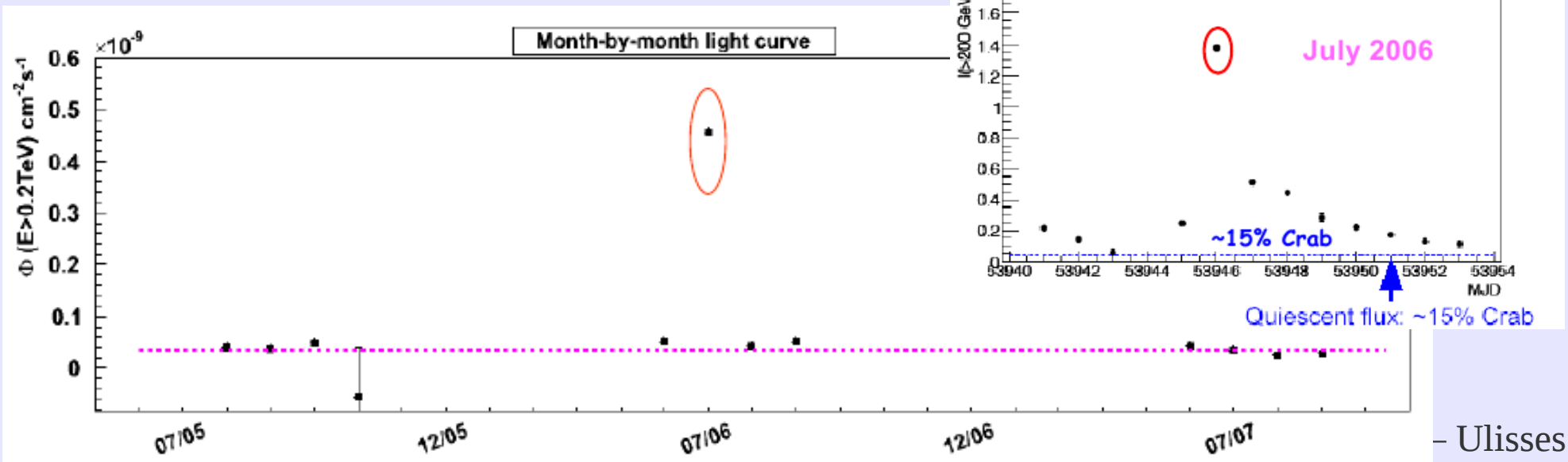




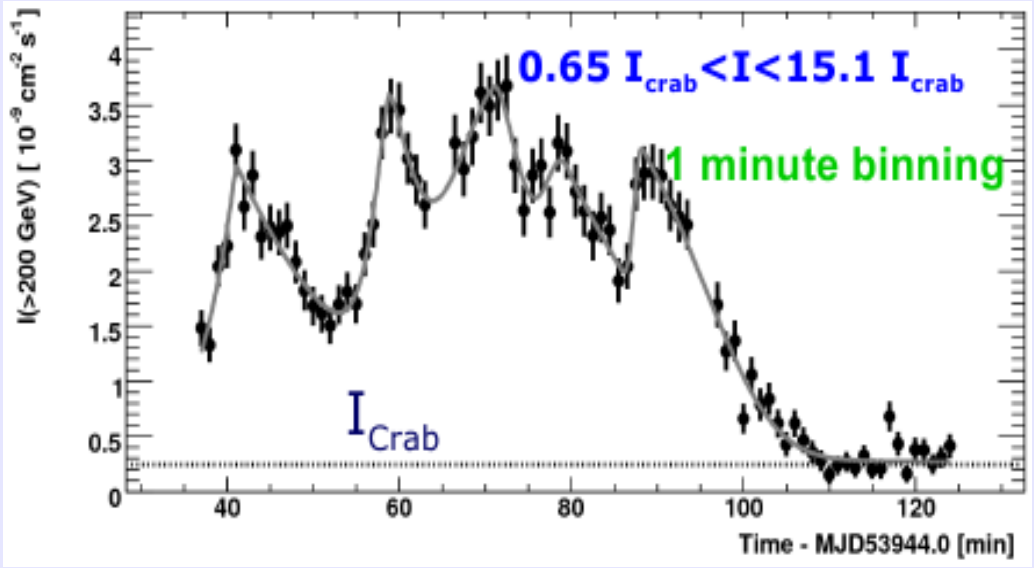


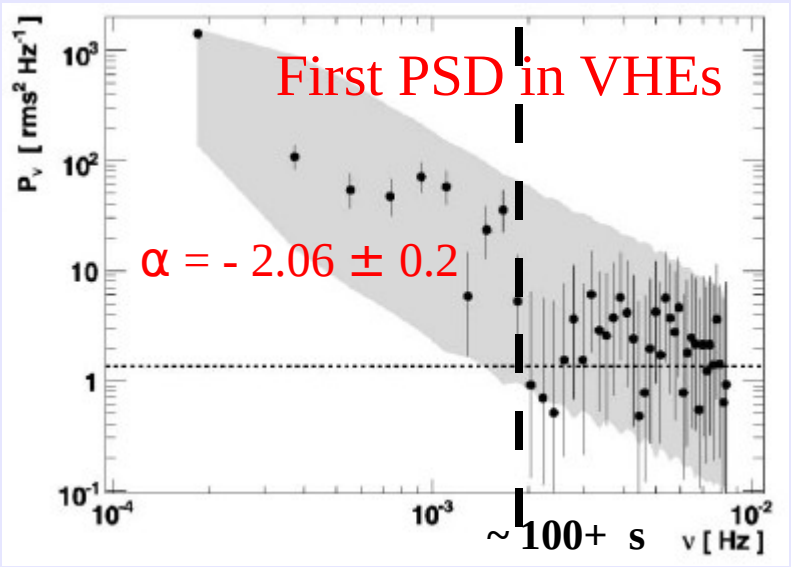
The Extreme TeV Blazar PKS 2155-304 (z = 0.116)

- Discovered by *Durham Mark VI* in '99 (Chadwick et al.)
  - primary xgal monitoring target for H.E.S.S. (2003-2009)
  Aharonian et al. A&A, 430, 864 (2004); Aharonian et al., A&A, 442, 895 (2005)
- only source HESS detects at quiescent state: 0.15 Crab (>200 GeV; 4 σ in ½ hr)
- most extreme variability registered for an AGN in July 2006
  Aharonian et al. ApJL, 664, L71 (2006); Aharonian et al. A&A, 502, 749 (2009)
- quiescent state complete IC SED with HESS and Fermi.
  Aharonian et al. ApJL, 696L, 150 (2009)



Extreme Variability: July 28, 2006





Aharonian et al. ApJL, 664, L71 (2006)

- 1.32 hrs live time observations
- fastest rise time: 173 ± 28 s
- no spectral variability observed: broken pwl at ~ 430 GeV:
  $\Gamma_1 = 2.71 \pm 0.06 \pm 0.10$
  $\Gamma_2 = 3.53 \pm 0.05 \pm 0.10$

- **Causality arguments:**

  $R \leq c\, t_{var}\, \delta / (1+z)$

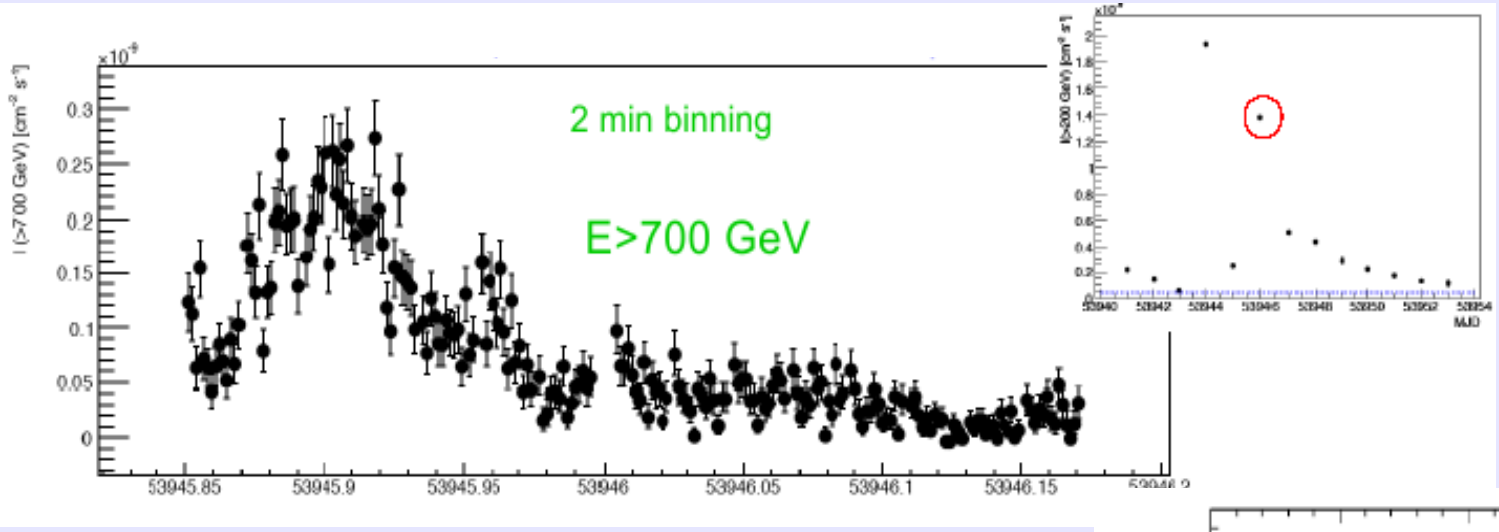
  $R\delta^{-1} \leq 4.65 \times 10^{12}\,\mathrm{cm} \leq 0.31\,\mathrm{AU}$

  $\therefore\ \delta > 50,\ \text{for } R > R_S$

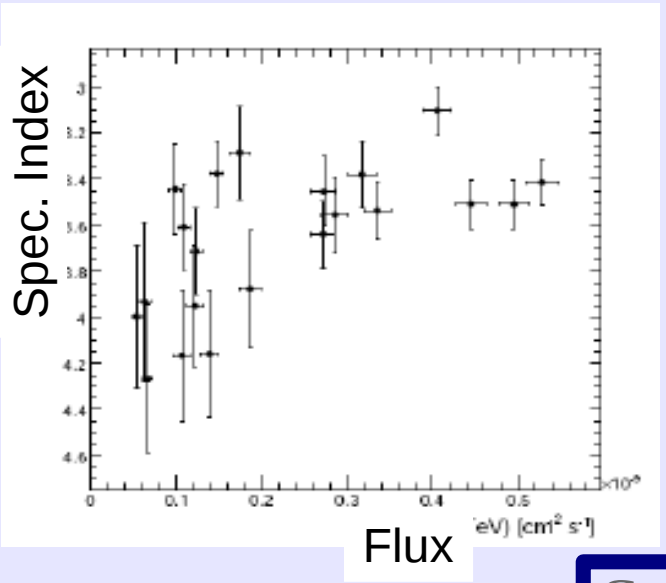
- Emission mechanism and site?

  Begelman '08: timescales not linked with the size of the BH

Extreme Variability: July 29-30

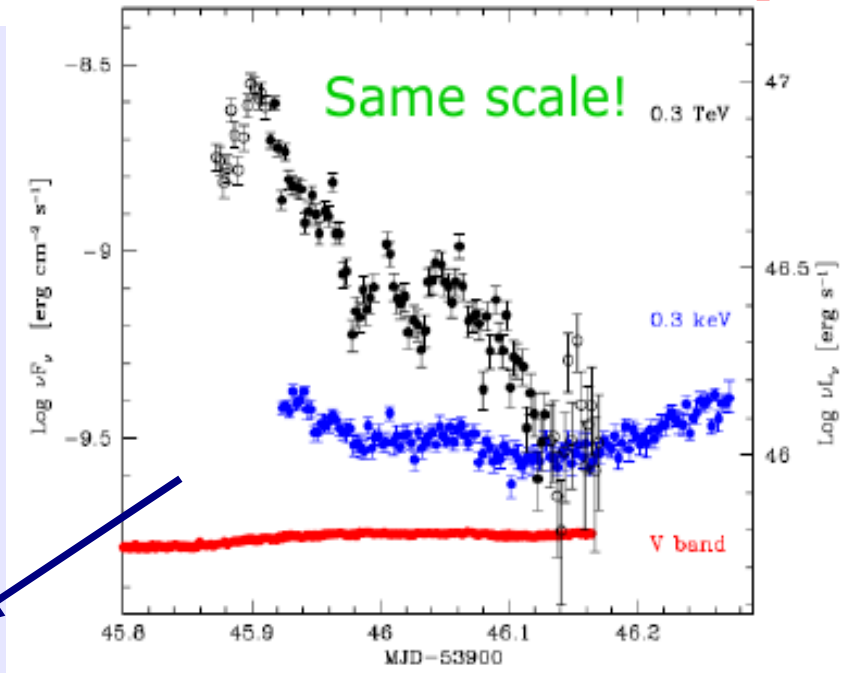


- HESS
- Chandra
- Optical



Slight spectral variability:

