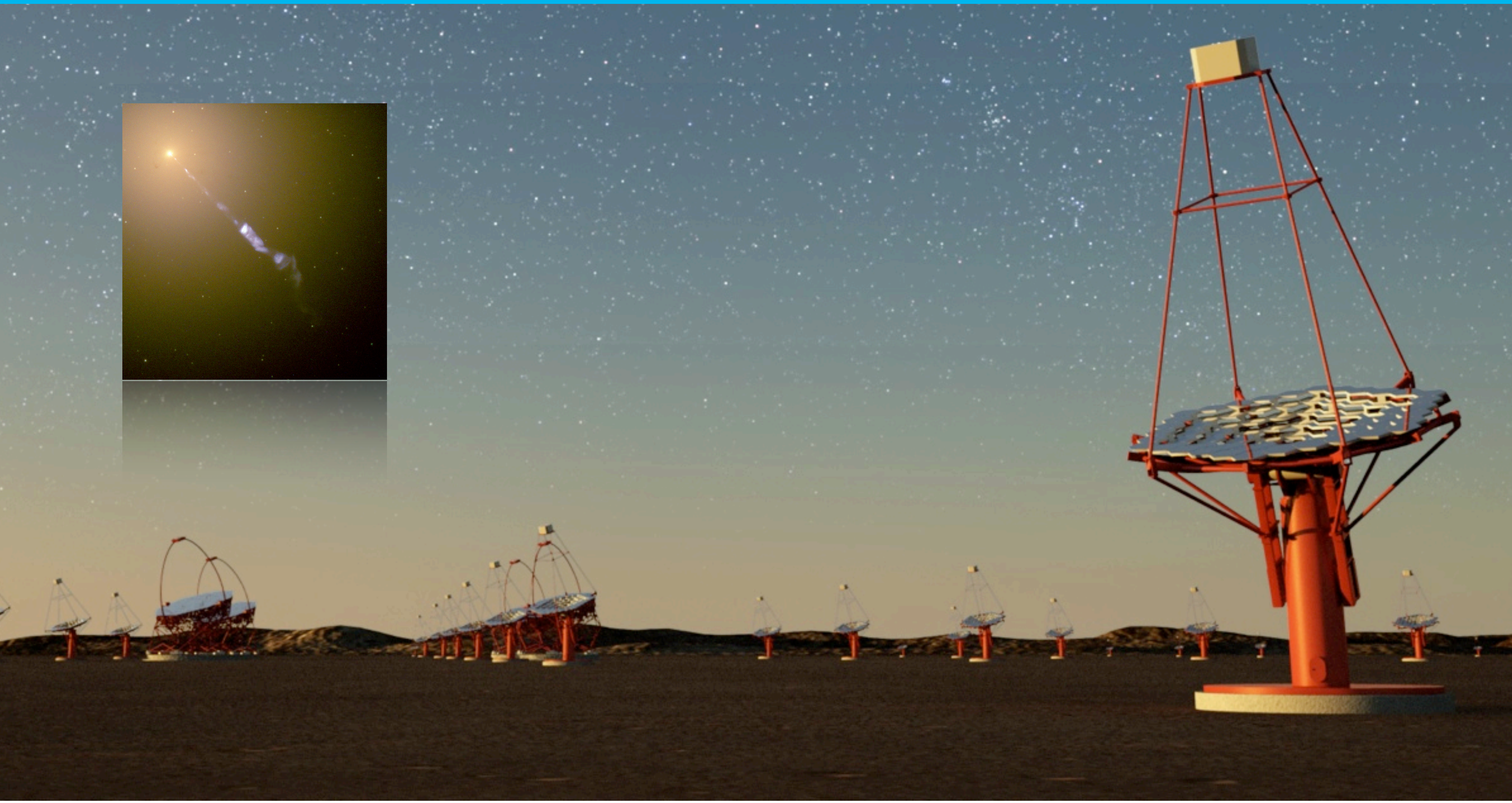
Cosmic Jets and Gamma Rays.



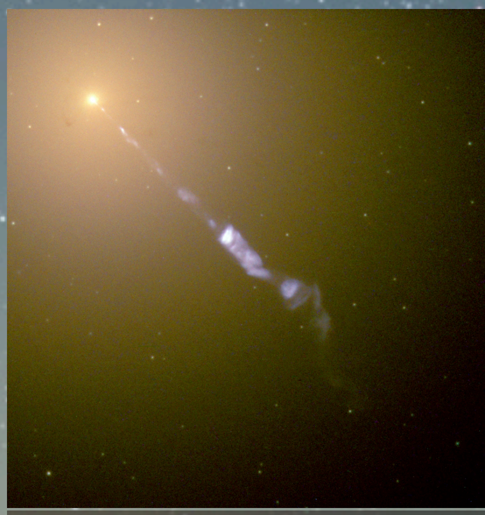
Gernot Maier

HUMBOLDT-UNIVERSITÄT ZU BERLIN

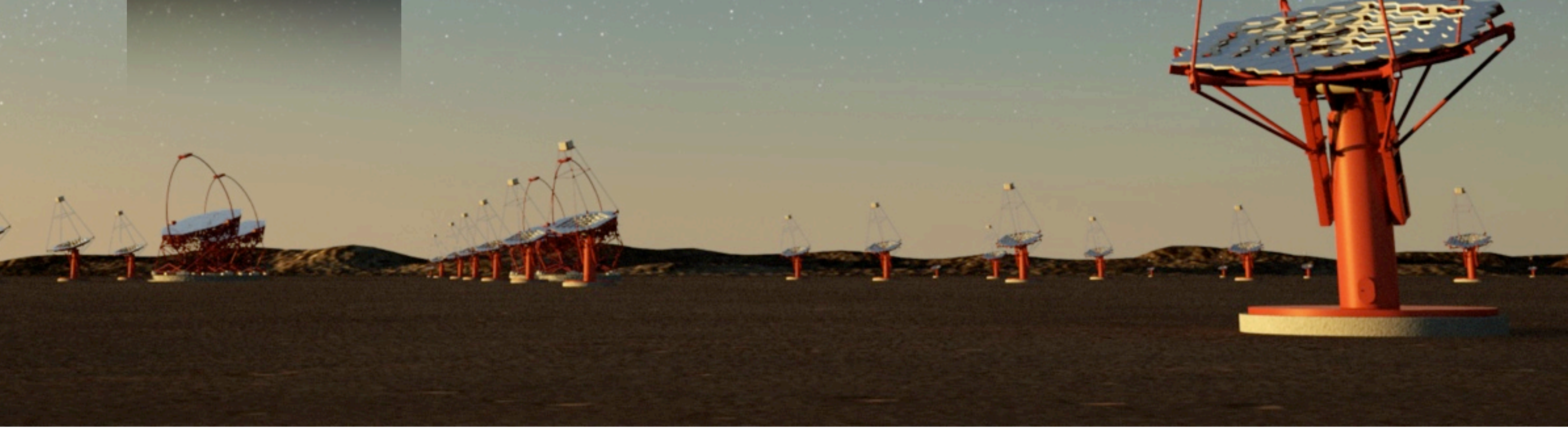
DESY

HELMHOLTZ ASSOCIATION

Cosmic Jets and Gamma Rays.



- Gamma-ray astronomy
- Observing gamma rays
- Observing particle acceleration in jets
- The Cherenkov Telescope Array (CTA)



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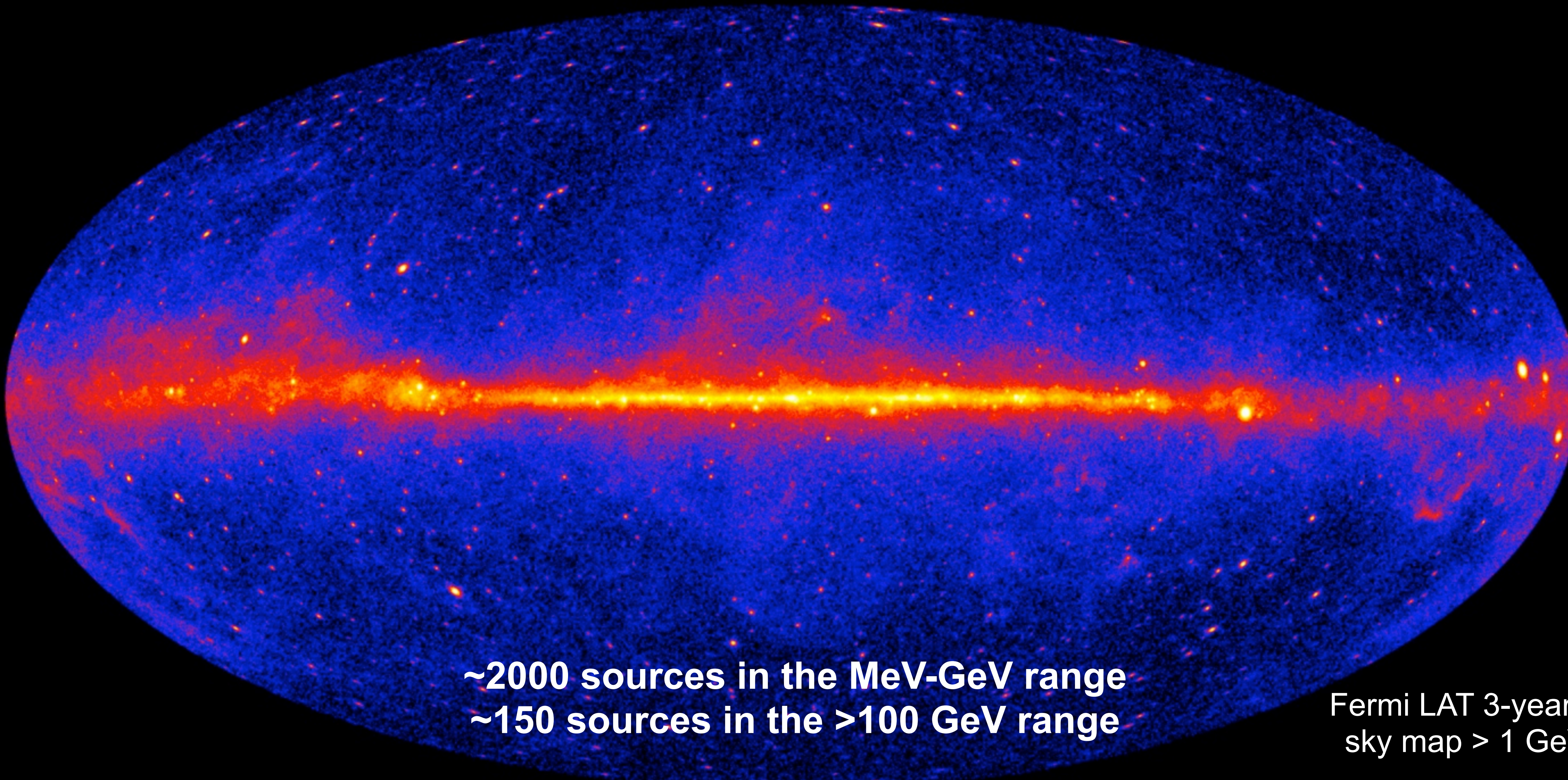
Gamma-ray astronomy: GeV-TeV photon astronomy

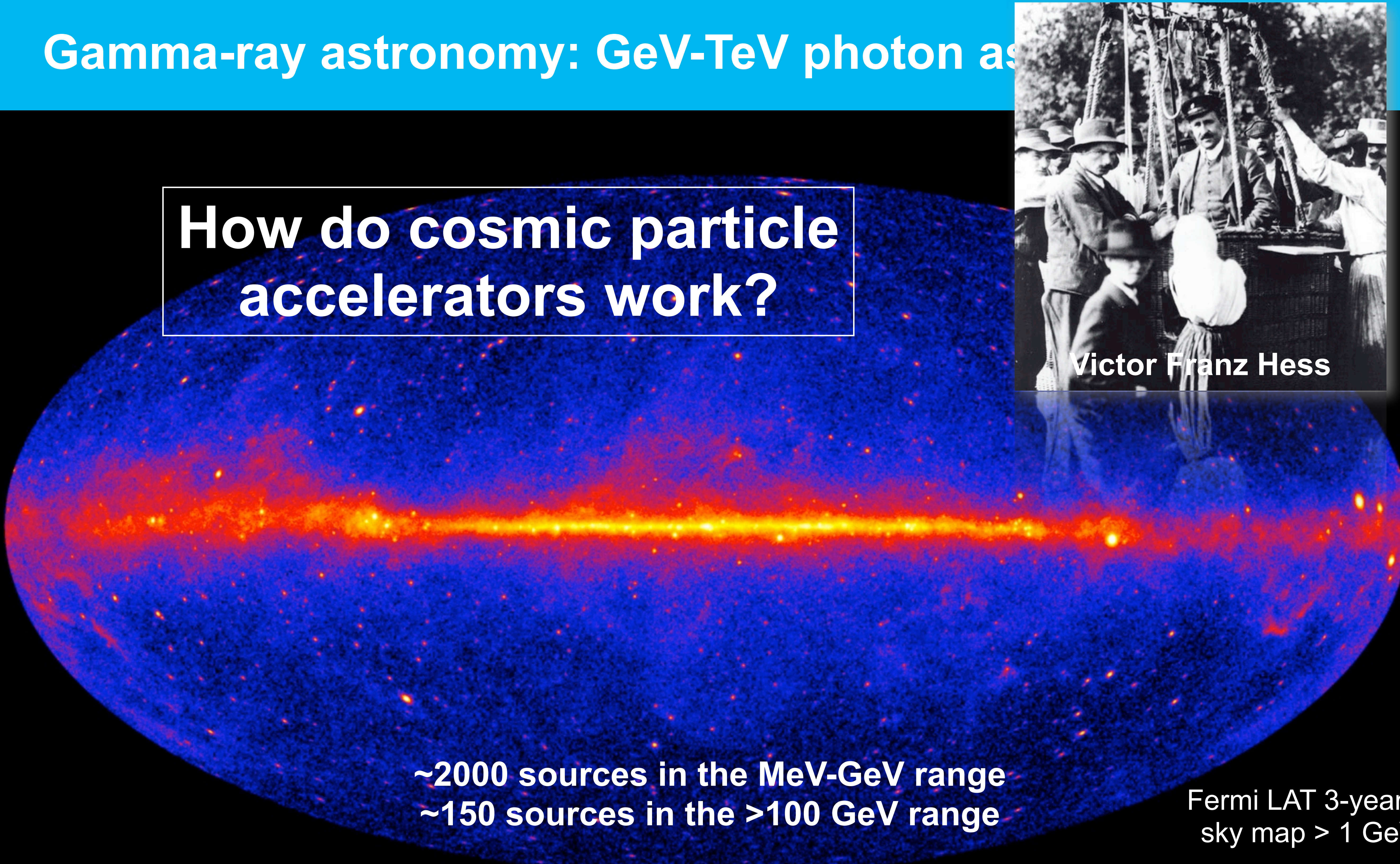


~2000 sources in the MeV-GeV range
~150 sources in the >100 GeV range

Fermi LAT 3-years
sky map > 1 GeV

GeV/TeV radiation is ubiquitous to a wide range of astrophysical environments
non-thermal processes

Gamma-ray astronomy: GeV-TeV photon as

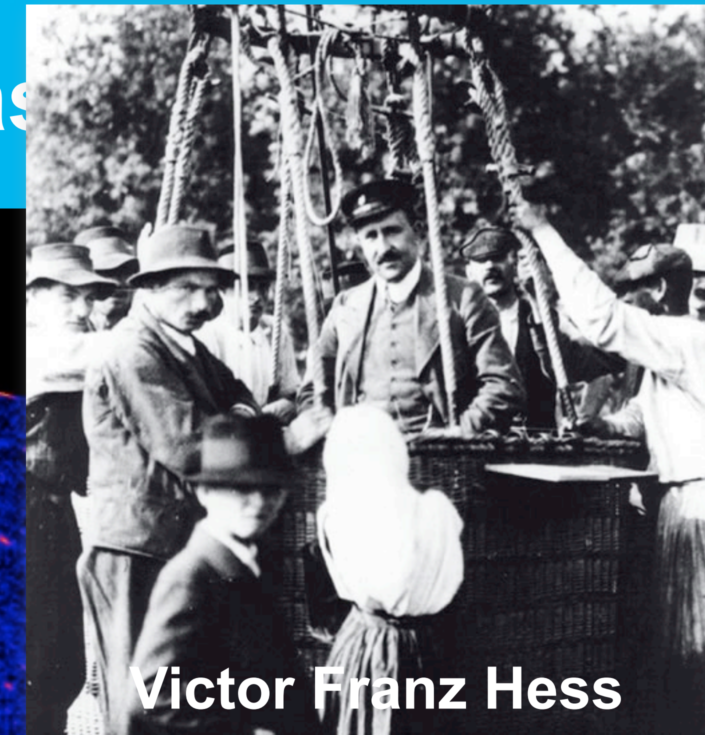


Fermi LAT 3-years sky map > 1 GeV

GeV/TeV radiation is ubiquitous to a wide range of astrophysical environments
non-thermal processes

Gamma-ray astronomy: GeV-TeV photon as

How do cosmic particle accelerators work?



Science News Reports on the Top Mysteries

Science June 2012

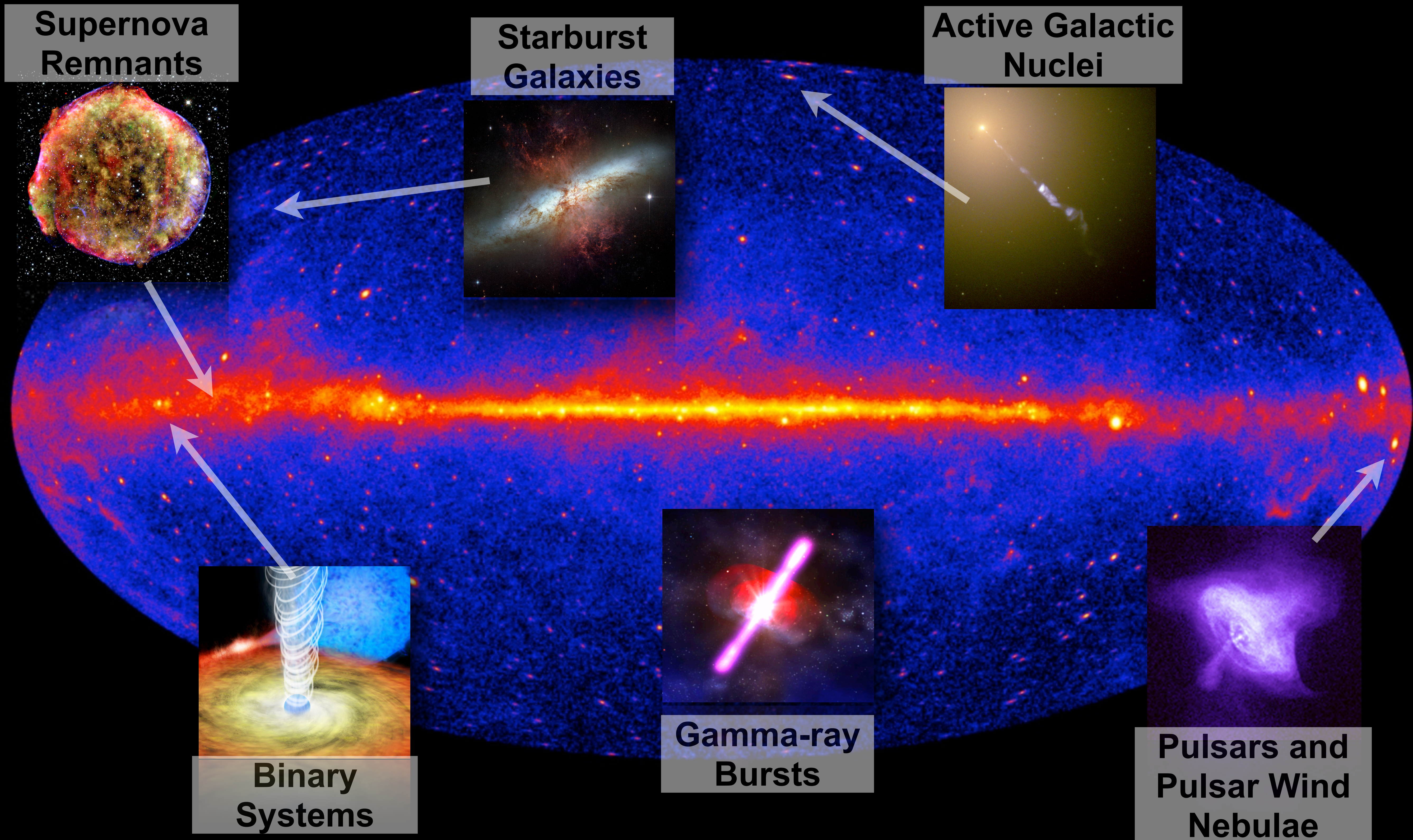
true mysteries must have staying power

(as opposed to mere "questions" that researchers might resolve in the near future)

DESY

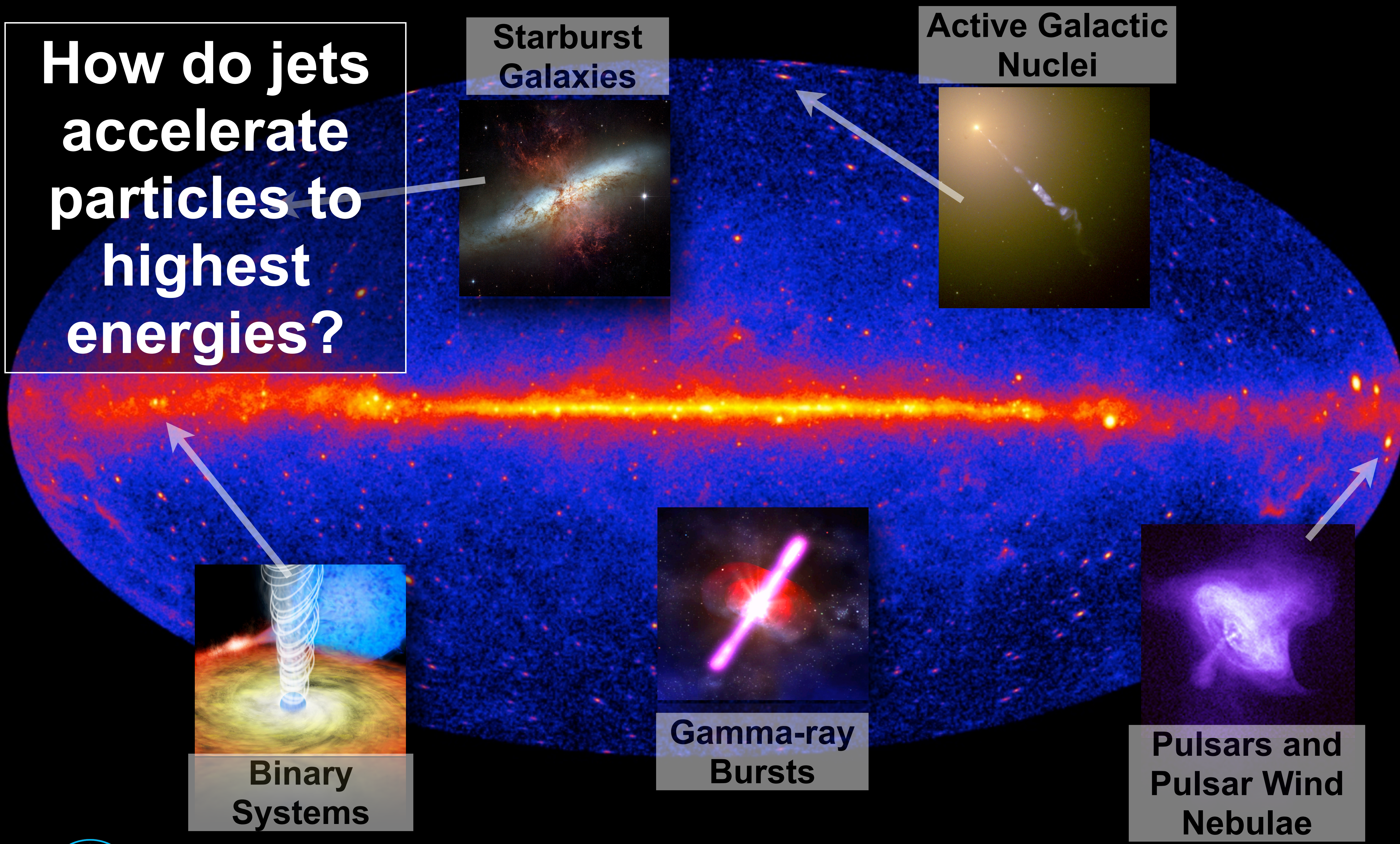
Cosmic Jets and Gamma Rays

Fermi LAT 3-years sky map > 1 GeV

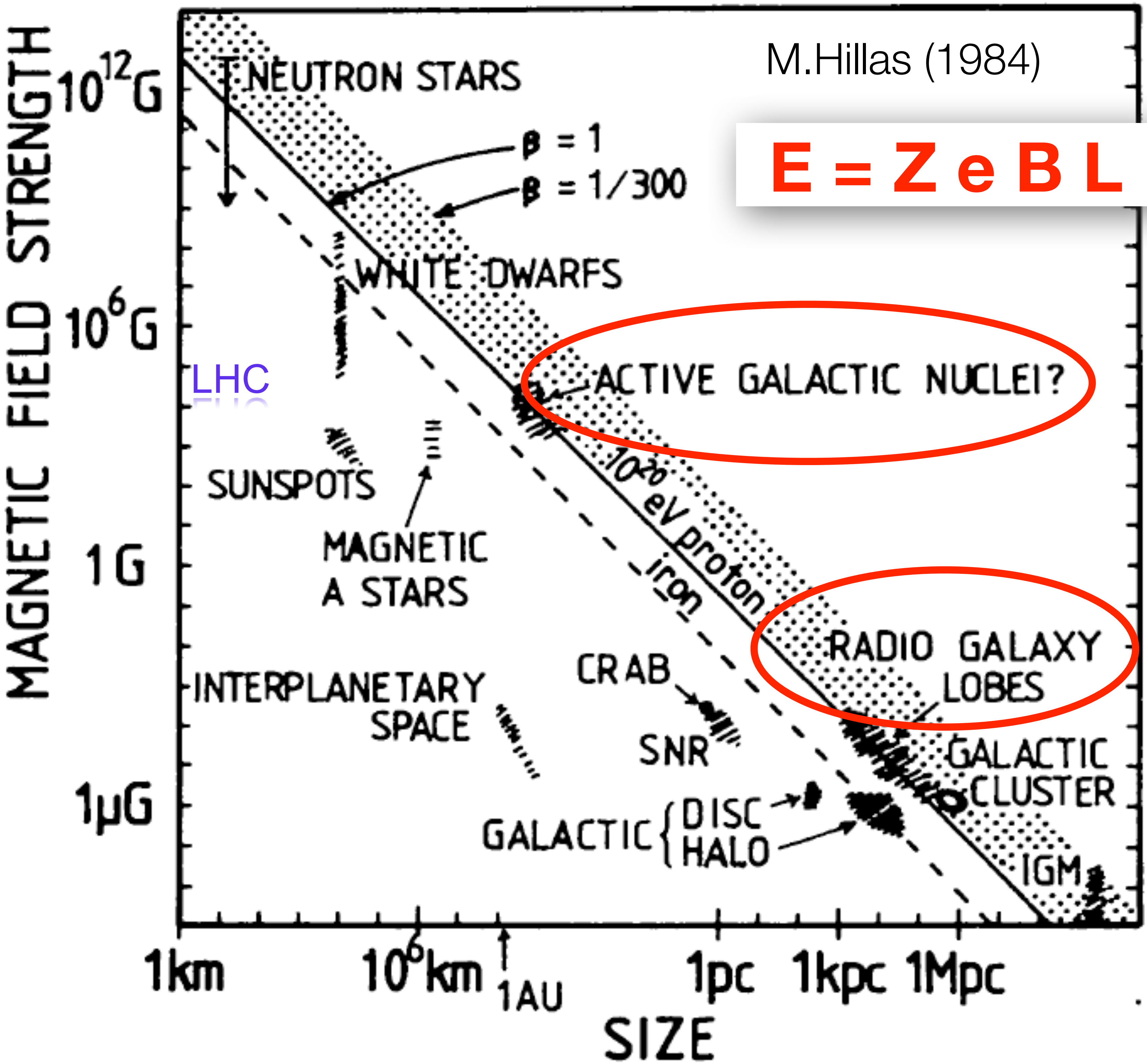


Cosmic Jets and Gamma Rays

Fermi LAT 3-years
sky map > 1 GeV

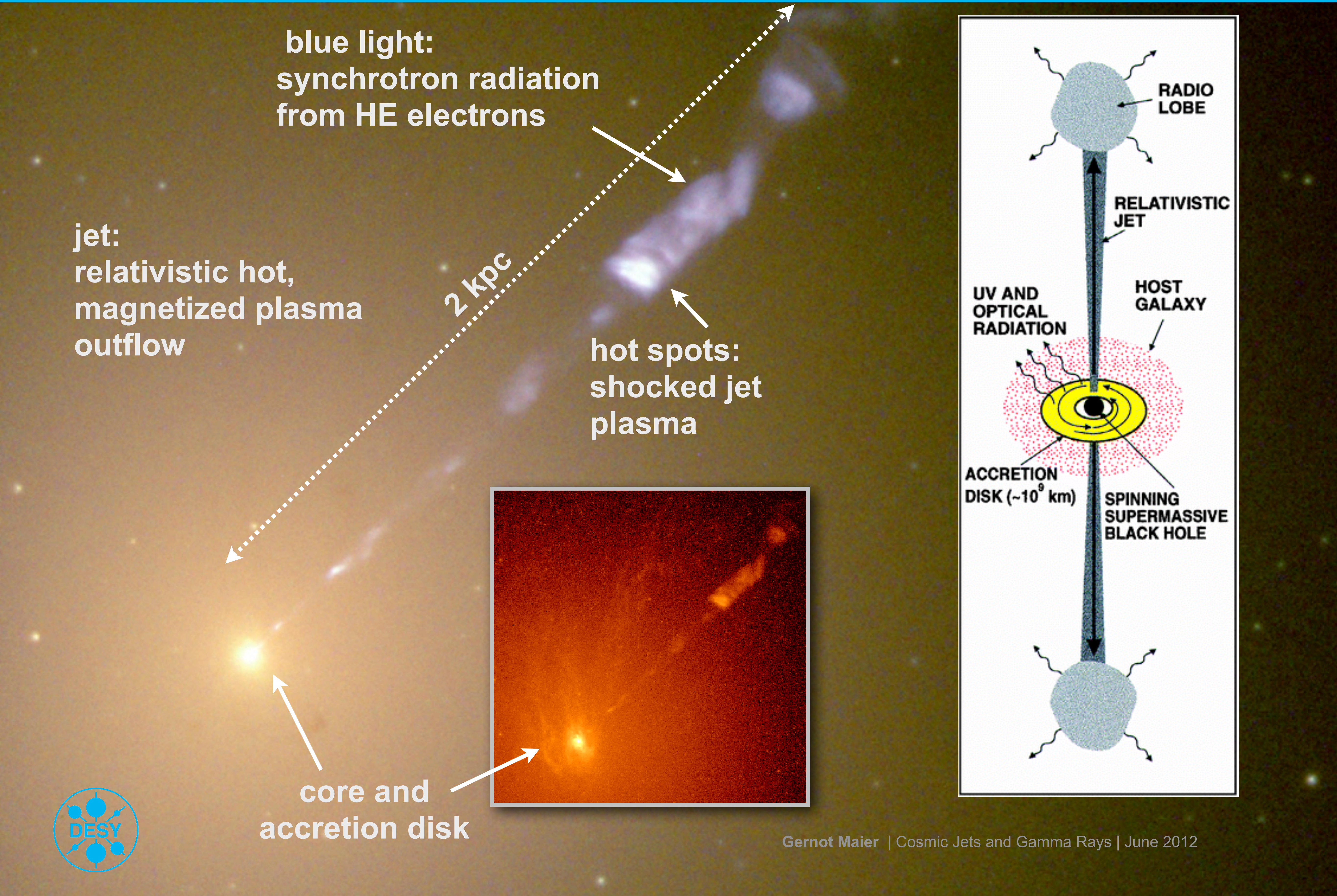


Ultra-high energy cosmic rays - 10^{20} eV



Active Galactic Nuclei

Active Galactic Nuclei



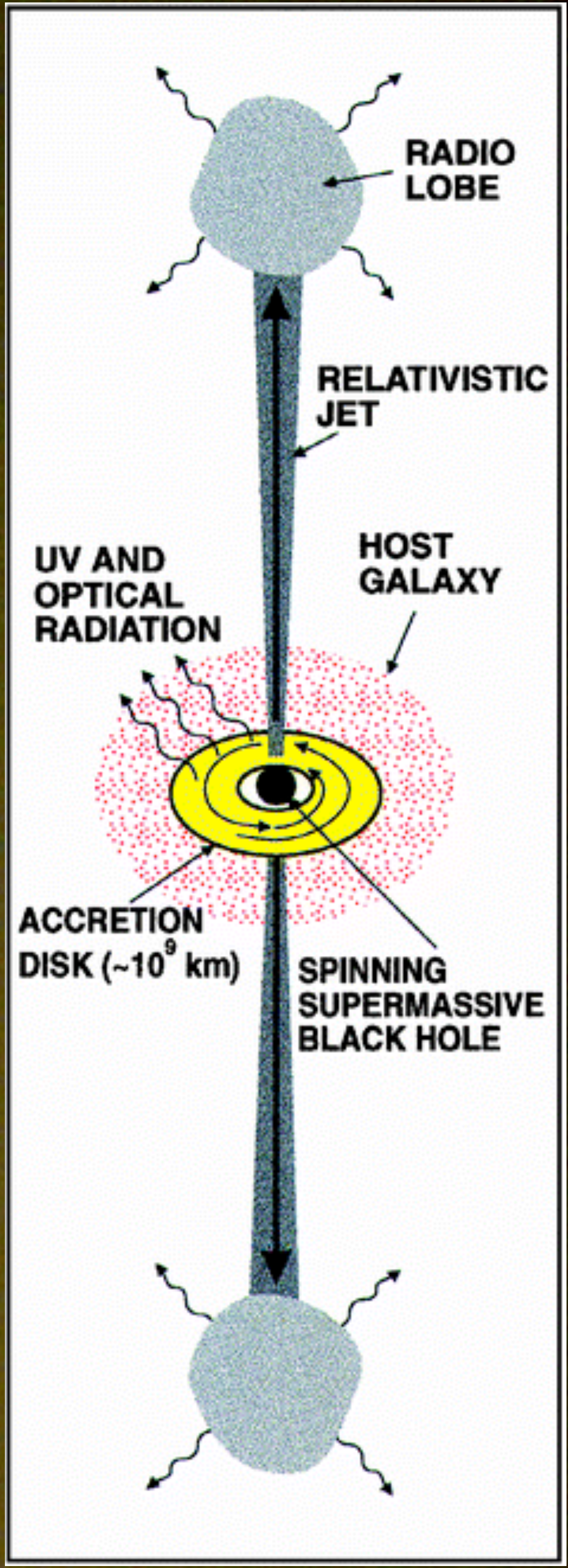
Active Galactic Nuclei: The power of accretion

