MWL behavior of Cyg-X1: a review

New results in the gamma-ray energy band

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MAX-PLANCK-GESELLSCHAFT

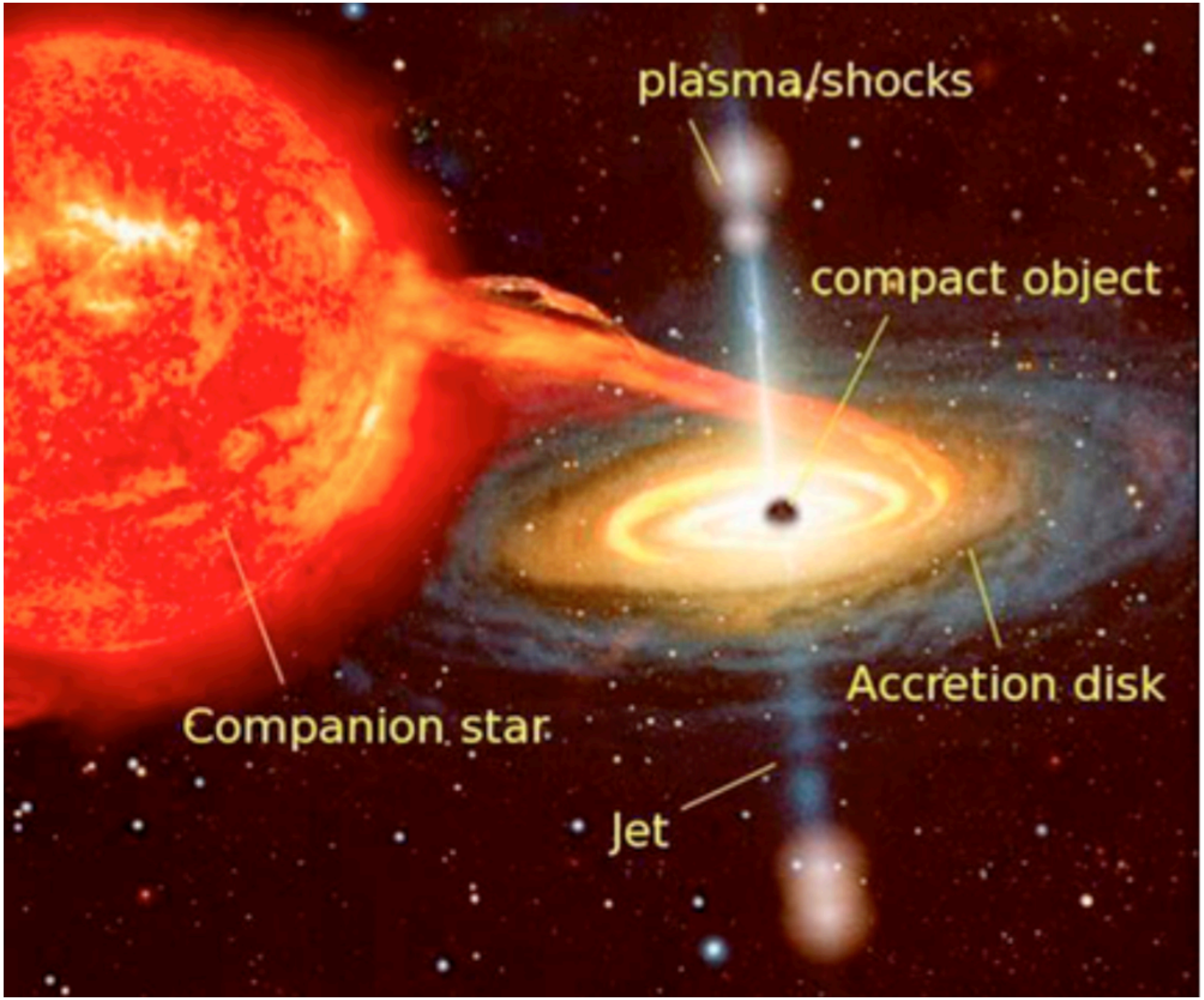
Workshop on variable gamma-ray sources, Tokyo July 2017