$\Delta\Gamma \sim 0.5$

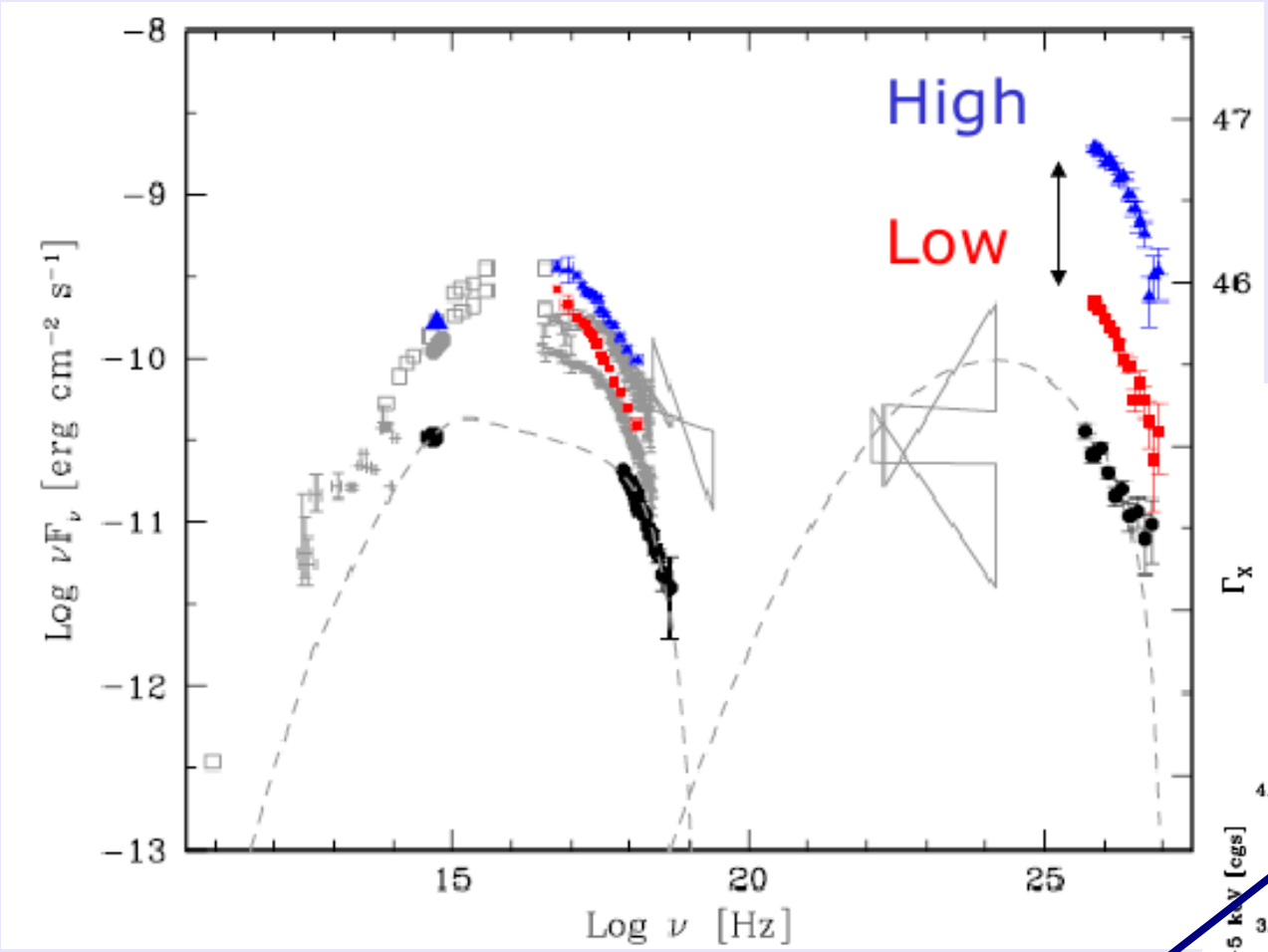


Compton dominance

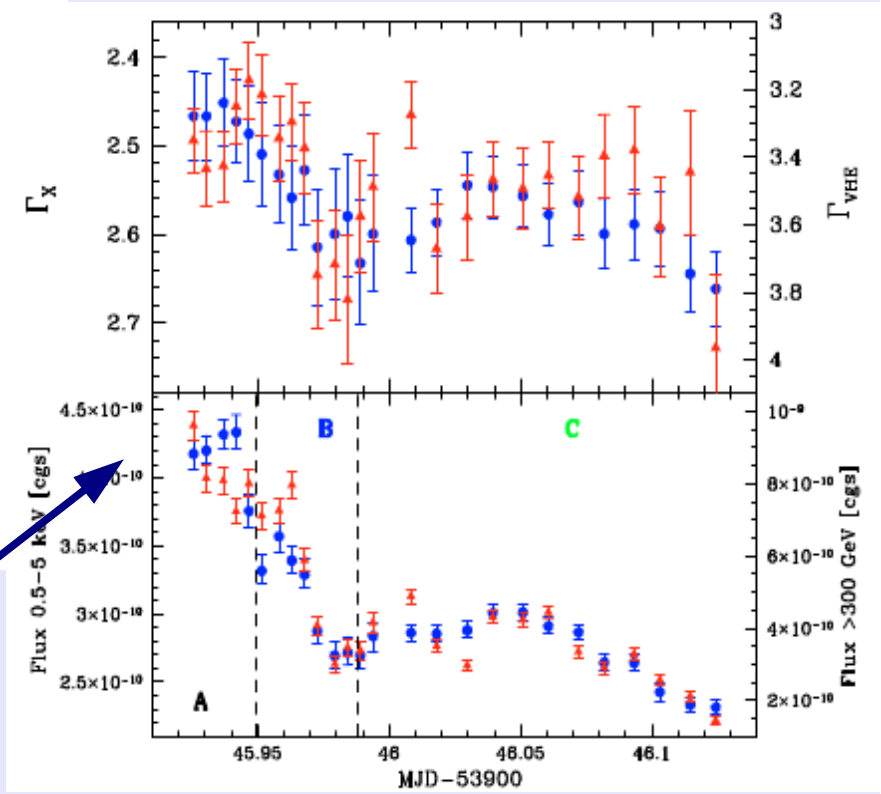
$L_C/L_S \sim 8\text{-}10$

Aharonian et al. A&A, 502, 749 (2009)

Extreme Variability: July 29-30 SED

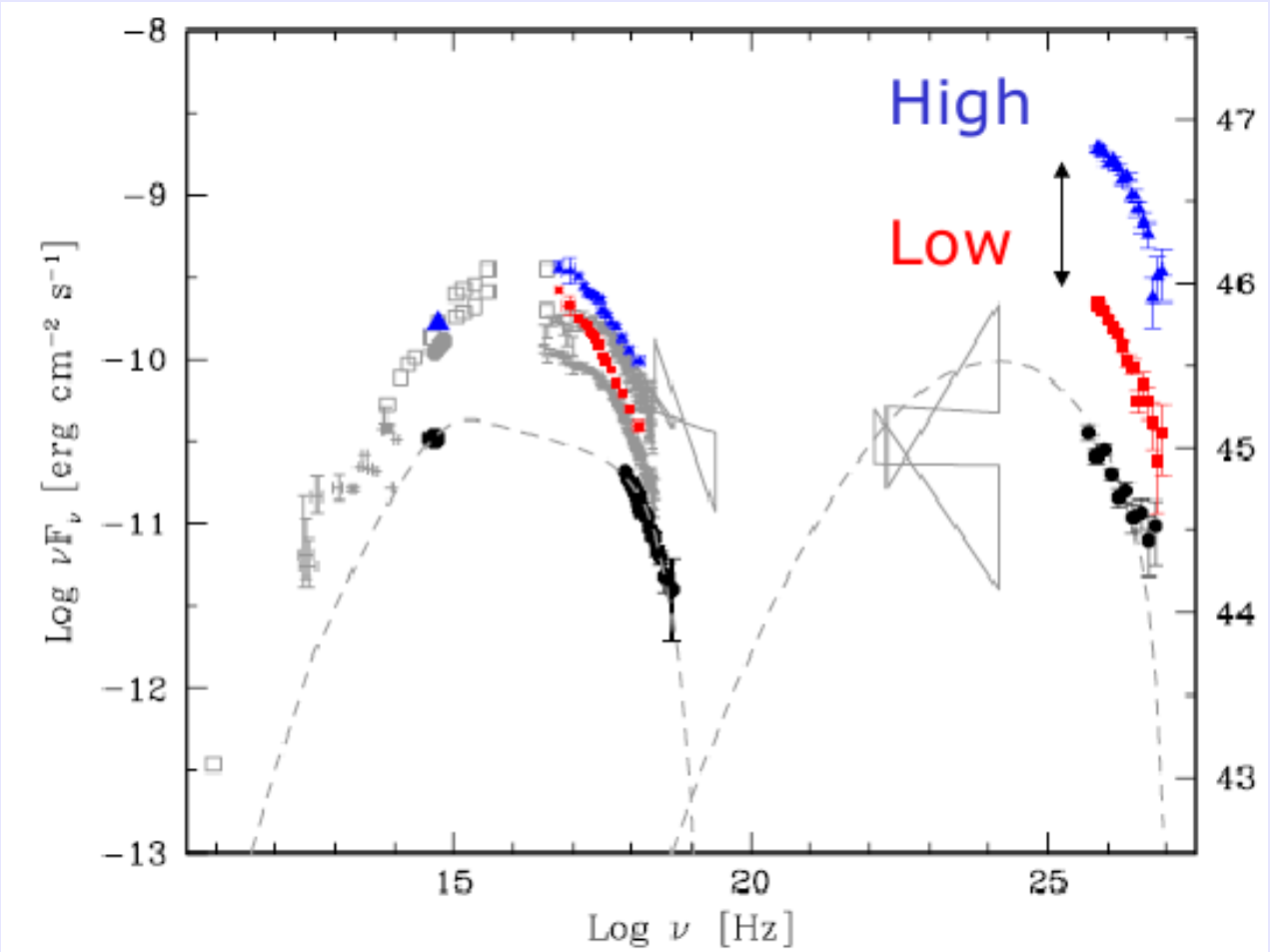


Increase of the flux but no frequency shift of the Synchrotron or IC peak.



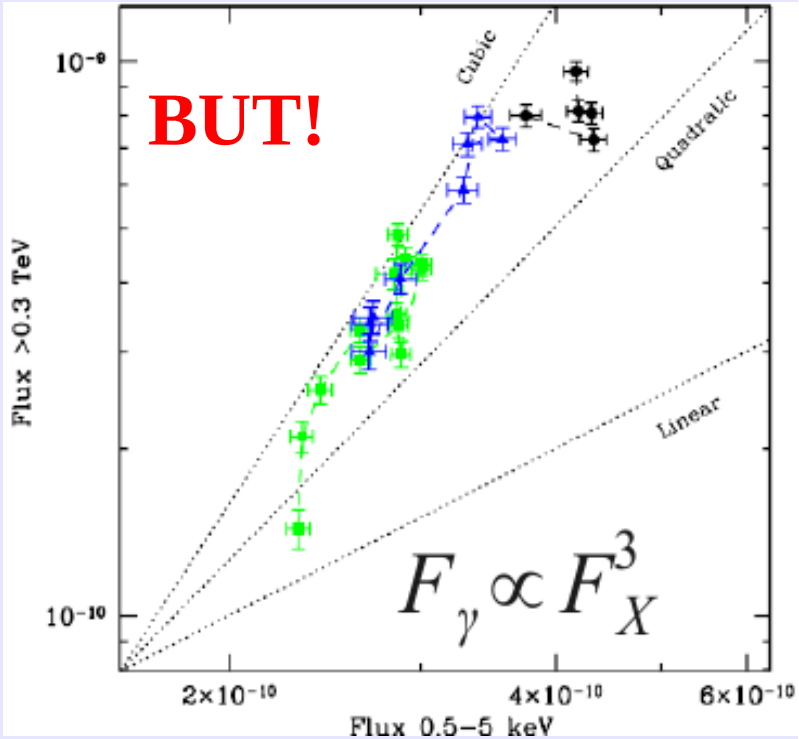
Excellent X-ray and VHE flux and spectral index correlation indicating Sy and IC emissions are closely related.

Extreme Variability: July 29-30 SED



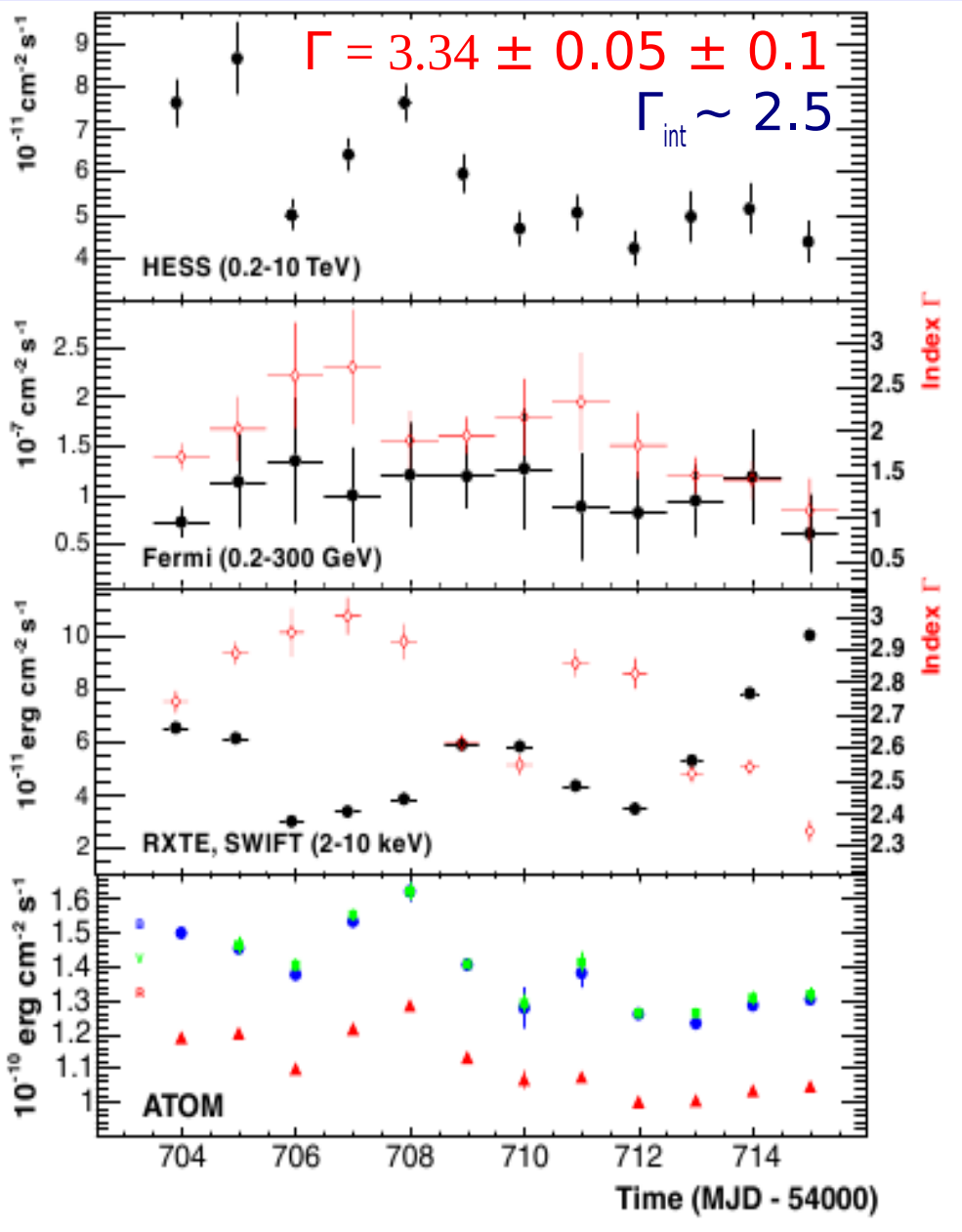
Excellent X-ray and VHE flux and spectral index correlation indicating Sy and IC emissions are closely related... **BUT?**

Cubic relation in the decaying phase:



MULTIPLE EMISSION ZONES?

H.E.S.S./Fermi 2008 campaign

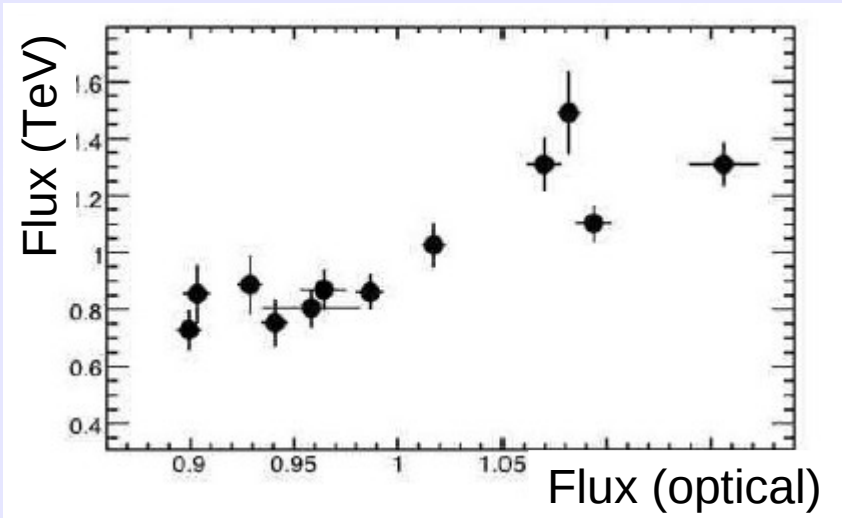


HESS/Fermi ApJL, 2009

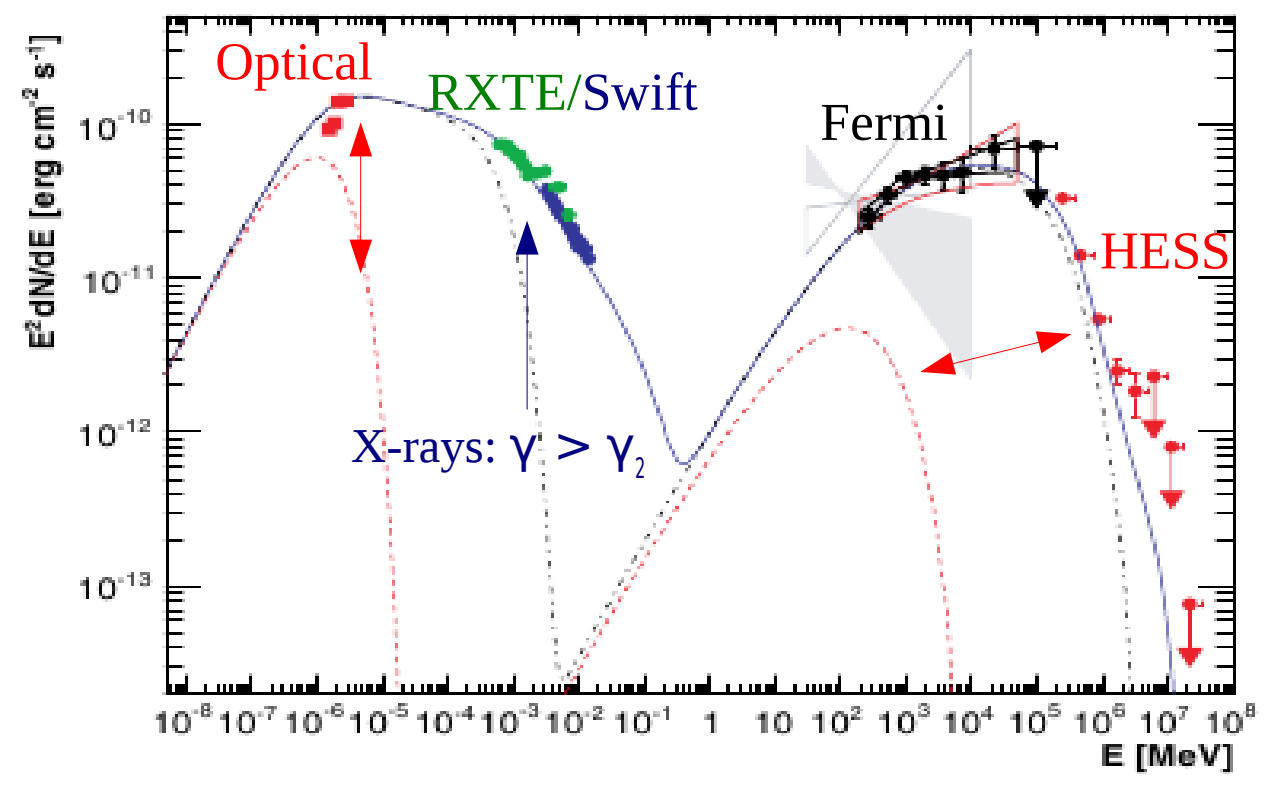
- Quiescent in VHE (20% rms var) and X-ray (30% rms var) bands
- 5x quiescent optical state and bright at Fermi/LAT bands
- Variable Fermi (1.5) & X-ray (0.5) spec. indices