Gravitational energy released :

$$\Delta E_{acc} = GMm/R_*$$

Nuclear fusion of hydrogen to helium:

$$\Delta E_{nuc} = 0.007mc^2$$



Active Galactic Nuclei: The power of accretion

1 erg = 10^{-7} J

Gravitational energy released :

$$\Delta E_{acc} = GMm/R_*$$

Neutron star with R~10 km and M~M$_\Theta$:

$$\Delta E_{acc}/m \sim 10^{20} erg/g$$

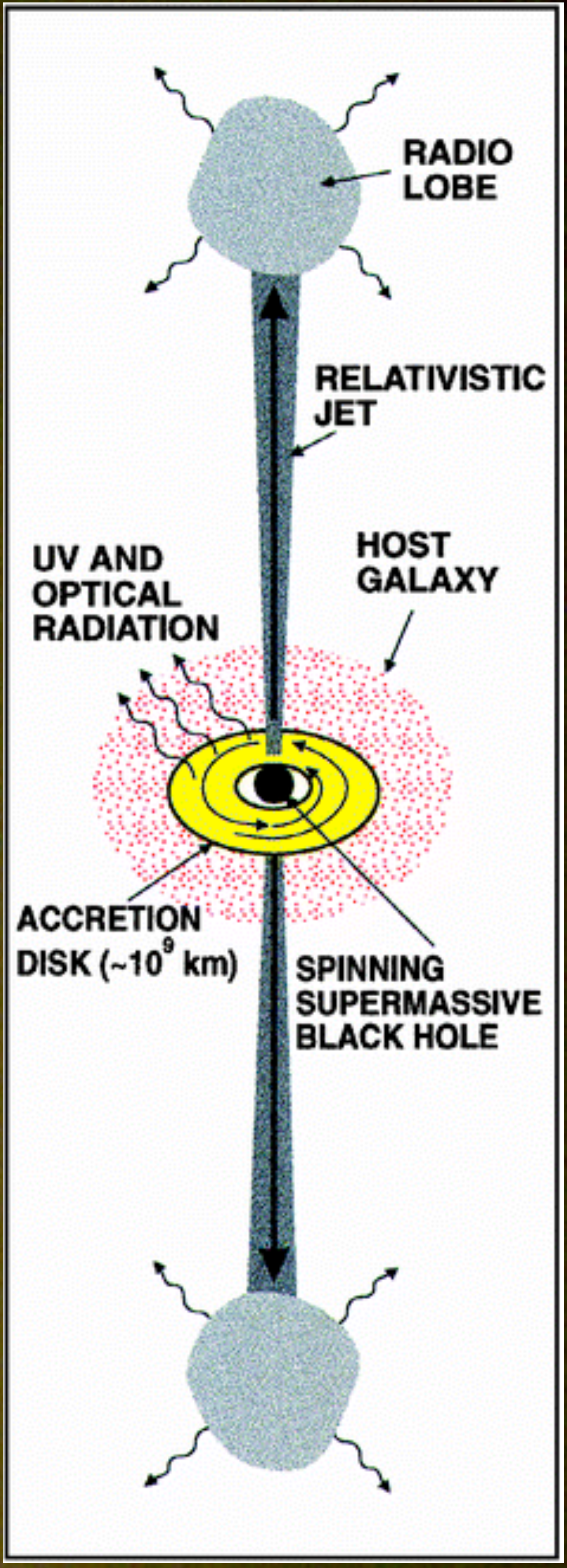
Black hole with R~6x10^9 km and M~3x10^9 M$_\theta$

$$\Delta E_{acc}/m \sim 5 \times 10^{23} erg/g$$

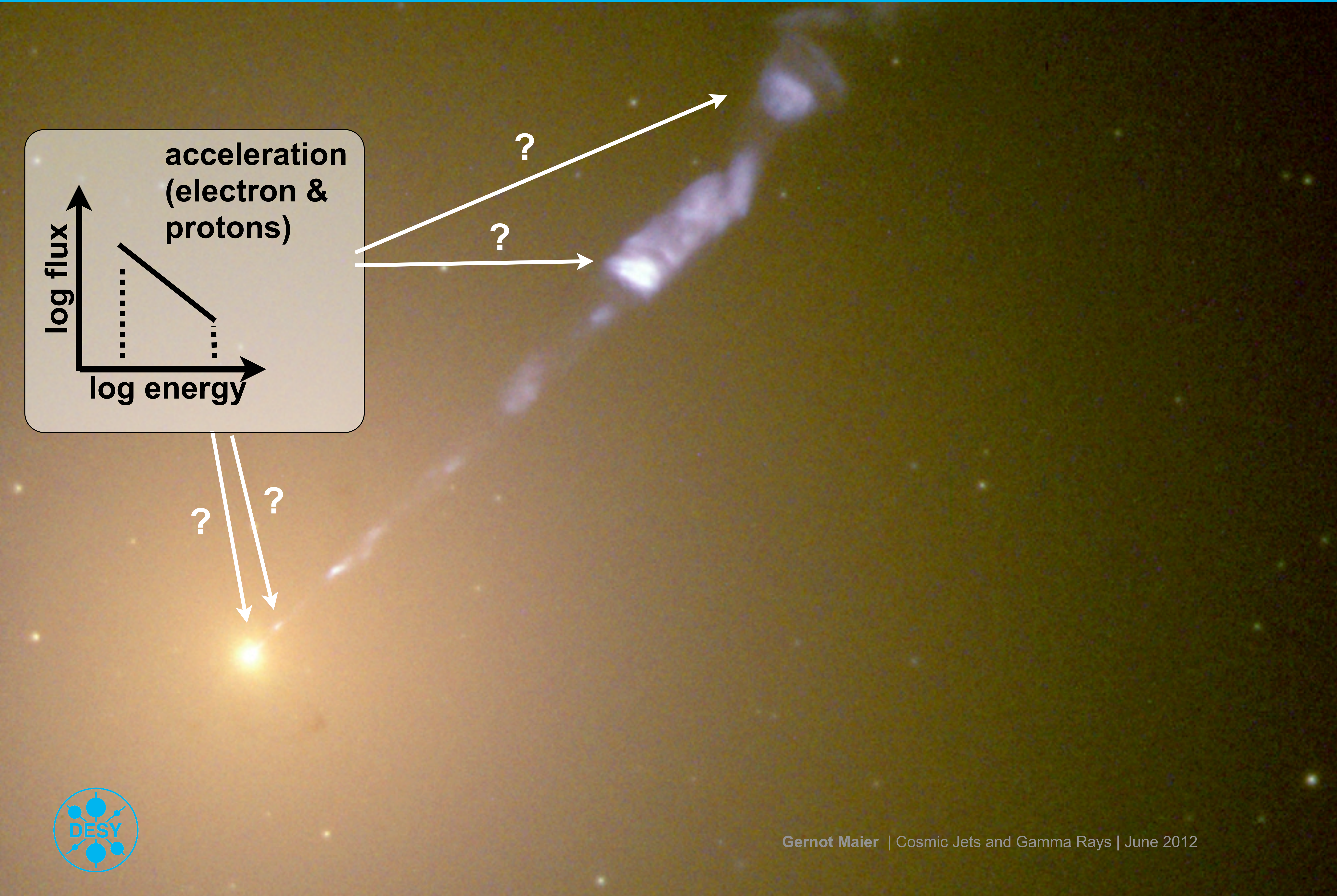
Nuclear fusion of hydrogen to helium:

$$\Delta E_{nuc} = 0.007mc^2$$

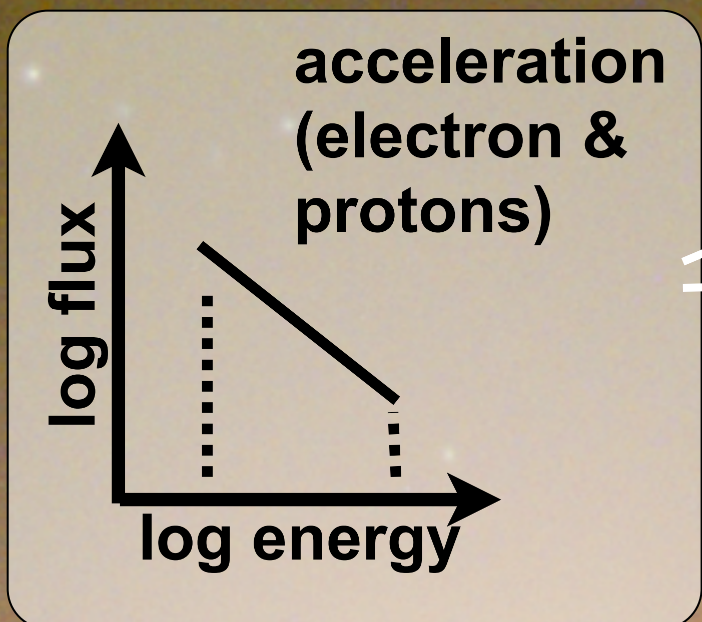
$$\Delta E_{nuc}/m \sim 6 \times 10^{18} erg/g$$



Active galactic nuclei & gamma-ray emission



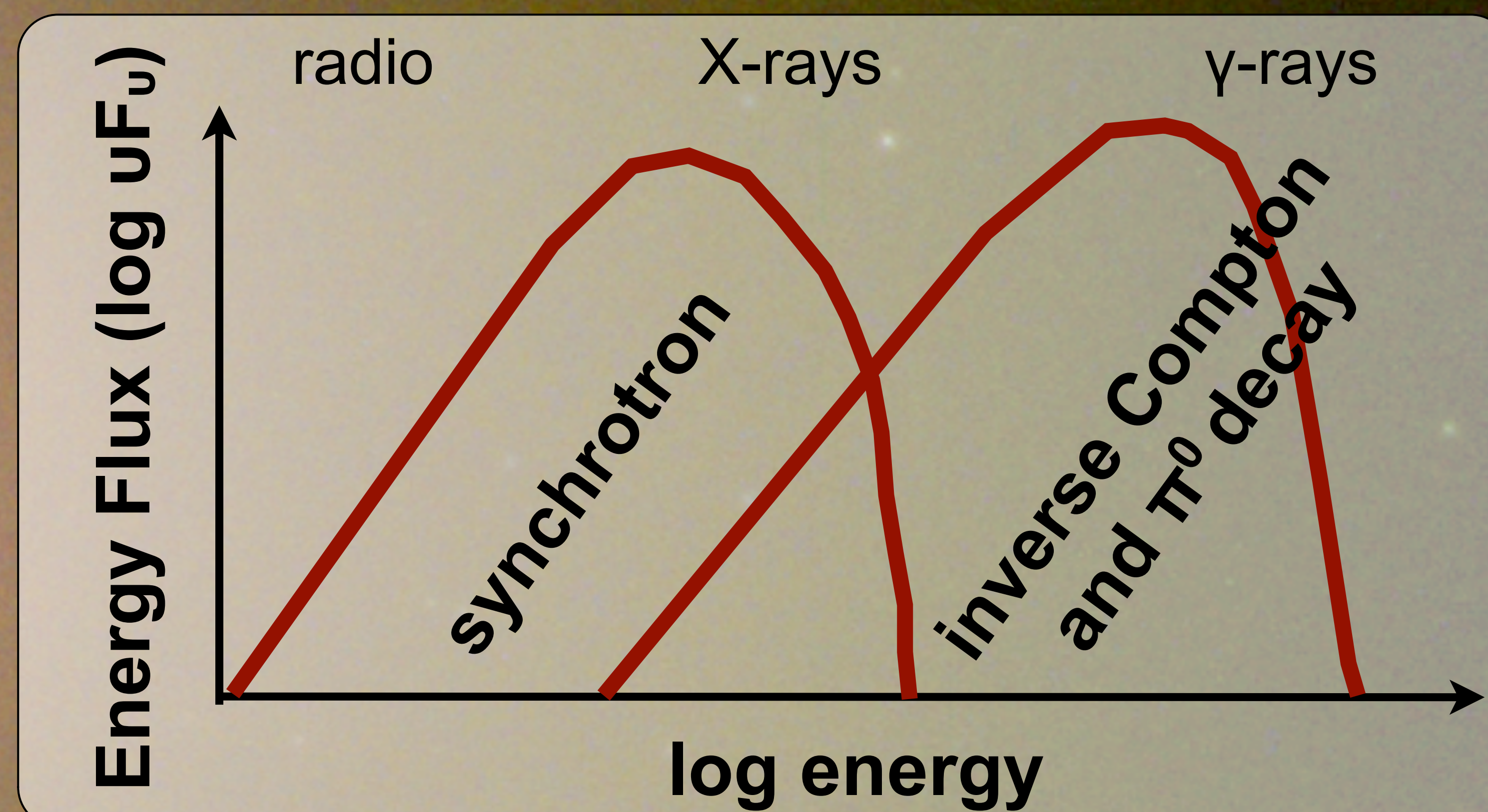
Active galactic nuclei & gamma-ray emission



Leptonic emission:
Inverse Compton emission
(synchrotron self Compton and
external Compton)

Hadronic emission:
π^0- decay; proton and
secondary μ/e-synchrotron
radiation; cascades

TeV-Blazars:
AGN seen under
small viewing angle



Doppler boosting in jets

$$D = \frac{\sqrt{1-\beta^2}}{1-\beta\cos\Theta}$$

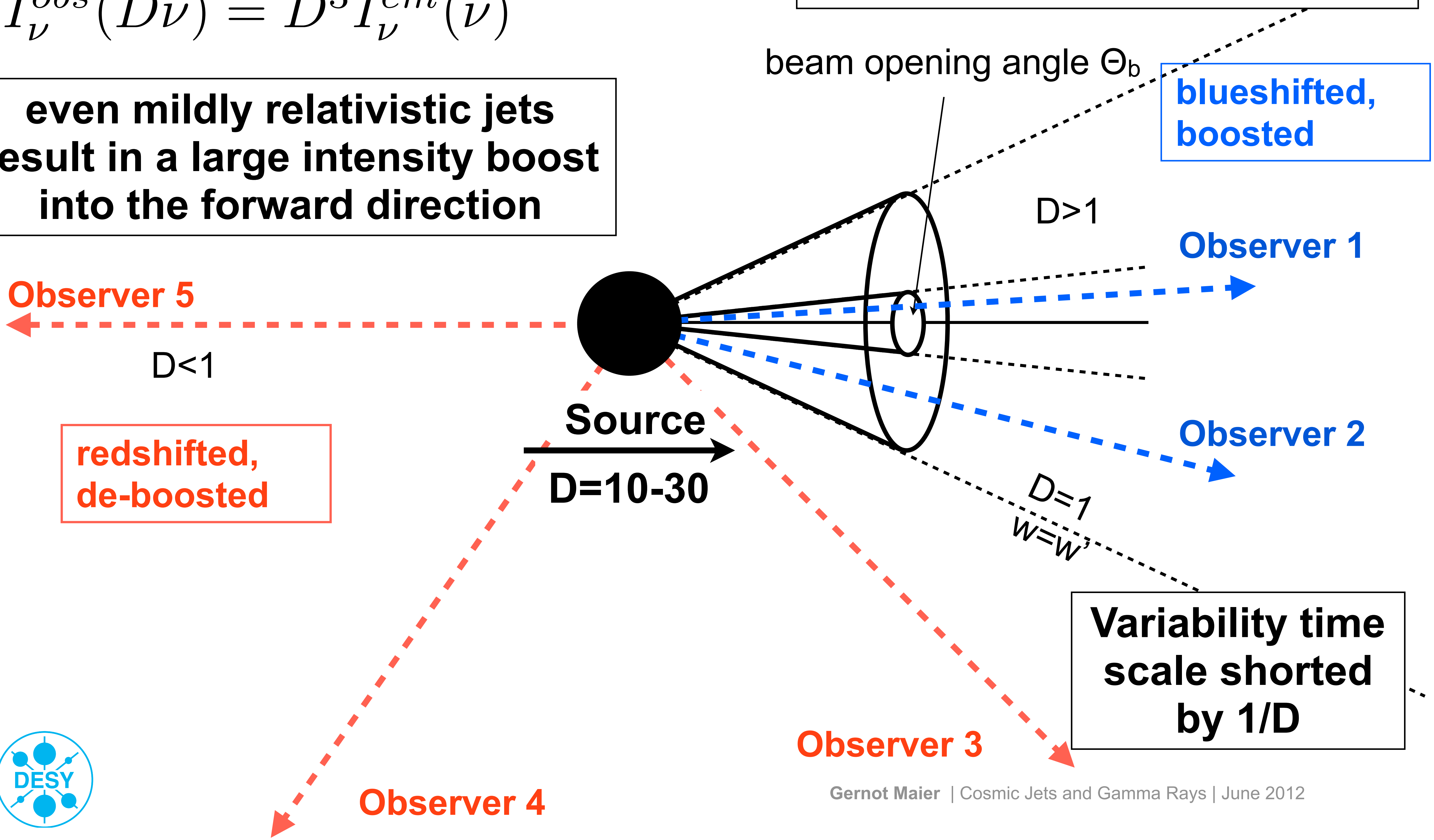
$$I_\nu^{obs}(D\nu) = D^3 I_\nu^{em}(\nu)$$

Doppler boosting of a power-law source:

$$I_\nu^{em}(\nu) \propto \nu^{-\alpha}$$

$$I_\nu^{obs} = D^{3+\alpha} I_\nu^{em}(\nu)$$

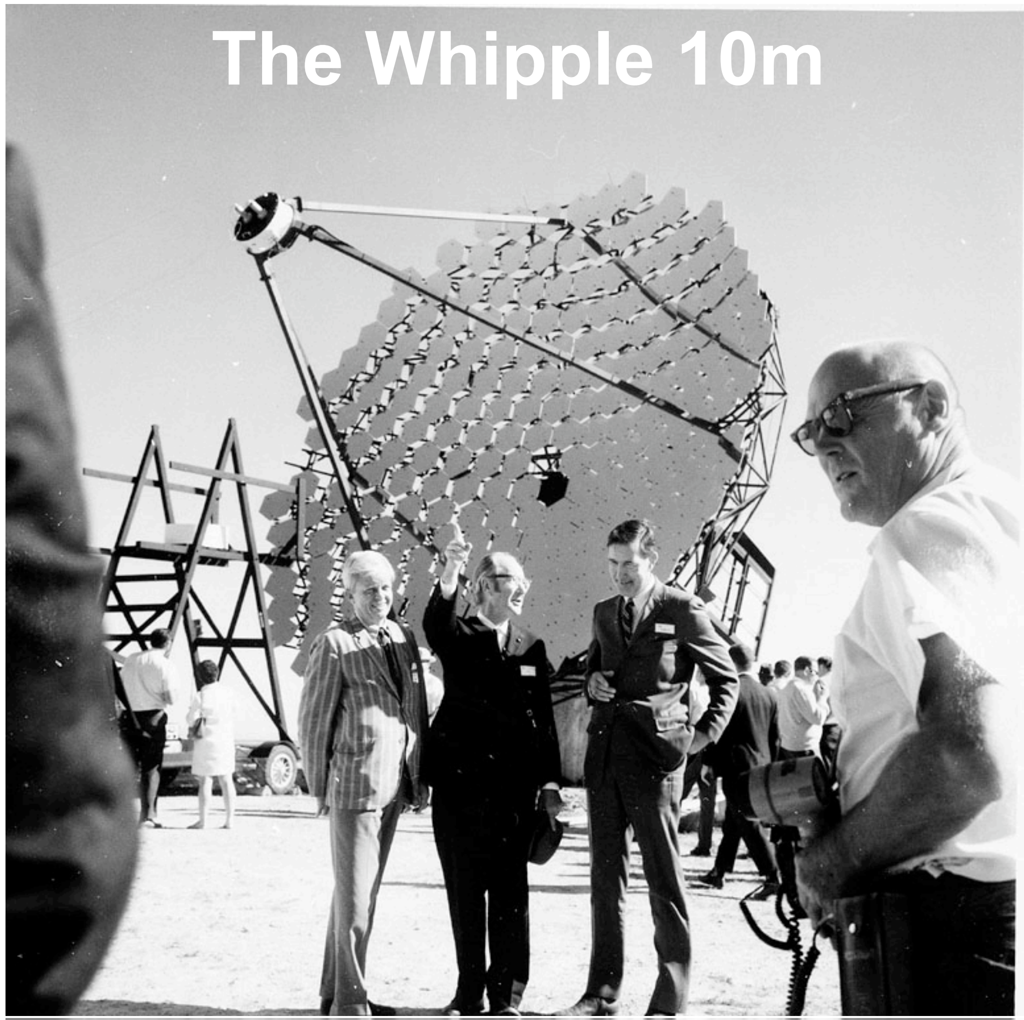
even mildly relativistic jets result in a large intensity boost into the forward direction



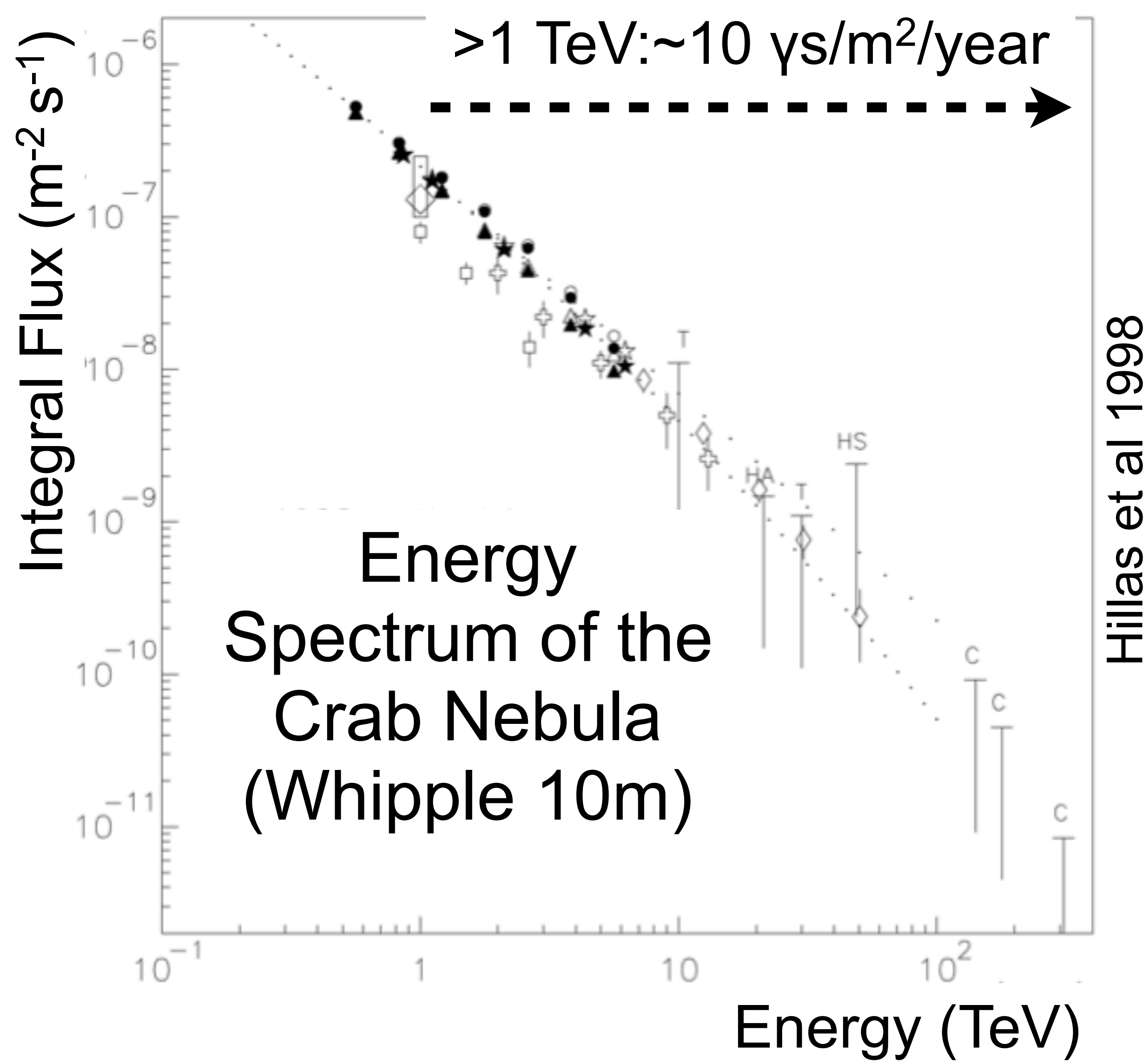
Variability time scale shorted by 1/D

Ground-based gamma-ray astronomy

The Whipple 10m

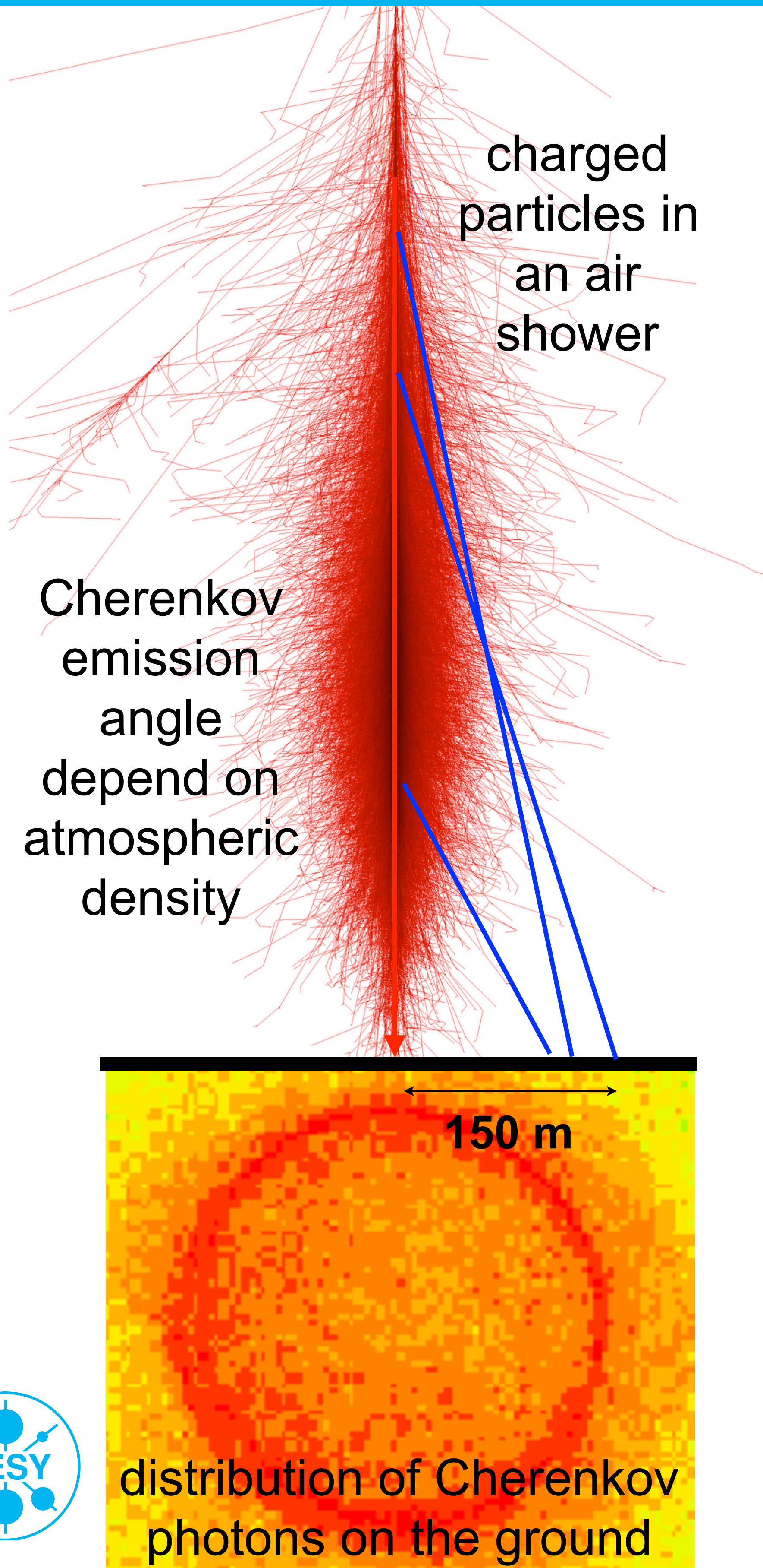


started operation in 1968
first source in 1986
retired in 2011

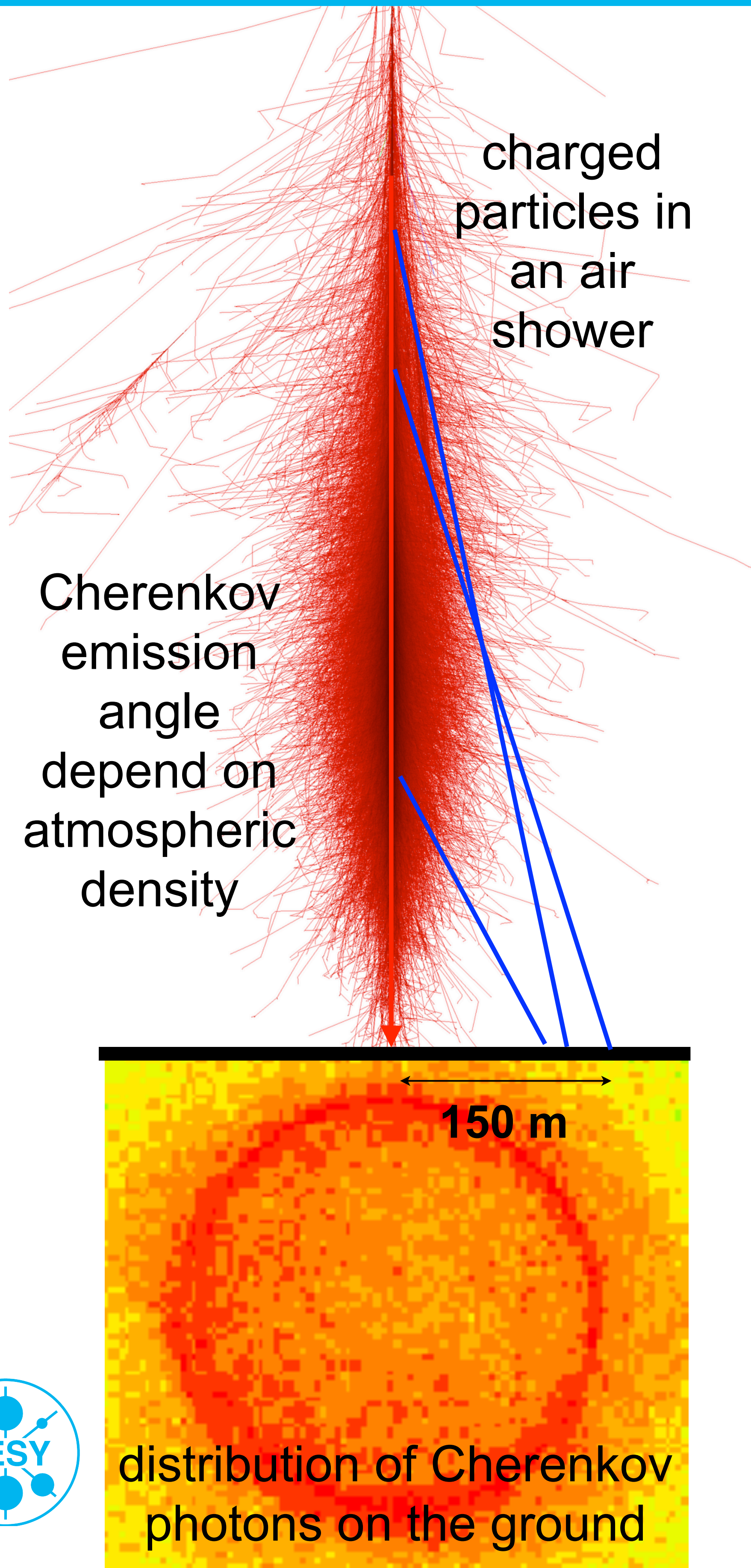


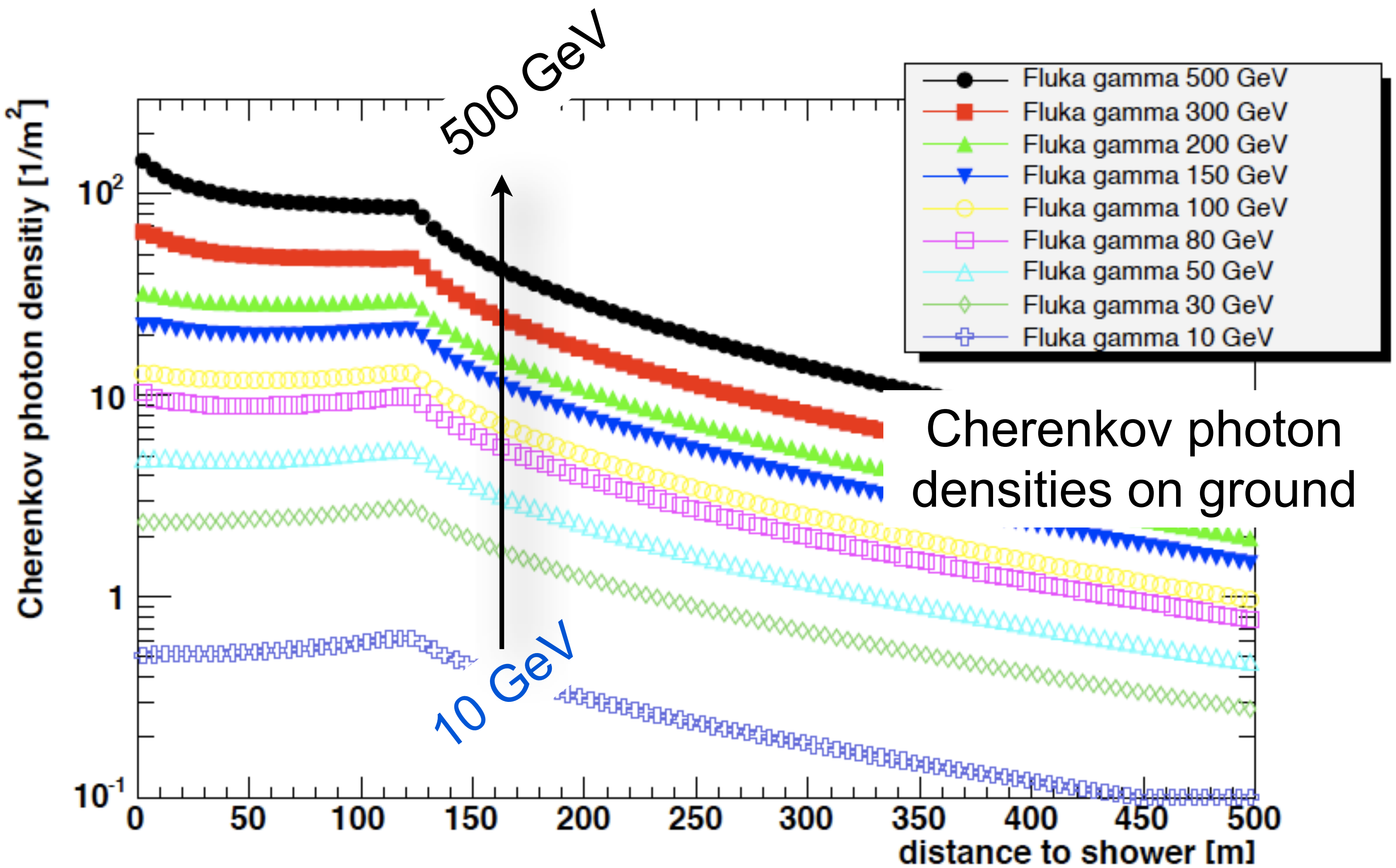
compare to flux >100 MeV: ~30 γs/m²/day

Extensive Air Showers and Cherenkov Emission



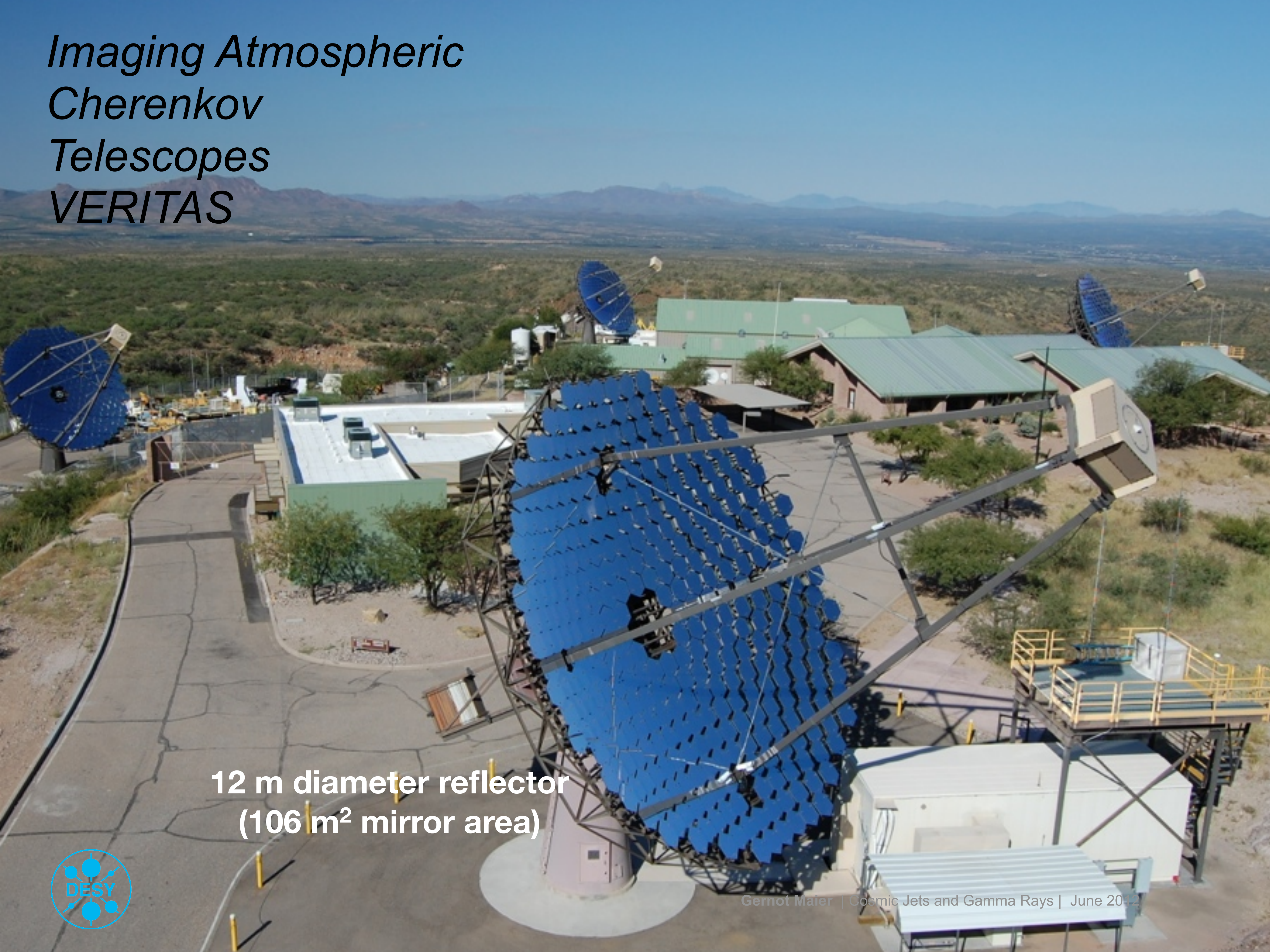
Extensive Air Showers and Cherenkov Emission