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Outline

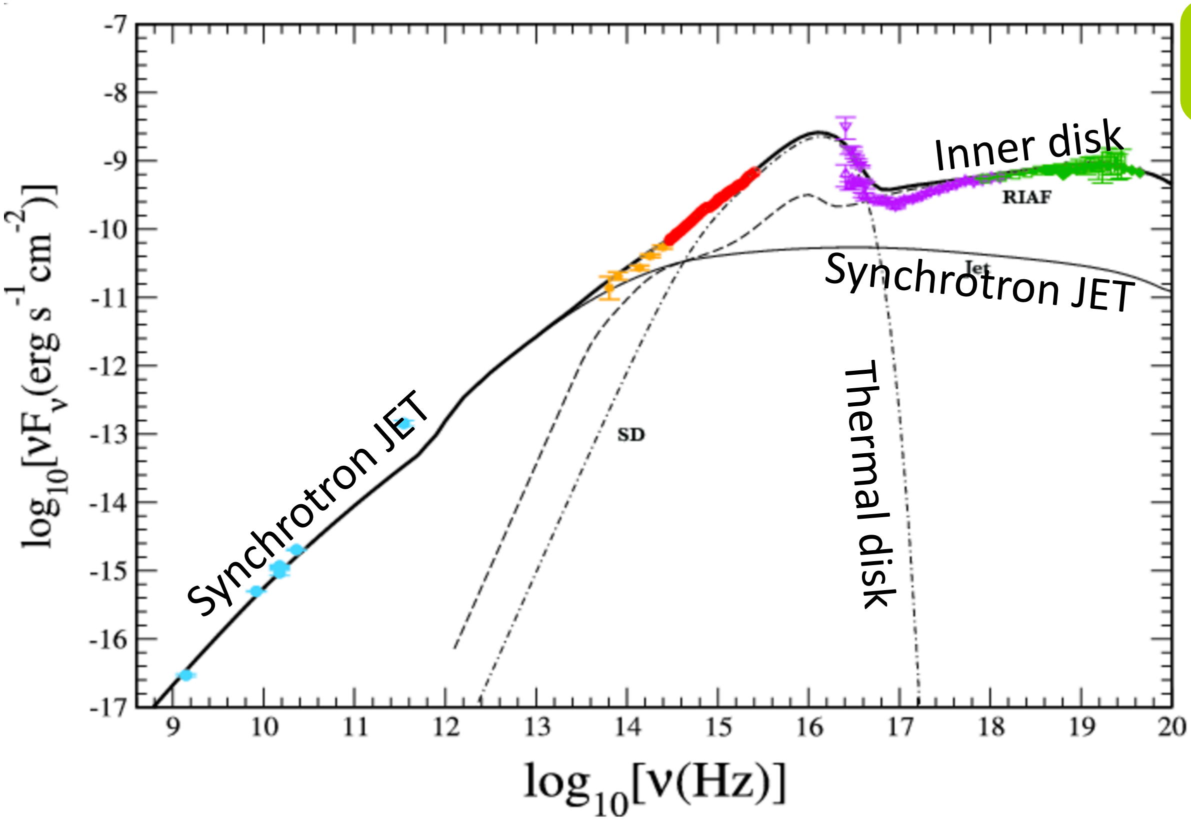
- Introduction to microquasars
- Cygnus X-1: the prototype black hole microquasar and its peculiarities
- Cygnus X-1 in the gamma-ray band: new results

Microquasars



Microquasars: MWL emitters

TRANSIENT SOURCES: USUALLY DISCOVERED IN X-RAYS WHEN FLARING



SYNCHROTRON EMITTING JETS

2 X-RAY SPECTRAL COMPONENTS REQUIRE 2 DIFFERENT ACCRETION FLOW STRUCTURES:

1. a cold optically thick Shakura & Sunyaev disk
2. a hot optically thin flow (CORONA)

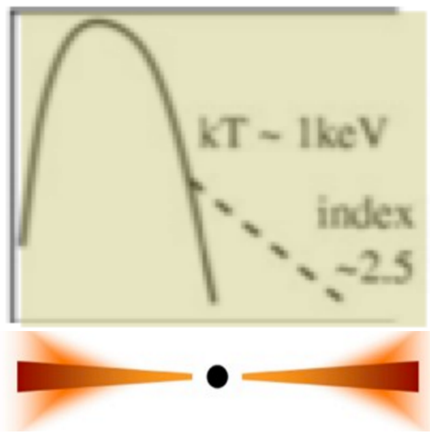
THE FORMATION OF THE CORONA IS DUE TO INCOMPLETE THERMALIZATION CAUSED BY A LOWER ACCRETION RATE