Correlations:

- Flux: Optical and VHE flux (no X-rays!)
- Spectral index: X-rays and high-energies



H.E.S.S./Fermi 2008 campaign



Single-zone SSC

No-e⁻ above $\gamma_1 = 1.4 \times 10^4$

No-e⁻ above $\gamma_2 = 2.3 \times 10^5$

SSC model

"Blob" R ~10^{17} cm

Doppler factor Γ ~30

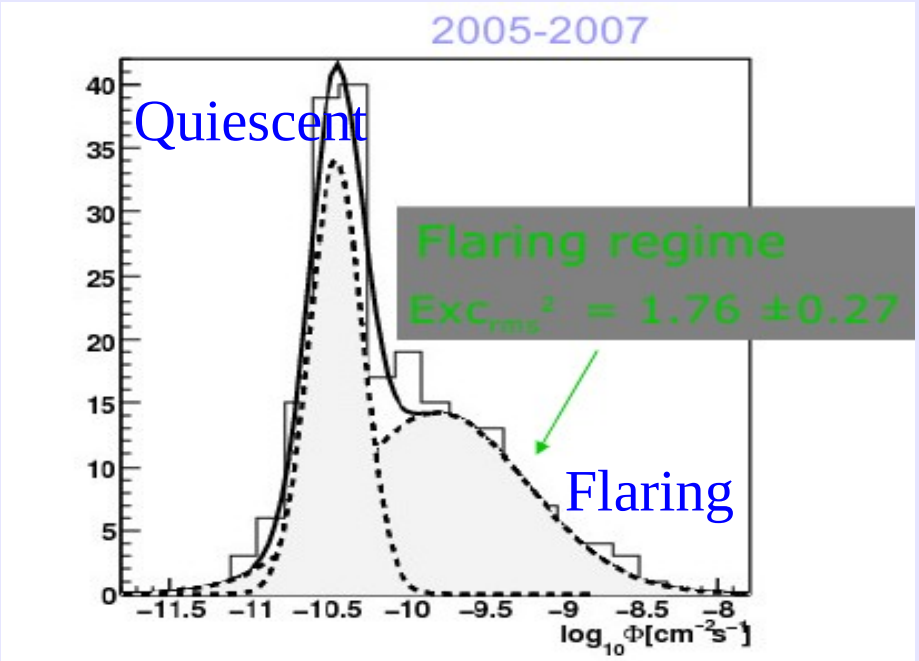
Field B ~ 0.02 G

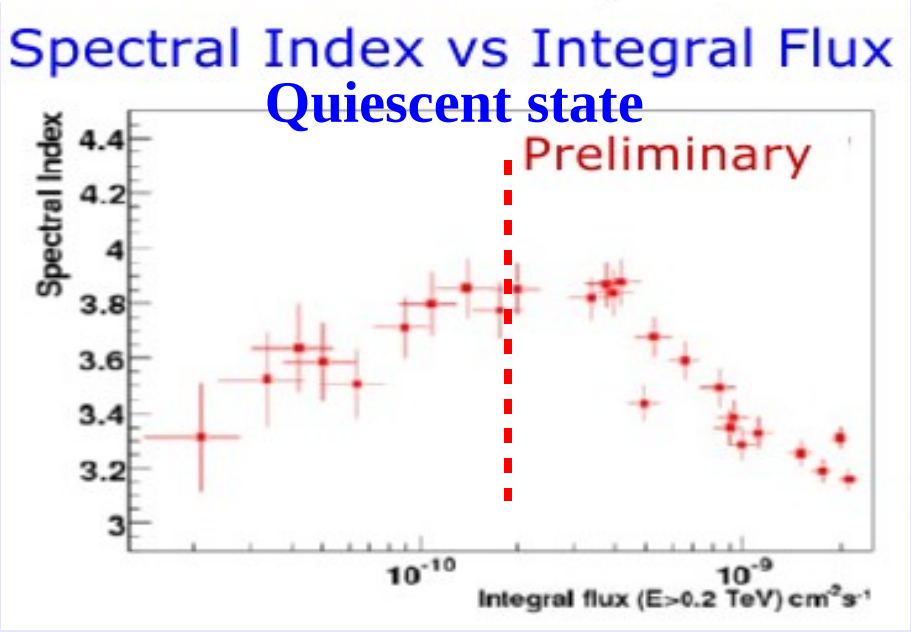
- Klein-Nishina suppression of IC from $e^- > \gamma_2$ explains lack of Xrays-VHE correlation
- VHE variability seems sensitive to variations on optical seed photons rather than injection of energetic particles.

→ optical variability does not affect the GeV flux, suggesting different particle populations (and possibly physical origins) for both?

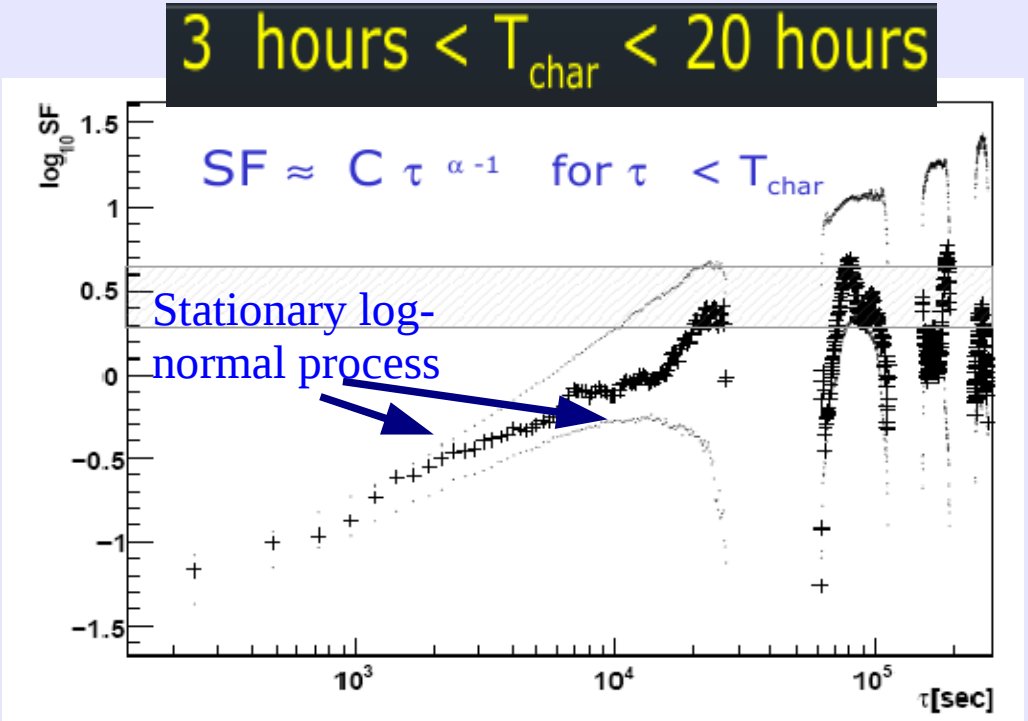
3-year variability picture

Aharonian et al., in prep.



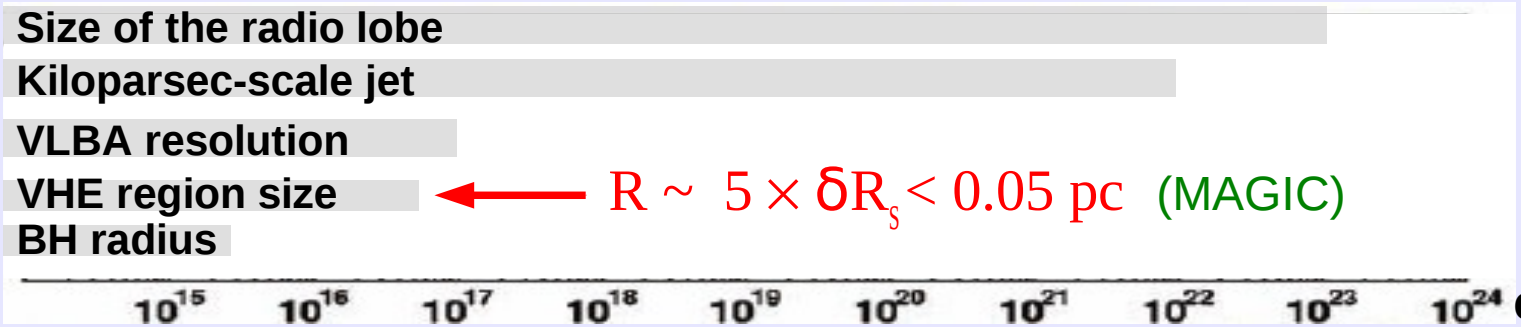


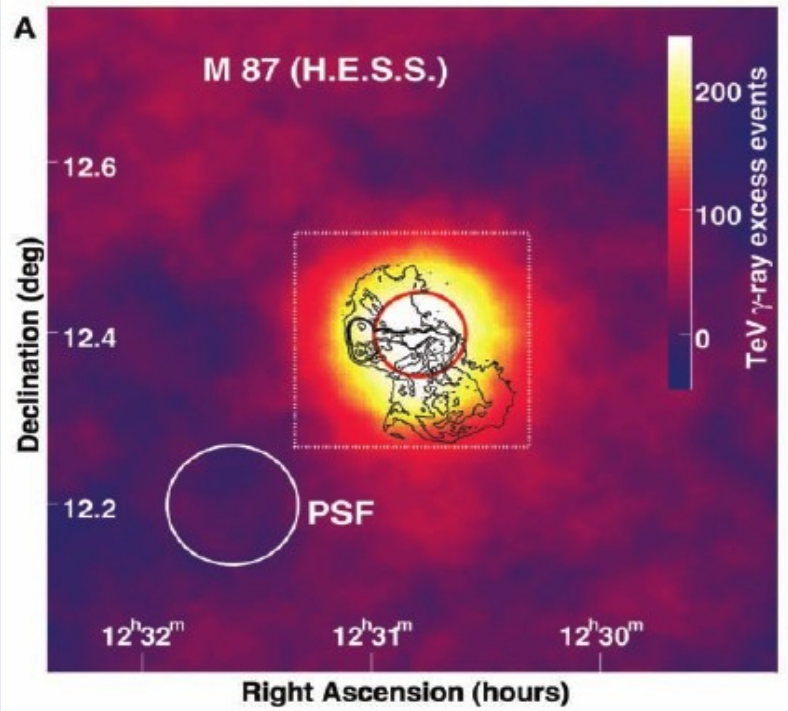
- well characterised quiescent state:
  $F(>200GeV) \cong 3.5 \pm 1.5 \times 10^{-11}$ cm^{-2} s^{-1}
- non-monotonic behaviour of Γ with flux.
- Flaring regime: $F_{var} \propto E^{\sim 0.2}$
  - variability produced by multiplicative process
  - correlation average flux and variability rms

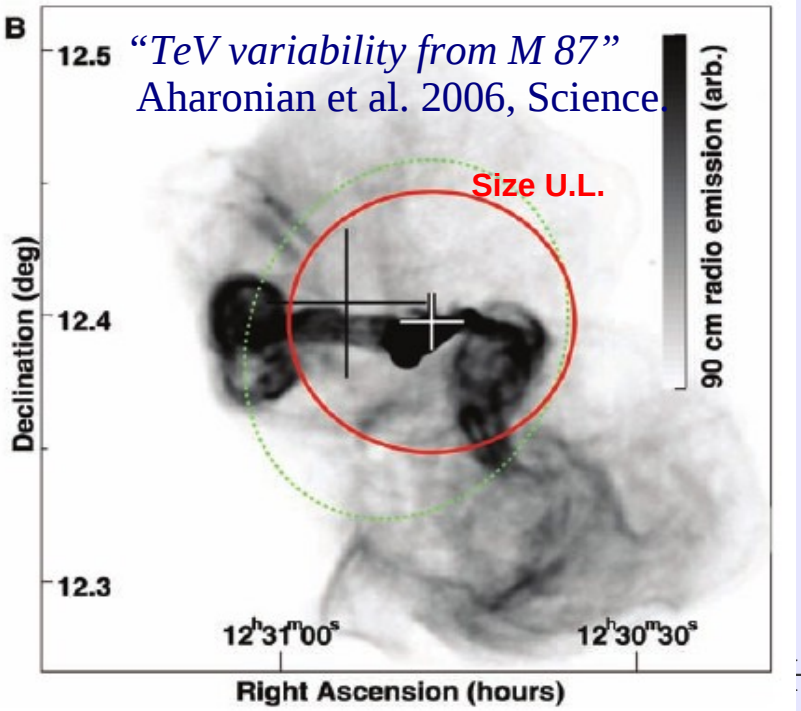


Radio Galaxy M 87: a unique laboratory for jet physics

- Distance: 16 Mpc; Outer radio lobes: 0.2 x 0.2 deg *vs.* 0.1 deg PSF
- TeV source position excludes outer regions as source of γ-rays.
- Flux (> 250 GeV) ~ 0.8 – 1.5 % Crab; Γ ~ 2.6 - 2.2