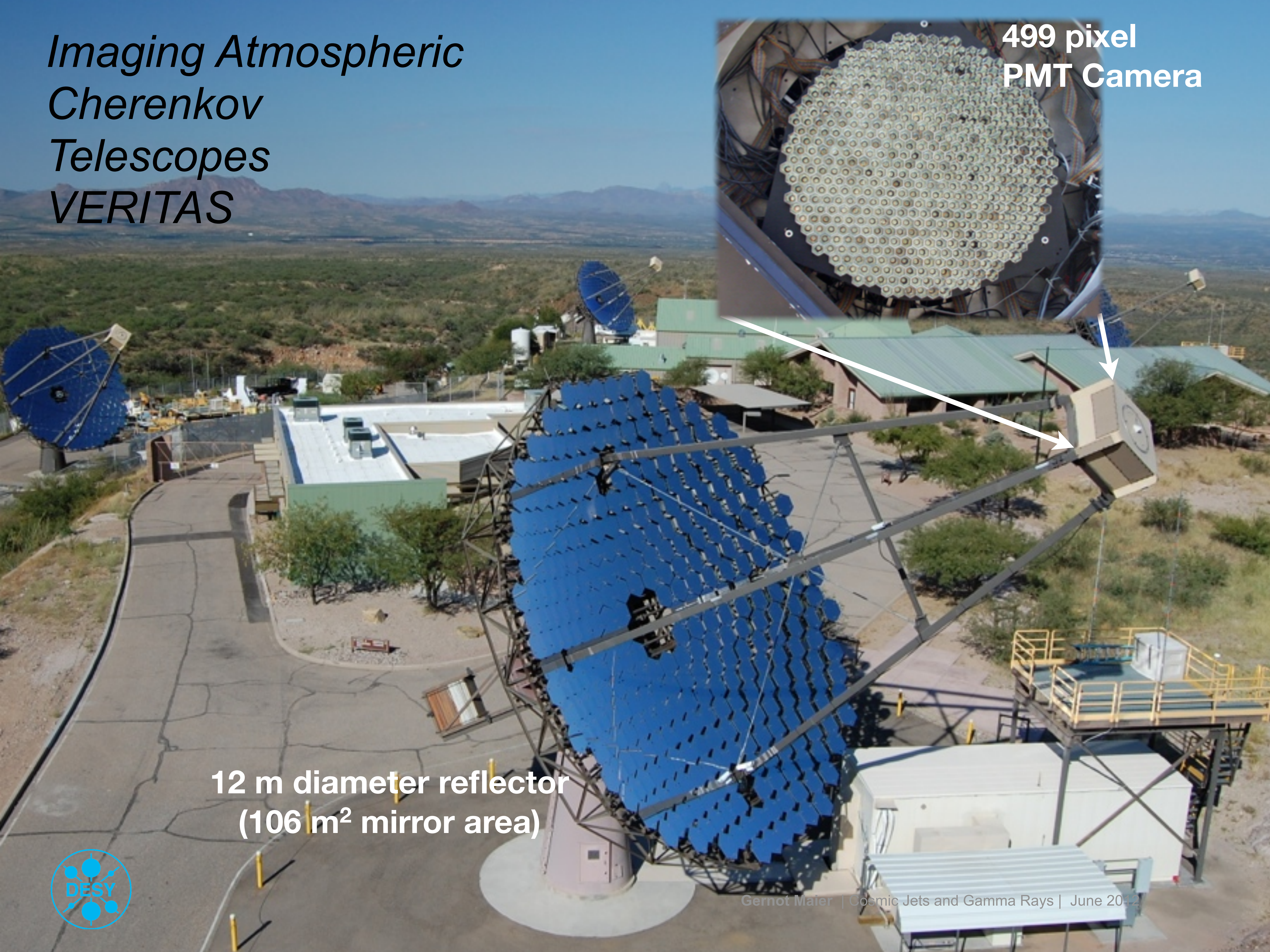


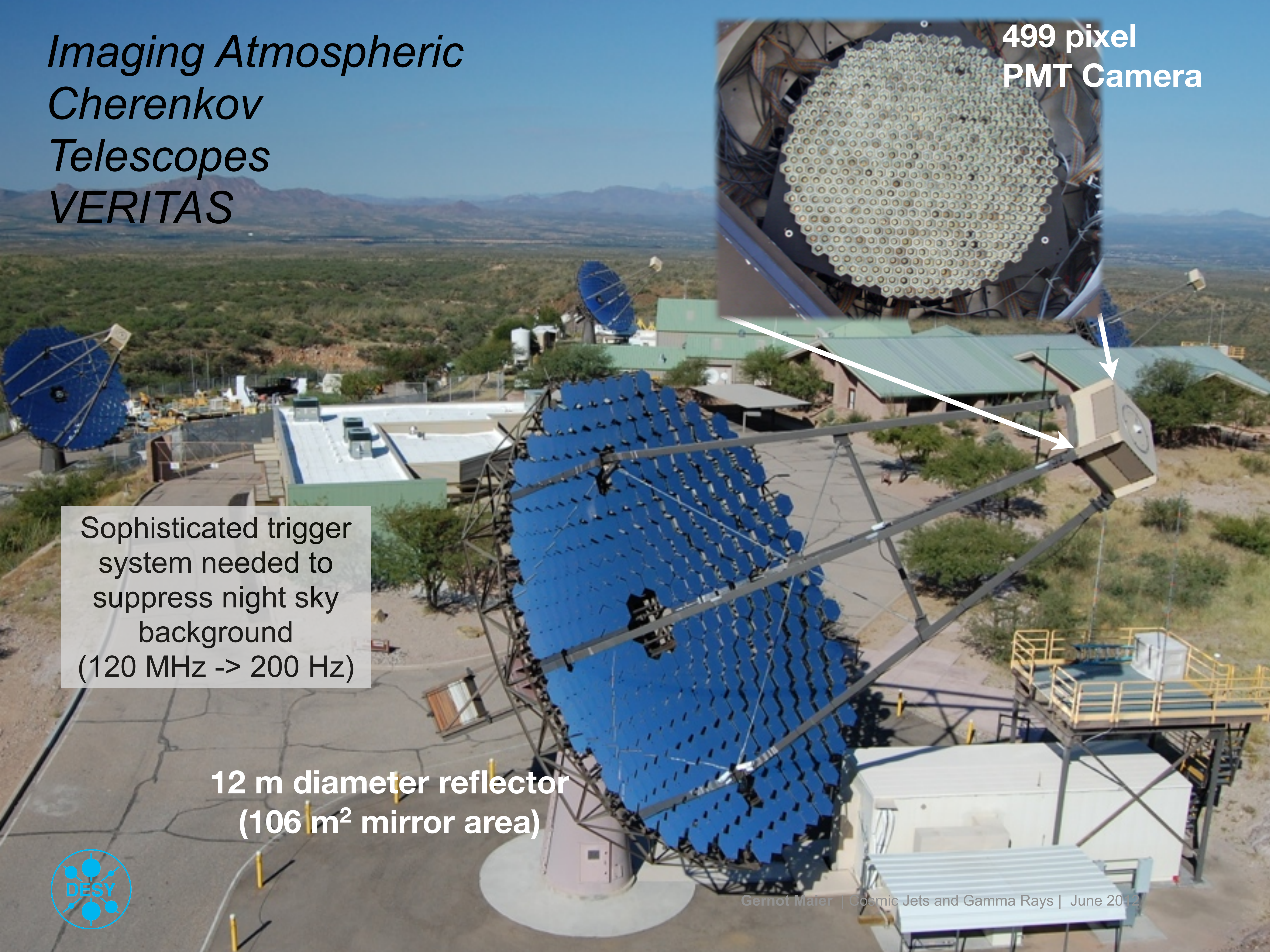
Cherenkov light from air showers:
weak (~10 ph/m²), short (~ns),
blue (300-550nm) flash of light

Imaging Atmospheric Cherenkov Telescopes VERITAS



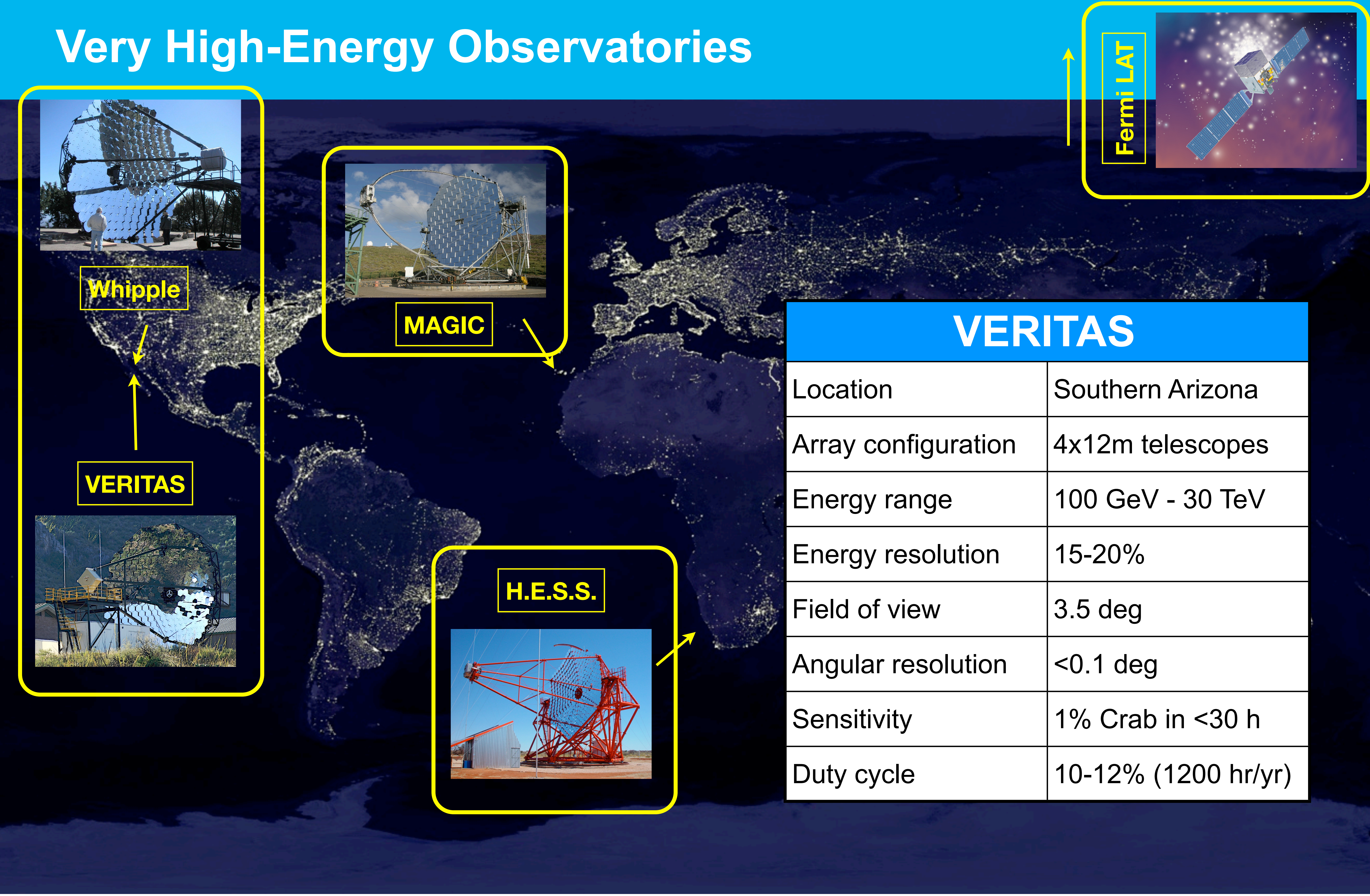
Imaging Atmospheric Cherenkov Telescopes VERITAS





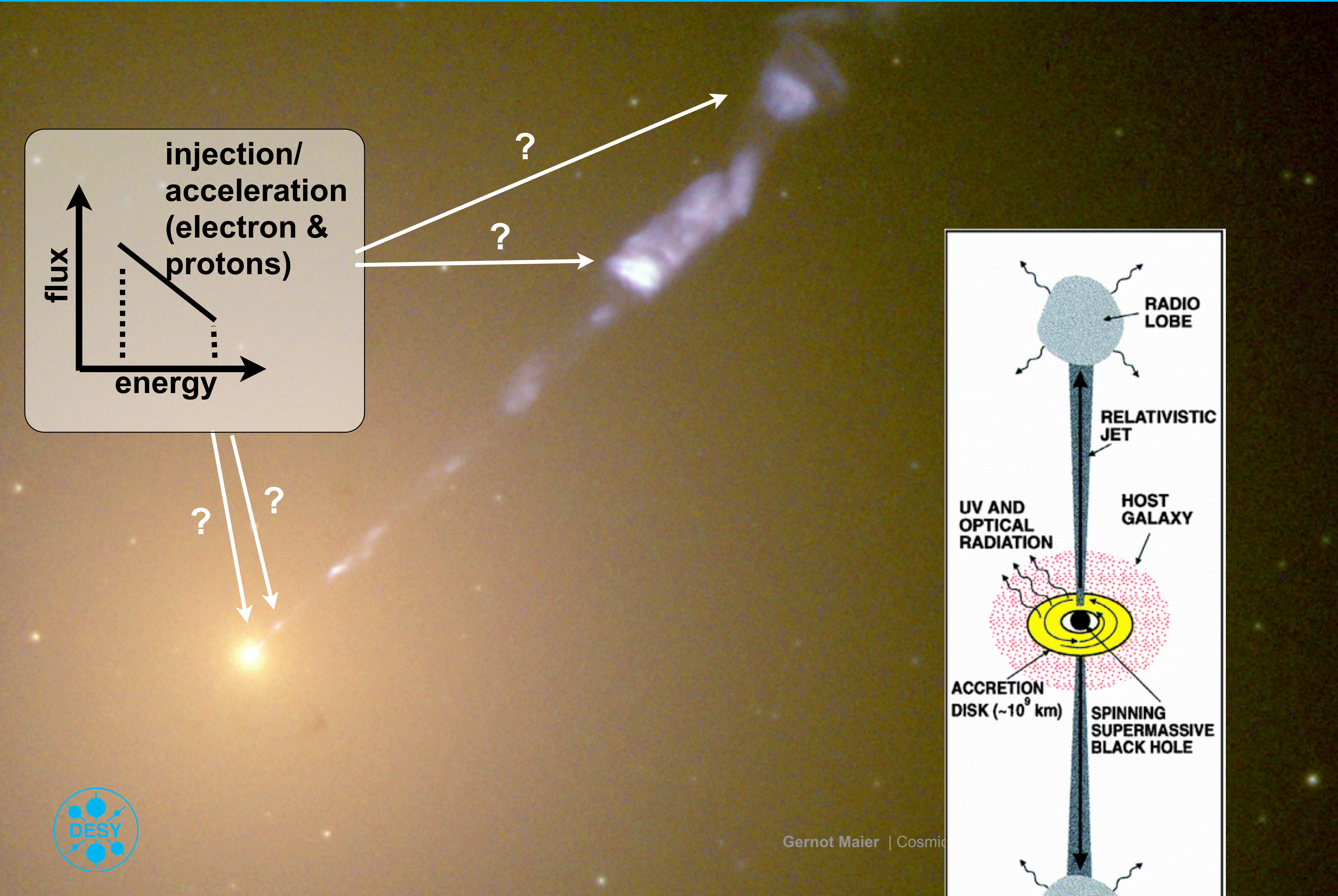
Imaging Atmospheric Cherenkov Telescopes VERITAS
499 pixel PMT Camera
Sophisticated trigger system needed to suppress night sky background (120 MHz -> 200 Hz)
12 m diameter reflector
(106 m² mirror area)
DESY

Very High-Energy Observatories



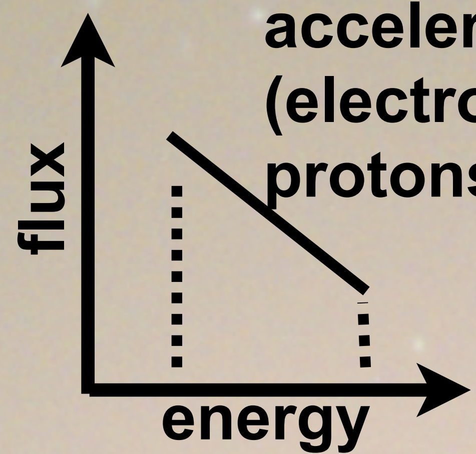
VERITAS	
Location	Southern Arizona
Array configuration	4x12m telescopes
Energy range	100 GeV - 30 TeV
Energy resolution	15-20%
Field of view	3.5 deg
Angular resolution	<0.1 deg
Sensitivity	1% Crab in <30 h
Duty cycle	10-12% (1200 hr/yr)

Acceleration: related to accretion or ejection?



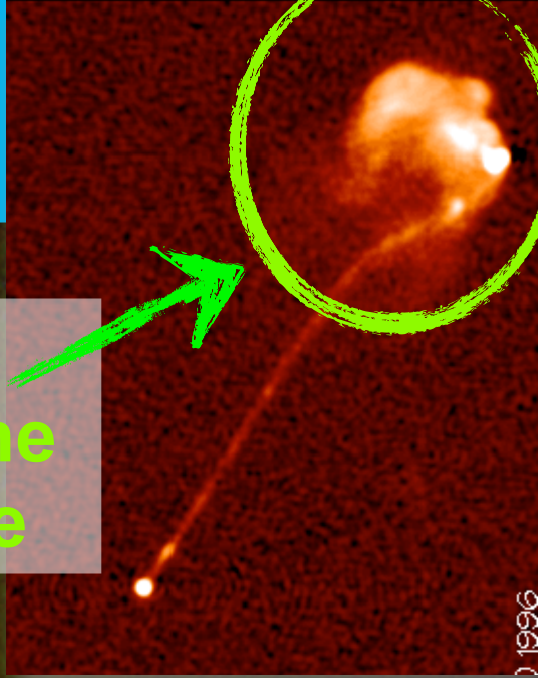
Acceleration: related to accretion or ejection?

injection/ acceleration (electron & protons)



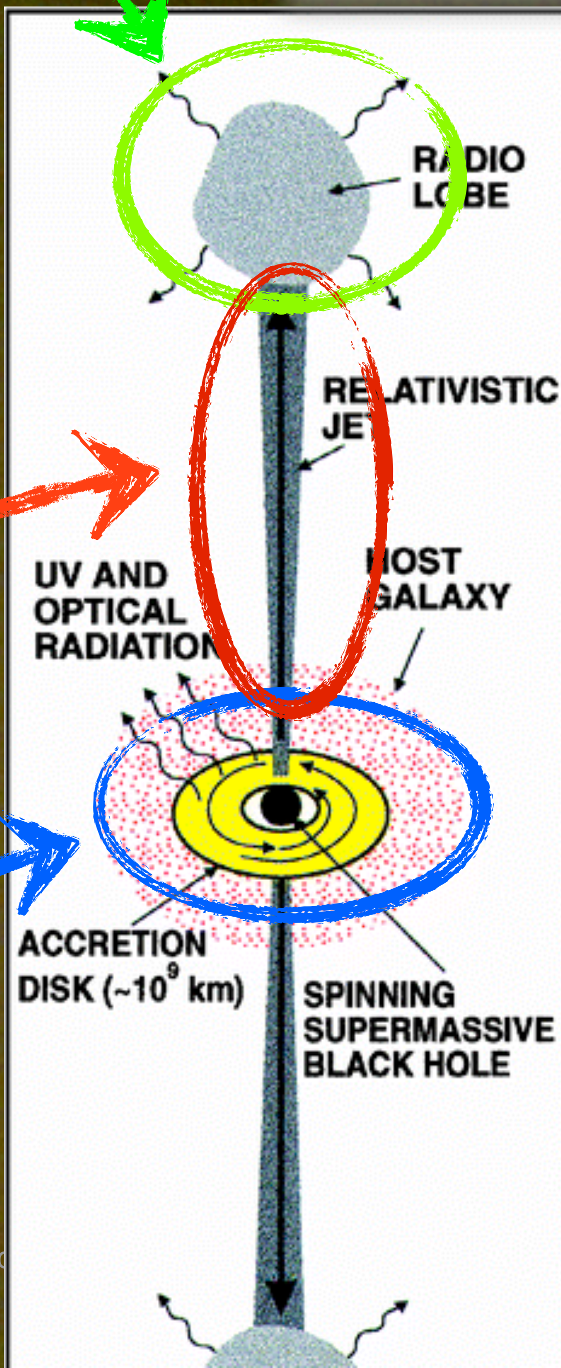
?
?
?
?

Fermi shock acceleration in the termination zone

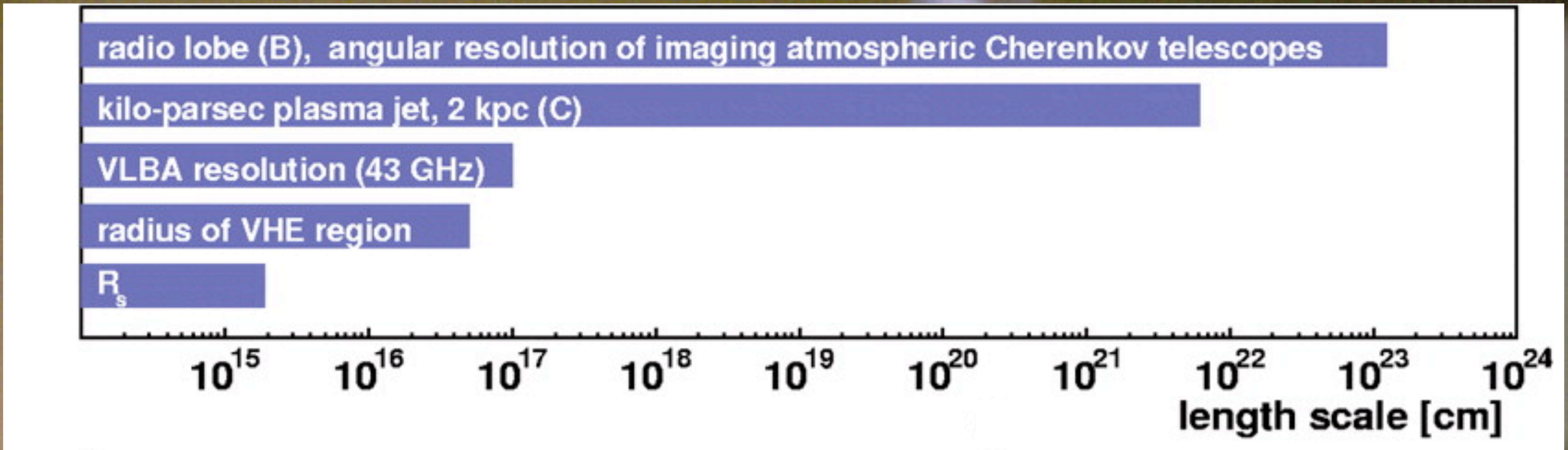


Fermi acceleration in shocks and turbulences along the jet

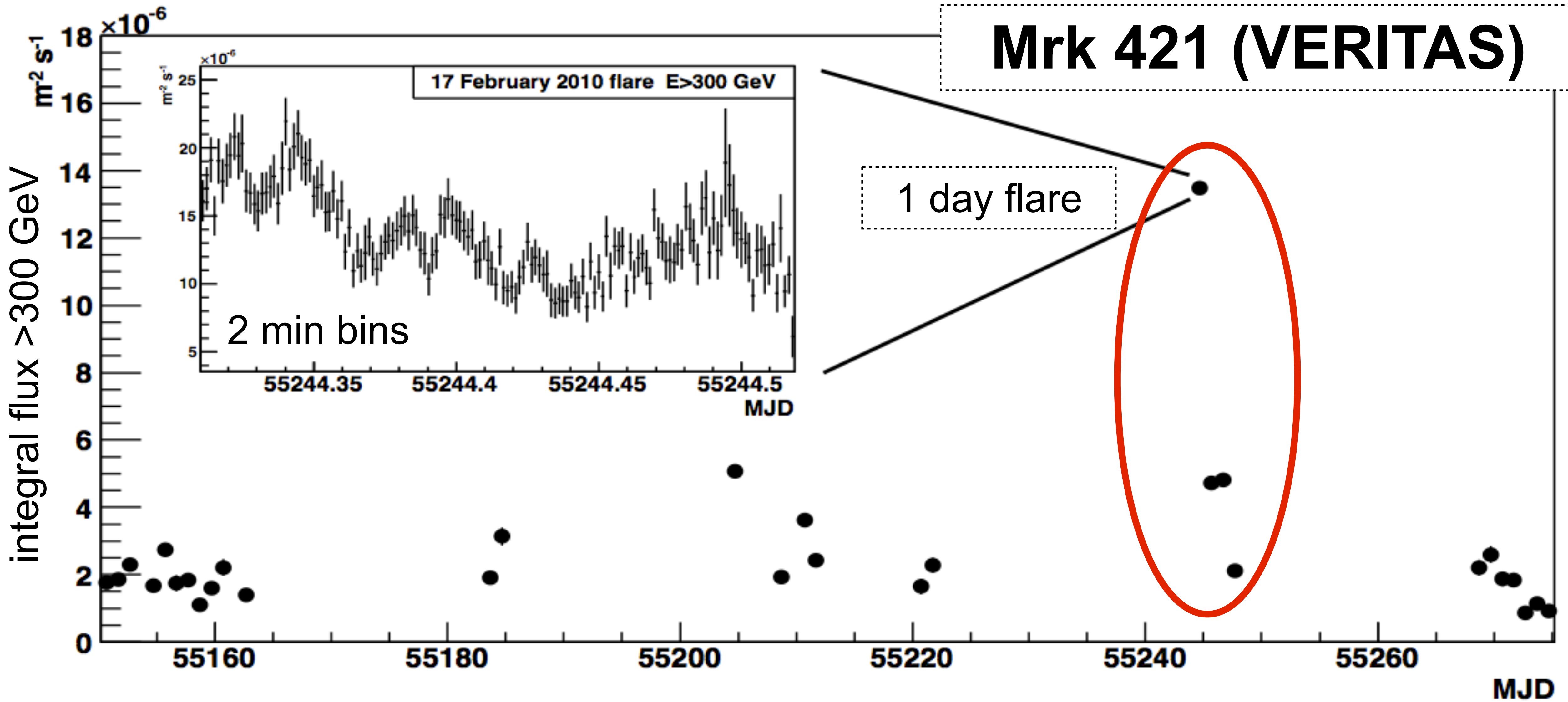
acceleration close to rotating compact object



Acceleration: related to accretion or ejection?



Variability: related to accretion or ejection?



> jet (e.g. turbulences, "jets-in-a-jet")

> accretion

Causality argument:

$$R \leq c t_{var} \delta$$

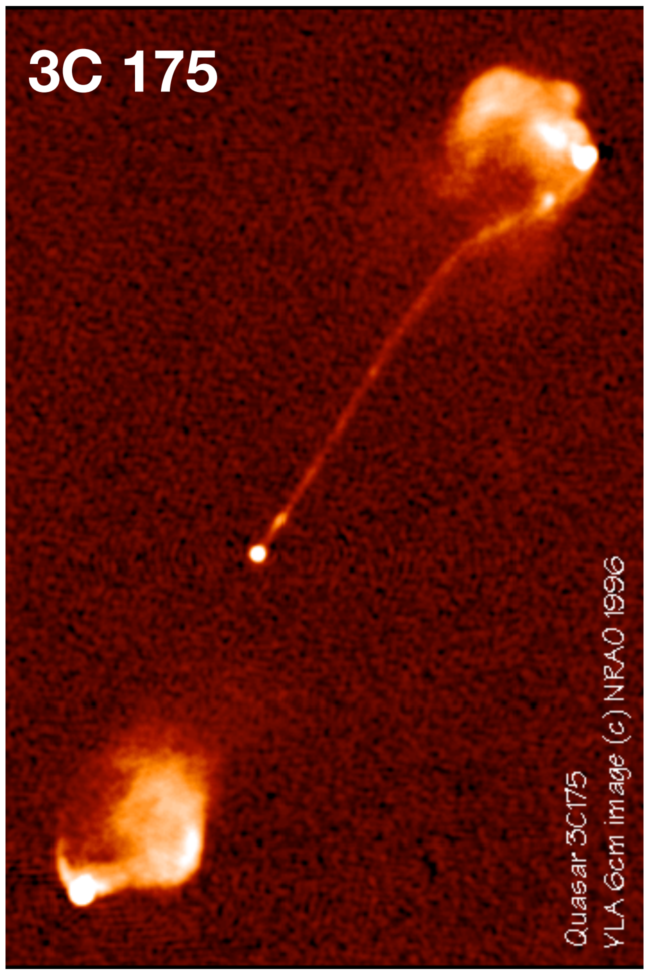
Doppler factor

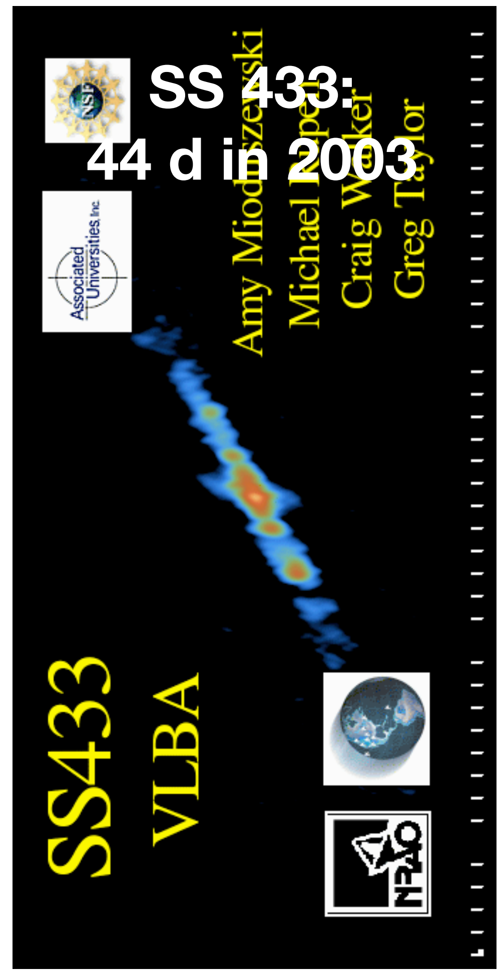
$$\delta = \frac{1}{\gamma(1-\beta\cos\Theta)}$$

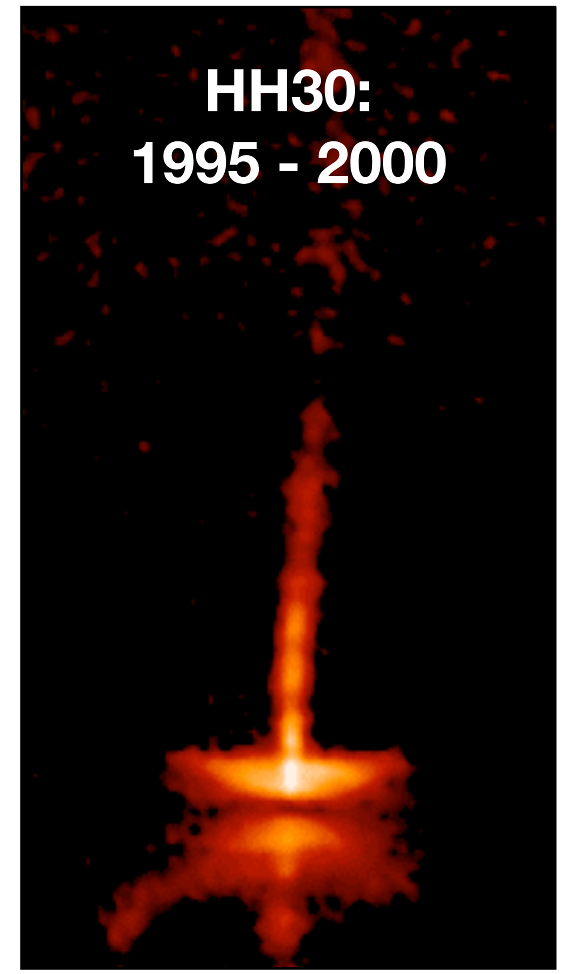
see as well variability observed in PKS 2155-304, Mrk 501, ...