The X-ray spectral states

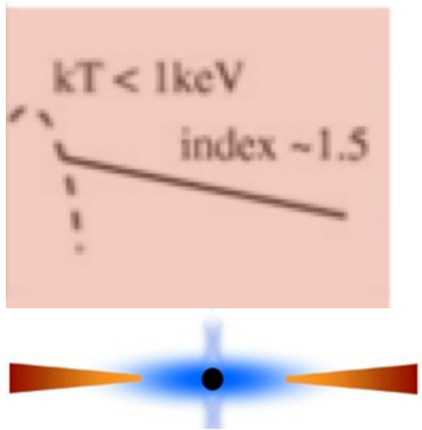
THE RELATIVE CONTRIBUTION OF THE TWO ACCRETION FLOWS DETERMINE THE 2 MAIN X-RAY SPECTRAL STATES

(Done+2007)

SOFT



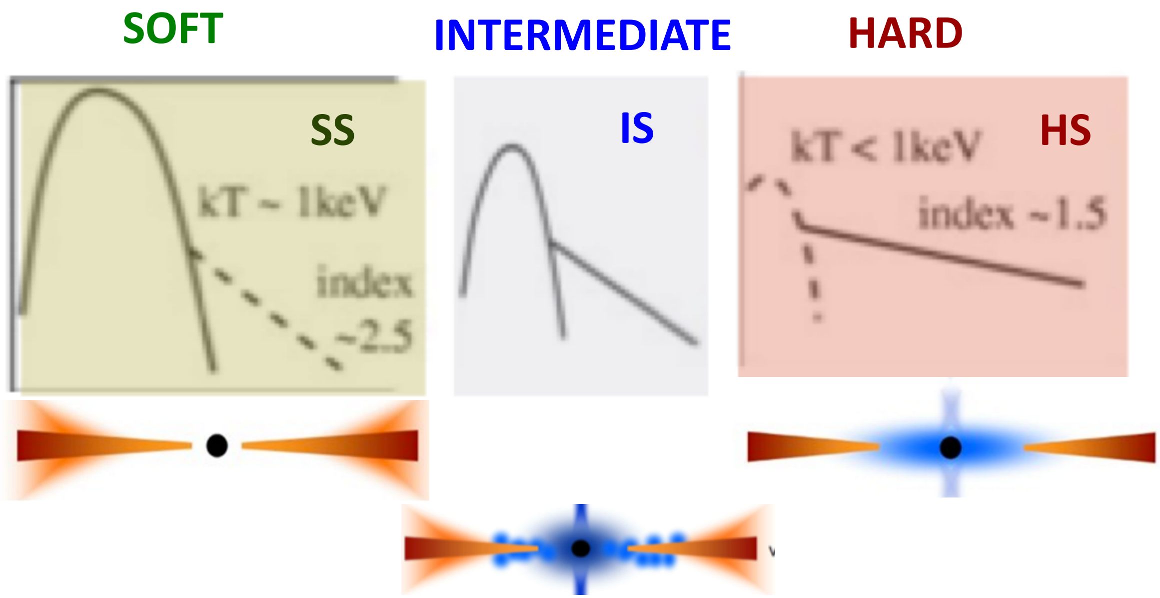
HARD



IN THE CORONA HEATING AND COOLING **(THERMAL COMPTONIZATION)** ARE BALANCED BY THE POWER OF ELECTRONS TO THAT OF THE SEED PHOTONS ILLUMINATING THEM

The X-ray spectral states

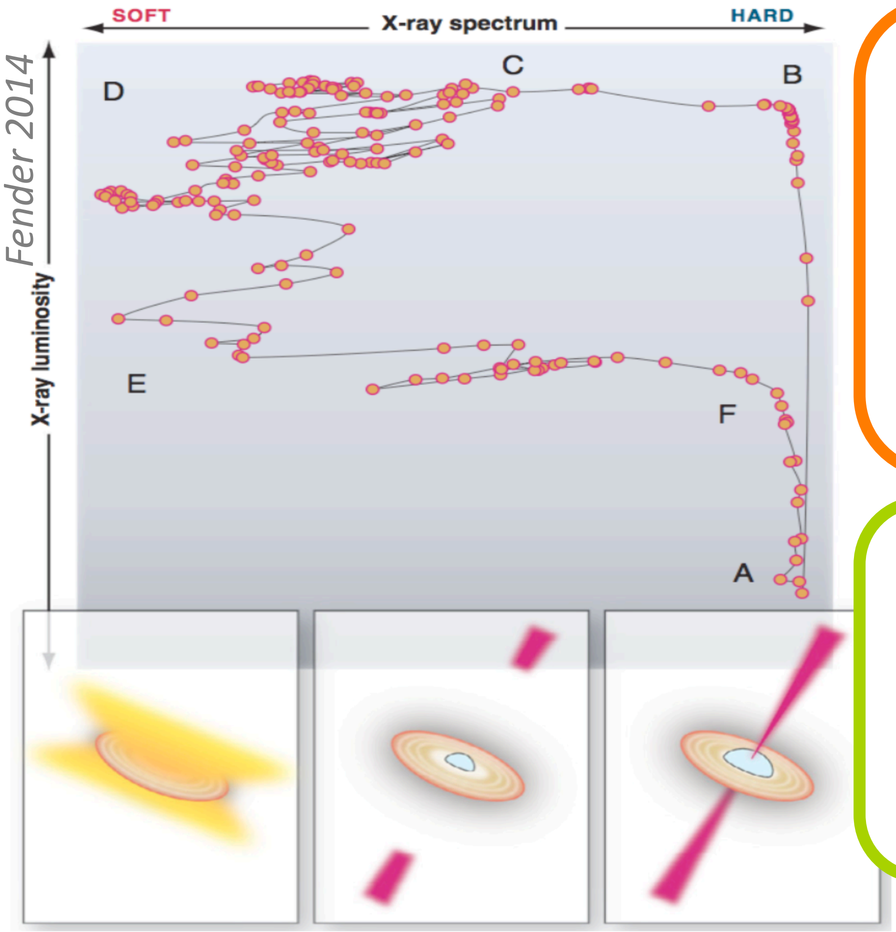
THE RELATIVE CONTRIBUTION OF THE TWO ACCRETION FLOWS DETERMINE THE 2 MAIN X-RAY SPECTRAL STATES