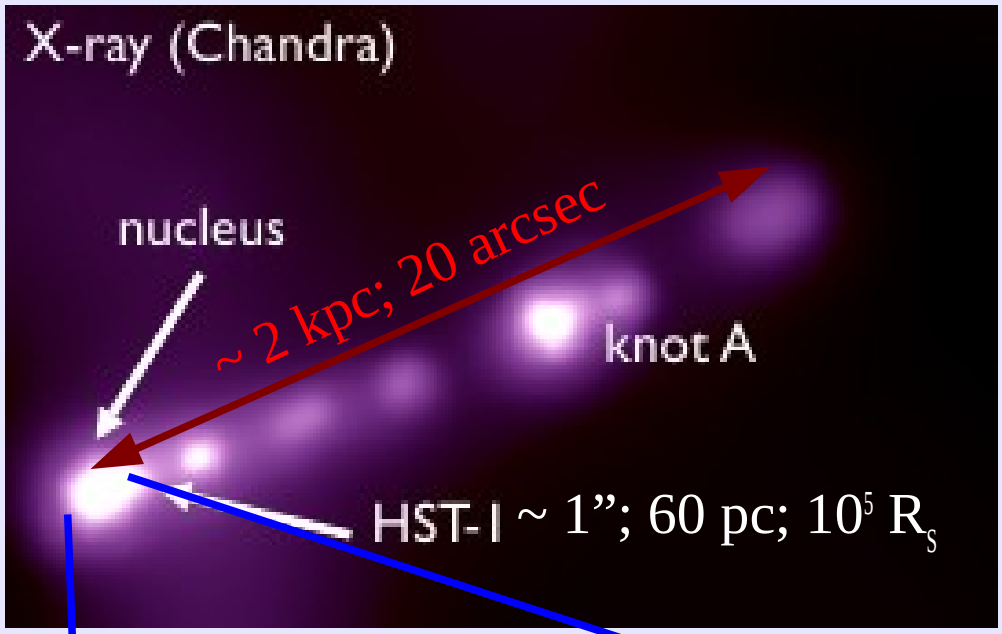


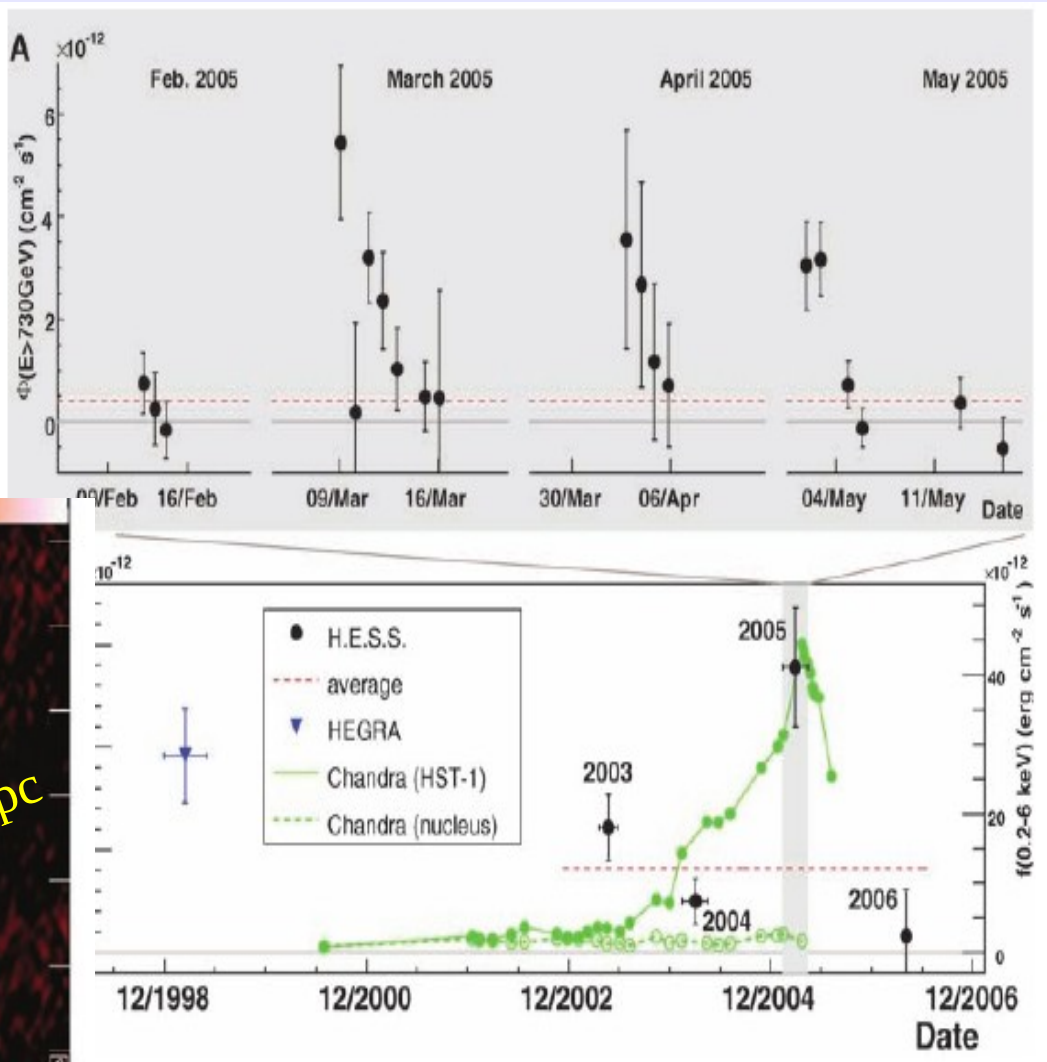
Origin of the γ-rays?

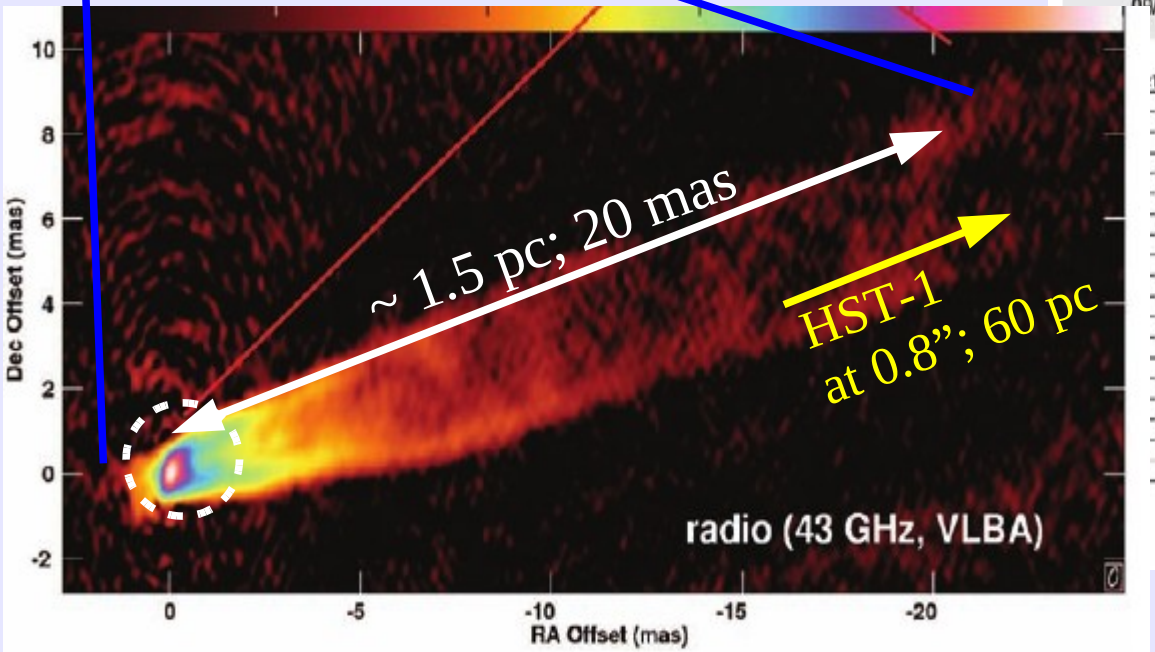
- ∠(jet-los) ~ 20⁰

CORE?
HST-1?
} **MWL**

Variability and Origin of TeV emission





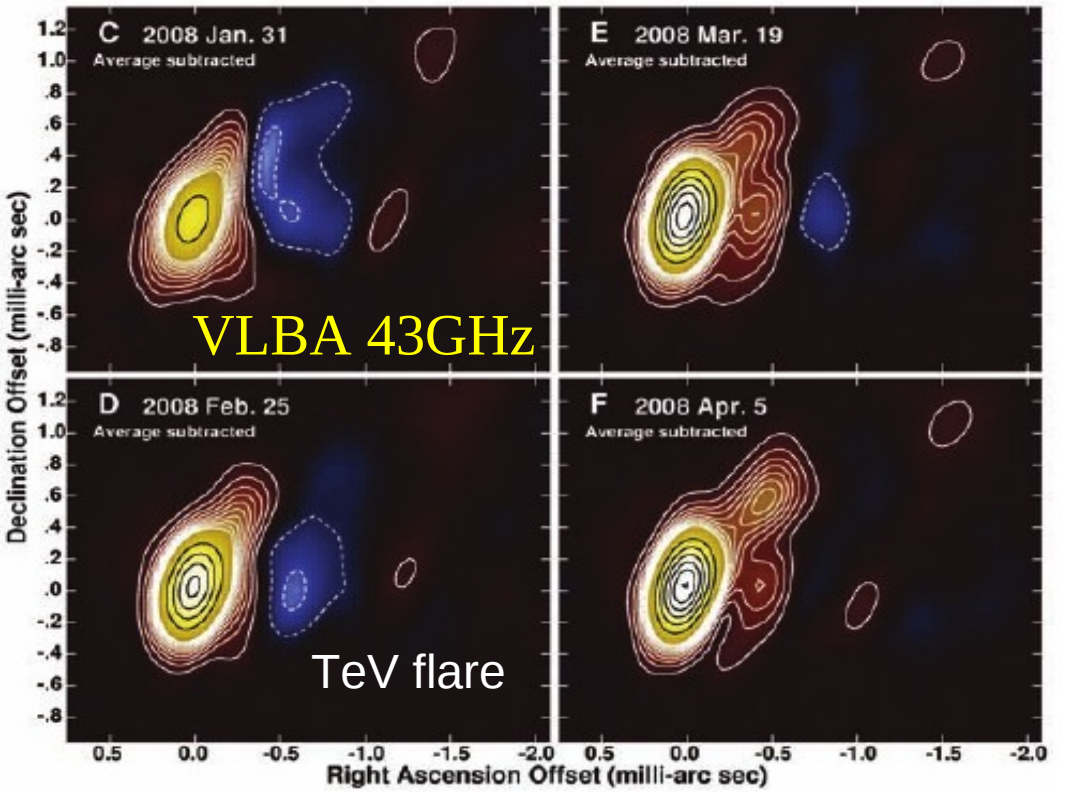


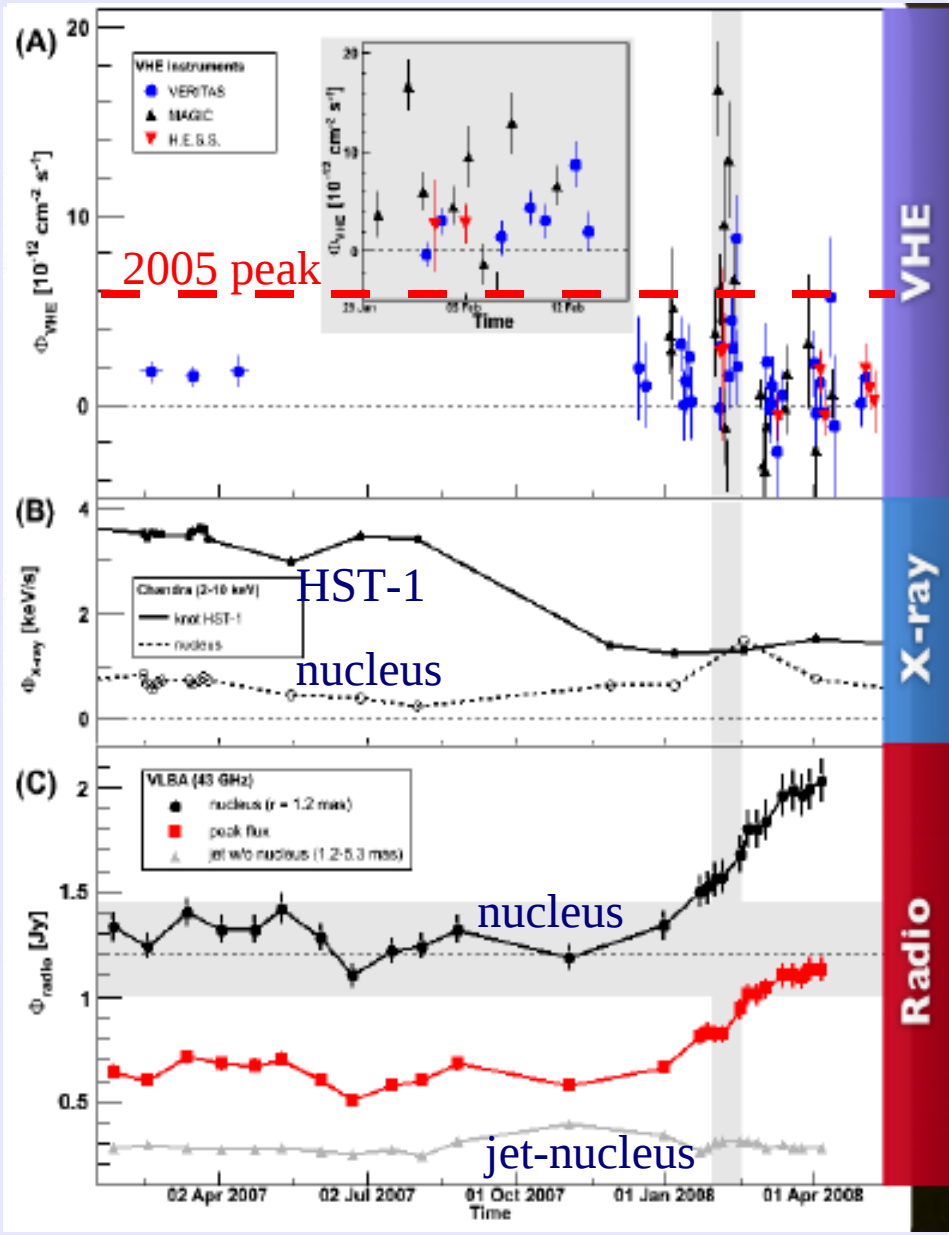
"TeV variability from M 87"
Aharonian et al. 2006, Science.

M87 2008 Joint MWL Campaign

VERITAS+VLBA+HESS+MAGIC 2009, Science.

- Total of ~ 95 hrs good data with 3 VHE experiments in 50 nights (Jan-May)





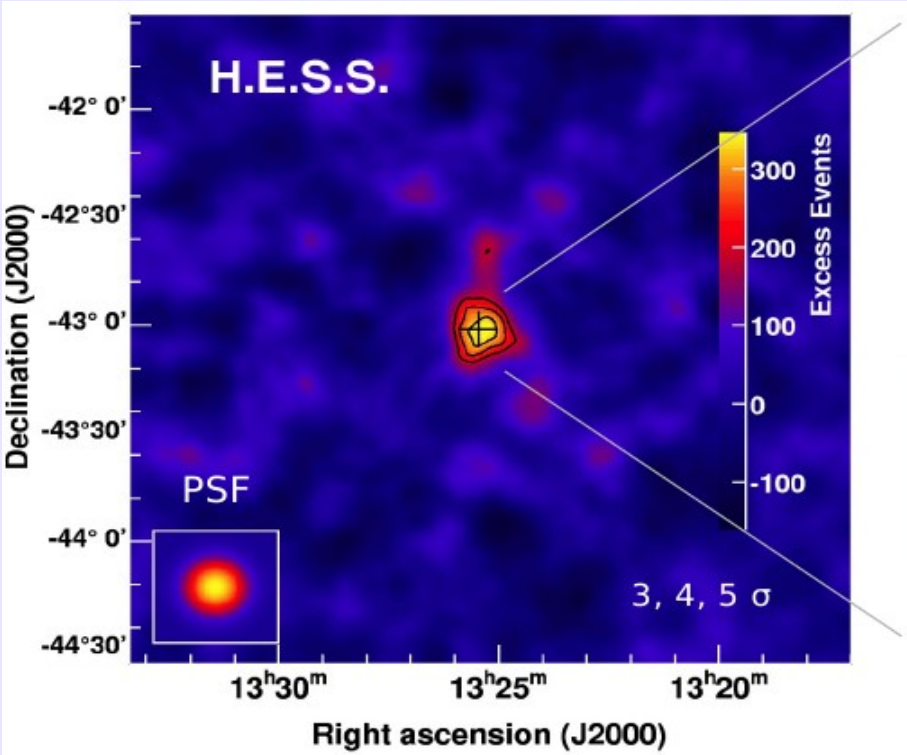
- X-ray **core** flux peaks ~days after VHE flare and emission of radio knot is registered.

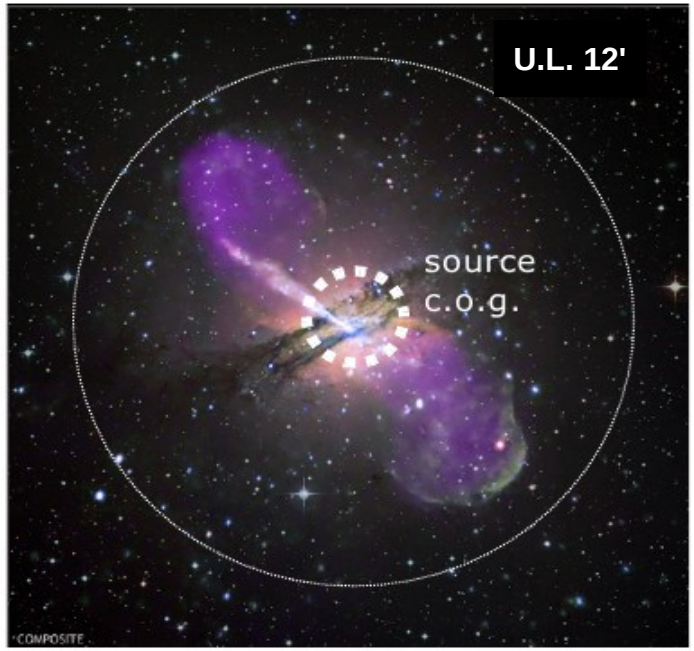
- **HST-1** flux was low during the 2008 flare.