Jets on all scales: universal mechanism?

key features: central compact object, an accretion disk, a jet, non-thermal particle population, V_{jet}/V_{escape}~1







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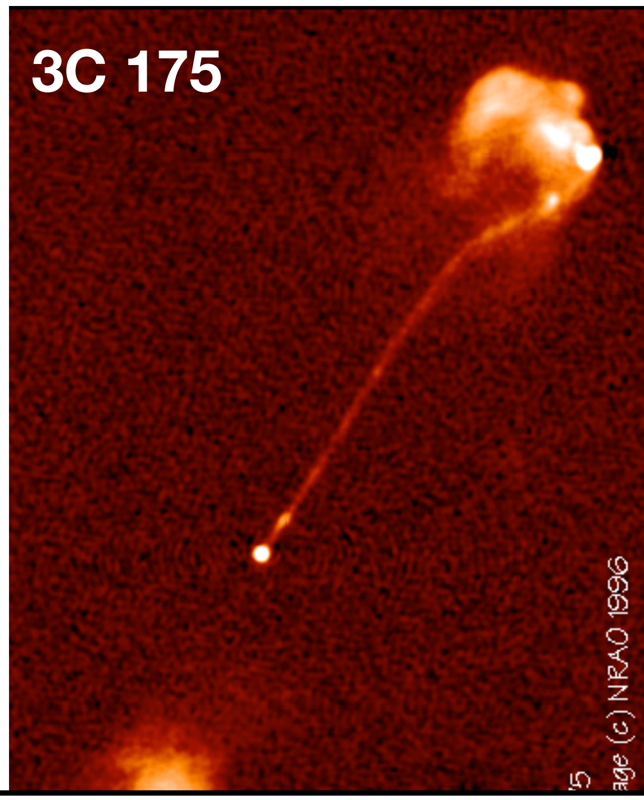
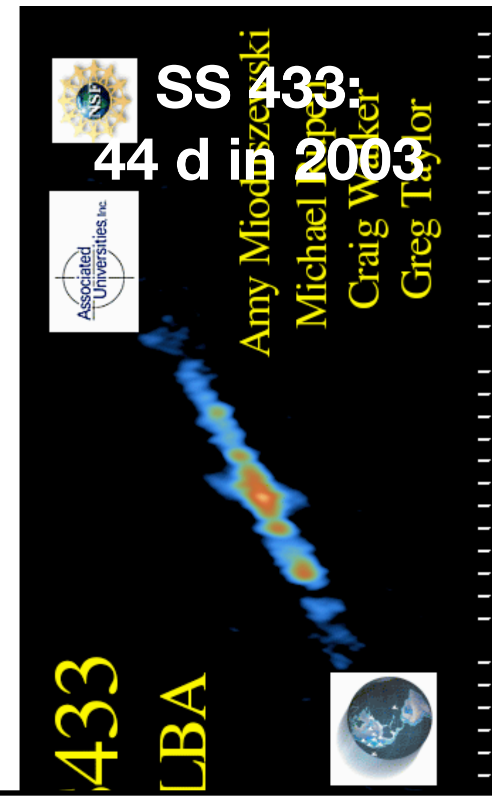
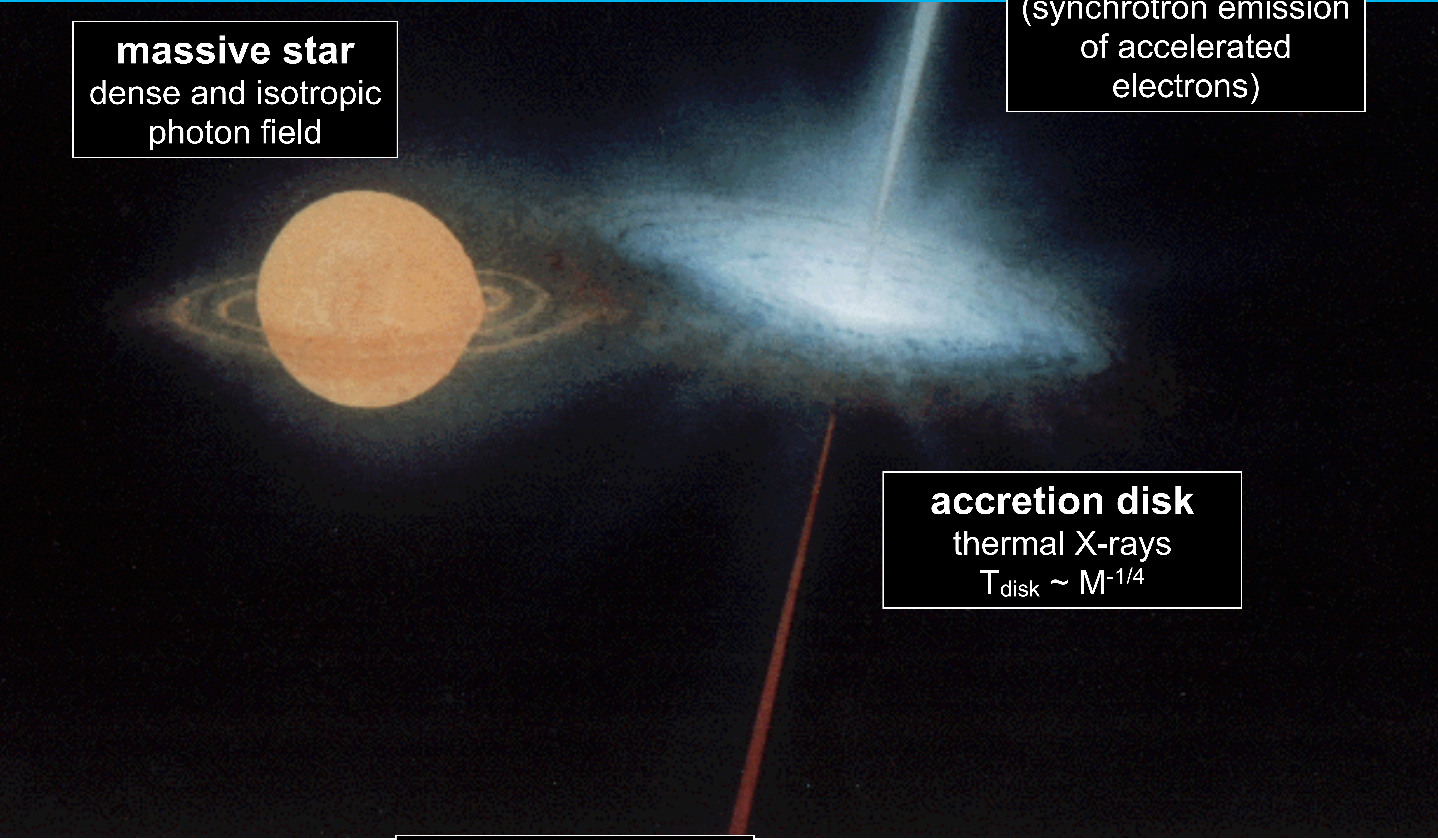




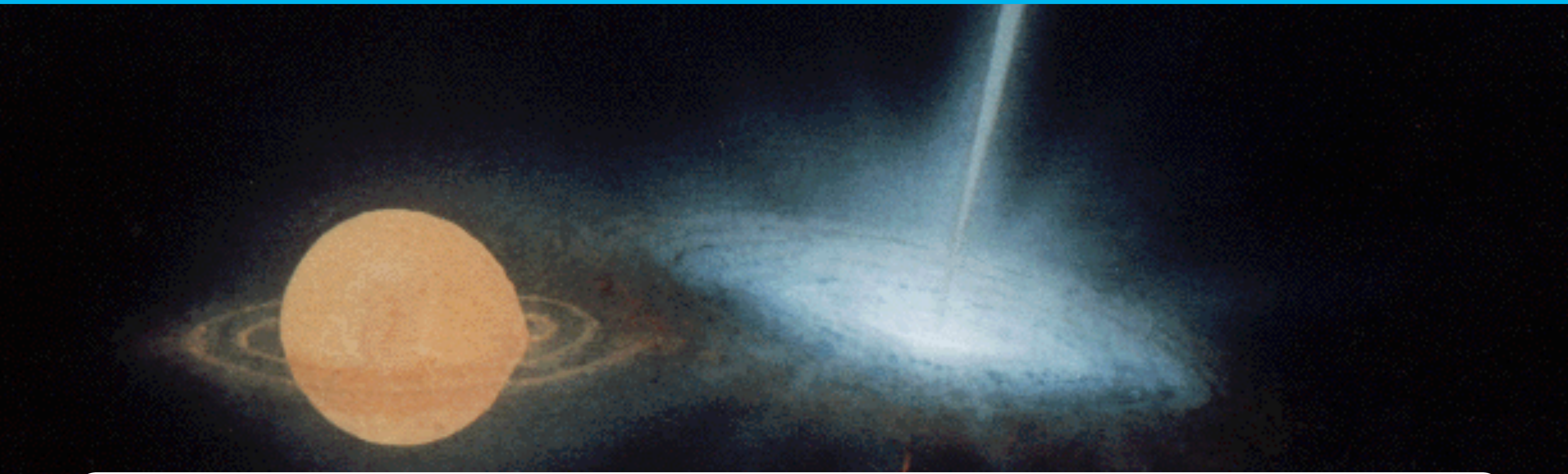
Object	AGN	μ–quasars	H–H	GRB
Size [pc]	$\sim 10^5$	$\lesssim 10$	$<$ a few	$\sim 10^{-5} - 10^{-1}$
Luminosity $[L_\odot]$	$10^7 - 10^{19}$	$< 10^5$	$10^1 - 10^4$	10^{21}
Central mass $[M_\odot]$	$10^6 - 10^9$	$1 - 10$	< 10	$1 - 10$
Lorentz factor $[\Gamma]$	$10 - 10^3$	> 10	$\lesssim 1.0000005$	$100 - 300$
Magnetic field [G]	~ 100	~ 100	< 200	$\sim 10^{16}$

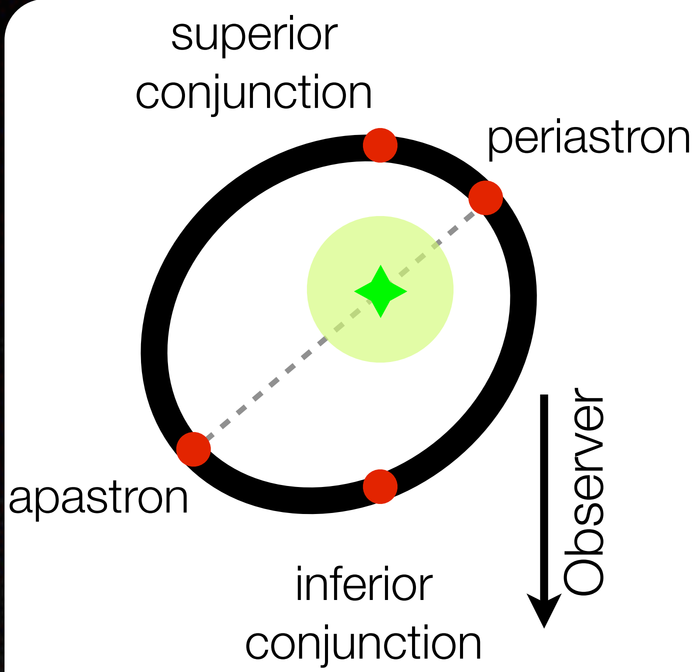
Huarte-Espinosa & Mendoza (2006)

Microquasars



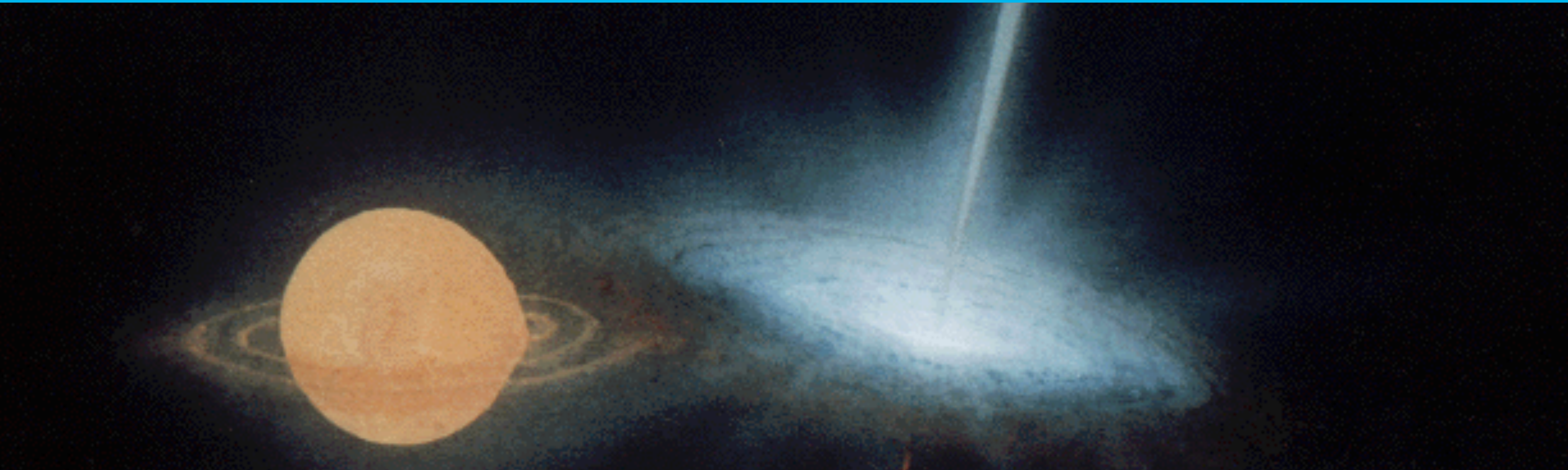
Microquasars - the nice side

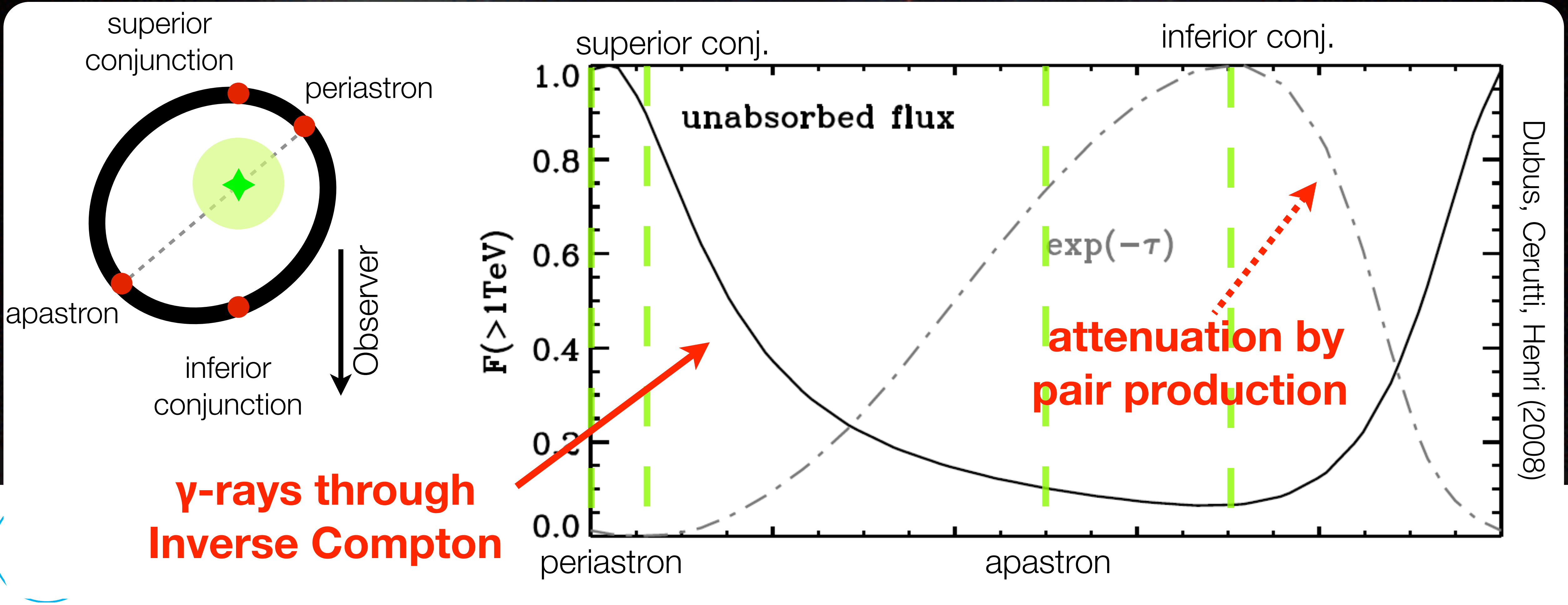




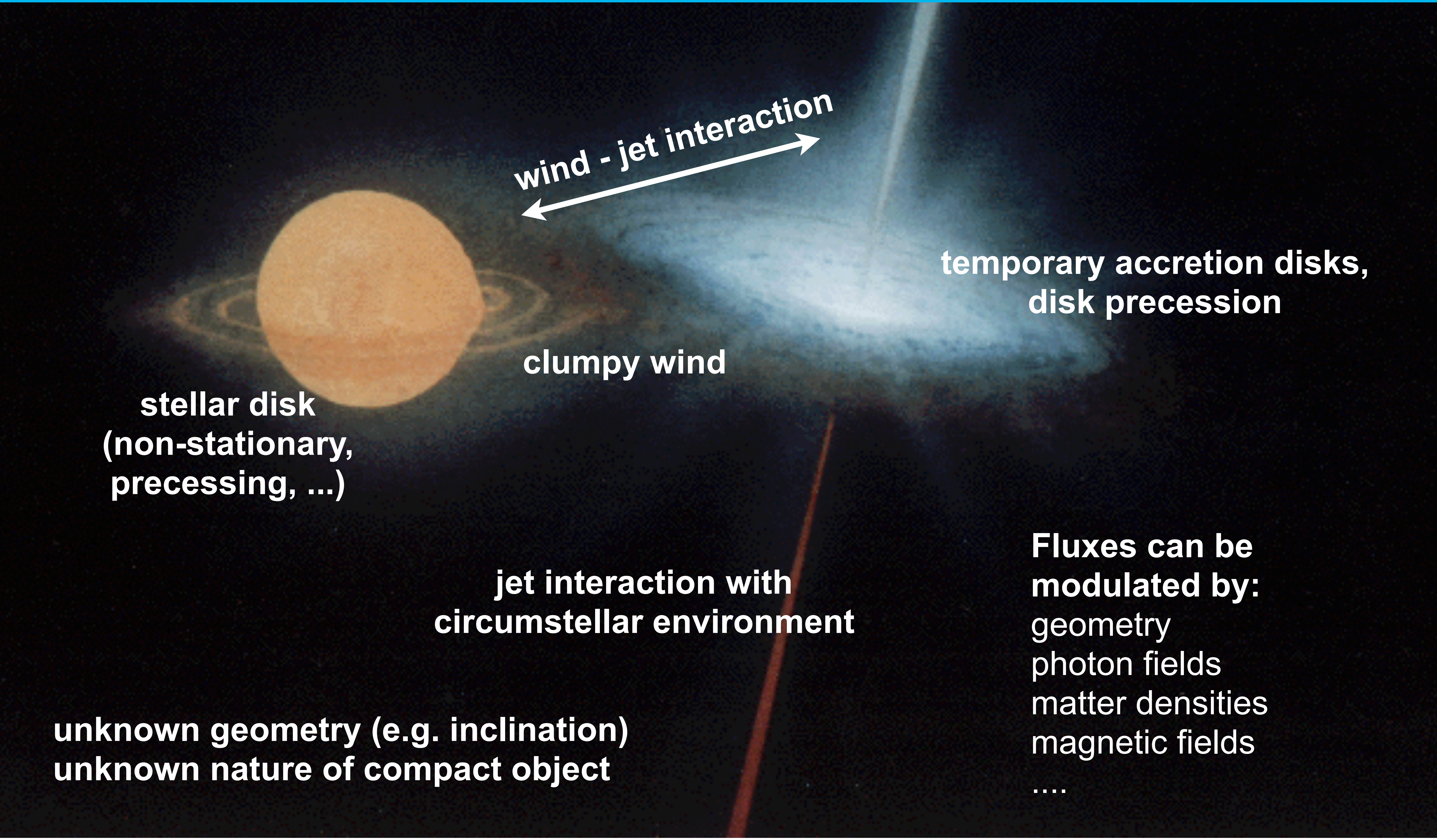
Binaries are particle accelerators operating under varying, but **regularly repeating**, environmental conditions

Microquasars - the nice side





Microquasars - the complicated side

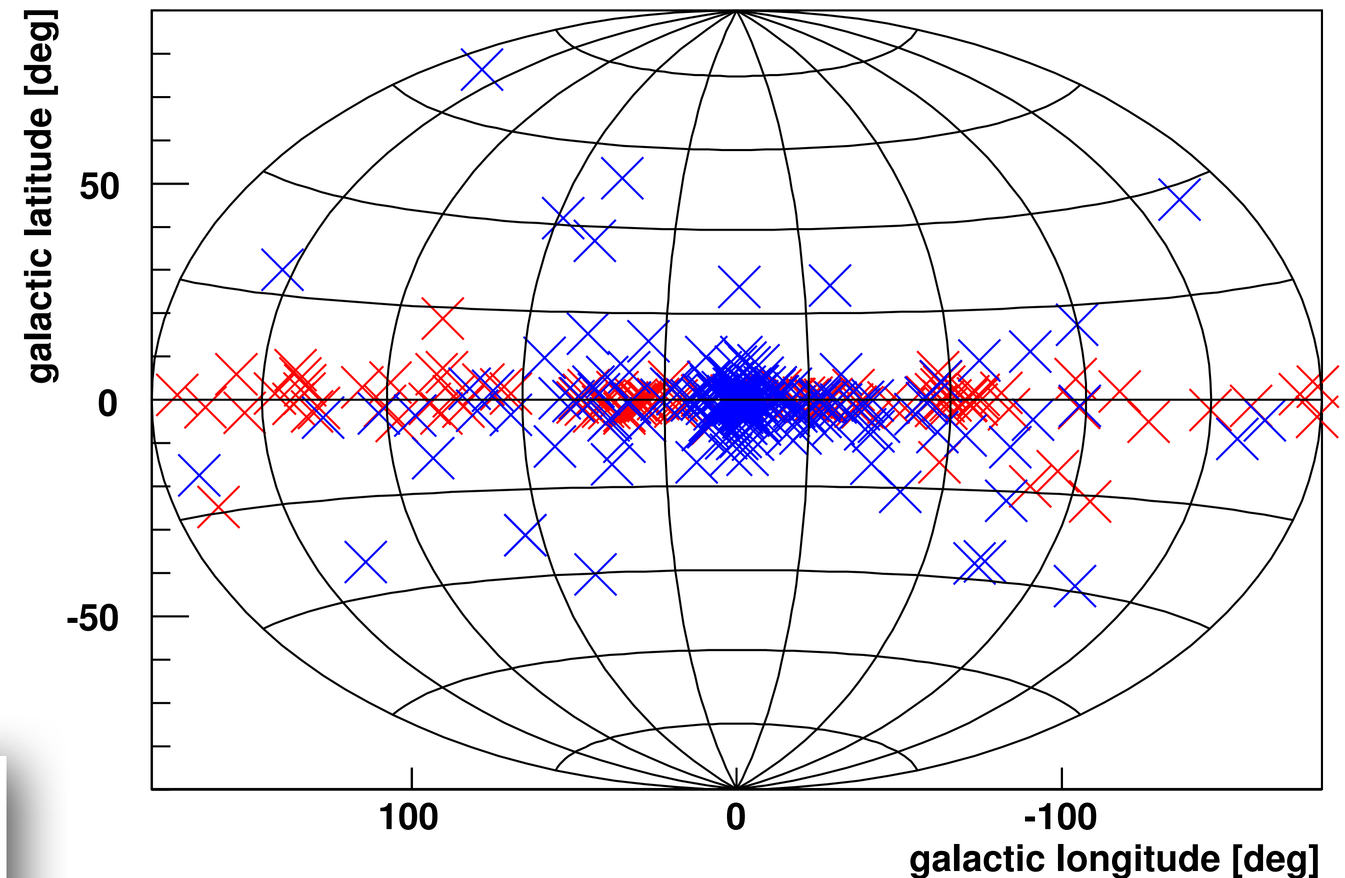


unknown geometry (e.g. inclination)
unknown nature of compact object

Fluxes can be modulated by:
geometry
photon fields
matter densities
magnetic fields
....

X-ray binaries as gamma-ray emitters

- Liu catalogues
  - 114 high-mass X-ray binaries
  - 187 low-mass X-ray binaries
- <20 microquasars known
  - identified by radio jet



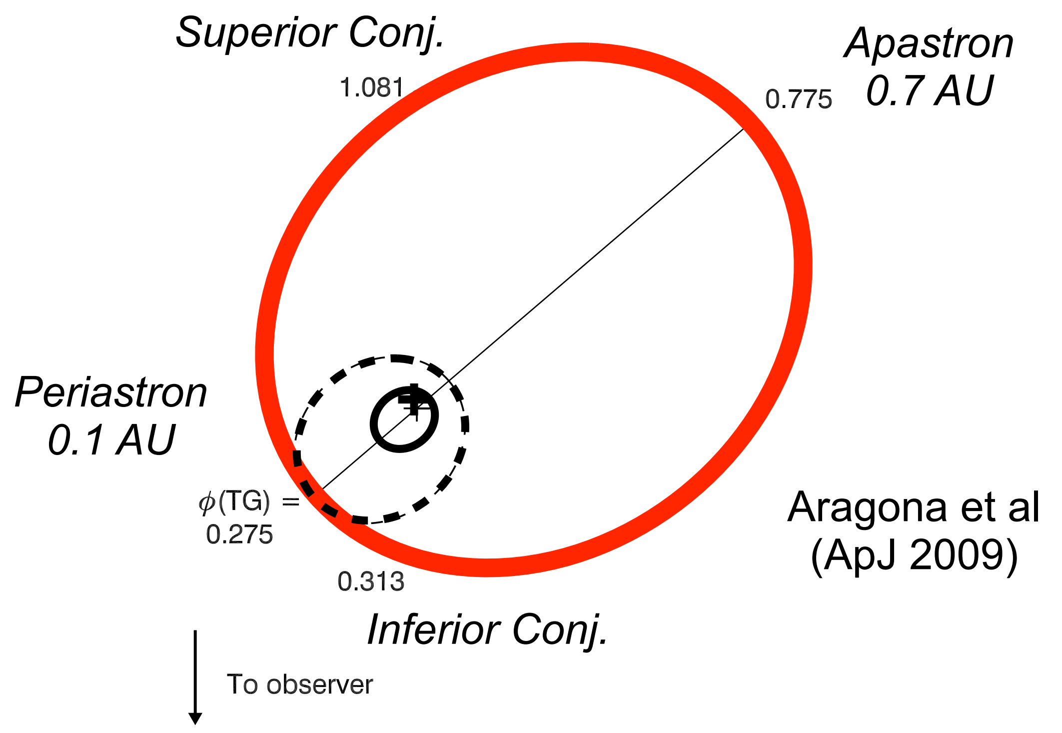
Name	Companion	Accretor	Jet size (AU)
	HMXBs		
LS I +61 303	B0V	NS/BH?	10–700
V 4641 Sgr	B9III	Black Hole	–
LS 5039	O6.5V((f))	NS/BH?	10–1000
SS 433	evolved A	NS/BH?	10^4–10^6
Cygnus X-1	O9.7Iab	Black Hole	40
Cygnus X-3	WNe	NS/BH?	10^4
	LMXBs		
Circinus X-1	Subgiant	Neutron Star	10^4
XTE J1550-564	G8-K5V	Black Hole	10^3
Scorpius X-1	Subgiant	Neutron Star	40
GRO J1655-40	F3/5IV	Black Hole	8000
GRS 1915+105	K-M III	Black Hole	10–10^4
GX 339-4		Black Hole	<4000
1E 1740.7-2942		NS/BH?	10^6
XTE J1748-288		NS/BH?	10^4
GRS 1758-258		NS/BH?	10^6

Massi & Kaufman Bernadó (2008)

Name	GeV	TeV
PSR B1259-63	✔	✔
LS 5039	✔	✔
LS I +61 303	✔	✔
LS VI +05 11(HESS J062+057)	✘	✔
Cygnus X-1	✔	(?)
Cygnus X-3	✔	✘
1FGL J1018.8-5856	✔	✘

LS I +61 303: VERITAS observations 2006-2012

Collaboration:
A.Smith, J.Holder



Aragona et al (ApJ 2009)

- Be star + neutron star or black hole
- 26.5 day orbit; unknown inclination

LS I +61 303: VERITAS observations 2006-2012

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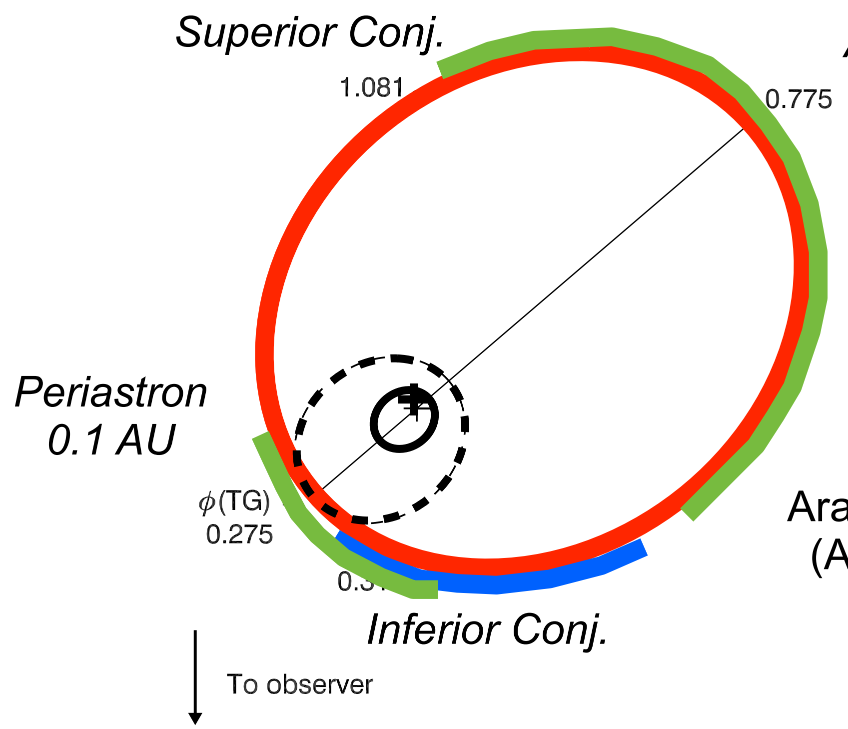

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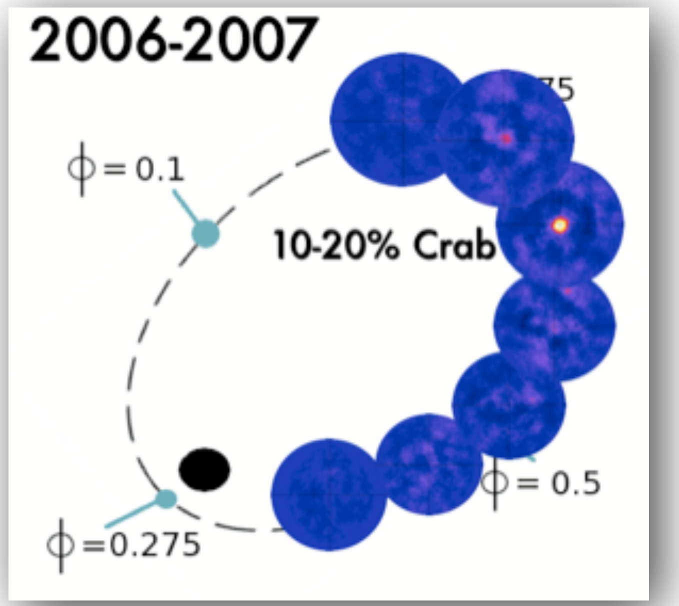
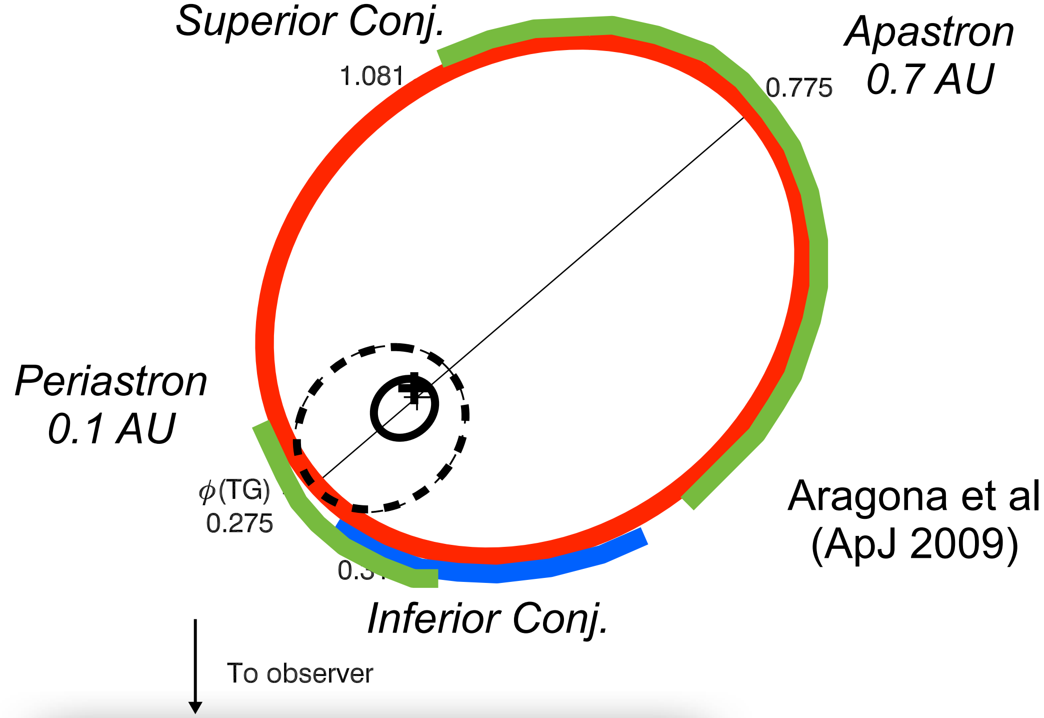


high X-ray activity throughout orbit (large variations)
radio emission peaks at periastron and apastron
MeV-GeV emission throughout orbit
(2008-2009: peak after periastron)