THE **INTERMIDIATE STATE** IS **SHORT-LIVED**

Disk-jet coupling

THE SEQUENCE OF THE STATES FOLLOWS A HYSTERESIS
(Fender 2004)



Fender 2014

IN THE HARD STATE: WEAK BUT STEADY JETS WITH A FLAT SPECTRUM AND LOW LEVEL OF POLARIZATION (continuously replenished alá FSRQ jets)
(Fender 2001, Brocksopp 2013, Russell+ 2014)

IN THE HARD-TO-SOFT TRANSITION: STRONG DESCRETE EJECTA
(RADIO KNOTS: INTERNAL SHOCKS IN A FLOW OF VARIABLE SPEED)
(Mirabel+94, MillerJones+2012)

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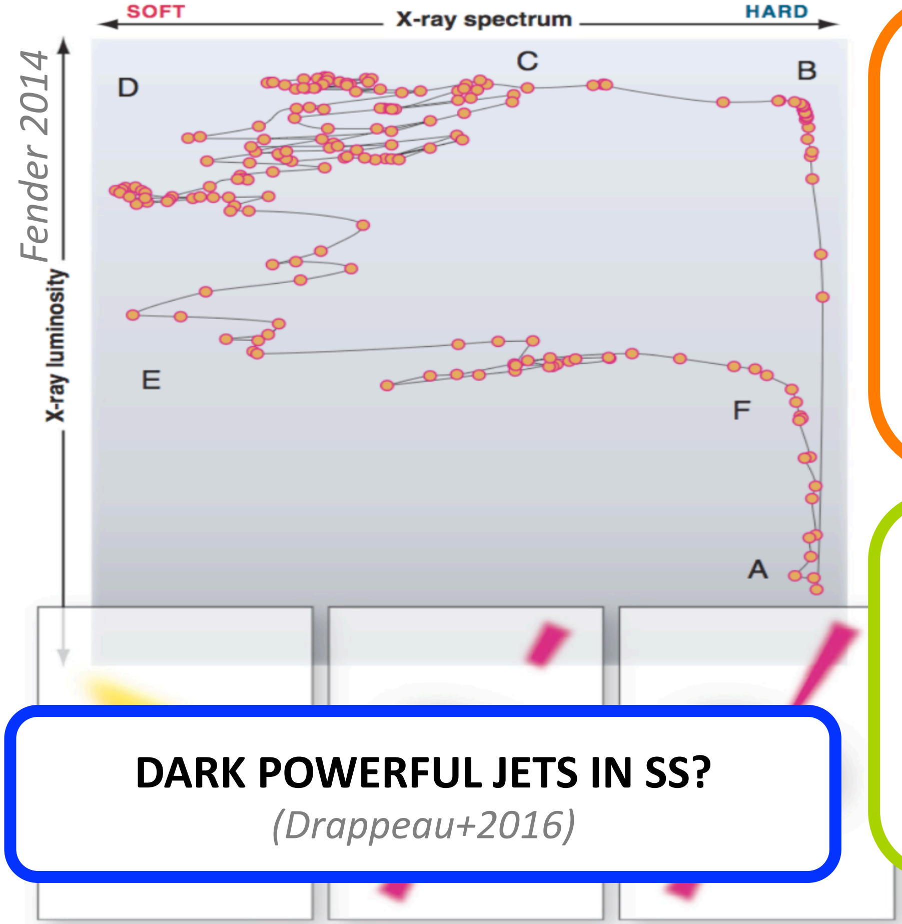