- radio coincidence constrains VHE w/in collimation zone.

Centaurus A

- Nearest (3.8 Mpc; kpc-scale jet resolvable @ TeVs) FRI radio galaxy
- Recent Detection: faintest Xgal VHE source seen by HESS
  Aharonian et al. 2009, "Discovery of VHE Emission from Cen A", ApJ, 695, L40.
- Flux (> 250 GeV) ~ 0.8% Crab (5σ; 120hrs); $\Gamma = 2.7 \pm 0.5_{stat} \pm 0.2_{sys}$
  - Sensitivity to variability: < 15x in a night; 3σ
- Source position consistent with the radio core and inner kpc-jet region



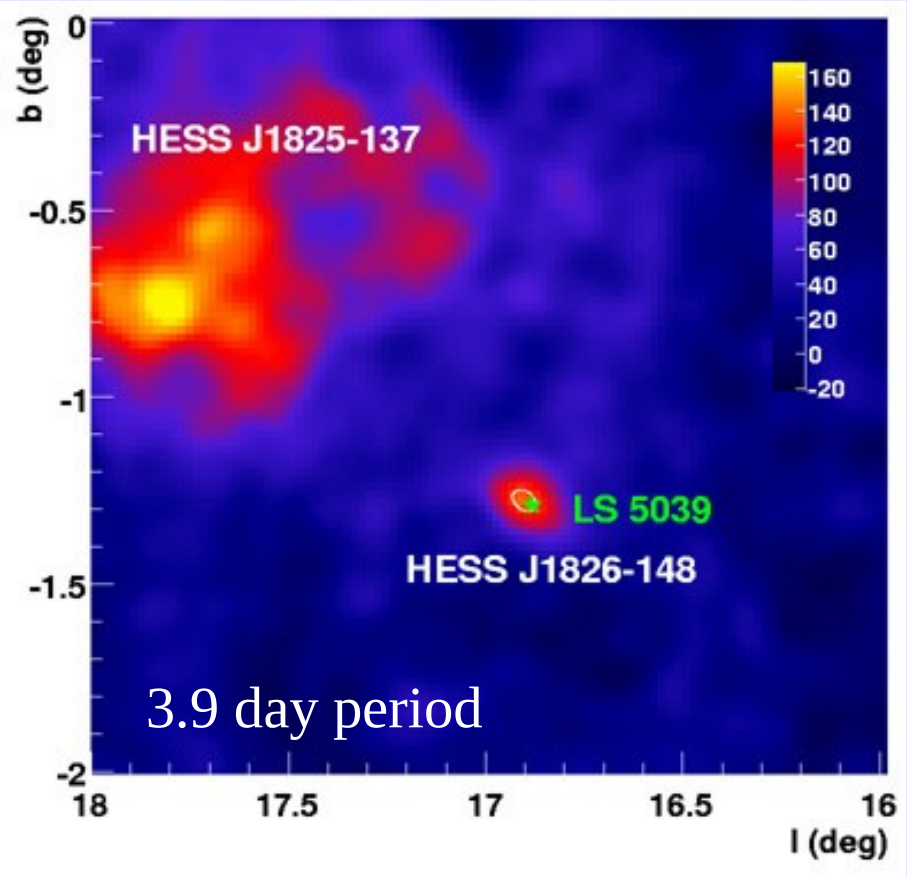


Origin of the γ-rays: core or extended inner jet?

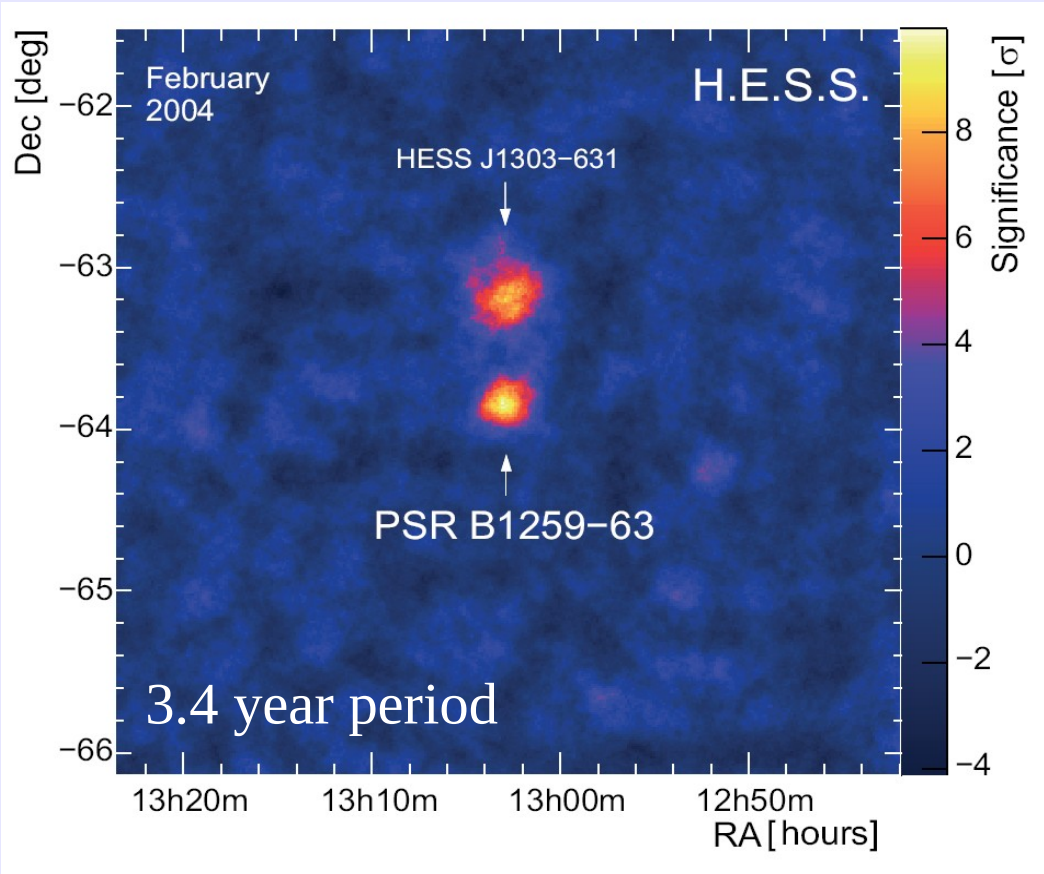
- ∠(jet-los) ~ 15^0+
- TeV point source

Variable Galactic H.E.S.S. Sources

LS 5039 HESS 2005, Science, 309, 746



PSR B1259-63 HESS 2006, A&A

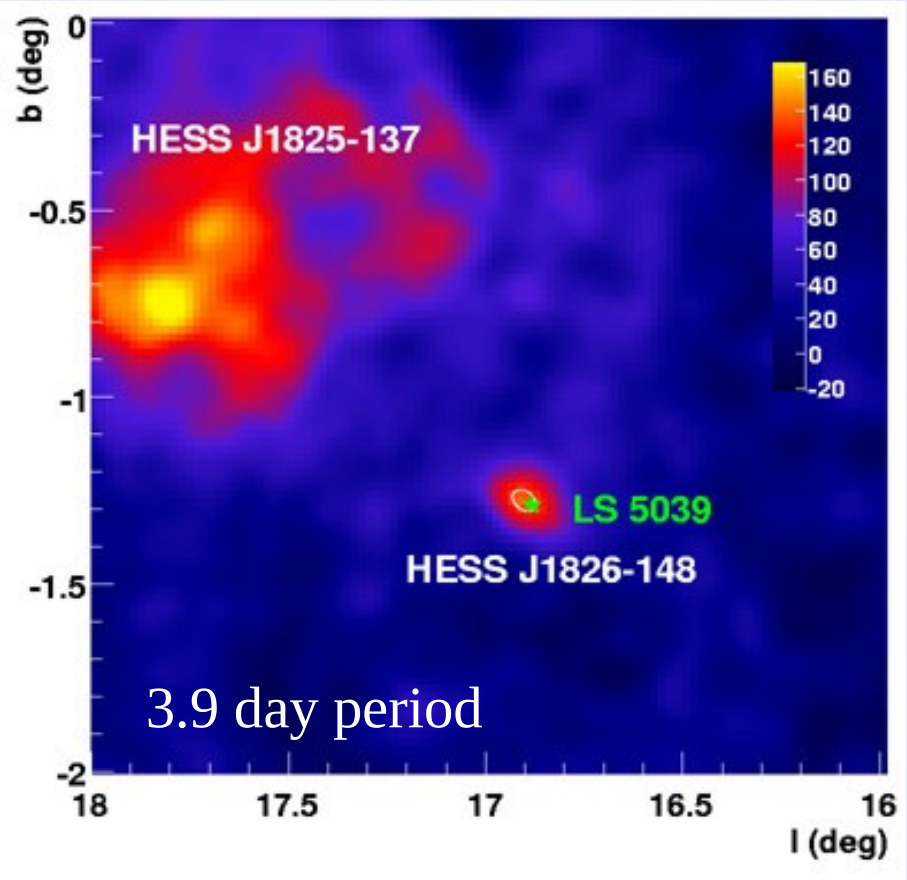


- Well known X-ray emitting binary systems
- Massive (O/B) stellar companion
- Variable radio and X-ray emission

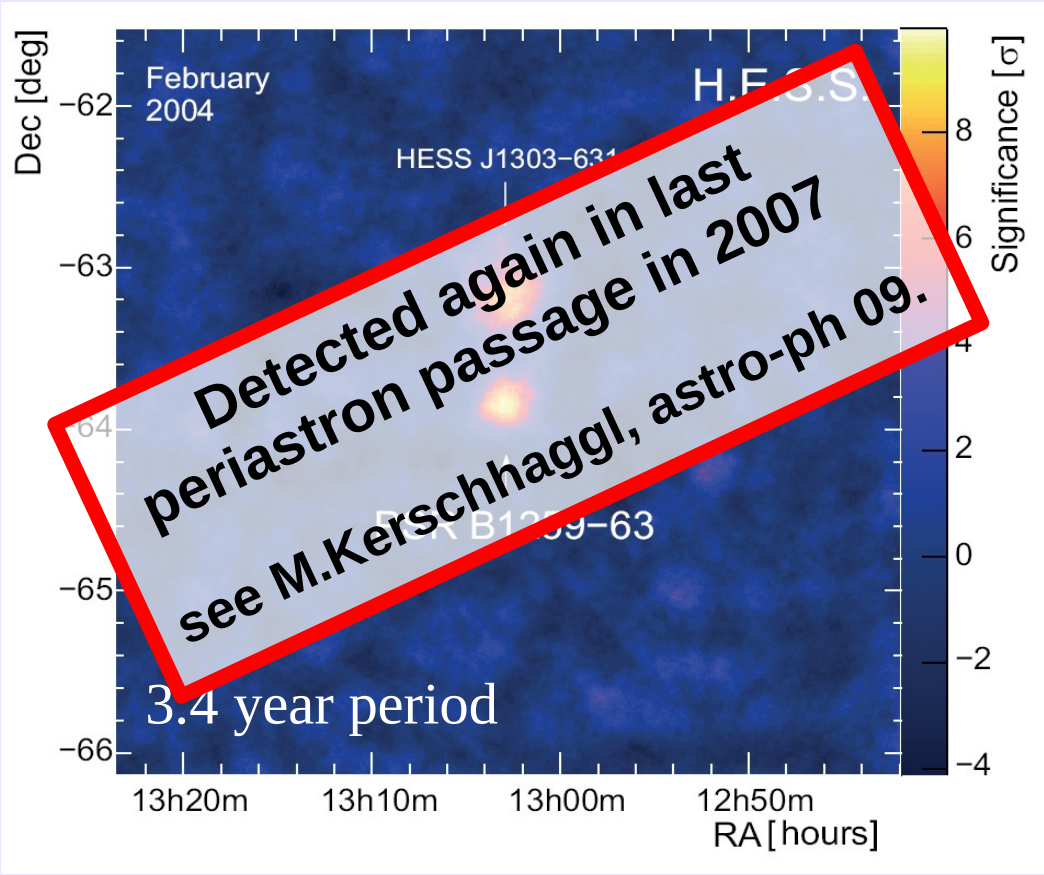
Gamma-ray binaries

Variable Galactic H.E.S.S. Sources

LS 5039 HESS 2005, Science, 309, 746



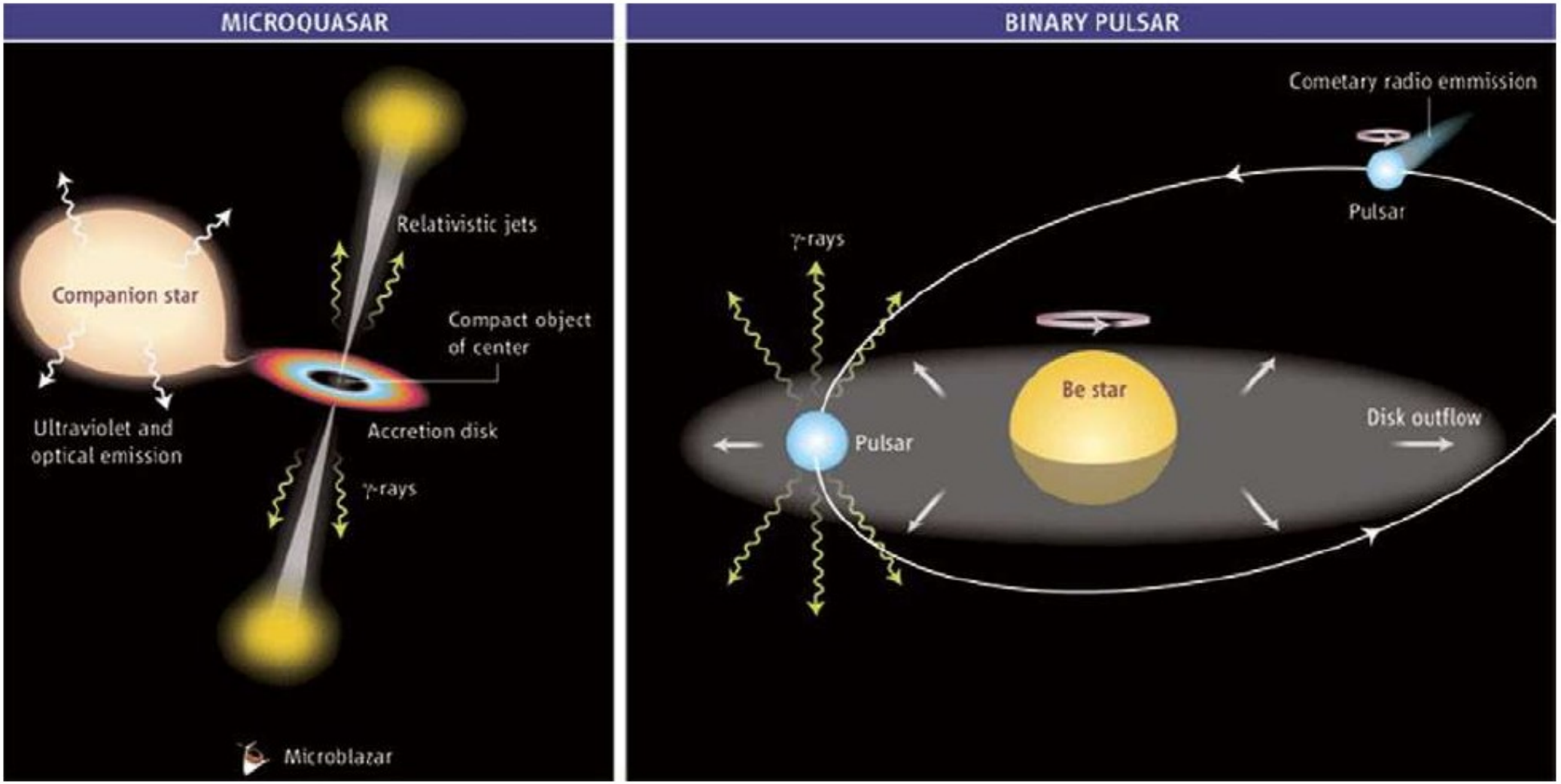
PSR B1259-63 HESS 2006, A&A



- Well known X-ray emitting binary systems
- Massive (O/B) stellar companion
- Variable radio and X-ray emission