LS I +61 303: VERITAS observations 2006-2012

Collaboration:
A.Smith, J.Holder



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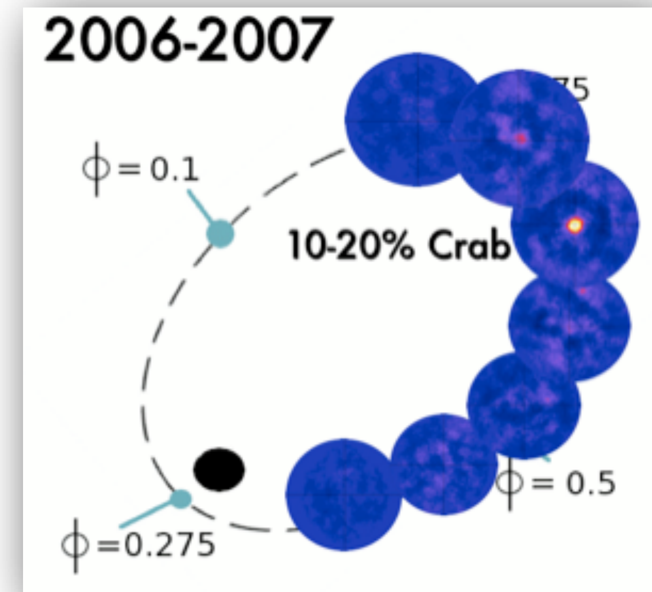
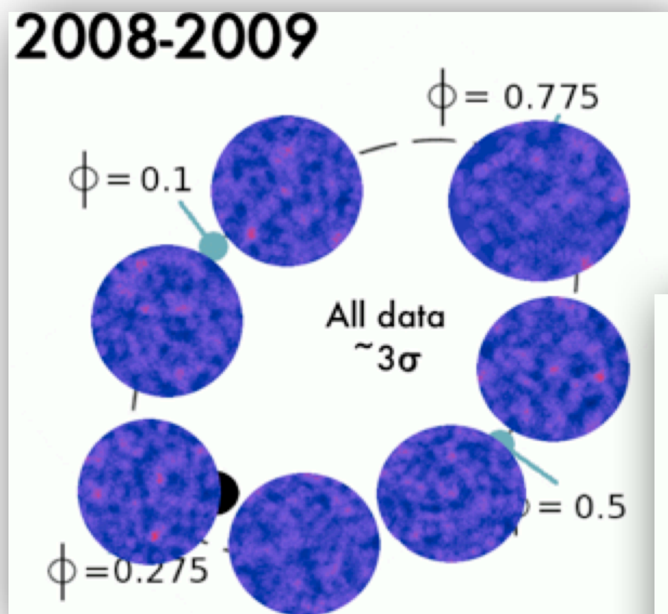
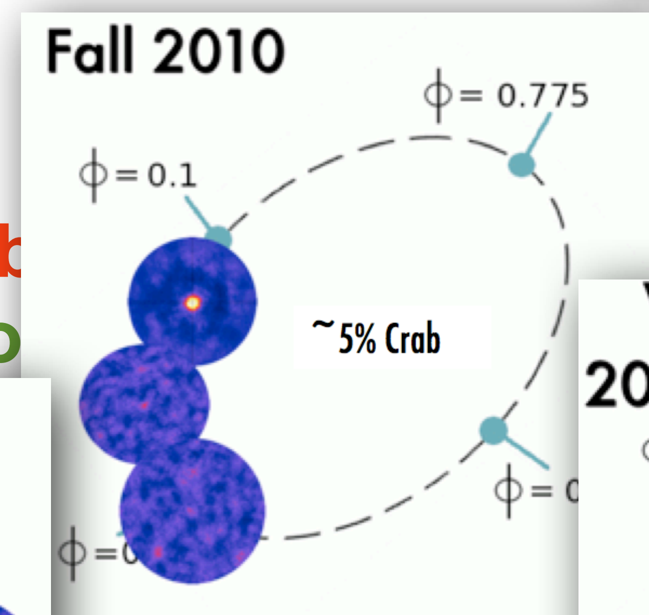
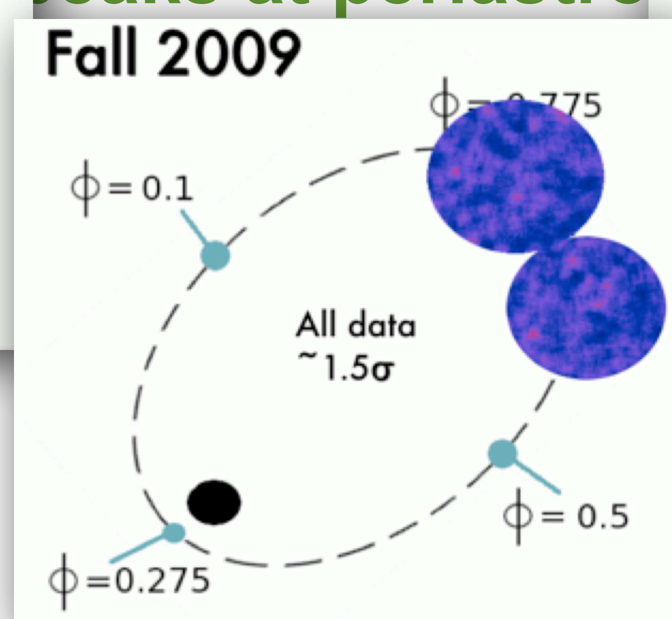
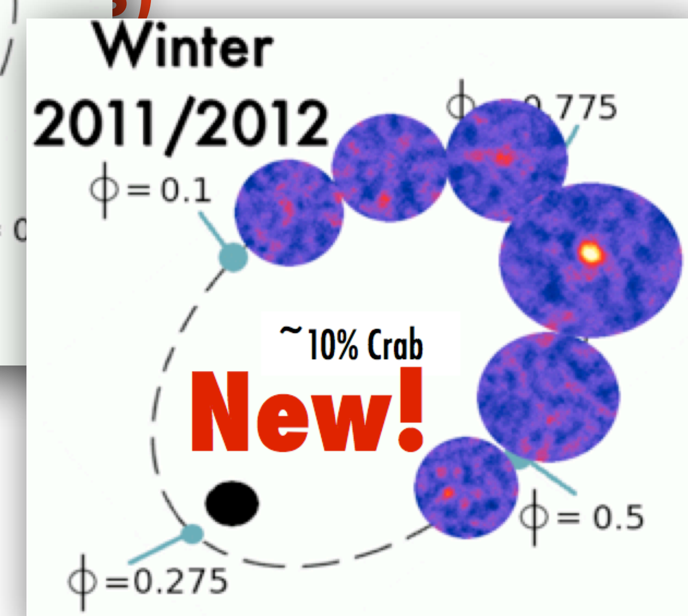




ity throughout orb
peaks at periastro







LS I +61 303: VERITAS observations 2012

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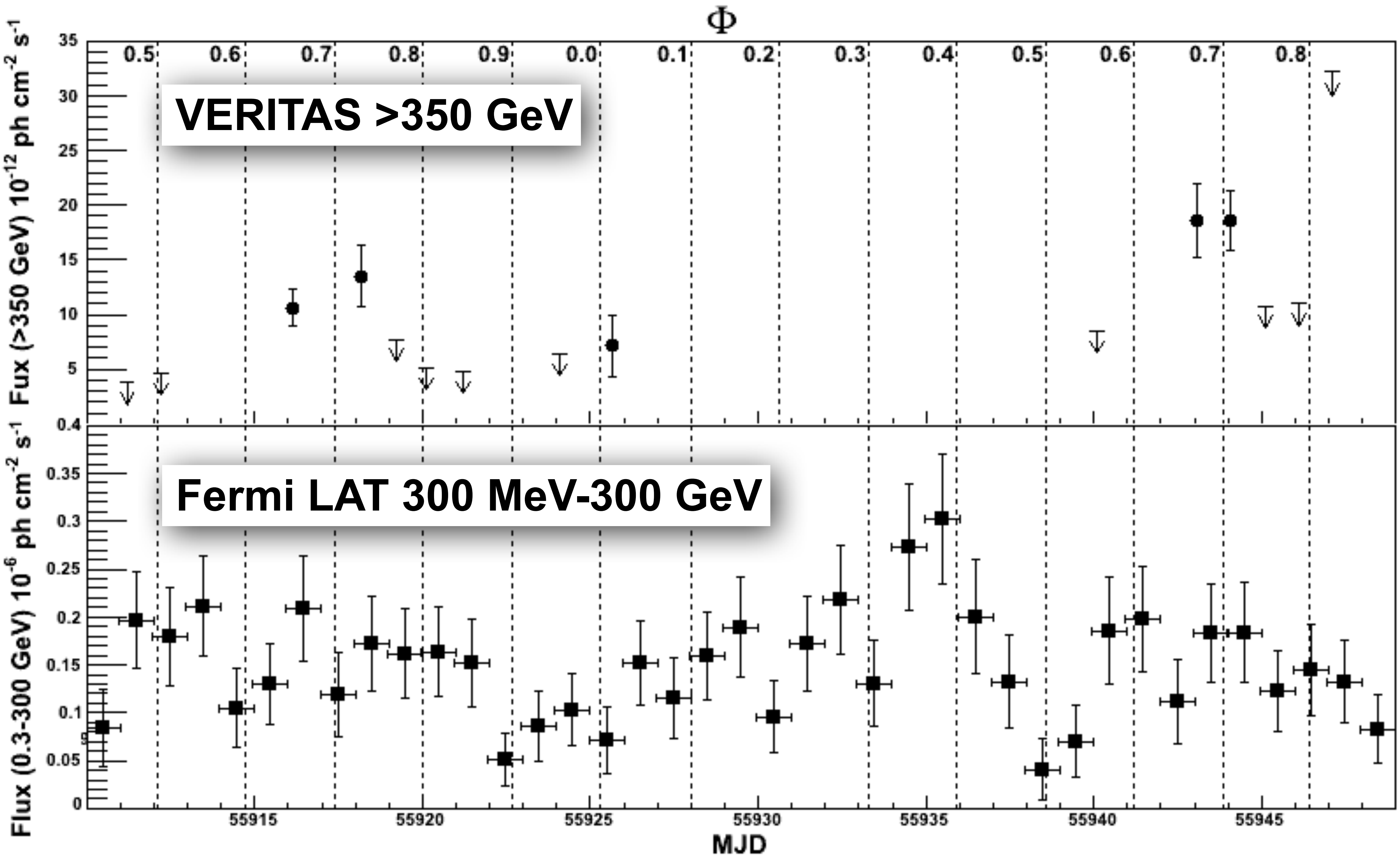
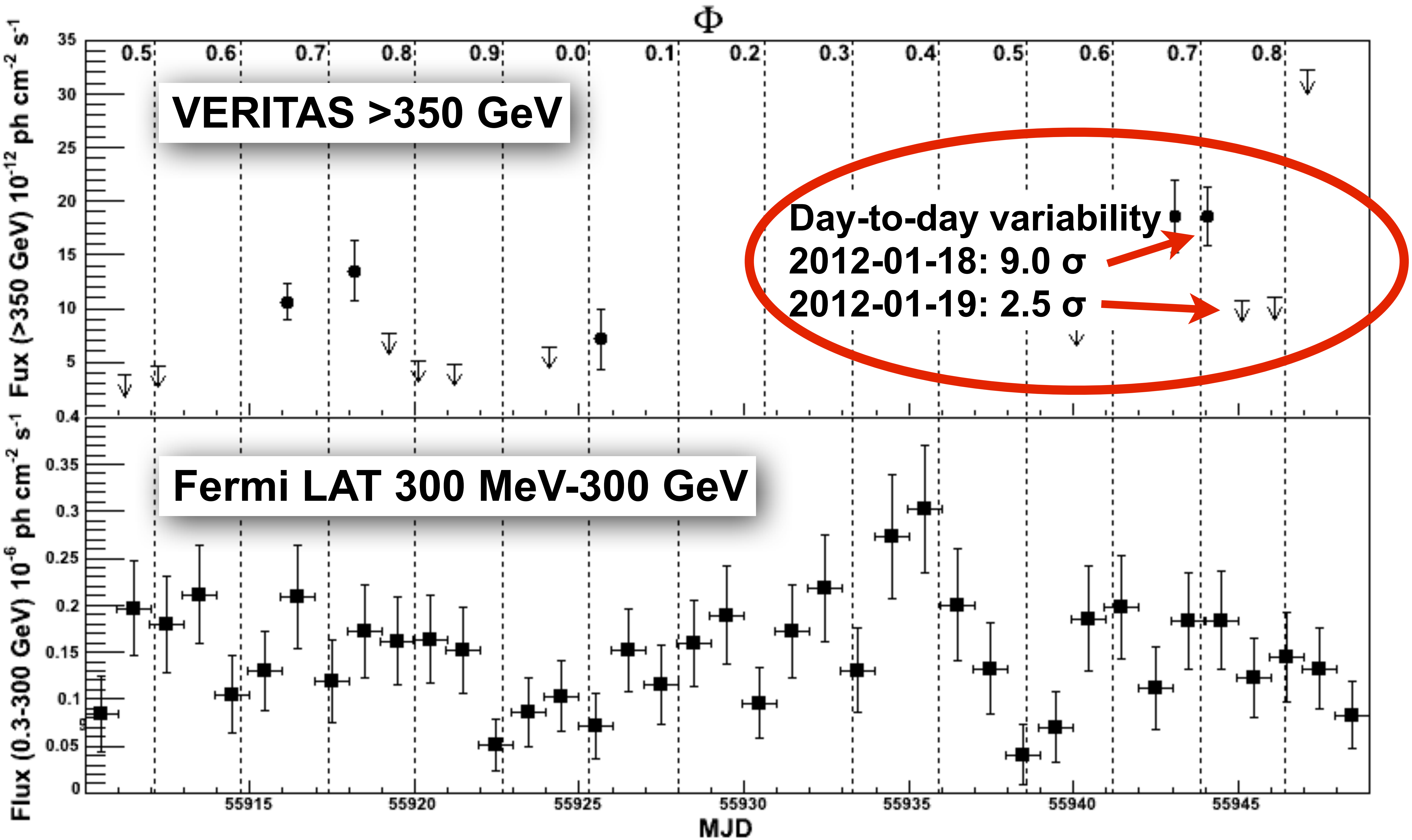


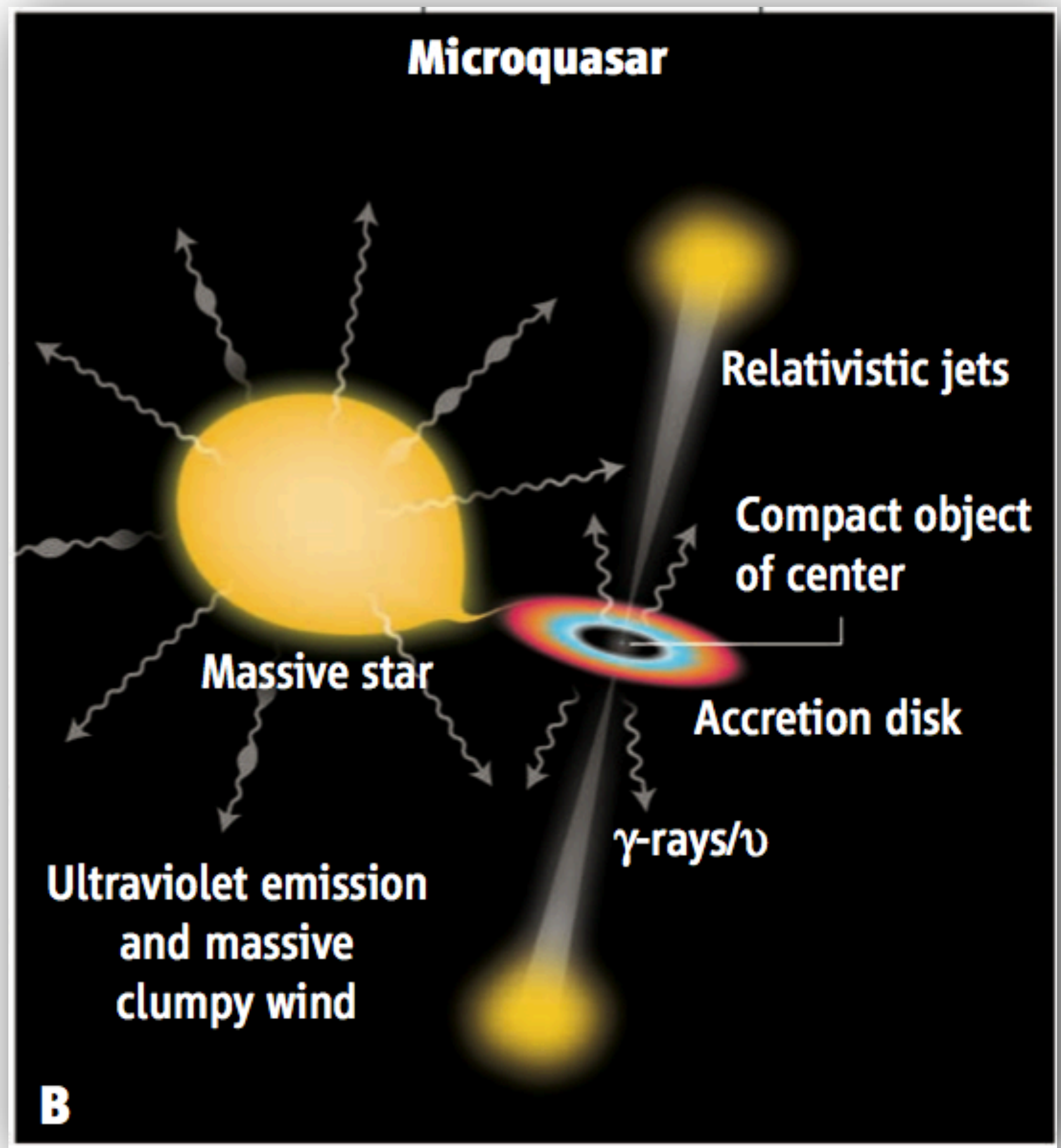
DESY

LS I +61 303: VERITAS observations 2012

Collaboration:
A.Smith, J.Holder

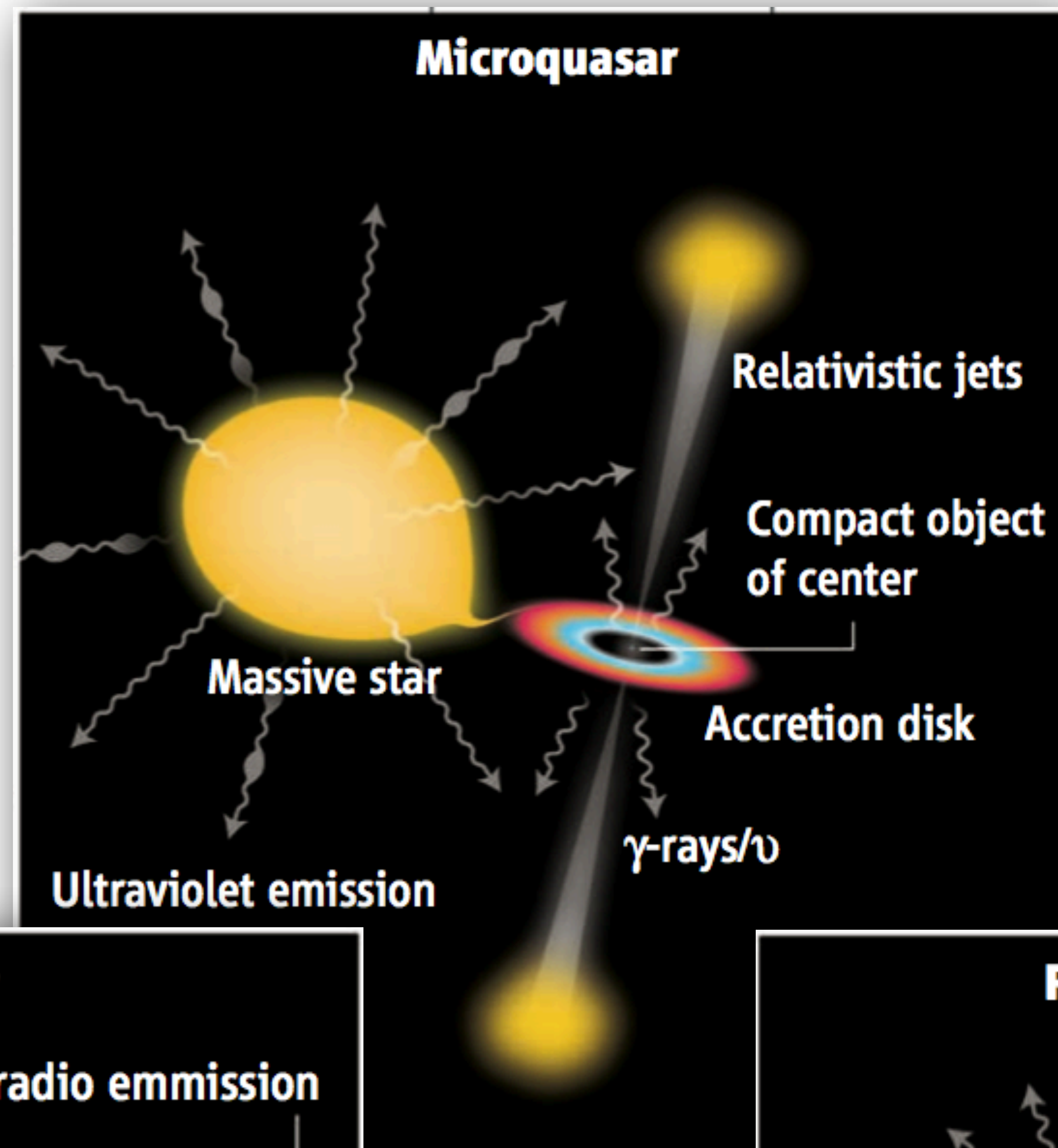


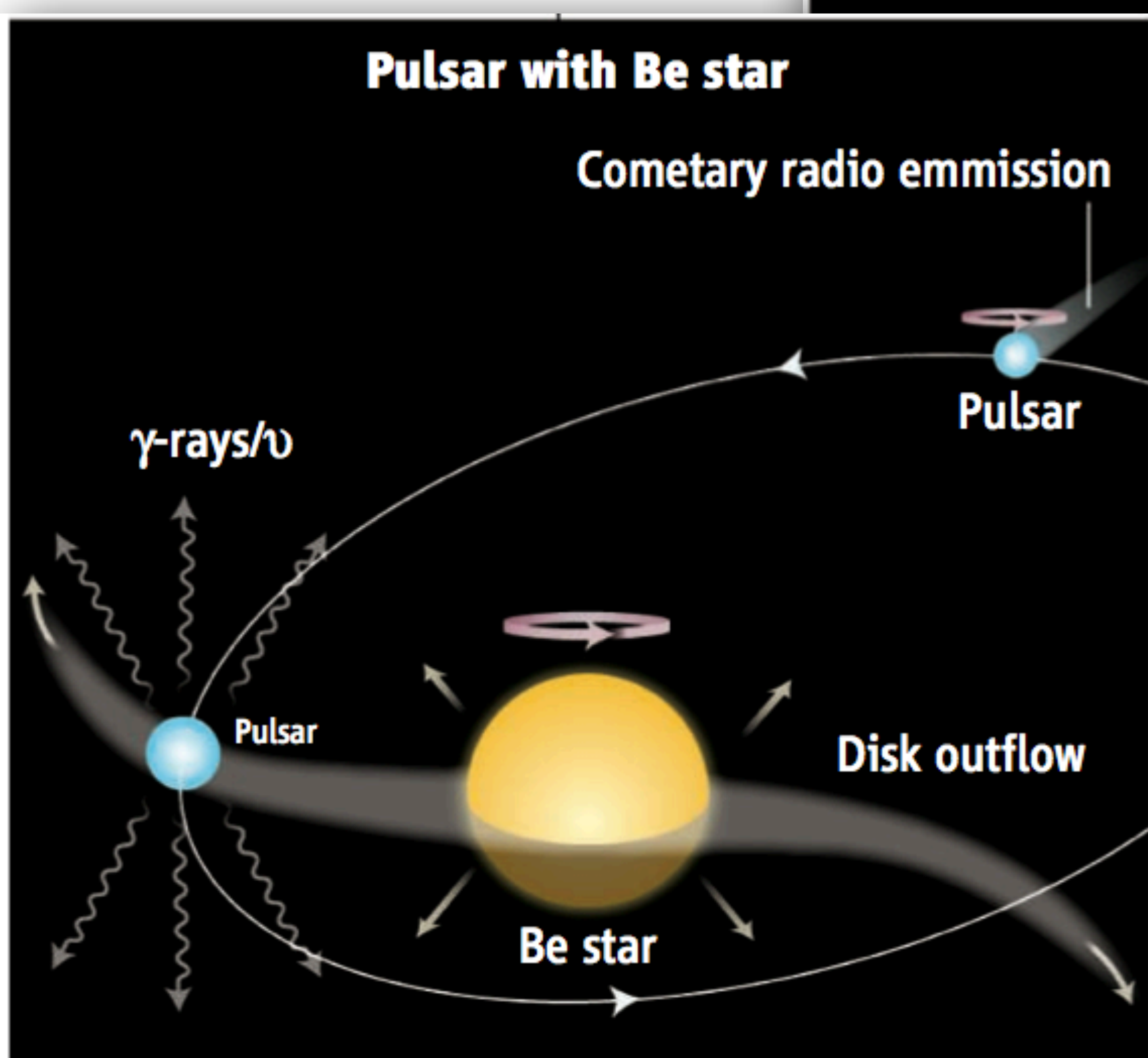
Situation far more complicated...

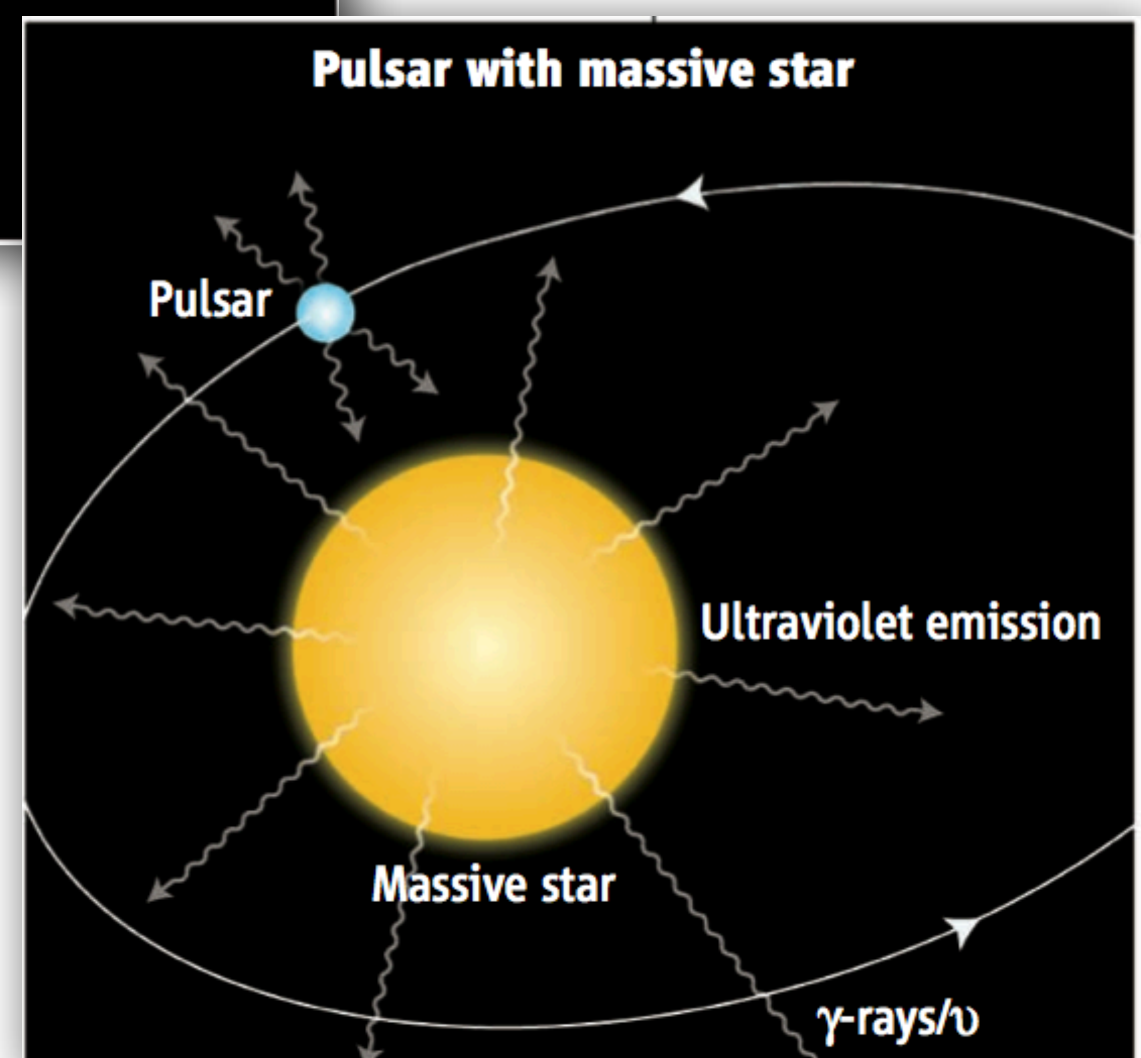


Mirabel (Science 2012)

Situation far more complicated...

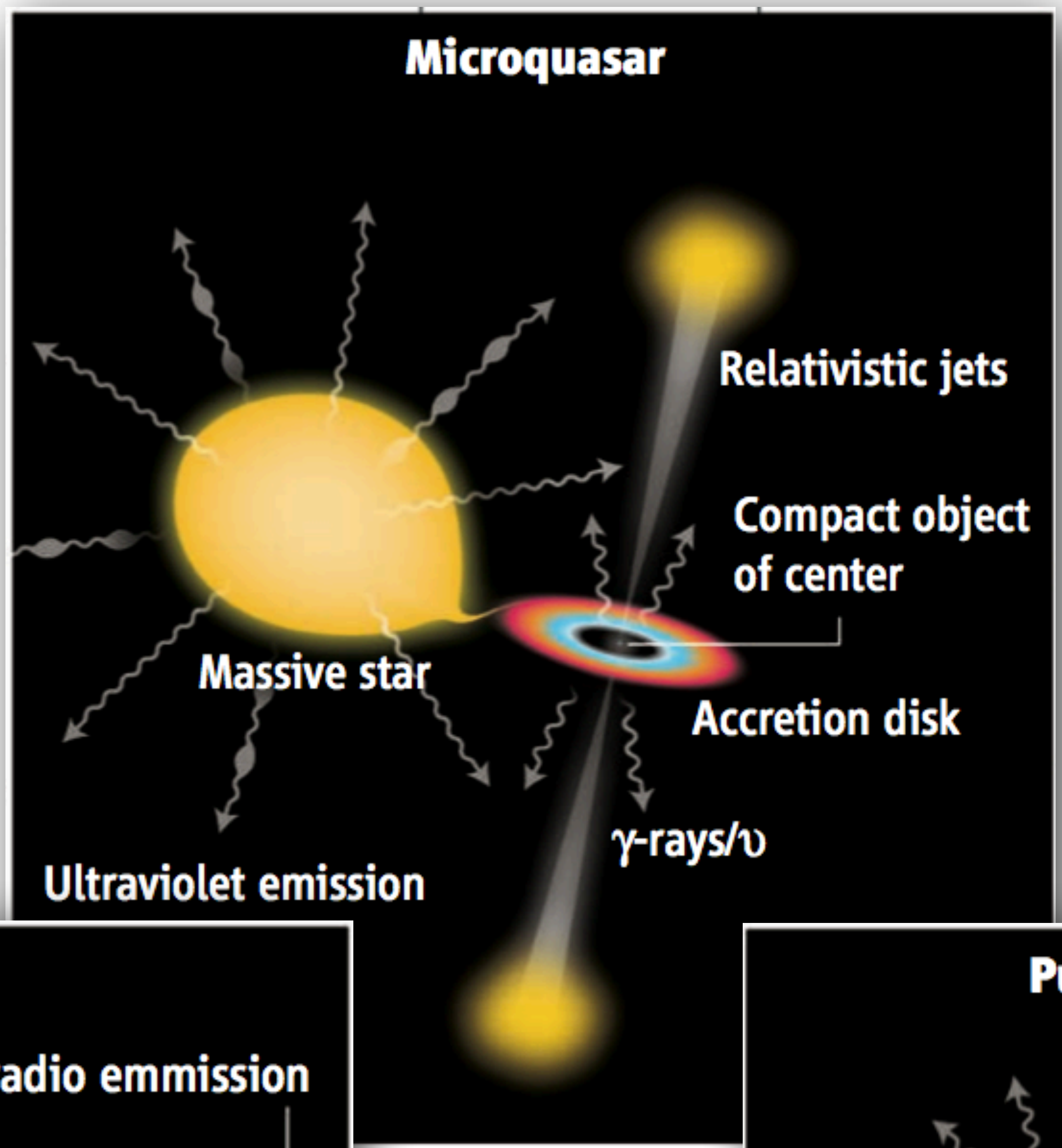


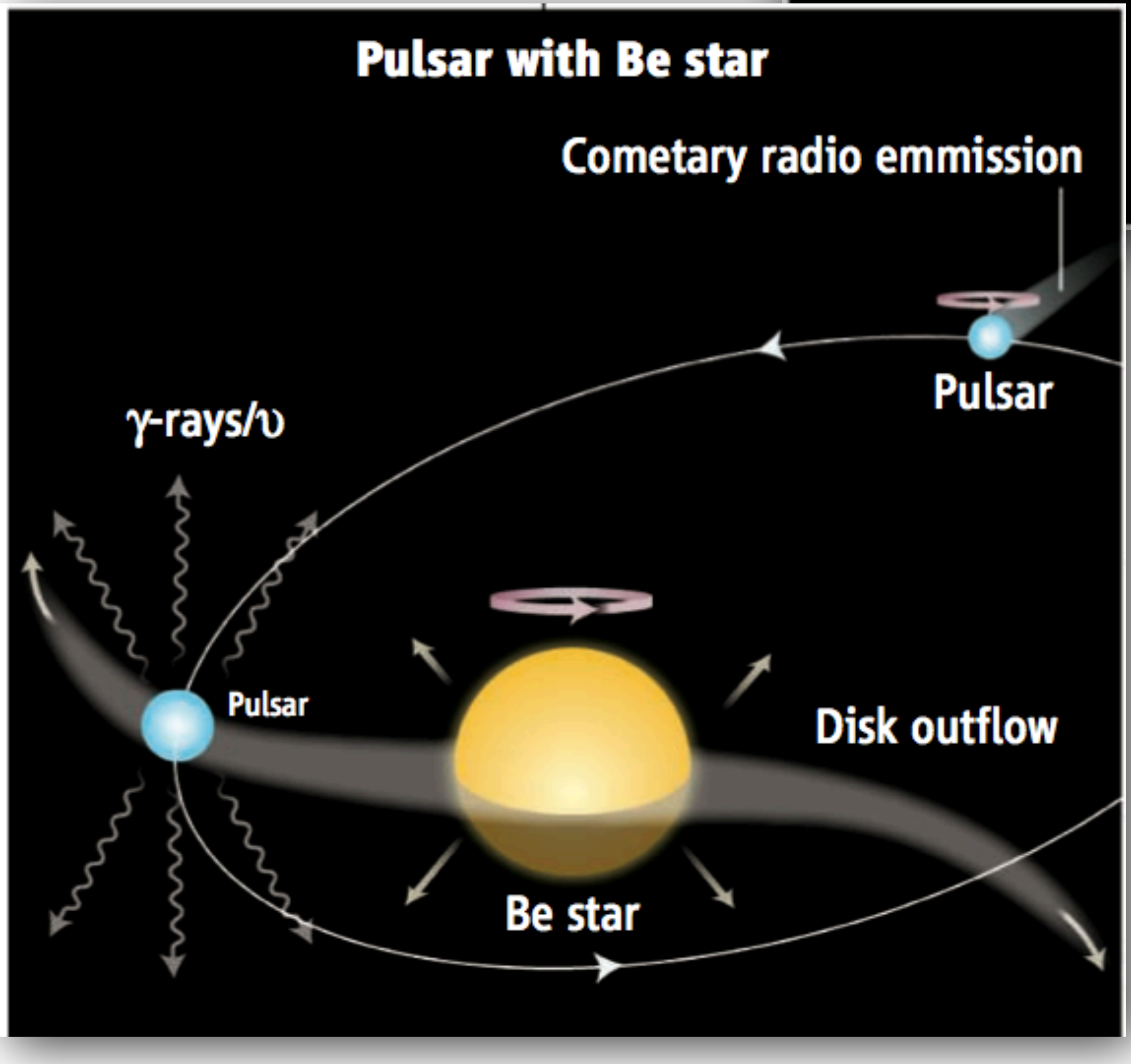


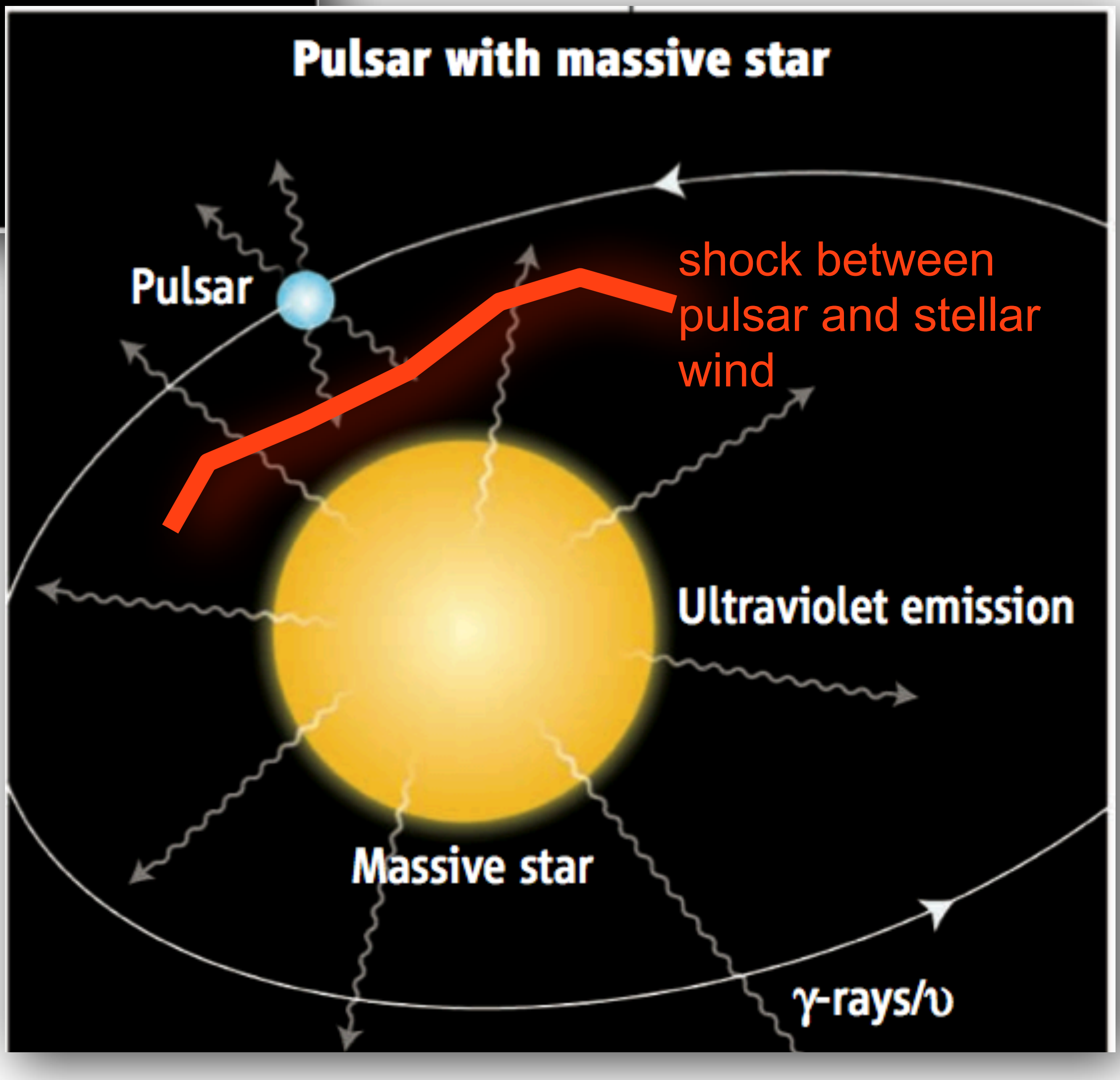


Mirabel (Science 2012)

Situation far more complicated...

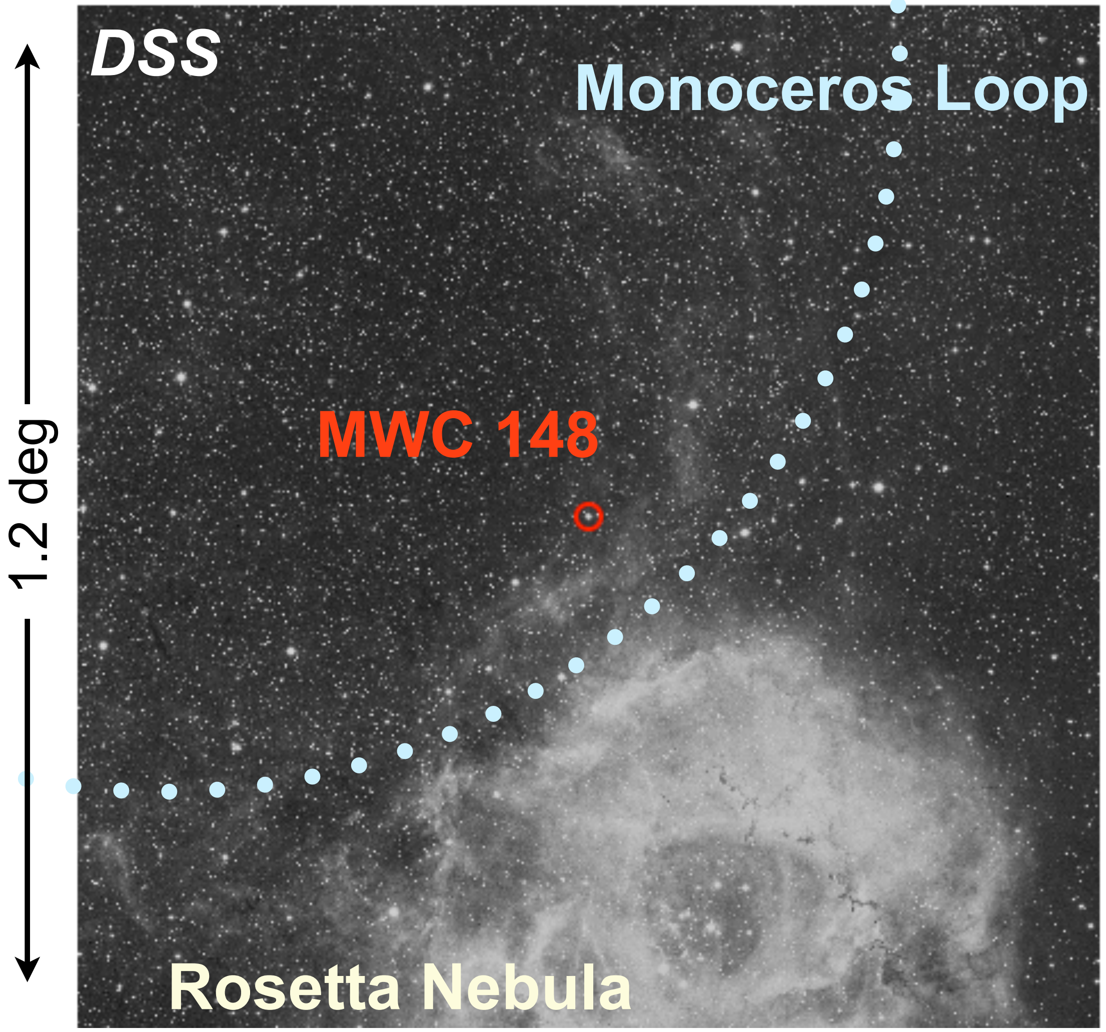


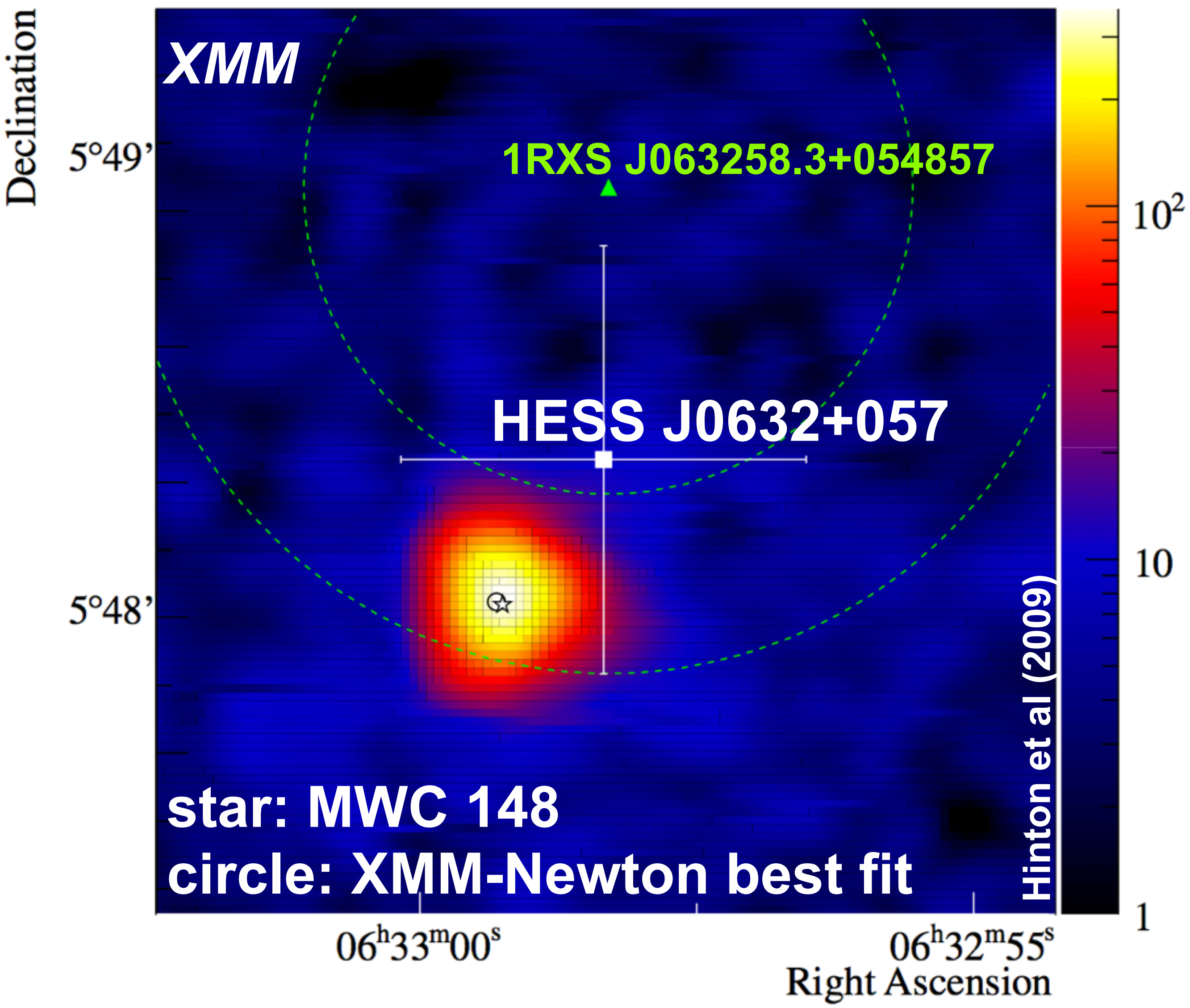




Mirabel (Science 2012)

HESS J0632+057 - A new TeV binary!



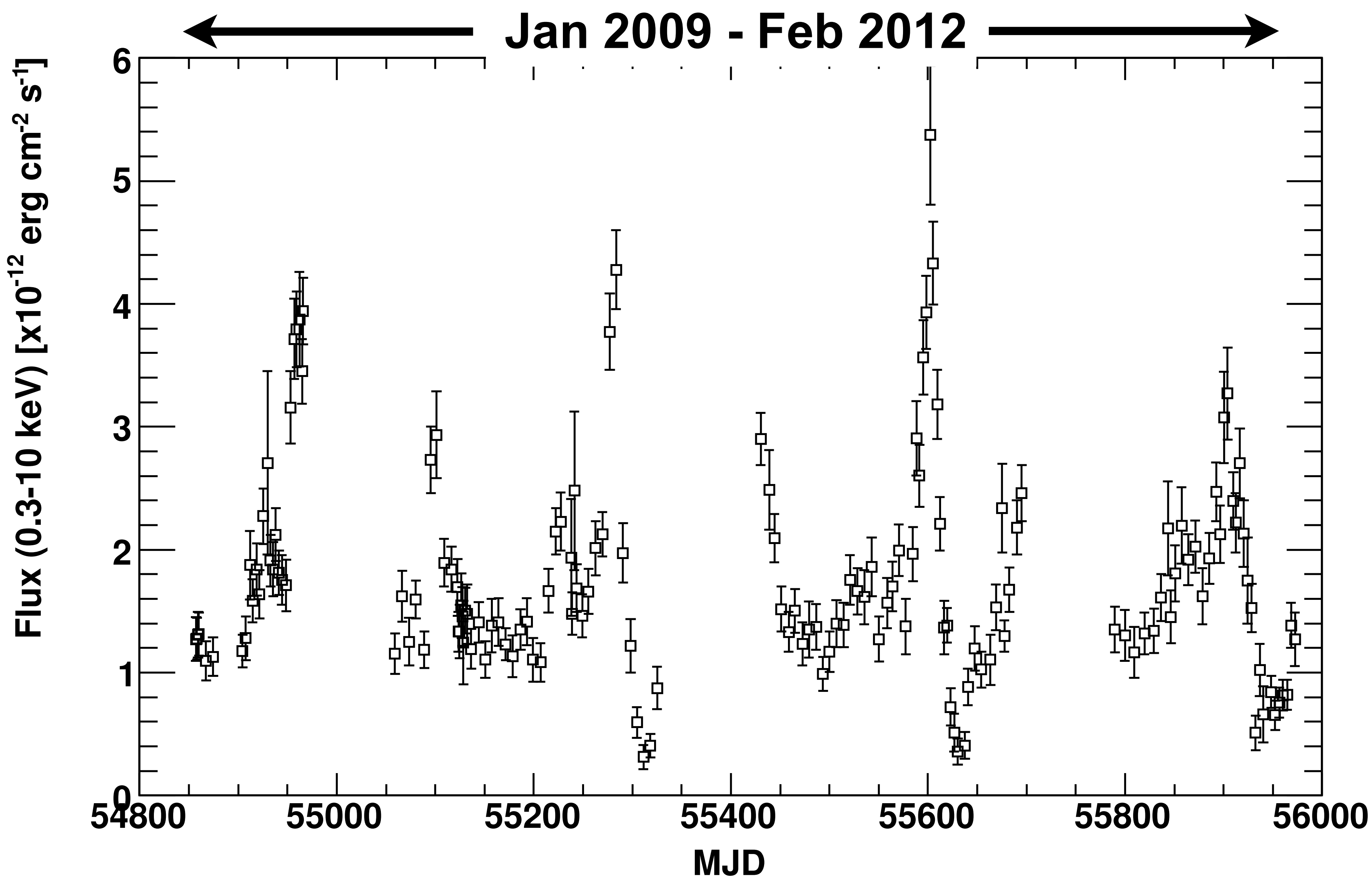


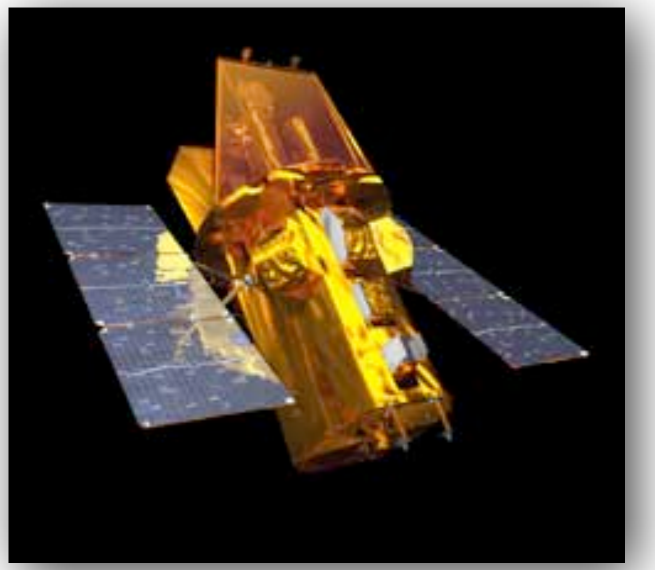
- discovered by H.E.S.S. in 2004
- until 2011: unidentified point source without obvious counterpart
- VERITAS: evidence for variability

- MWC 148: B0pe star; d=1.5 kpc
- no binary companion resolved in optical observations

HESS J0632+057 - long-term X-ray observations

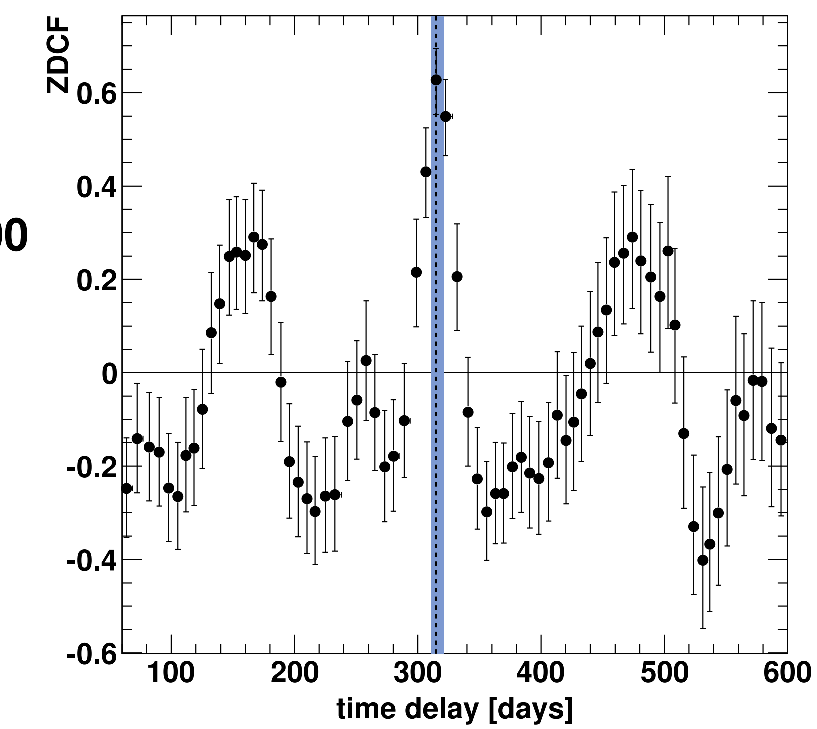
Collaboration:
A. Falcone, J.Holder





Z-transformed discrete correlation function:

period of 315^{+6}_{-4} days



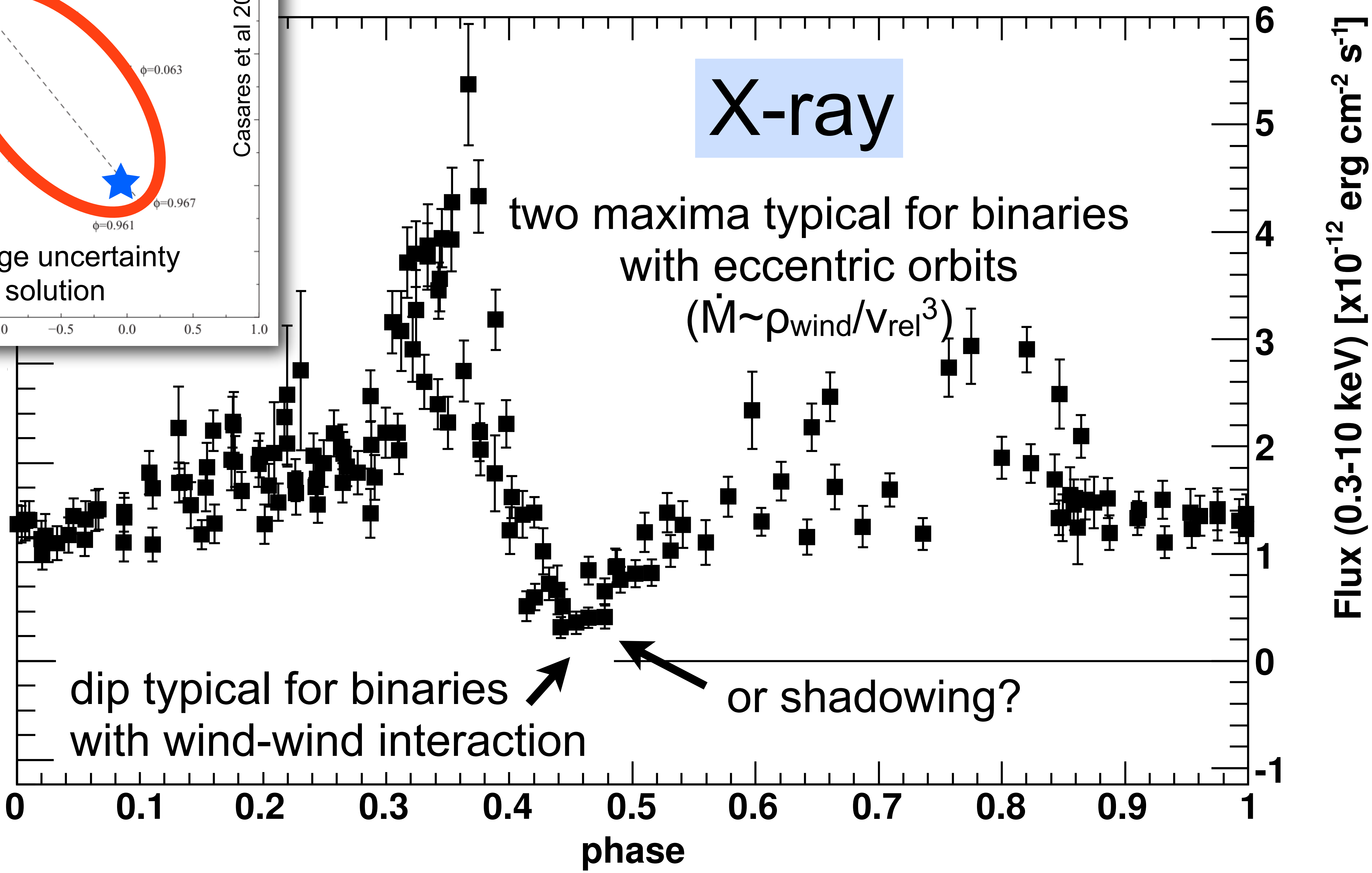
Swift XRT observations typically 5 ks per week for more than 3 years

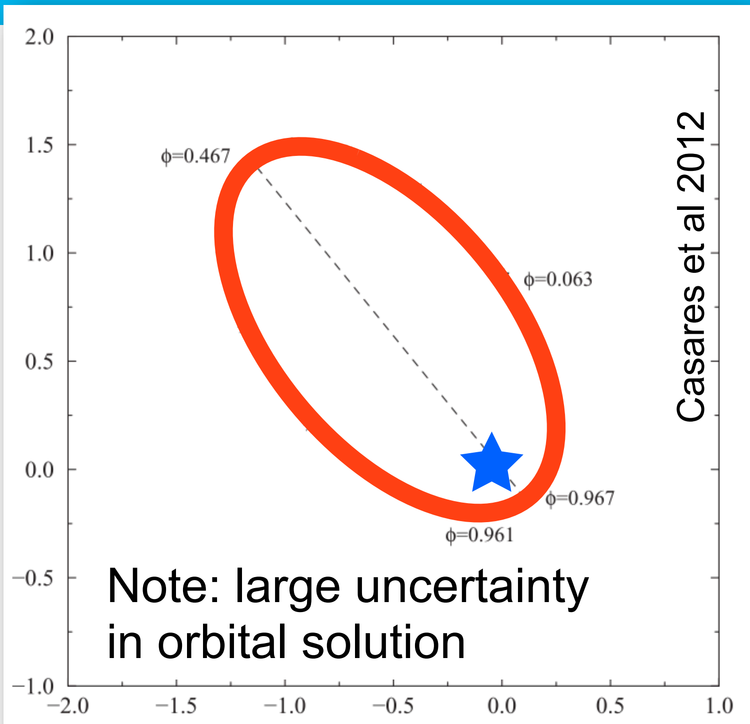
XRT data supplied by the UK Swift Science Data Centre at the University of Leicester.

DESY

HESS J0632+057 - phase folded light curve

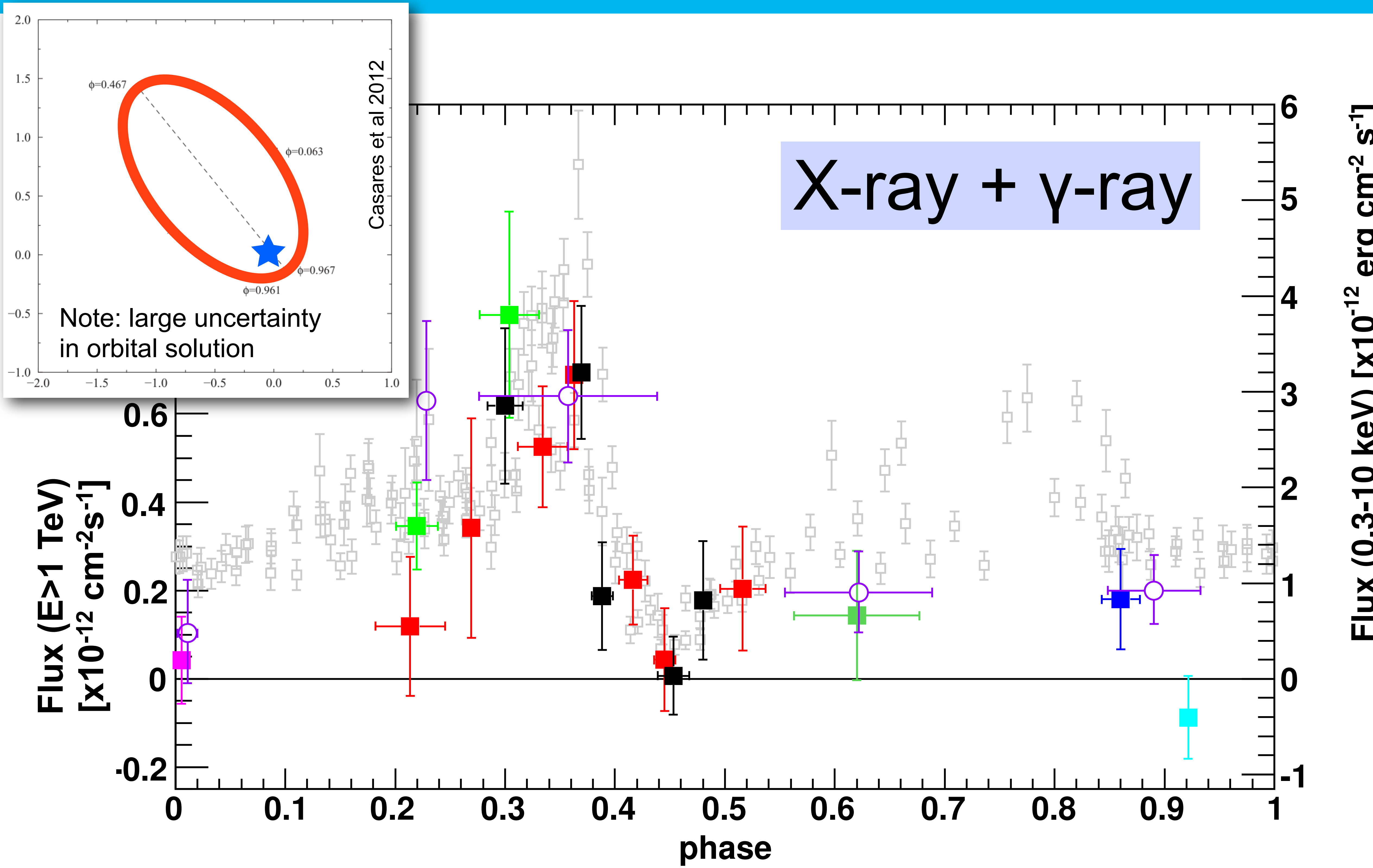
Collaboration:
A. Falcone, J.Holder





HESS J0632+057 - phase folded light curve

Collaboration:
A. Falcone, J.Holder



Color coding: TeV observation in different years

Gamma-ray binaries....

- 4 binaries detected at energies > 100 GeV
  - (expected a larger population from stellar evolution models)
  - first binary detected through gamma-ray observations (HESS J0632+057)
- each system is unique
  - lack of exact orbital solutions and inclination hampers identification of compact object (e.g. pulsation) and emission mechanisms
- role of massive star (Be or O type)
  - (62+1 Be/X-ray binaries in the galaxies)
- no clear identification of gamma-ray microquasars >100 GeV (yet)
  - LS I +61 303 best candidate? (see e.g. Masi et al 2012)
- observations difficult due to low fluxes and long orbital periods
- *unhealthy* situation of having far more emission models than data points....

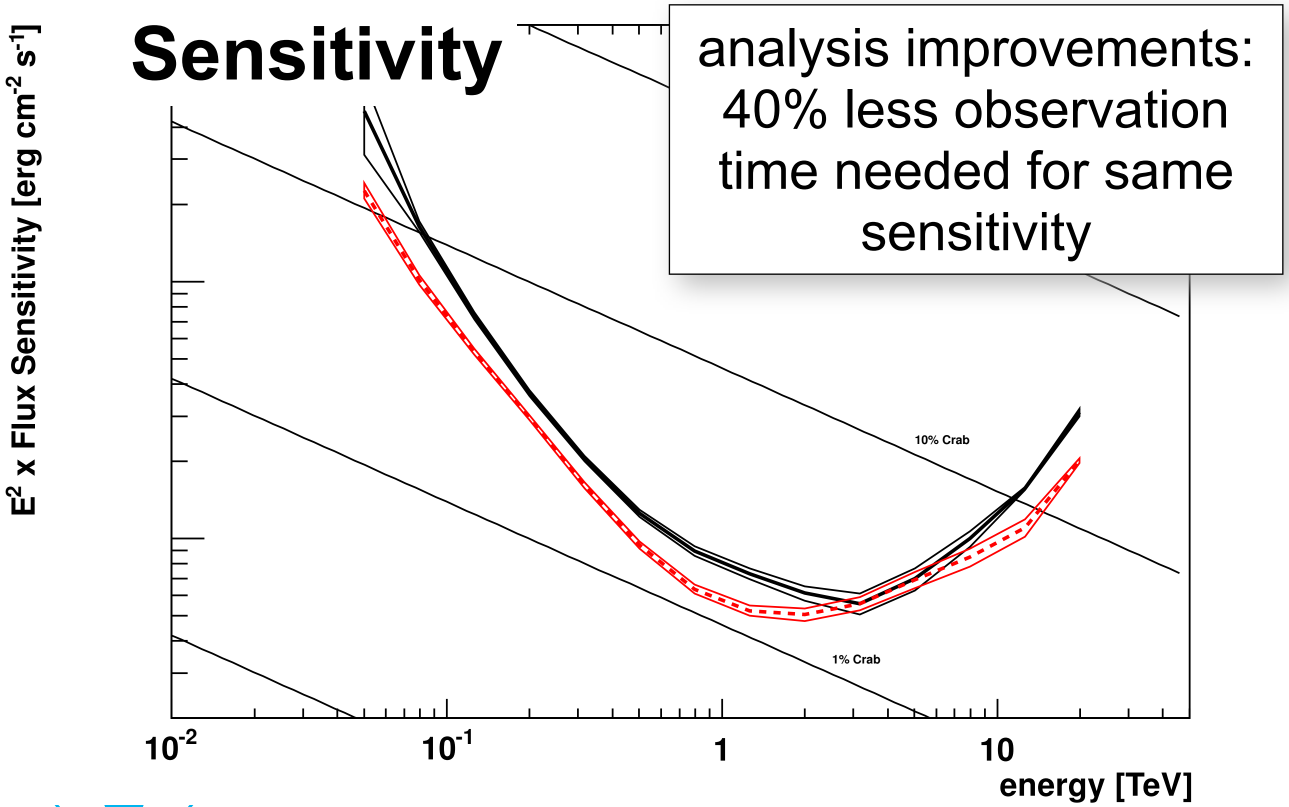
Steps forward

Collaboration

Steps forward

Collaboration

Sensitivity

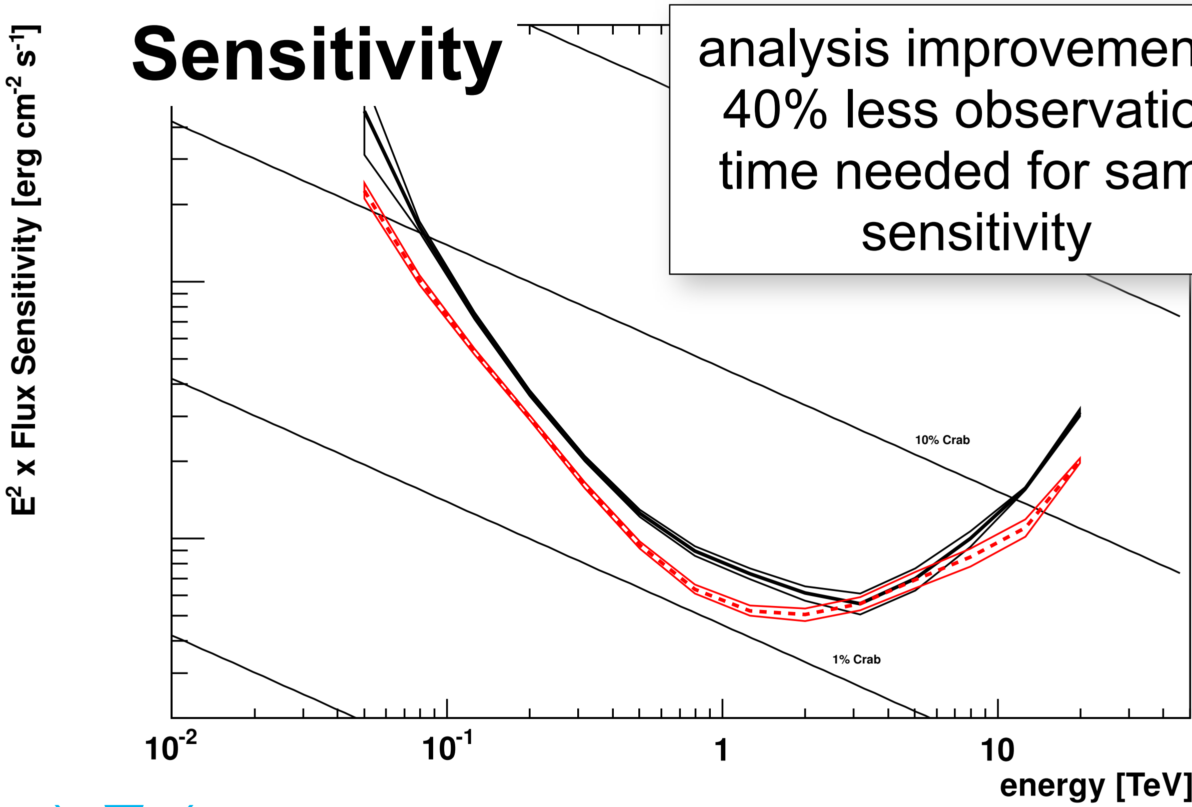


analysis improvements: 40% less observation time needed for same sensitivity

Steps forward

Collaboration

Sensitivity



analysis improvements: 40% less observation time needed for same sensitivity

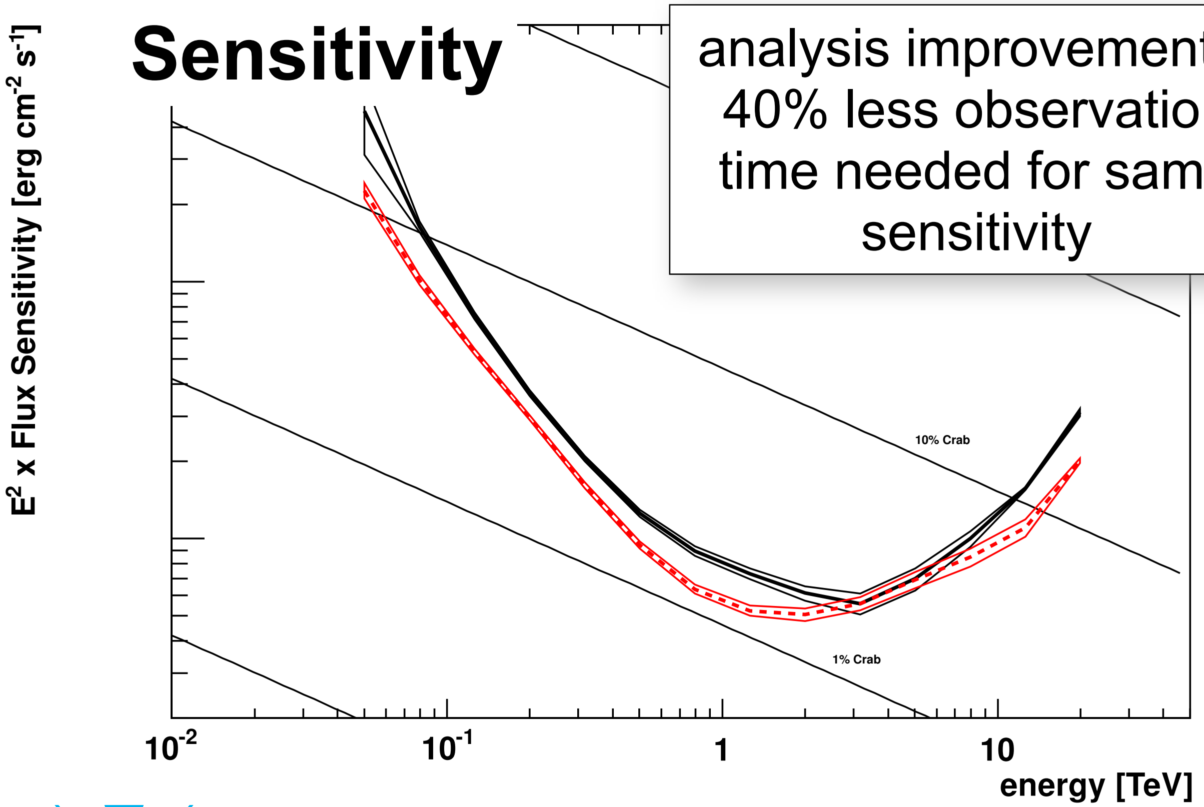
Moonlight observations

(Photo by N.Otte)