Gamma-ray binaries

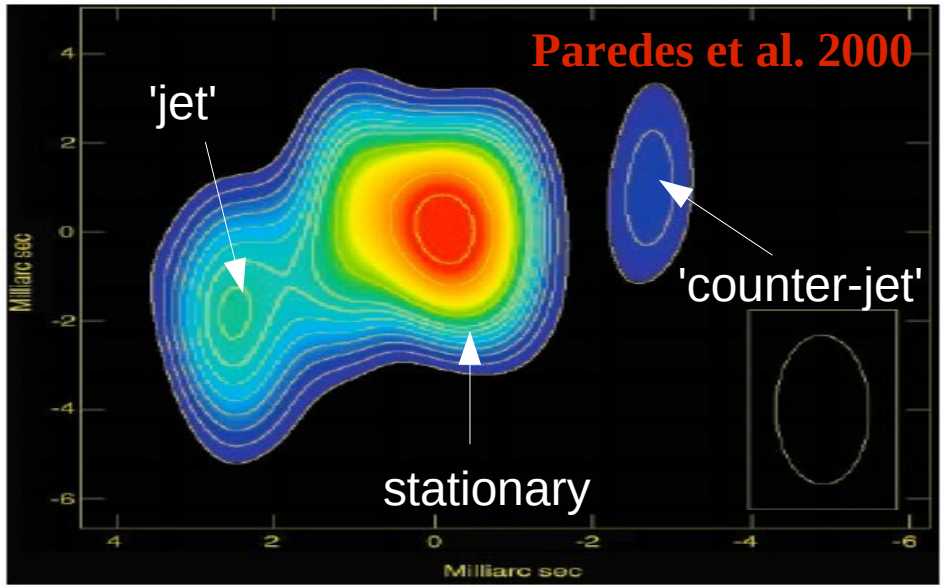
Microquasar and Binary Pulsar scenarios



Mirabel+, Science 2006

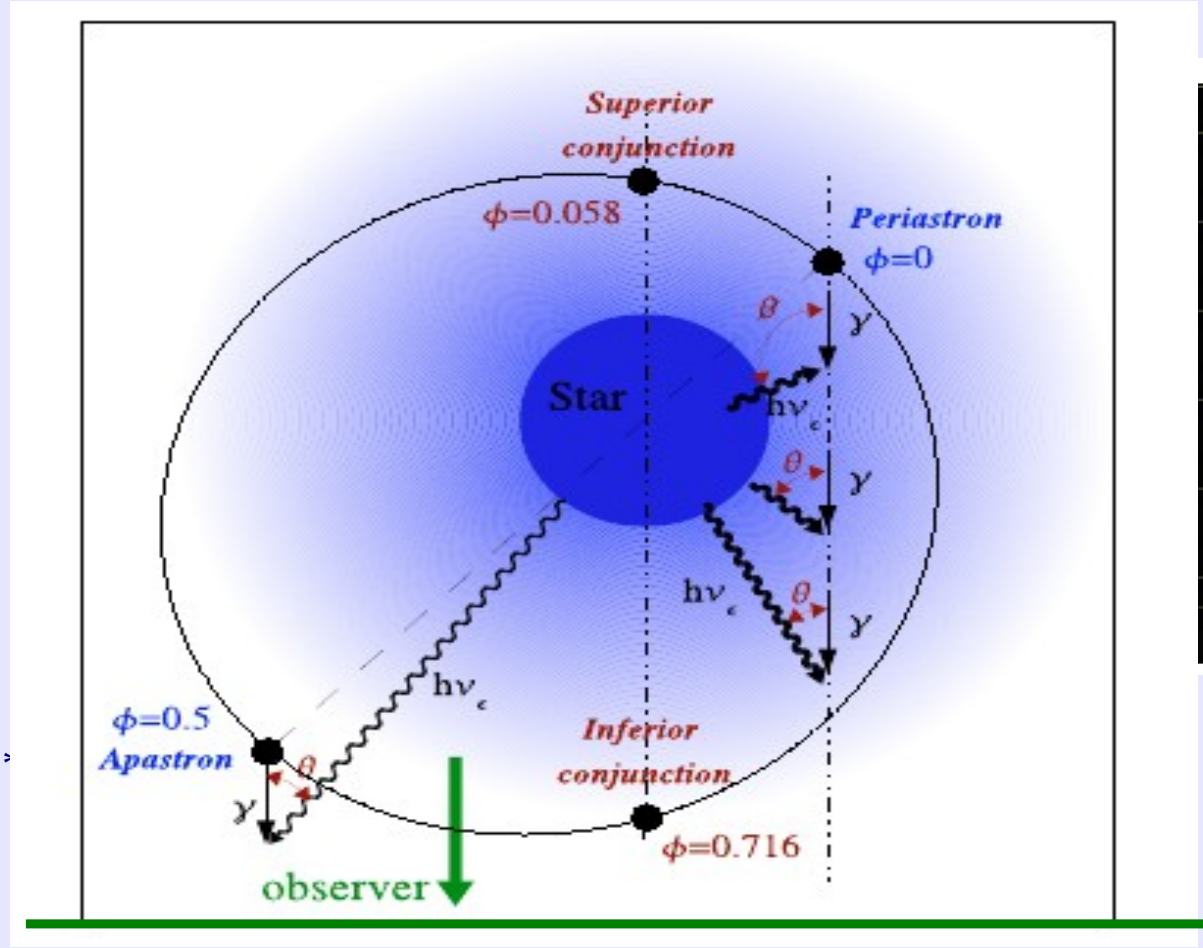
LS 5039: a candidate microquasar

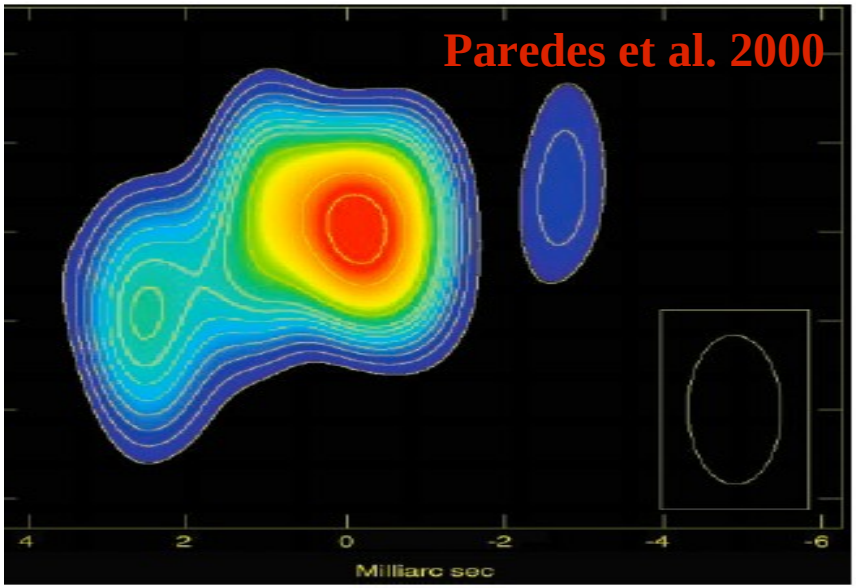
- Close binary system
  - Period: 3.9 days
  - O-star: 25 $M_\odot$
  - Distance 2.5 kpc
  - Compact object unknown*
- Exhibits radio extension
  - *if 2-sided jet: v ~ 0.2 c*
    aligned close to line of sight



* Casares 2005 → 3.7 $M_\odot$ black hole (**low *i***) or neutron star (**high *i***), depending on the inclination of the system.

LS 5039: a candidate microquasar



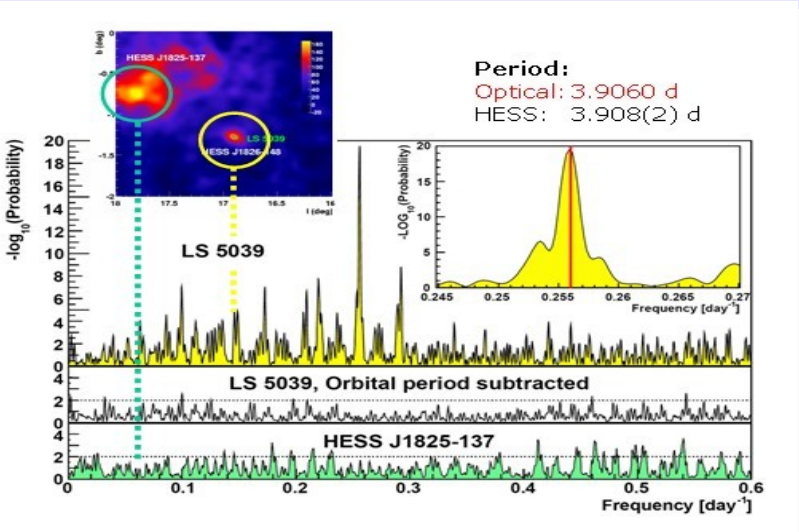


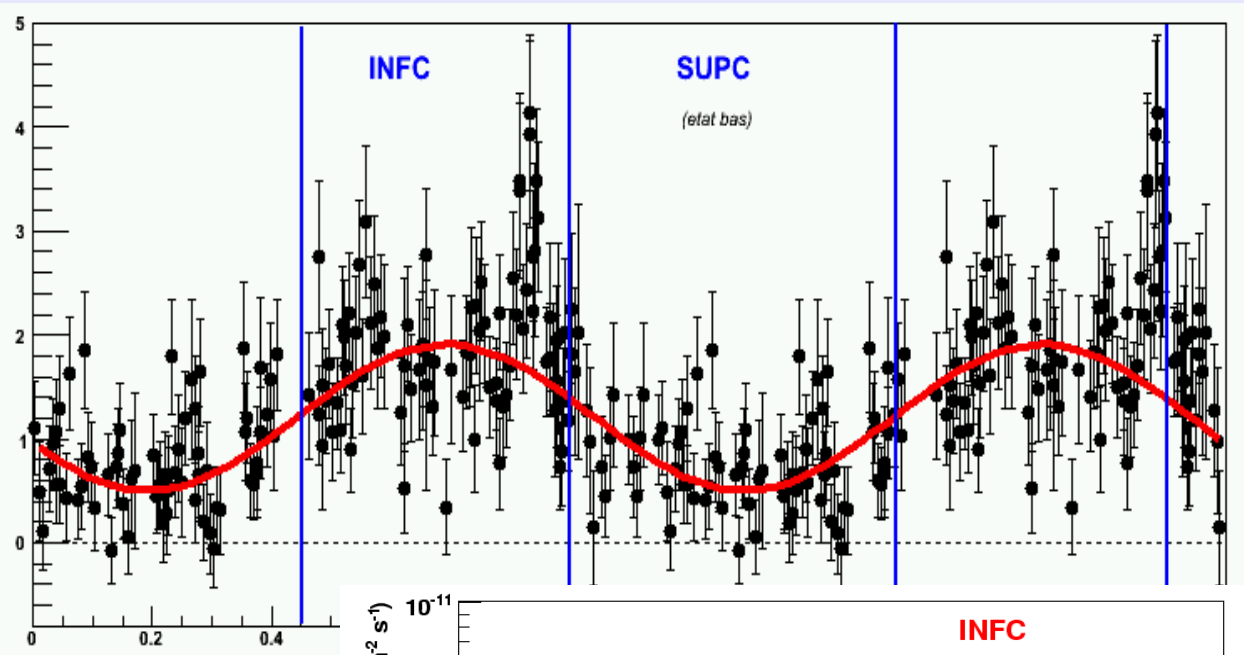
μquasar scenario (Mirabel, 2006):

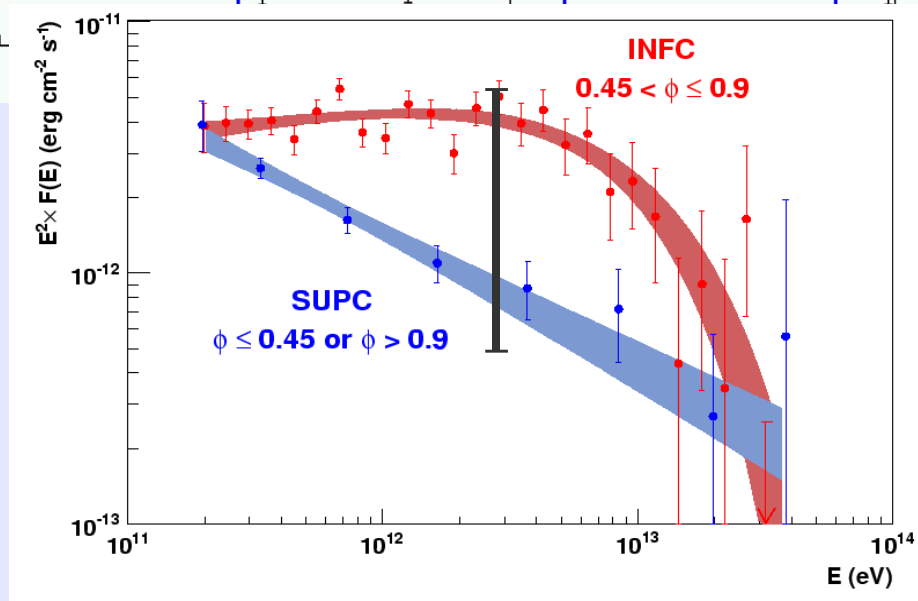
- Acceleration in jets
- Internal/external shocks

- Orbital-induced modulations expected

LS 5039: flux and spectral modulation







- Flux modulation coincident with orbital period and optical period.

- Modulation due to absorption.
  - minimum flux observed at SUPC
  - maximum modulation happens at ~ TeV
  - **non-zero flux at SUPC**
  - orbit inclination? Do we see pair-cascading?

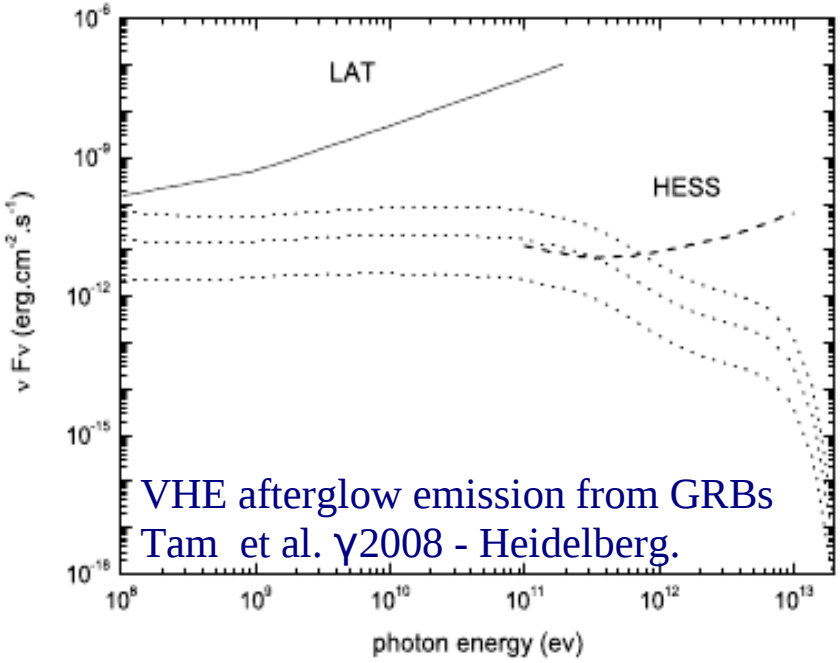
(Dubus, 2006)

HESS 2006, A&A 460, 743.

GRB Observations

- Highest energy GRB photons:
  - 18 GeV *(GRB 940217; Hurley et al. Nature '94)*
  - 33 GeV *(GRB 090902B; Fermi Collab. '09)*

- Relativistic *Fireball* models predict photons of energy up to ~ 10 TeV in afterglow phase.