Steps forward

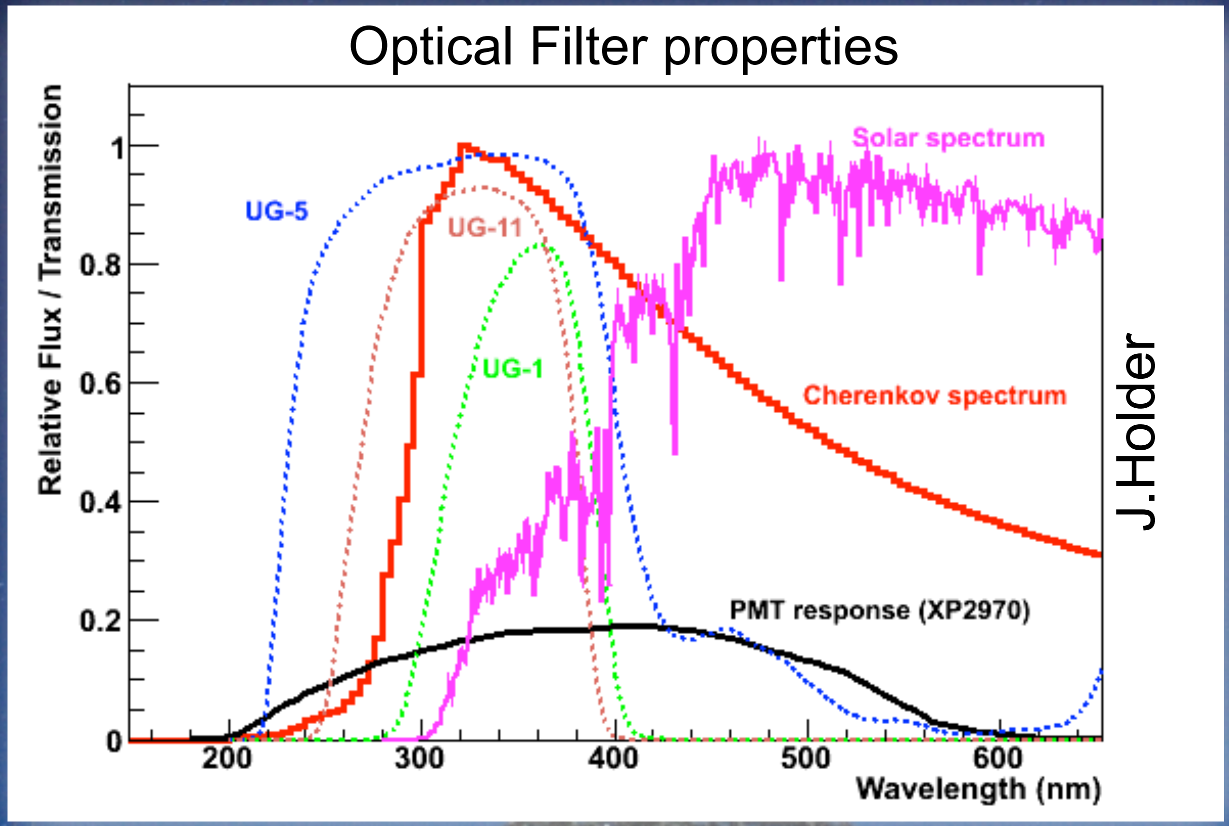
Collaboration

Sensitivity



analysis improvements: 40% less observation time needed for same sensitivity

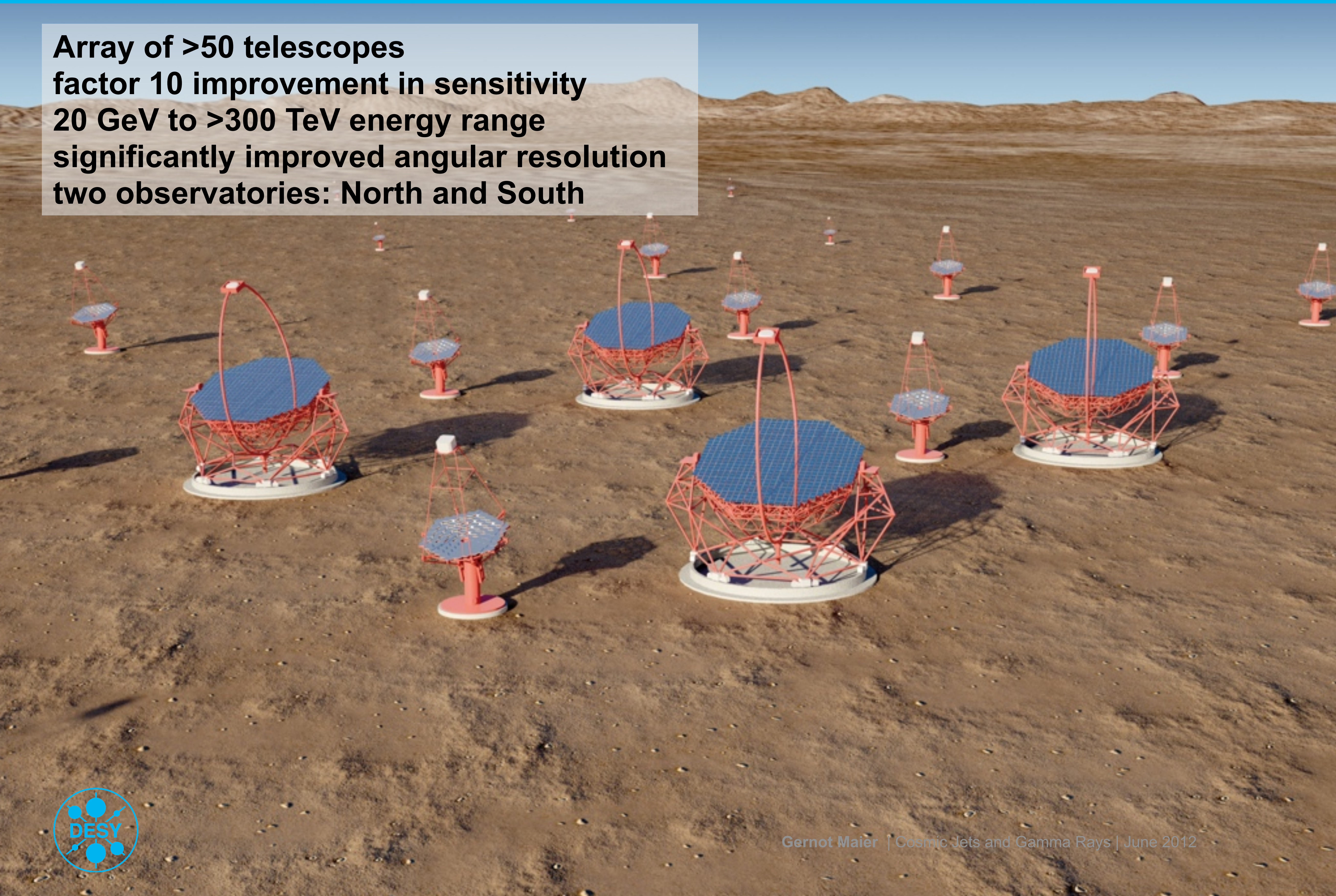
Moonlight observations



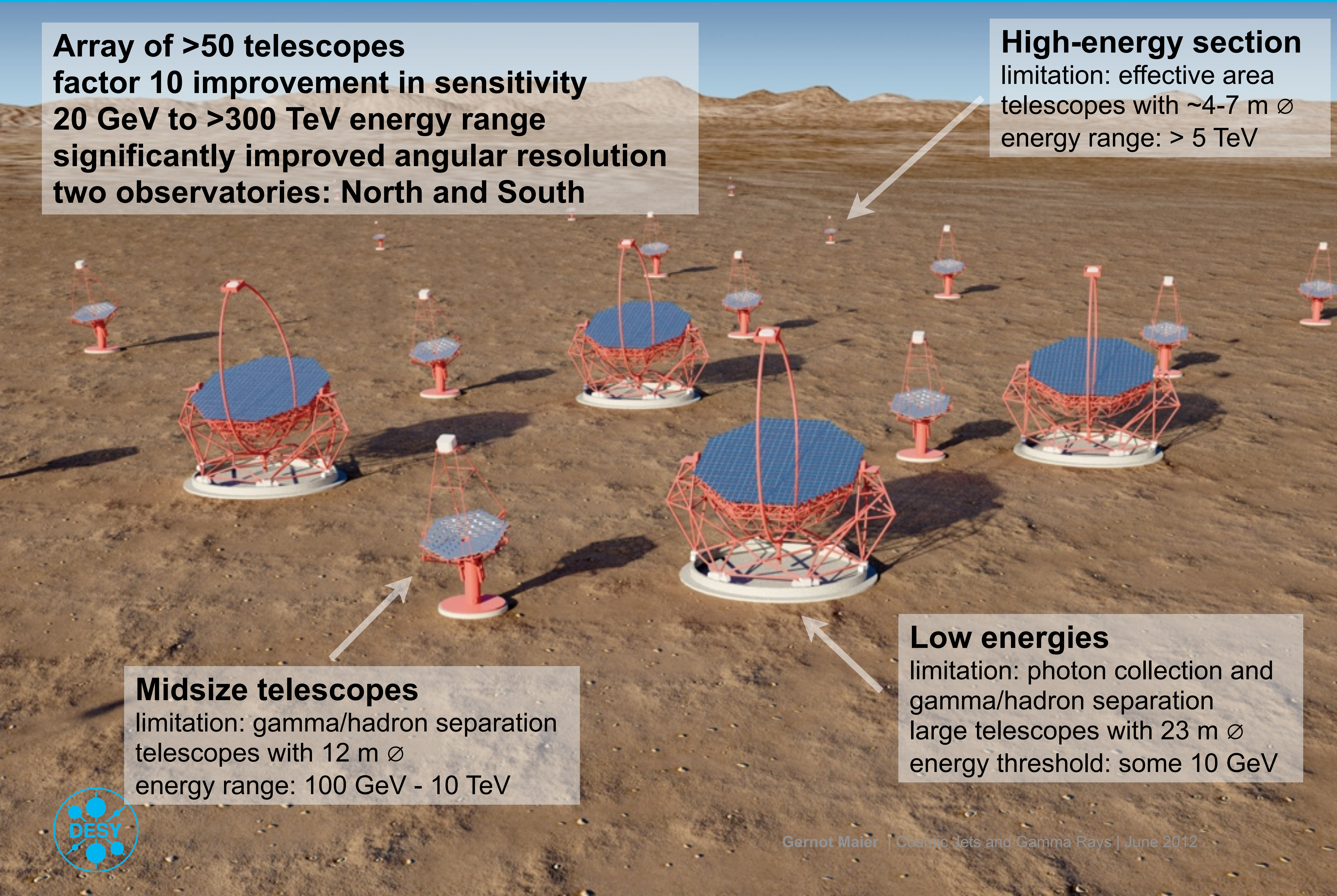
(Photo by N.Otte)

The Cherenkov Telescope Array (CTA)

Array of >50 telescopes
factor 10 improvement in sensitivity
20 GeV to >300 TeV energy range
significantly improved angular resolution
two observatories: North and South



The Cherenkov Telescope Array (CTA)



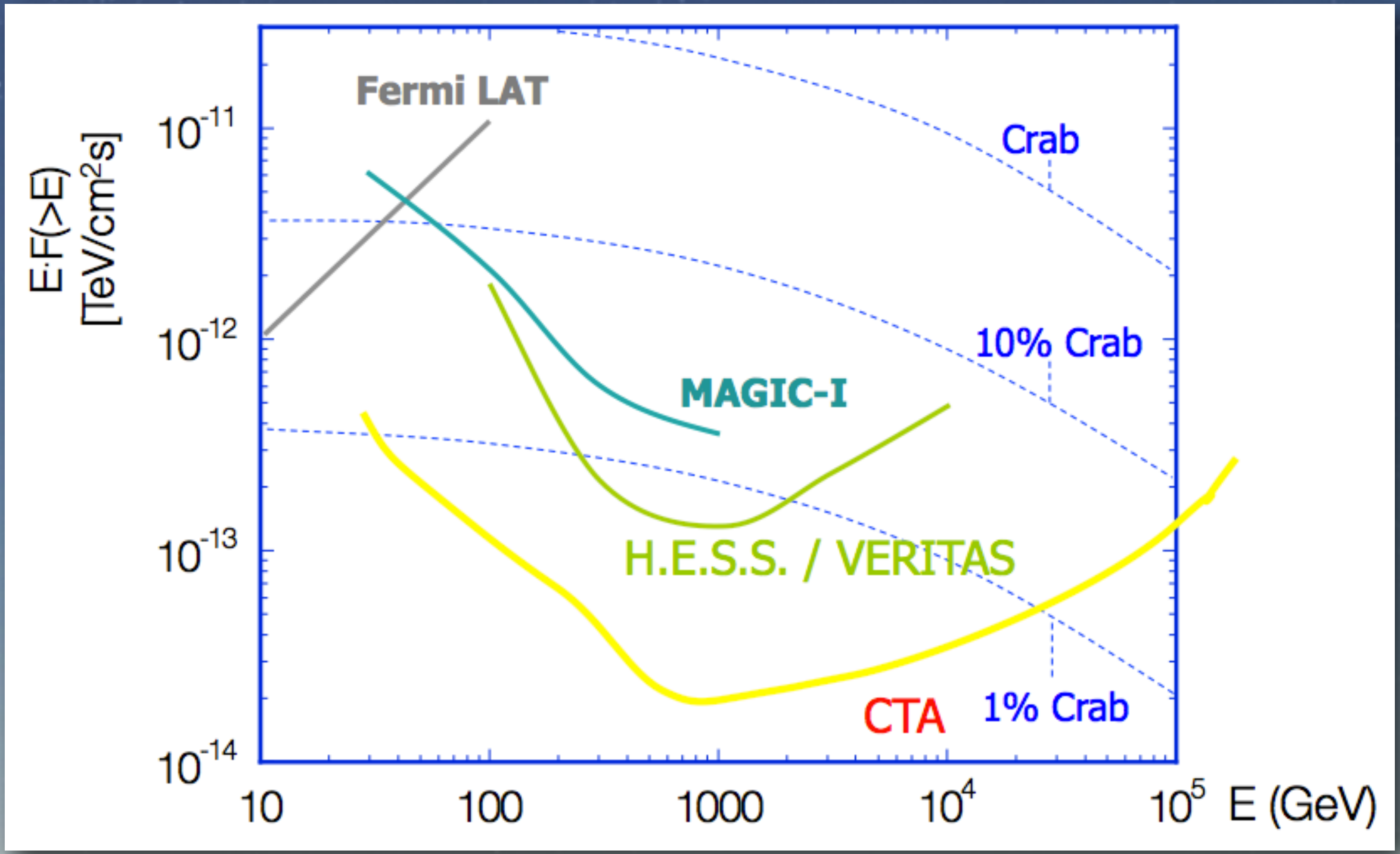
Array of >50 telescopes
factor 10 improvement in sensitivity
20 GeV to >300 TeV energy range
significantly improved angular resolution
two observatories: North and South

High-energy section
limitation: effective area
telescopes with ~4-7 m ∅
energy range: > 5 TeV

Midsize telescopes
limitation: gamma/hadron separation
telescopes with 12 m ∅
energy range: 100 GeV - 10 TeV

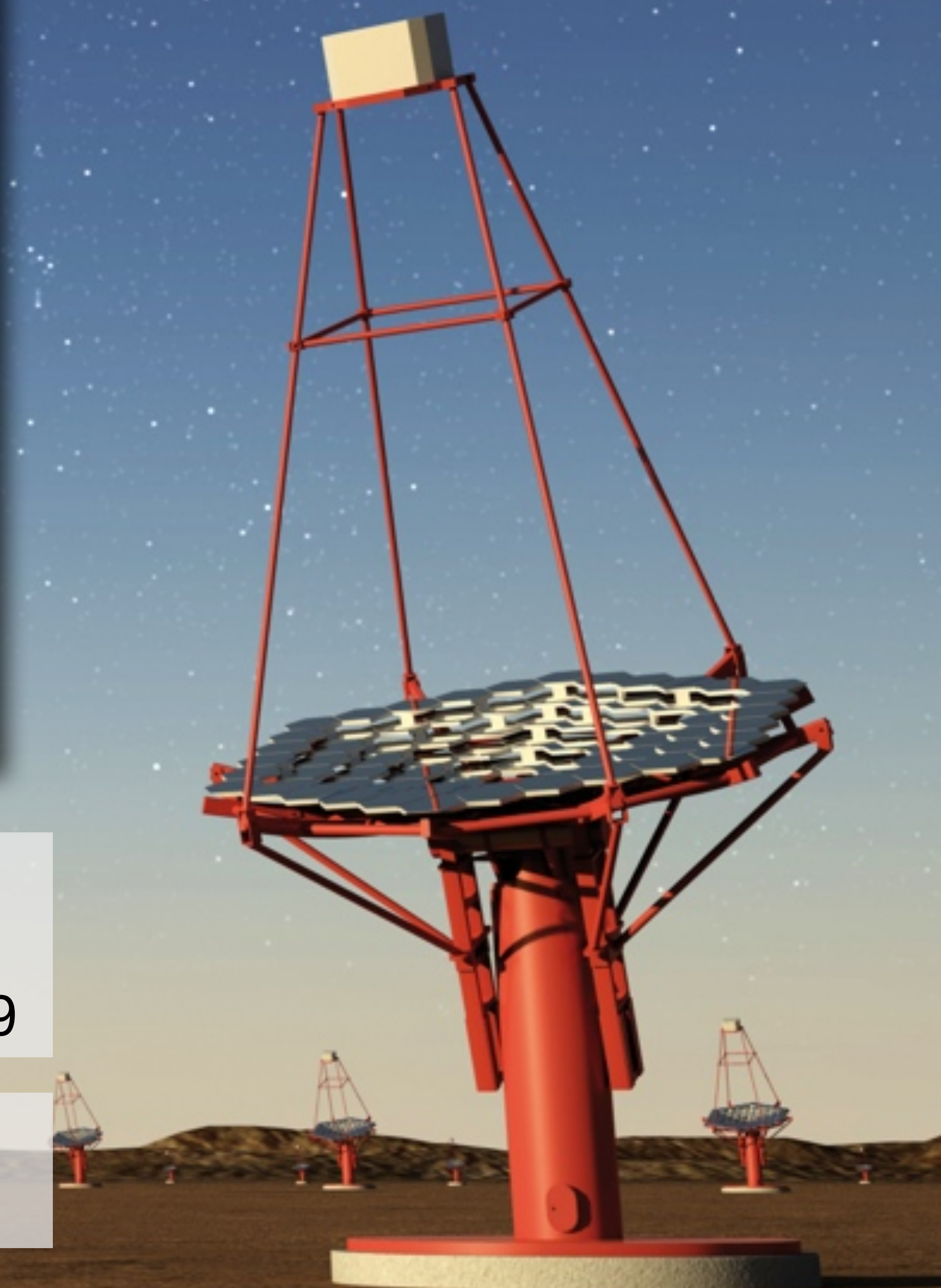
Low energies
limitation: photon collection and gamma/hadron separation
large telescopes with 23 m ∅
energy threshold: some 10 GeV

The Cherenkov Telescope Array (CTA)



CTA Consortium: world-wide effort
>1000 members
Design Prototyping 2011-2014, Construction 2015-2019

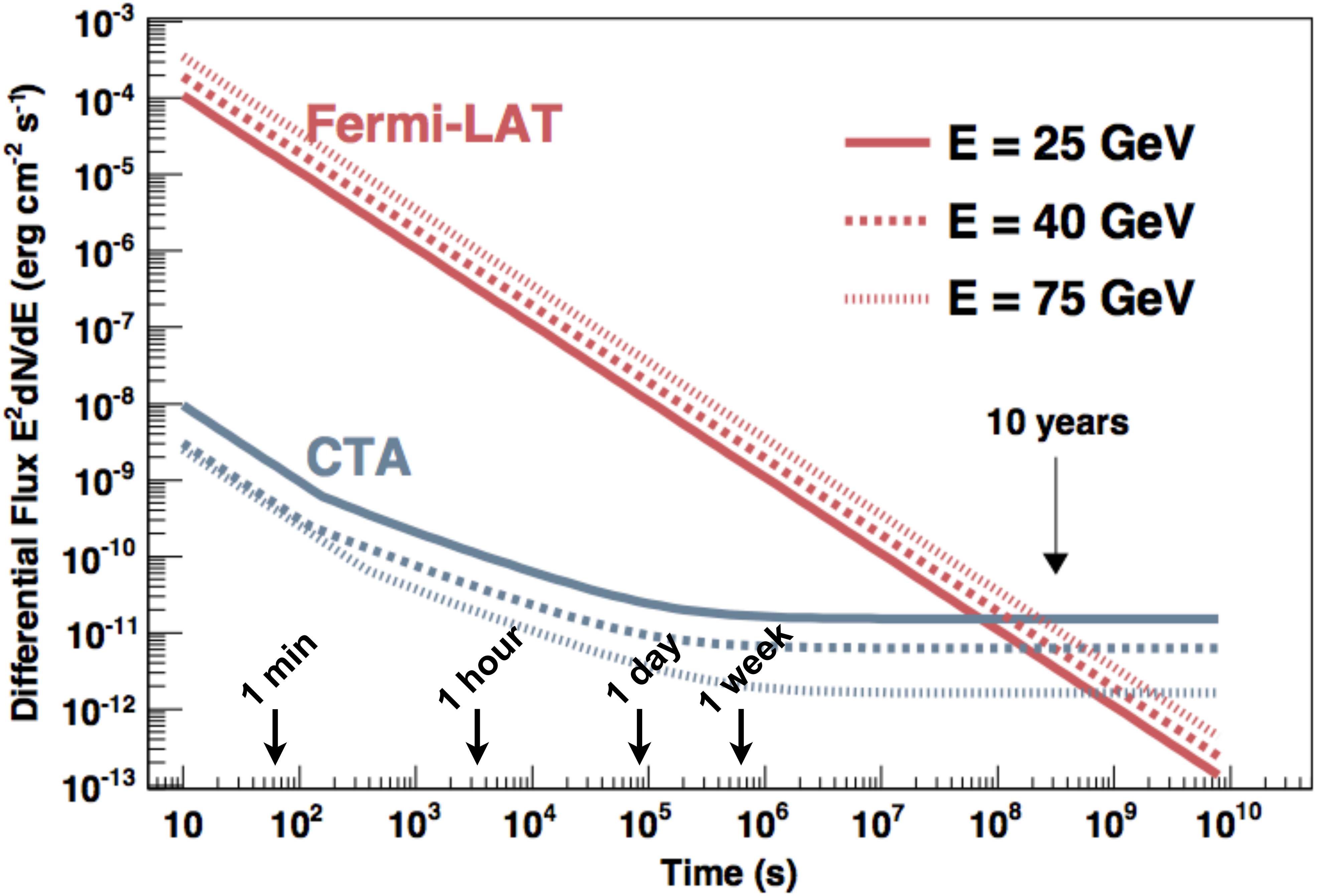
significant German contribution through DESY, Max-Planck Institutes (Heidelberg, München), 6 Universities



DESY

Transient sensitivity - CTA and Fermi LAT

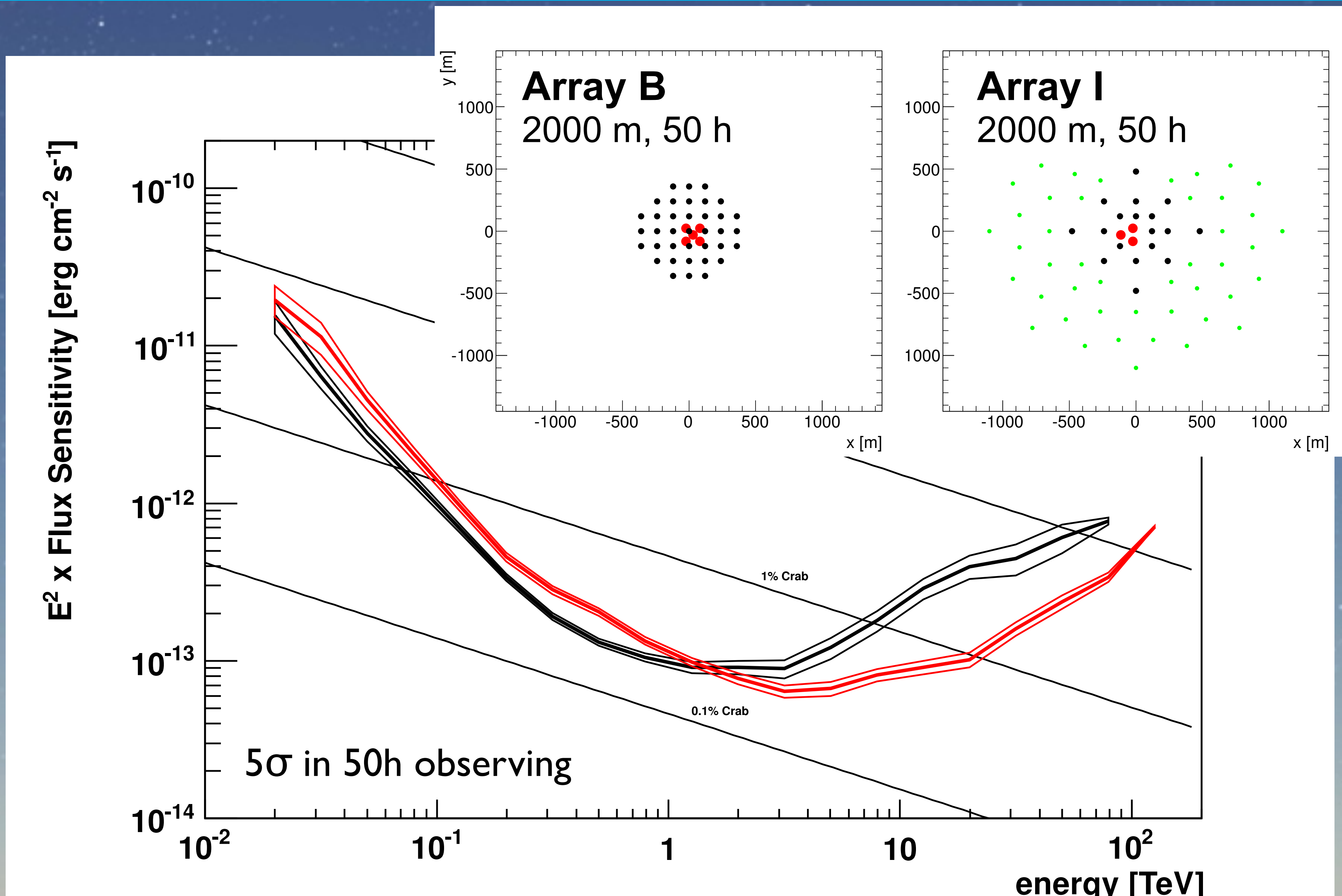
effective areas: 1 m^2 (LAT) vs 10^4 m^2 (CTA) at 40 GeV



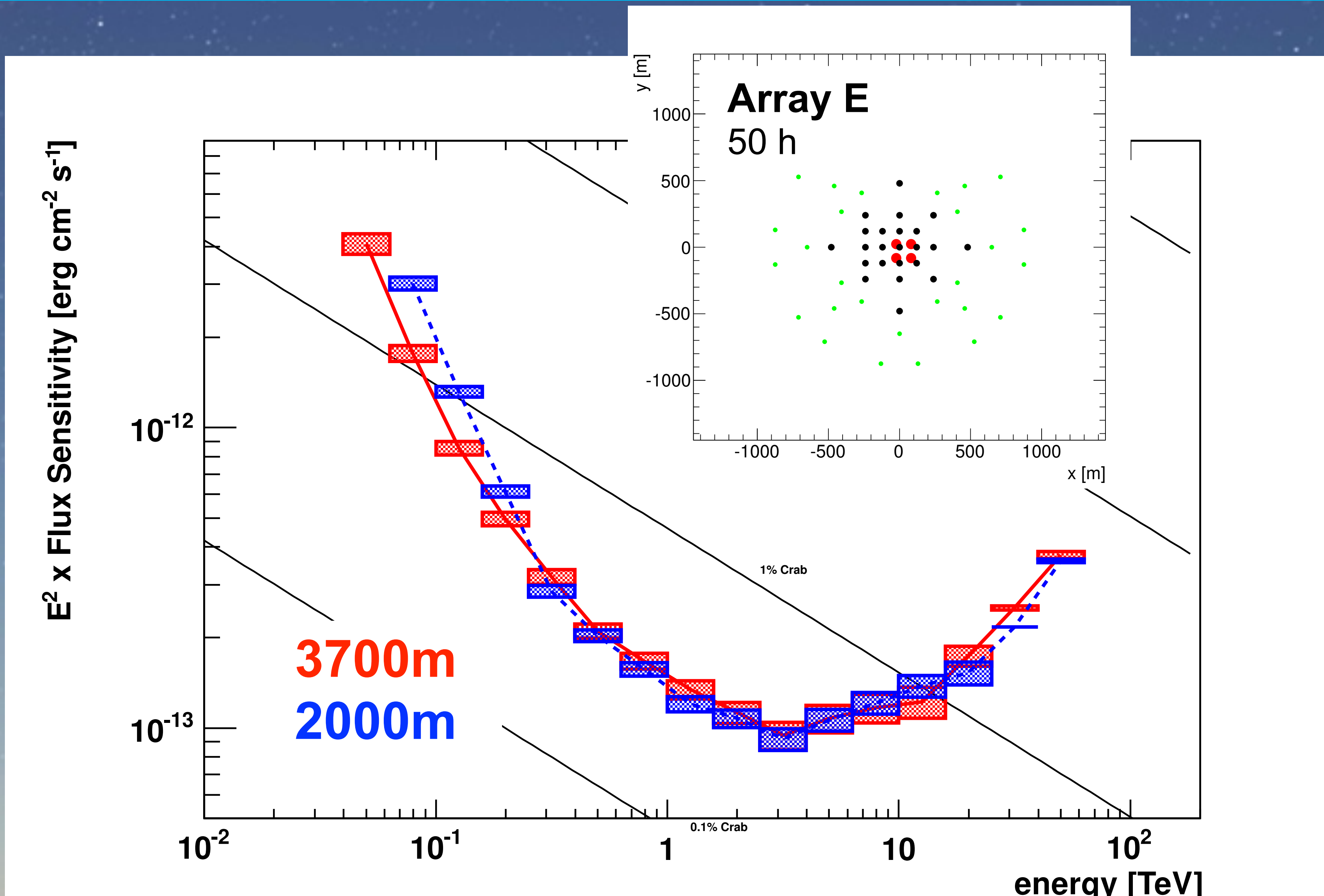
CTA collaboration (Funk et al 2012)

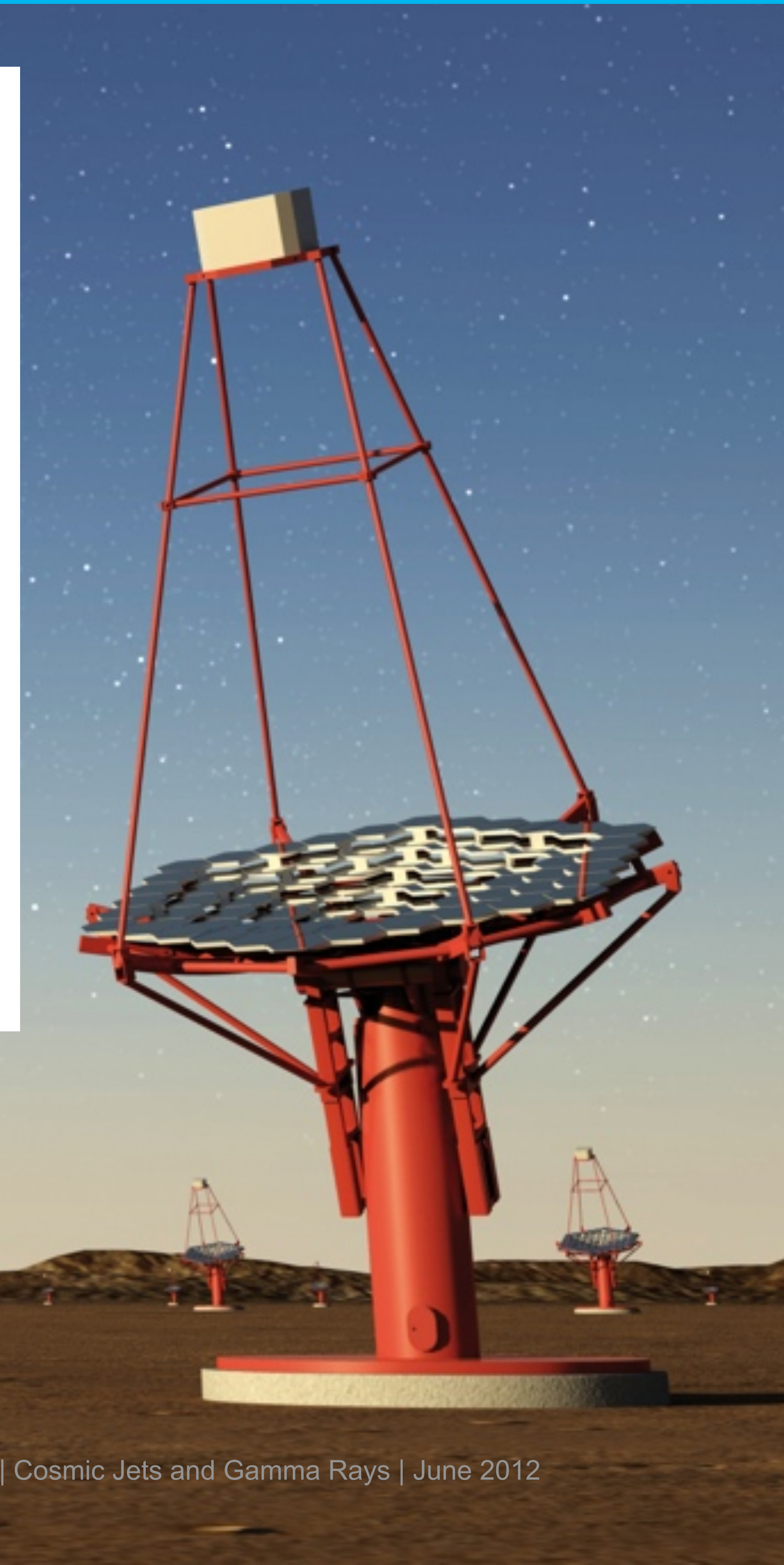
4 bins per decade energy
(equal bin size on log scale)

Cherenkov Telescope Array: Array optimization



Cherenkov Telescope Array: Site selection



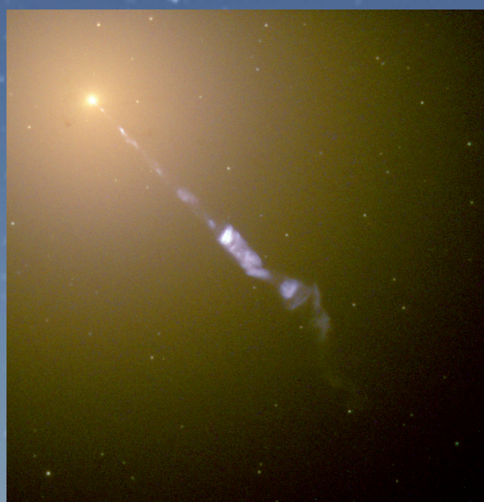


Site selection in progress

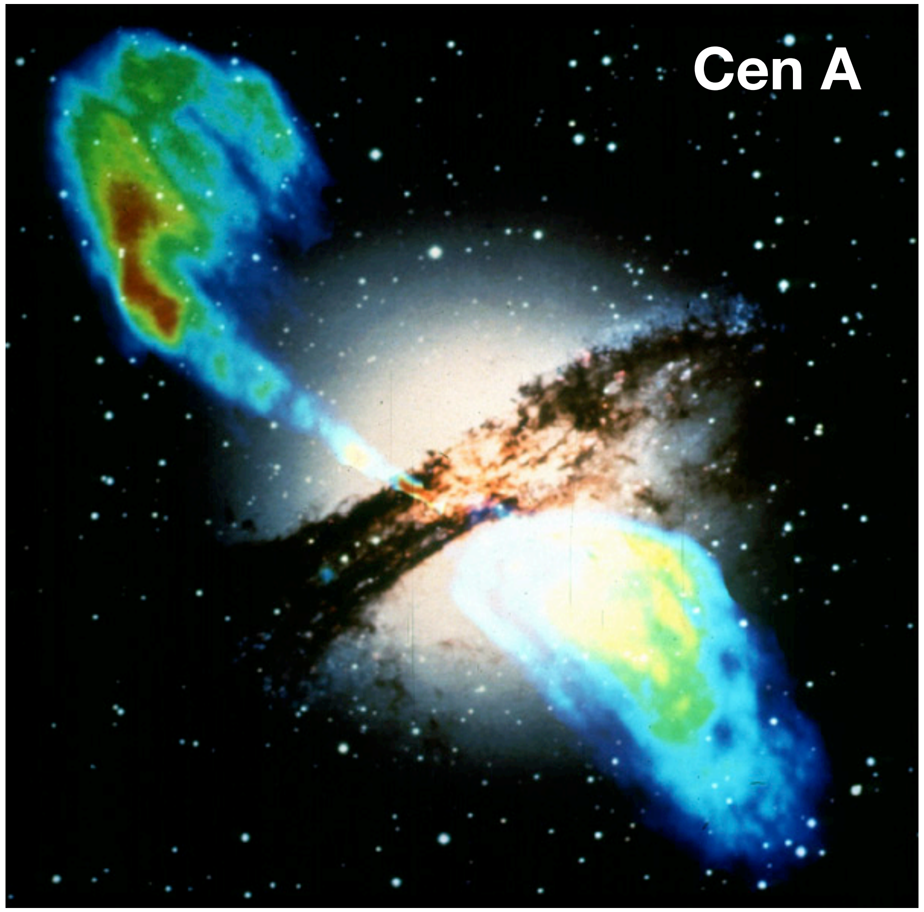
South: Namibia, Argentinia

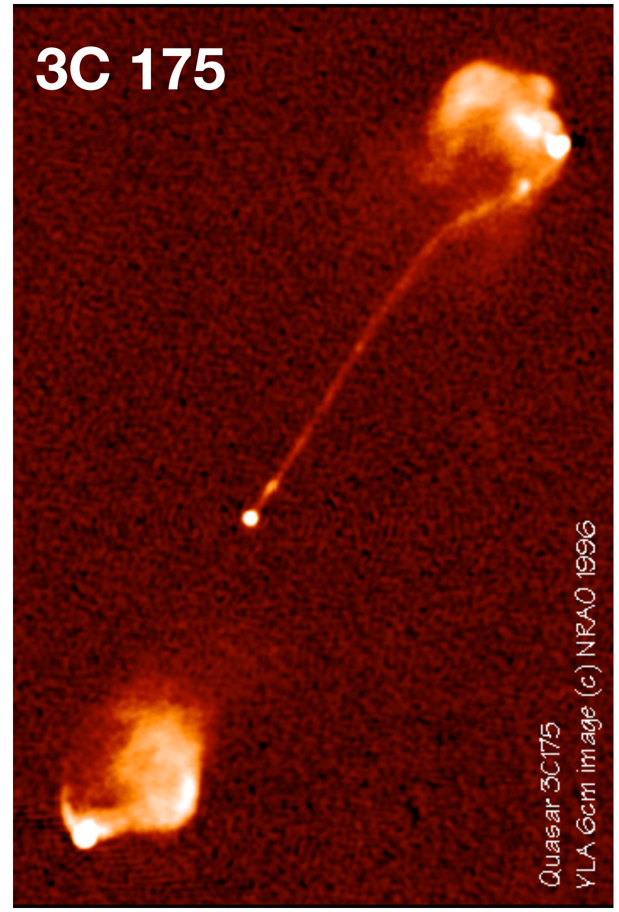
North: Arizona, Mexico, Spain, India, China

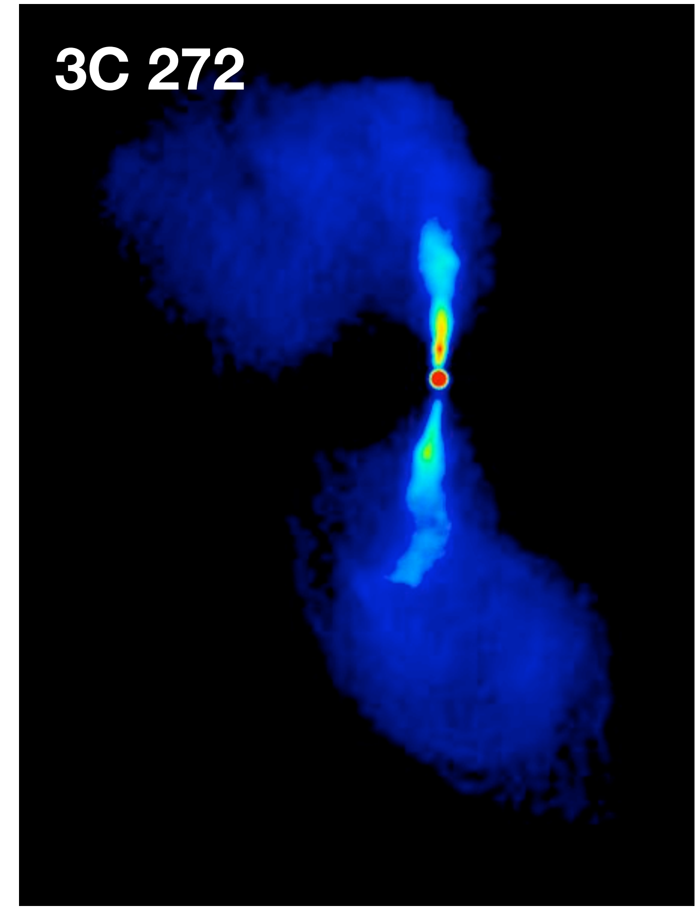
Summary

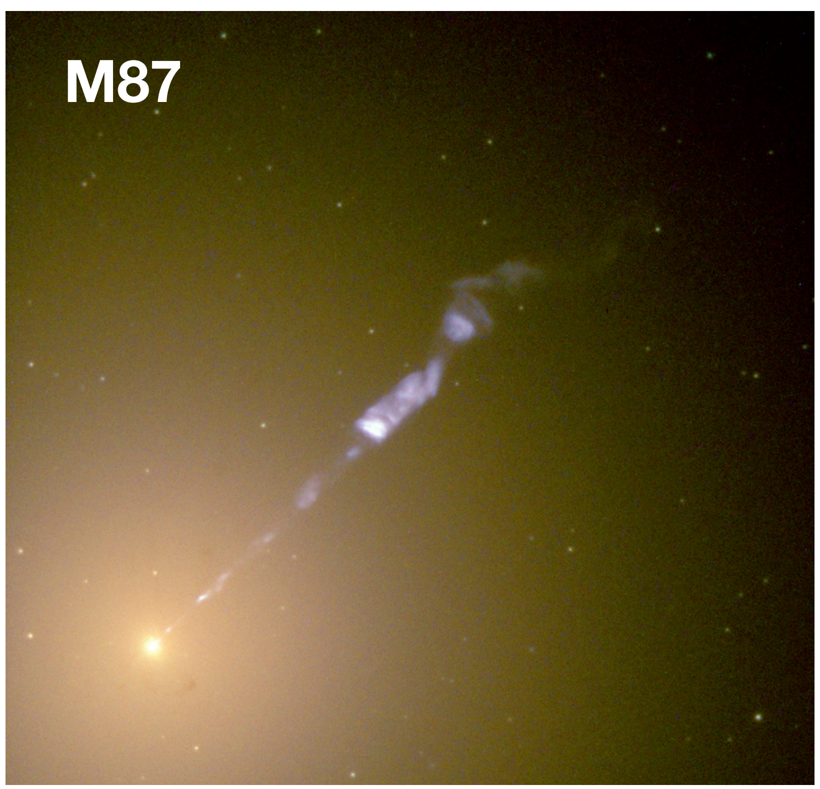


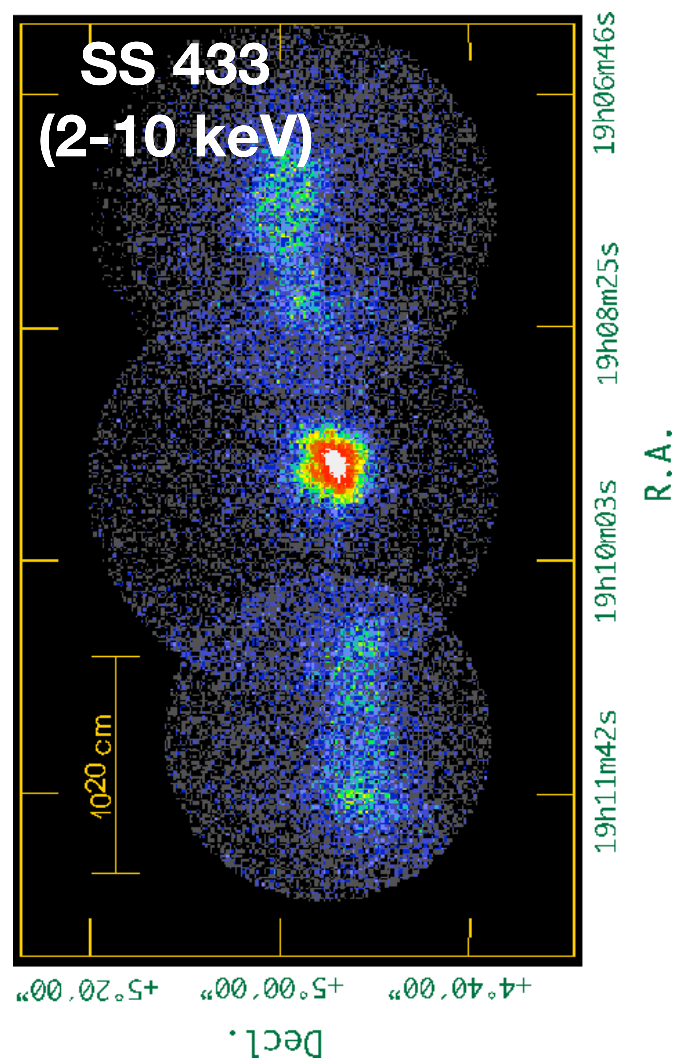
- **Jets are powerful particle accelerators**
- **Binaries constitute a small but unique population of high-energy sources**
  - *first binary detected through gamma-ray observations*
  - *excellent laboratories for particle acceleration, gamma-ray production, emission and absorption processes*
  - *maybe a bit complicated…"just" a matter of better data*
- **CTA will be able to probe the physical processes in jets with high precision**
  - *…and do many more cool things*

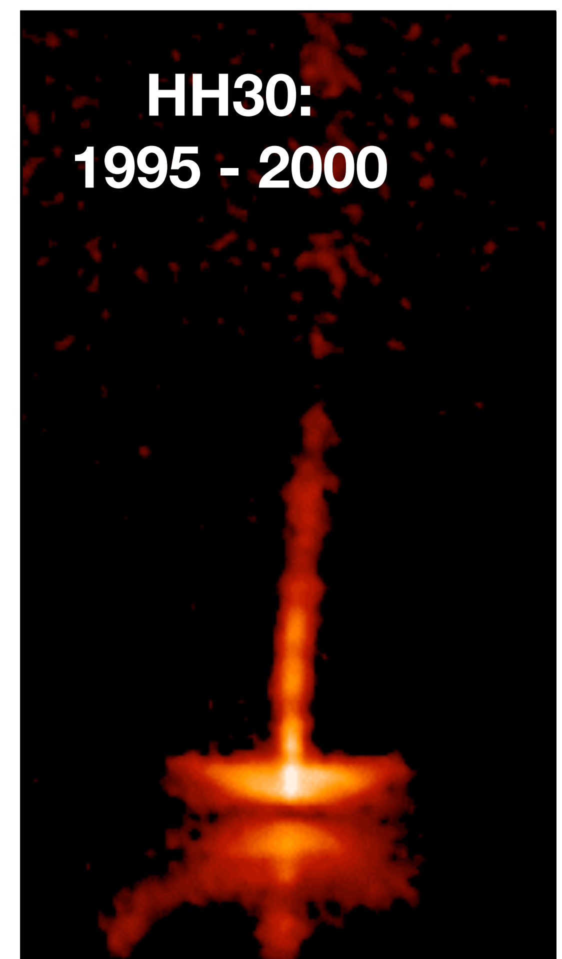

Cen A


3C 175
Quasar 3C175
VLA 6cm image (c) NRAO 1996

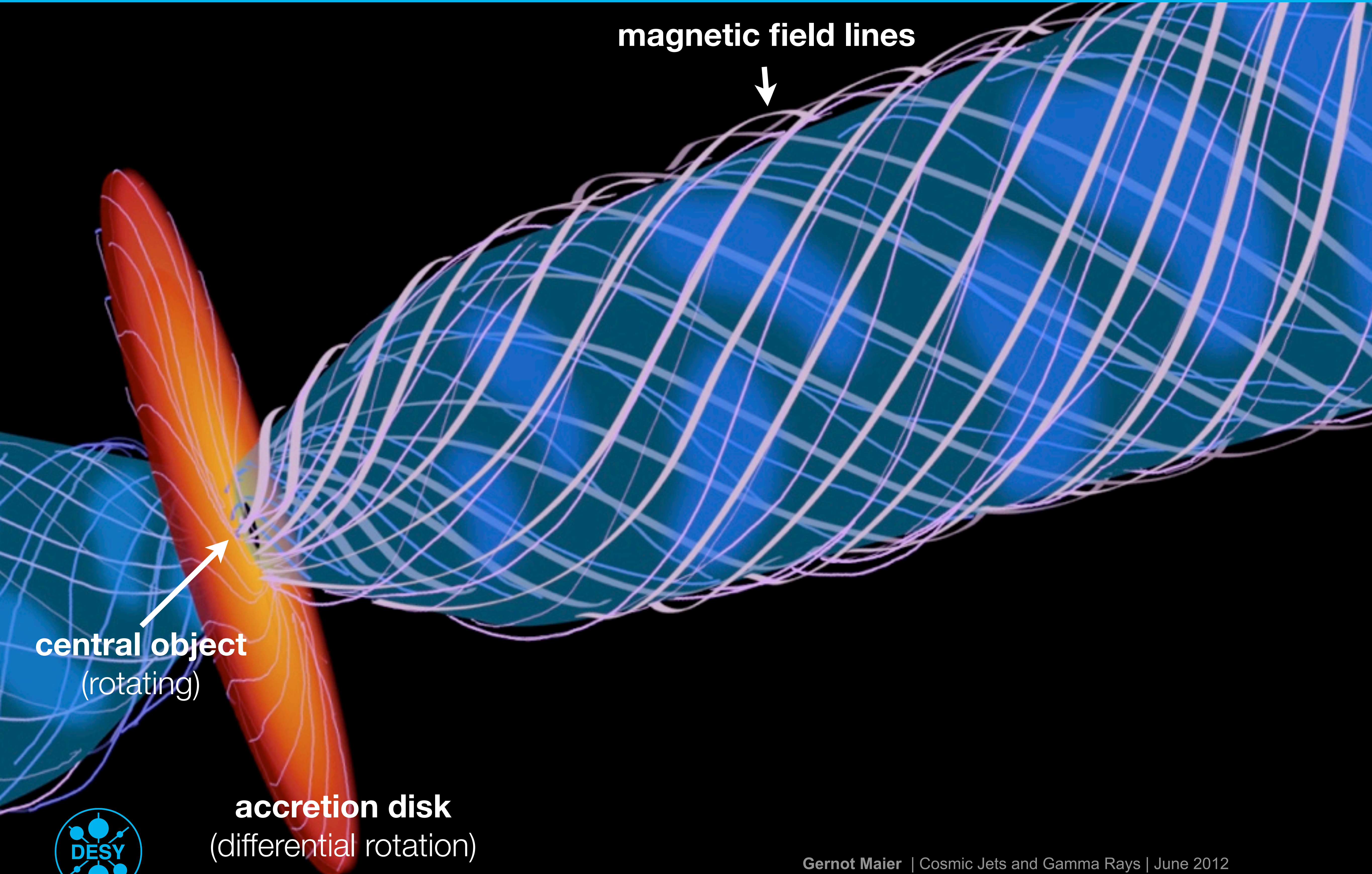

3C 272


M87

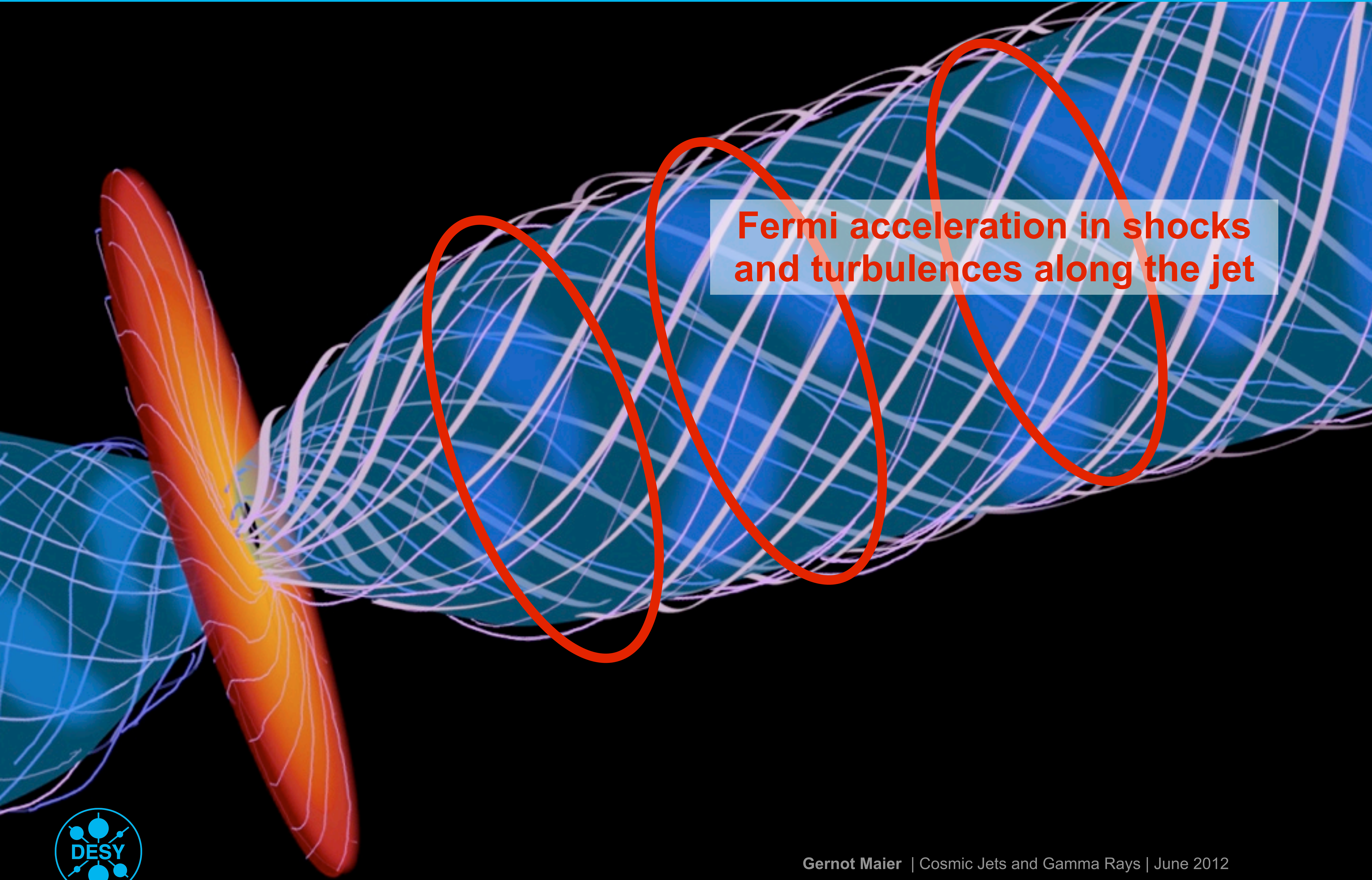

SS 433
(2-10 keV)
10^20 cm
19h06m46s
19h08m25s
19h10m03s
19h11m42s
R.A.
+5°20'00"
+5°00'00"
+4°40'00"
Decl.


HH30:
1995 - 2000

Acceleration: related to accretion or ejection?



Acceleration: related to accretion or ejection?



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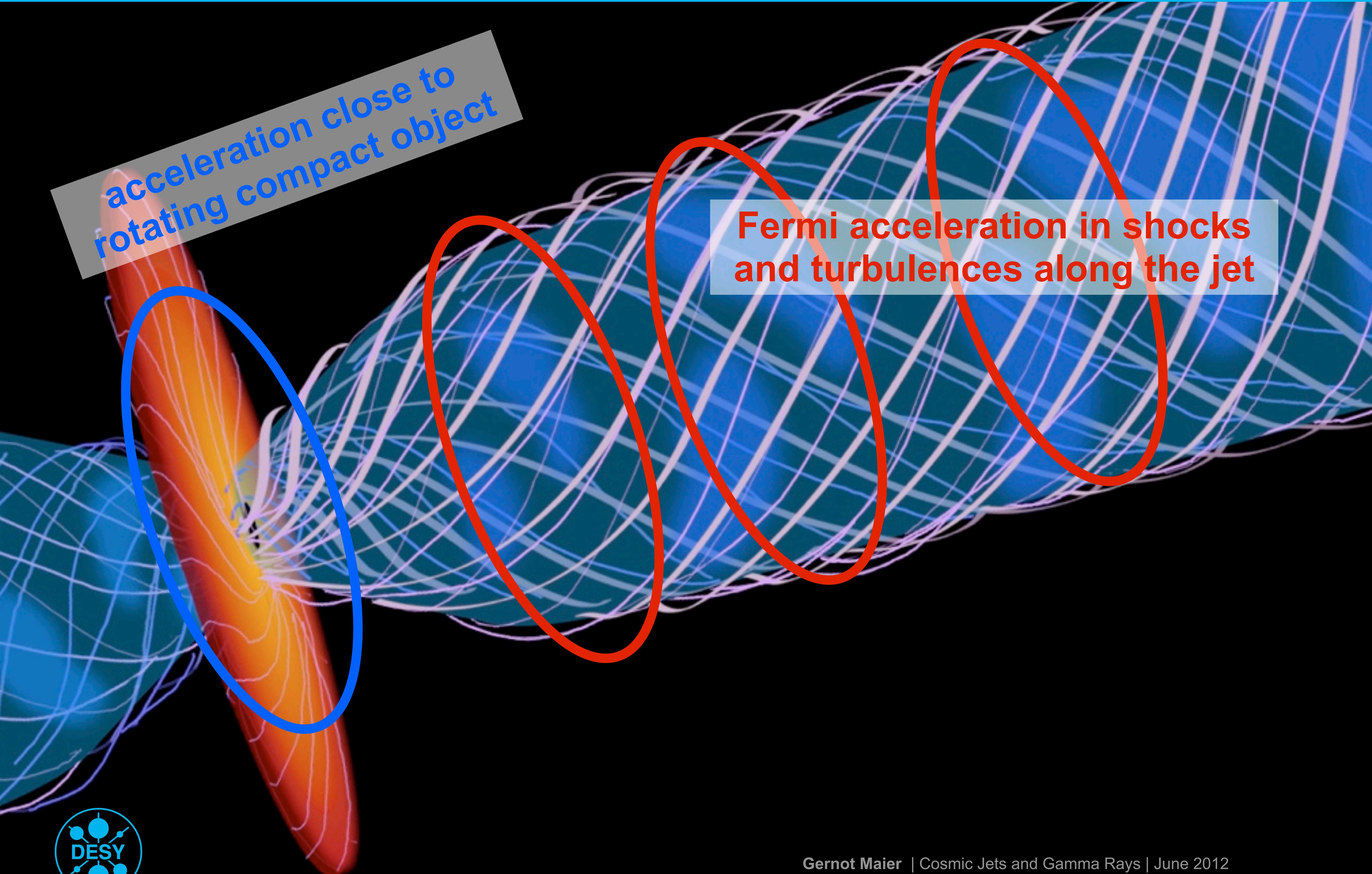

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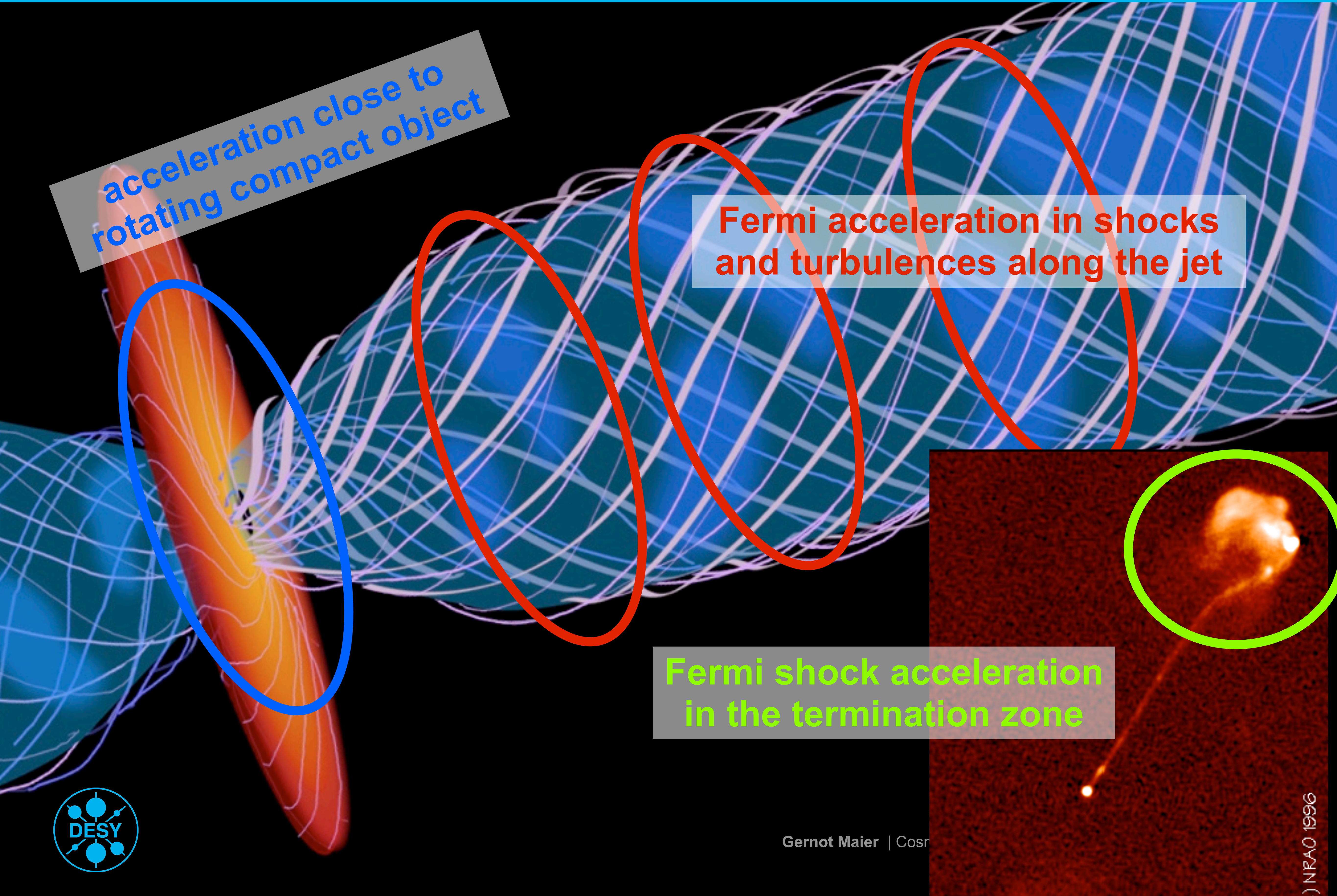
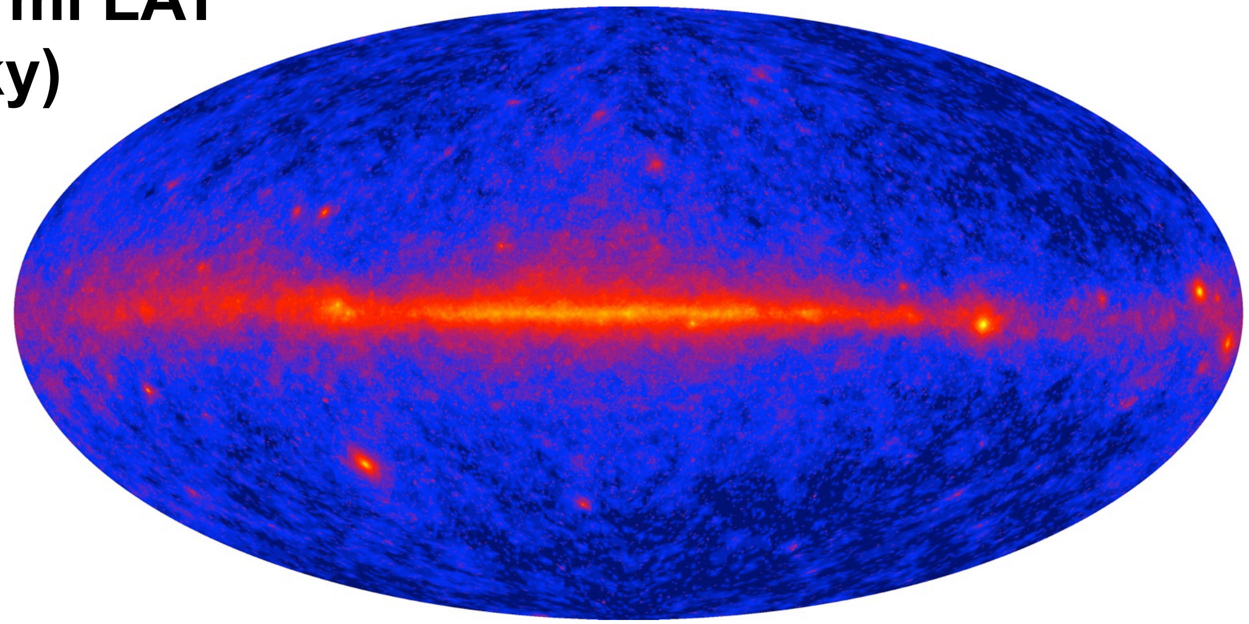
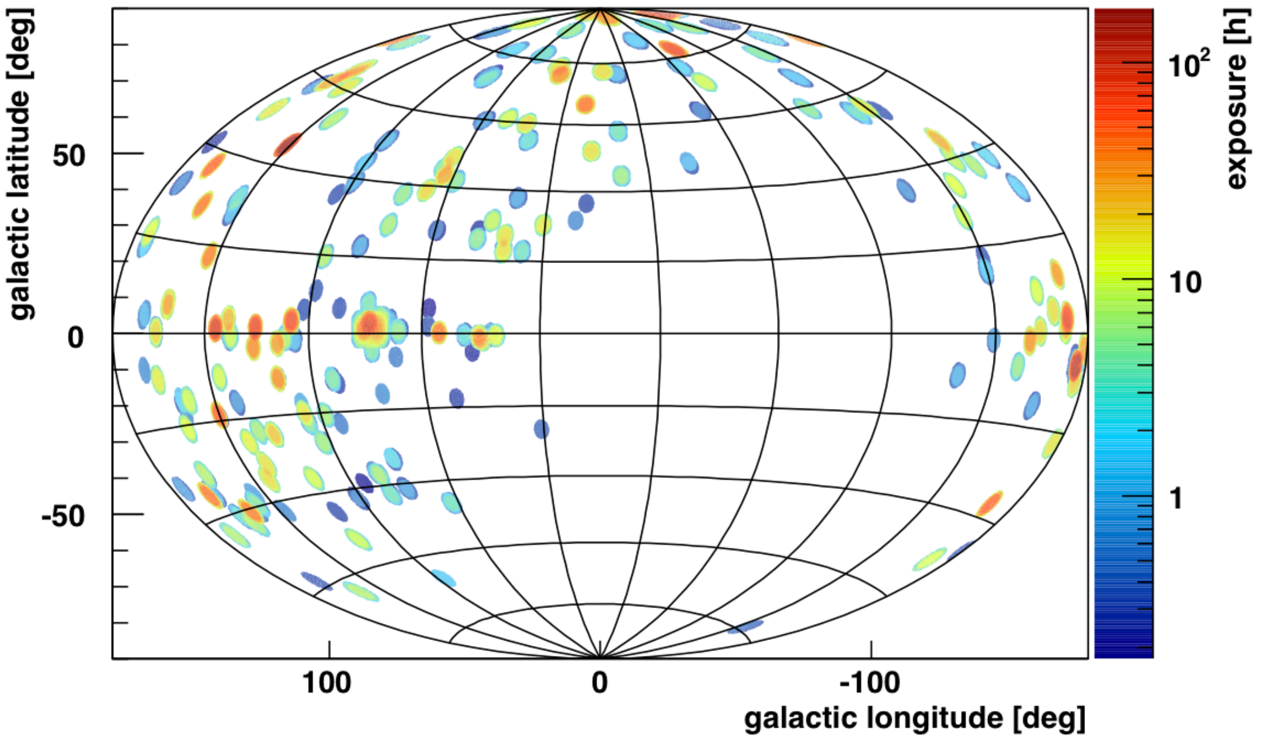


Field of View

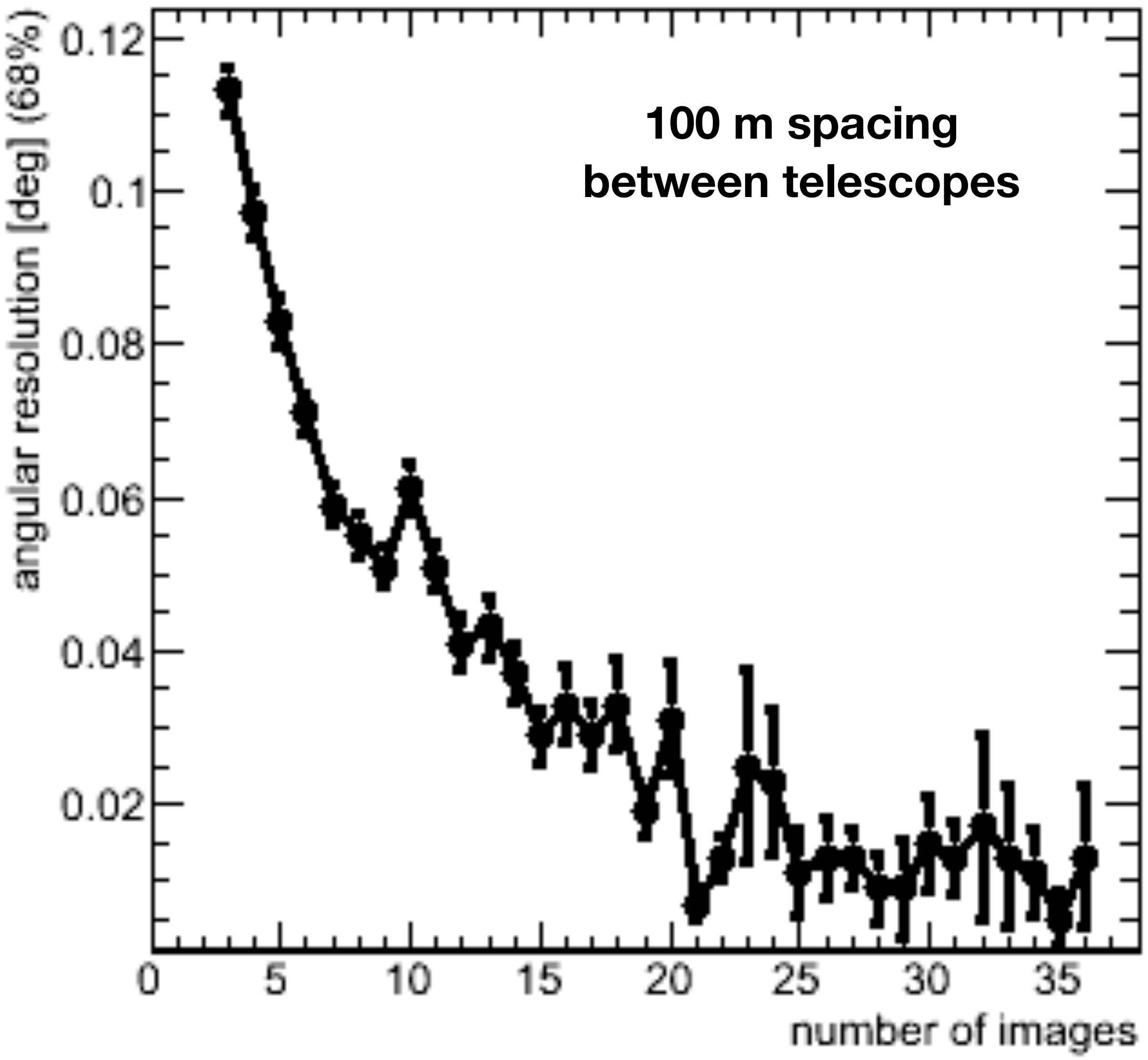
One year of Fermi LAT
(FOV 20% of sky)



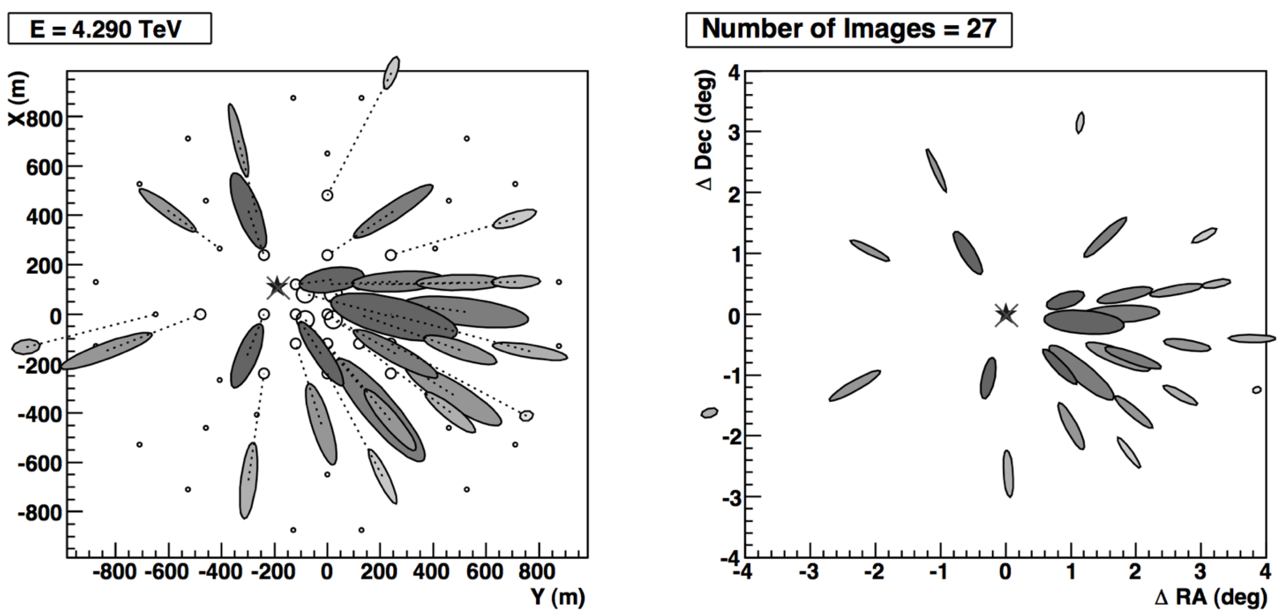
Three years of VERITAS
observations
(FOV 3.5°)



More telescopes are better...



majority of effective area is inside the array
improved angular resolution and better background rejection



The CTA Consortium 2010 (arXiv:1008:3703)

event confinement