H.E.S.S. Sensitivity (>1TeV; Γ = 2.6; 2hrs)

~ 1.4 x 10^{-11} ph cm^{-2} s^{-1}

H.E.S.S. GRB observing program

- triggers from *Swift* and Fermi

instant onboard triggers via GCN allerts + HETE II & INTEGRAL w/ ground-based analysis

- limited to Z.A. < 45^0

+ high SNR and no-coincidence w/ known sources

- sources followed for 2hs

for triggers up to 24hs after burst onset

- since 2003: 38 GRB afterglows

GRB 090510: first and only LAT trigger.

GRB observation summary

"*HESS observations of GRB 060602B*"
Aharonian et al. 09, ApJ, 690, 1068.

U.L. For GRBs with known z

GRB	Redshift	E_{th} (GeV)	F_{UL} [a]	$F_{corrected}$ [a]
060505	0.0889	400	3.9×10^{-14}	5.8×10^{-14}
030329	0.1687	1360	7.6×10^{-15}	9.7×10^{-14}
070209	0.314	370	1.2×10^{-13}	8.7×10^{-13}
070724A	0.457	200	2.1×10^{-13}	1.0×10^{-12}
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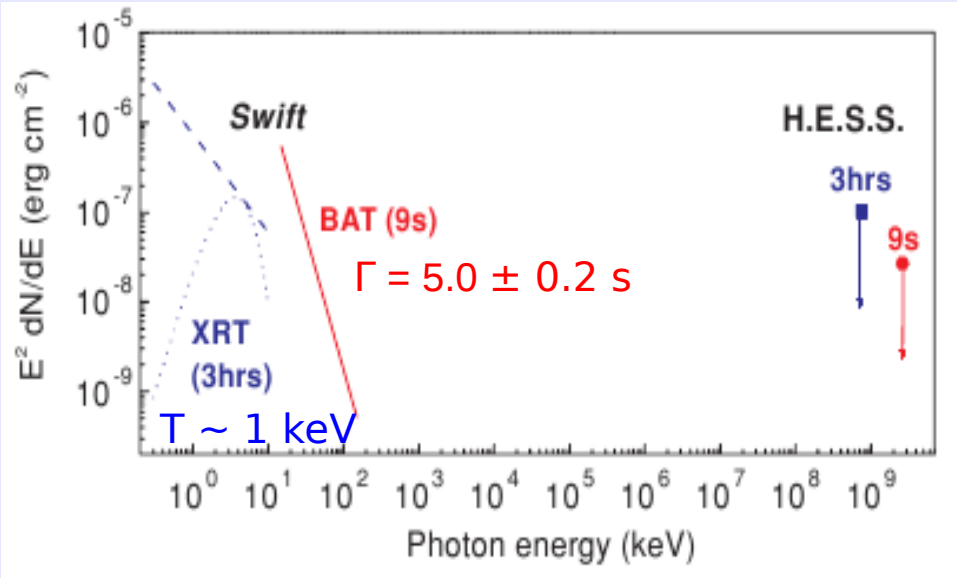
050801	1.56	310	2.1×10^{-13}	[b]
071003[c]	1.604	280	2.0×10^{-13}	[b]
060526	3.21	220	1.7×10^{-13}	[b]
070721B	3.626	320	1.1×10^{-13}	[b]

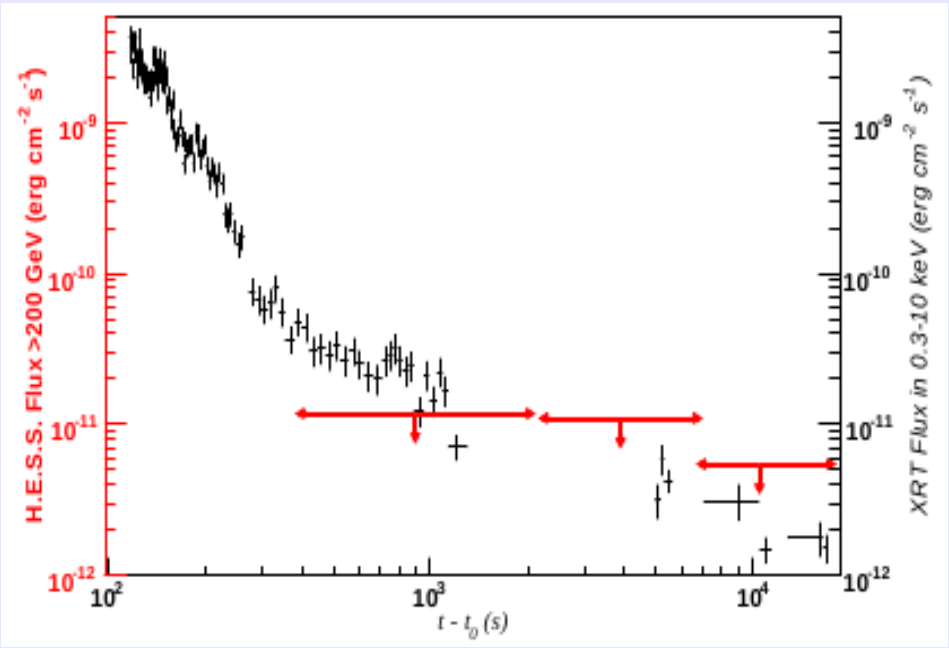
GRB 060602B: prompt and afterglow phases



U.L. (> 1 TeV) = 2.9 x 10^{-9} erg.cm^{-2}.s^{-1}
- if z < 0.2: no EBL; constrains $F_{VHE} < F_{MeV}$

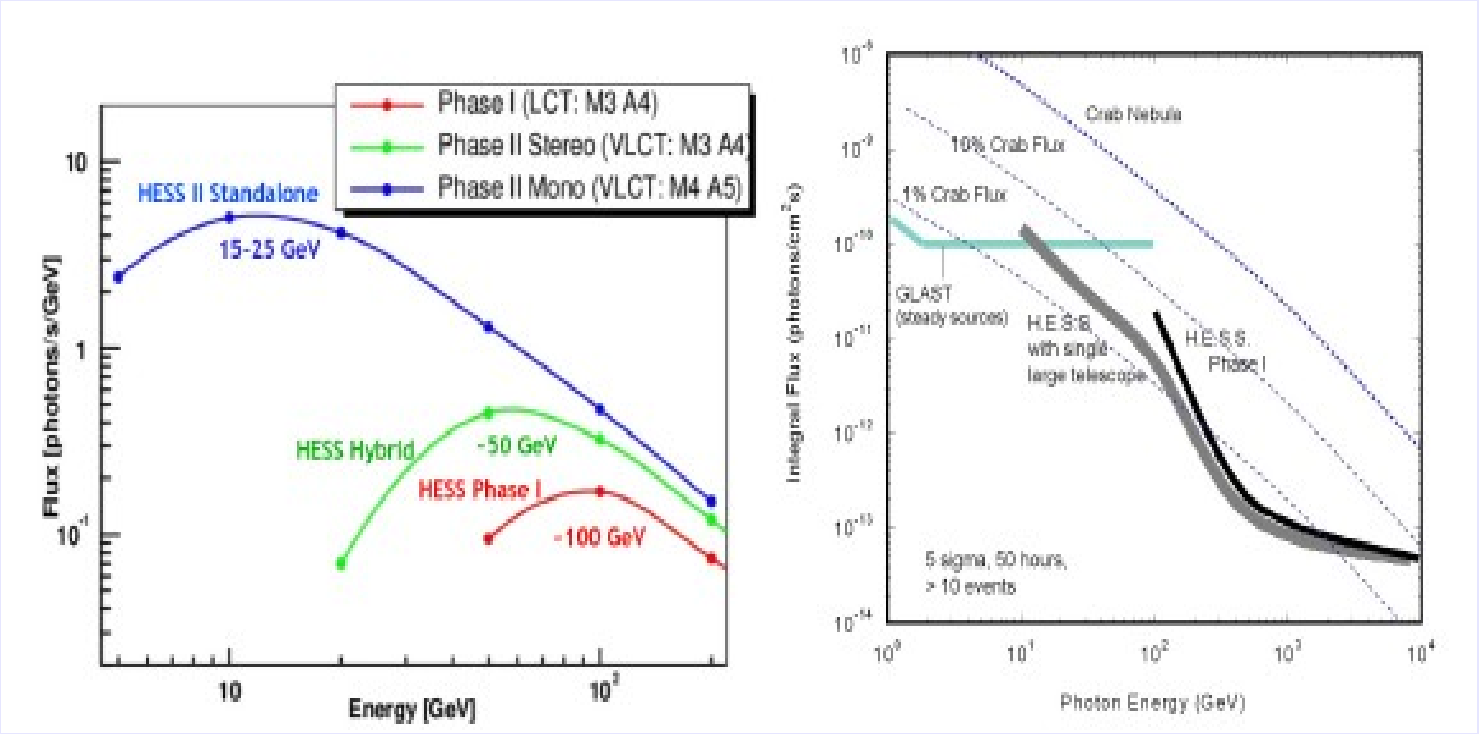
Likely Galactic origin: X-ray burster
(LMXBs have no known VHE counterparts)

GRB 070621: fastest-reaction GRB (6.5 min)



"*HESS Observations of GRBs in 2003- 2007*"
Aharonian et al. 09, A&A.

H.E.S.S. Phase II



- Improved Sensitivity:
  1.5 - 2x around 1 TeV
- Lower Energy Threshold:
  ~ 50 GeV reachable

"HESS- II" M. Punch, proceed. Palaiseau, 2005.

Summary

- Ground-based VHE observations have revealed a wealth of **galactic and x-galactic relativistic sources**

- **Xgal TeV sources** are mostly AGNs (exception: NGC 253) whose emission is powered by particle acceleration in relativistic jets

  - 3+ years of data on **PKS 2155-304** presents unprecedented new information about the emission mechanisms in blazars, both in high and low states.

  - detection of TeV emission from **M87 and CenA**, together with MWL observations, provides a unique opportunity to localise the sites of particle acceleration in jets.

- Study of galactic objects allows us to probe the sources and mechanisms of **particle acceleration in the Galaxy**

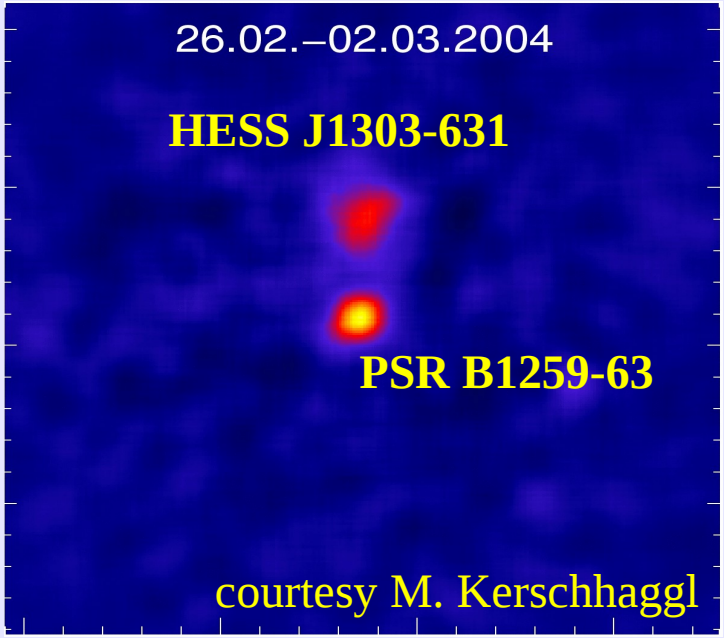
  - **variable sources** detected so far are binary systems, but their nature is still poorly understood: laboratory for studying the microquasar paradigm.

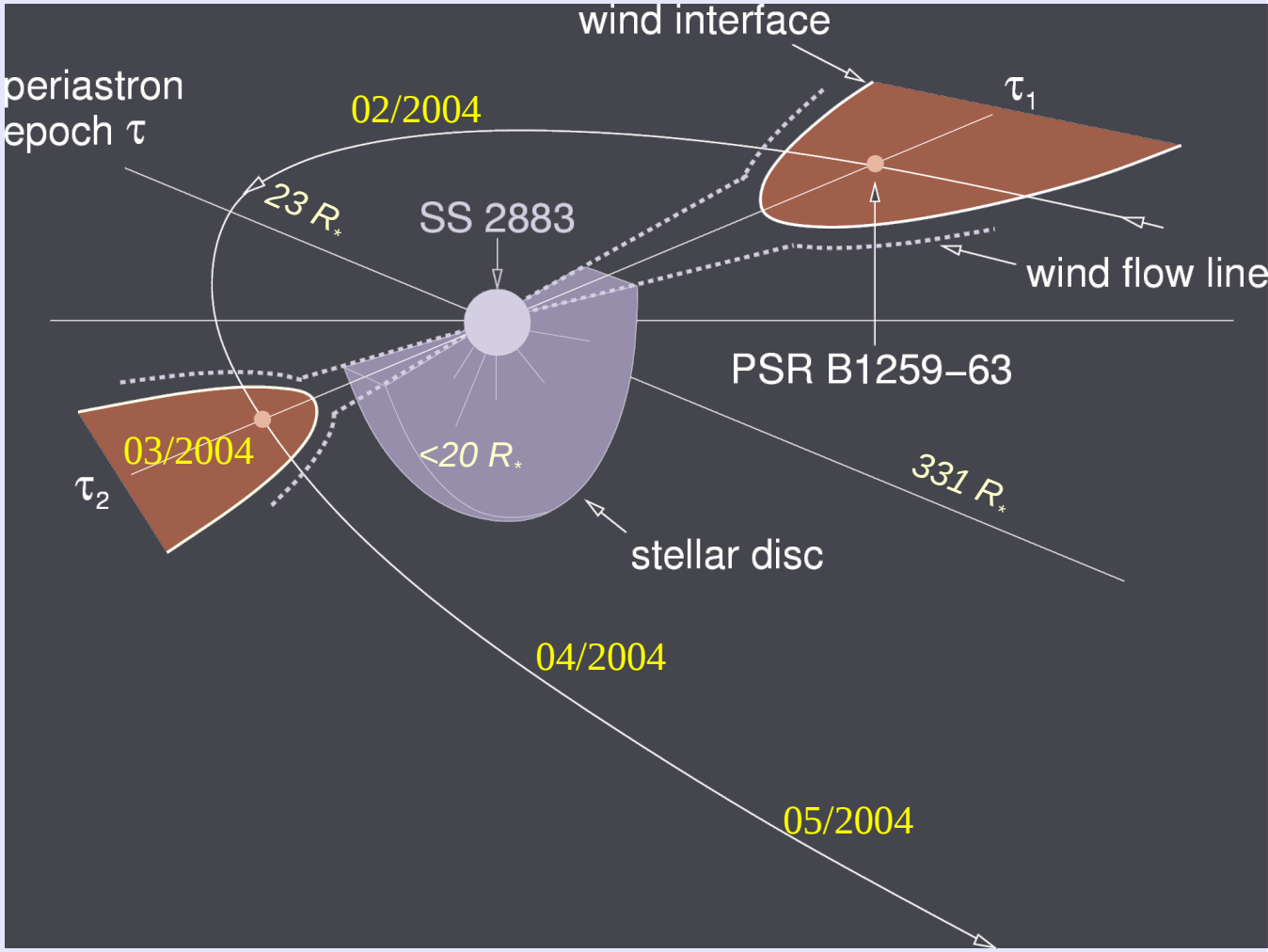
- HESS has observed over 30 **GRBs** in the afterglow and one in the prompt phase without any positive detection, even for those nearby and less affected by the EBL.

- **HESS-II**, to start activity in 2010, will bring significant improvement in all these areas of research, thanks to 2x increased sensitivity and lower (50 GeV) energy threshold.

Back-up material

PSR B1259-63



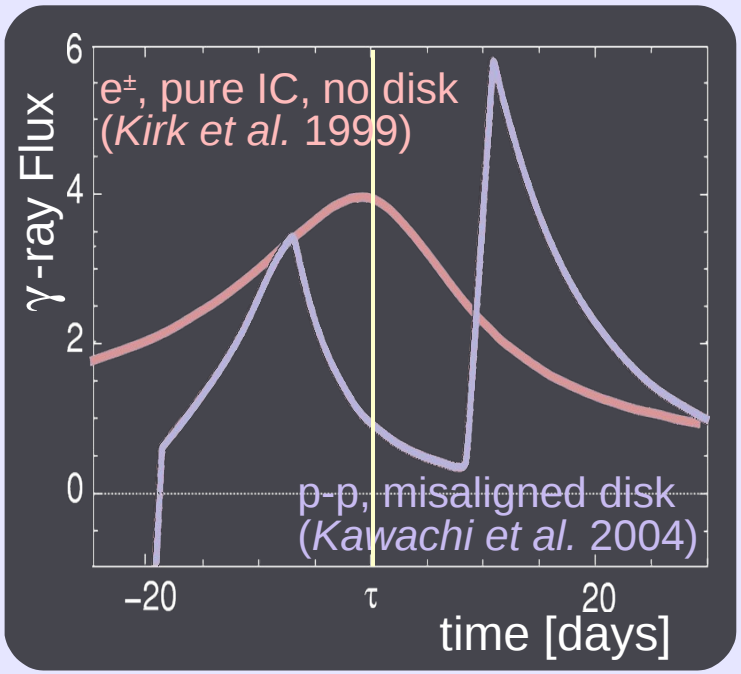


- Period 3.4 years
- Distance 1.5 kpc
- Be star (10 $M_\odot$)
- 47 ms pulsar
- Latest Periastron 27th July 2007

  - previous periastron 7th March 2004;
    next periastron ~October 2010

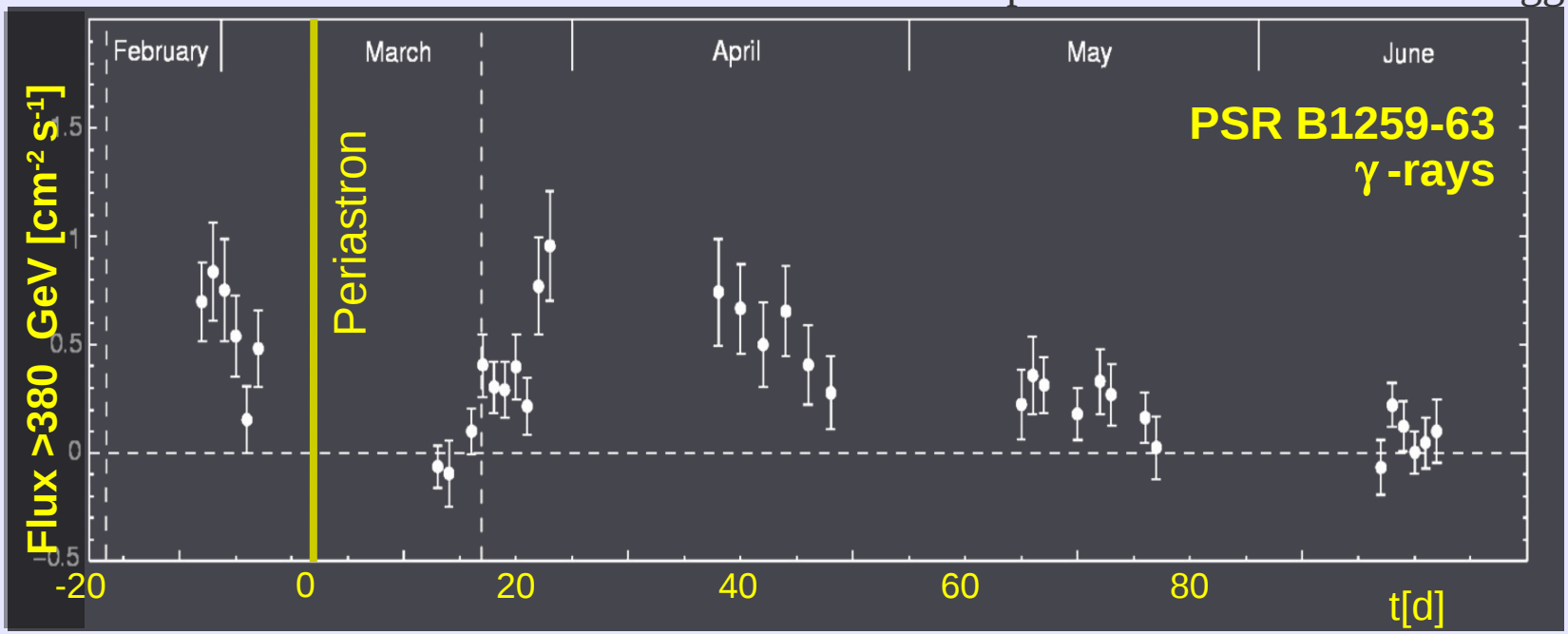
Johnston et al. 1995

PSR B1259-63: 2004 observations



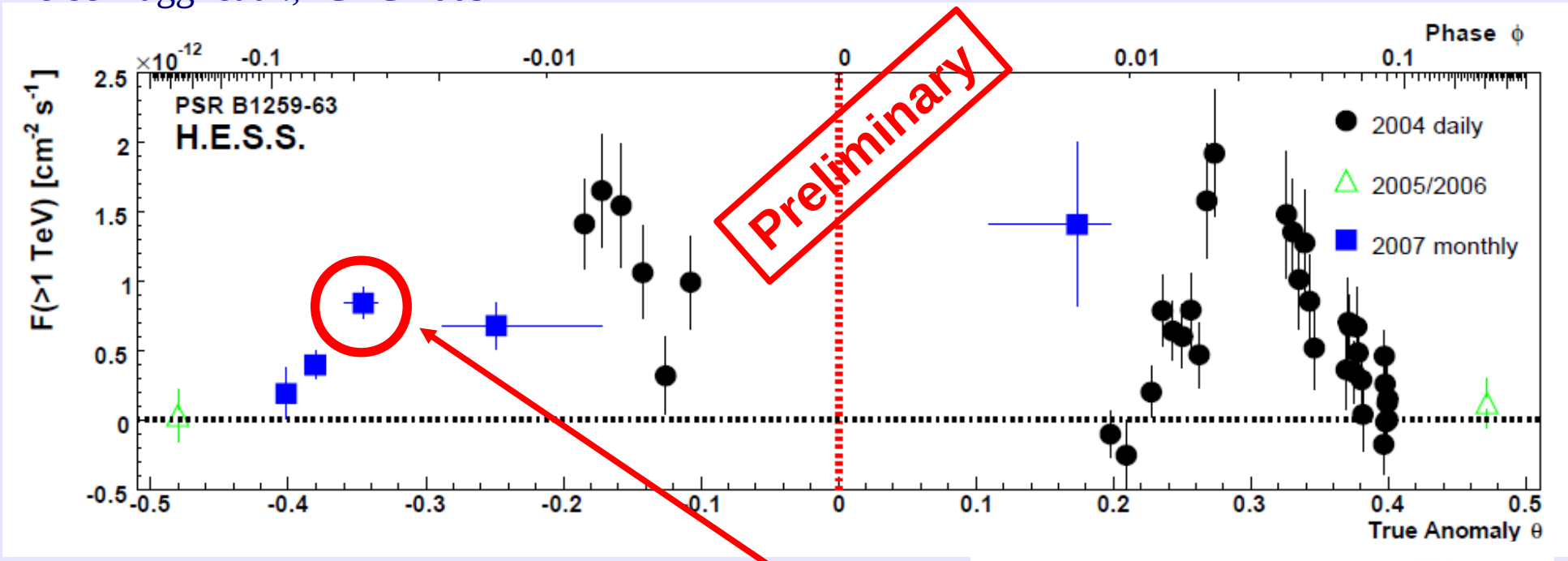
- No observations at periastron due to weather/moon constraints
- Emission increases as pulsar crosses stellar disk
  (~ τ-16 days and τ+13 days; Johnston et al. 2005)
- Particle acceleration at wind-collision zones
- Leptonic (IC) and hadronic (π^0-decay)

plots thanks to M. Kerschhaggl

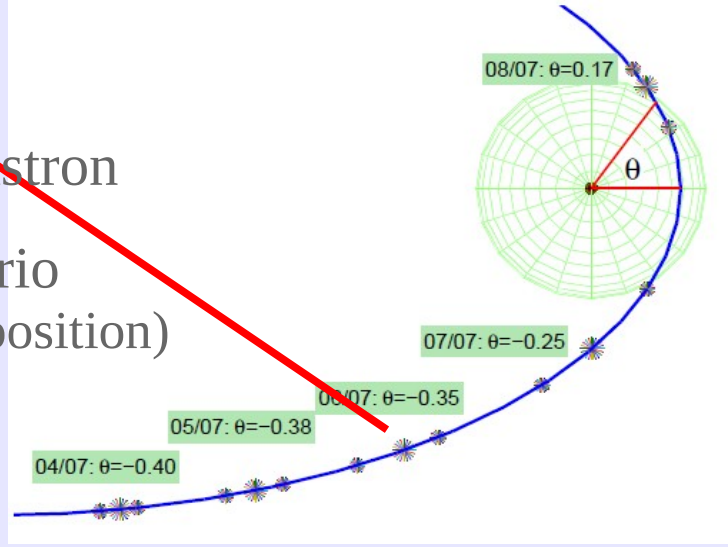


PSR B1259-63: 2007 TeV light-curve

Kerschhaggl et al., ICRC 2009



- No observations at periastron
- Detection of TeV emission far from periastron
- Excess in June disfavours hadronic scenario
(stellar-disk non-coincident with orbital phase position)



GRB observation summary

"*HESS Observations of GRBs in 2003- 2007*"
Aharonian et al. 09, A&A.

U.L. For GRBs with known z

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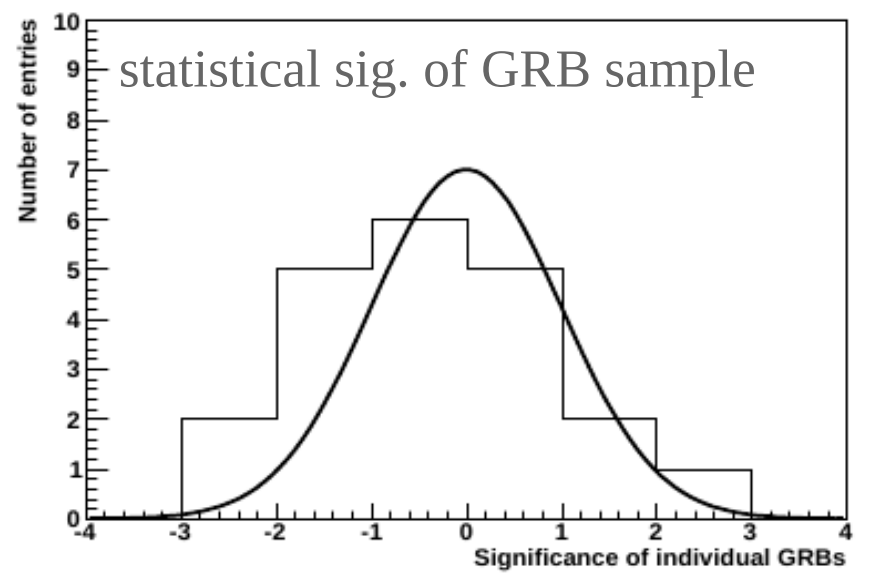
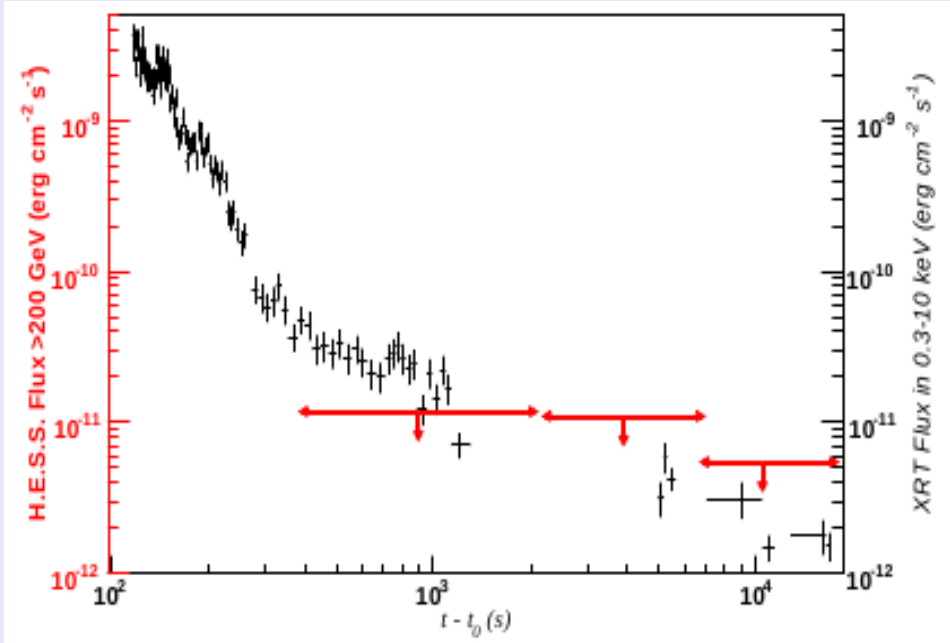
- stacking analysis of whole GRB sample yields -1.98 σ (soft cuts)



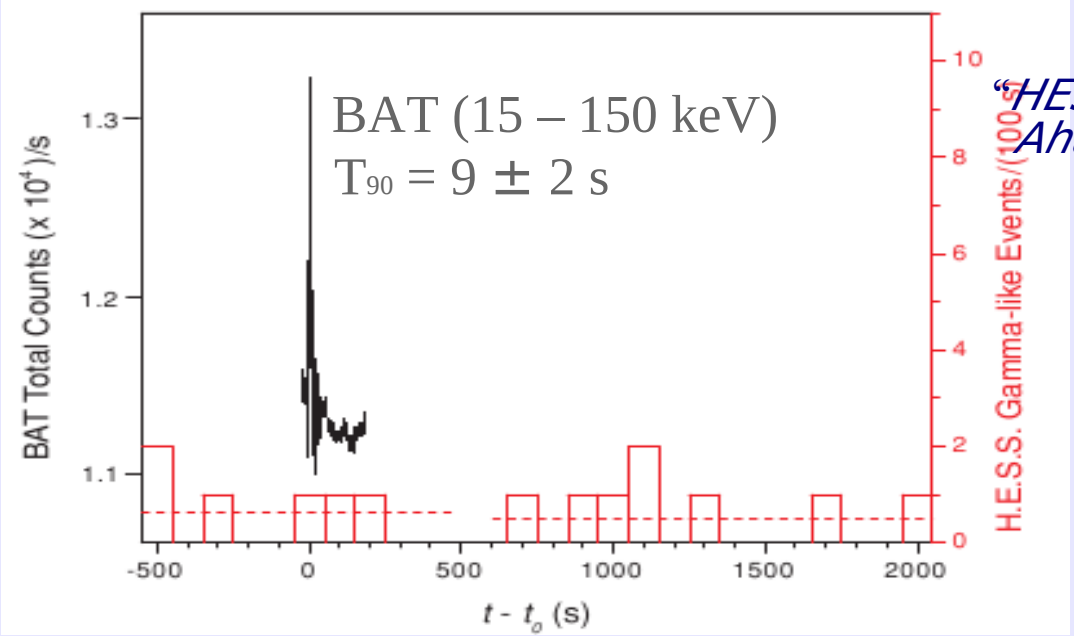
GRB 070621:

- fastest reaction GRB (6.5 min)
- highest expected $F_{VHE} \propto F_{15\text{-}150\ keV} \times T_0^{-1.3}$



Long GRBs known to emit at 10-20 GeV range, but no VHE counterpart detected in afterglow phase.

GRB 060602B: prompt and afterglow phases



"HESS observations of GRB 060602B"
Aharonian et al. 09, ApJ, 690, 1068.

H.E.S.S. serendipitous obs.
5hrs in 2006 June 2nd

- GRB?

  U.L. (> 1 TeV) = 2.9 x 10^{-9} erg.cm^{-2}.s^{-1}
  - z < 0.2: no EBL; constrains $F_{VHE} < F_{meV}$
  - z > 0.2: EBL corrections apply.

- LMXB (X-ray burst)?

  - near galactic plane + possible XMM assoc.
  - no VHE emission associated to LMXBs
  - persistent U.L. ~ 5 mCrab (128 hrs data)