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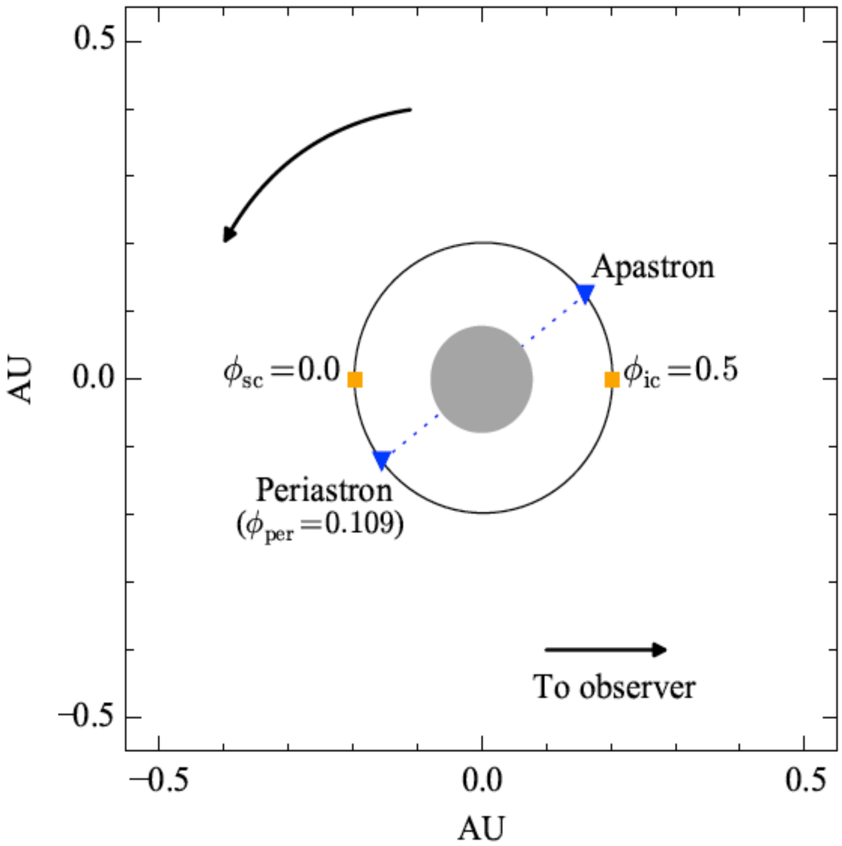
(Mirabel+94, MillerJones+2012)

DARK POWERFUL JETS IN SS?
(Drappeau+2016)

Cygnus X-1

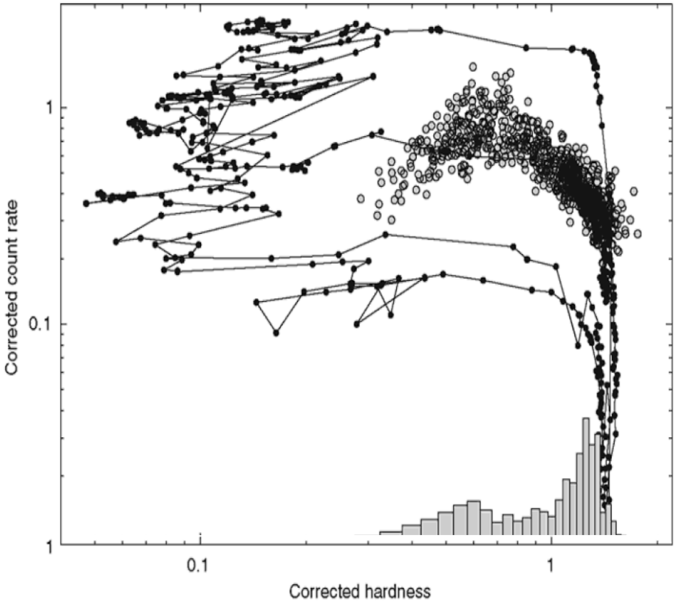
- 15 $M_\odot$ BH *(Oroz+2011)*
- 09.7Iab **SUPERGIANT** *(Walborn 1973)* WITH 25-35 $M_\odot$ *(Ziolkoswki2014)*
- 1.86 kpc *(Reid+2011)*
- ORBITAL PERIOD: **5.6 d** T_0=52872.788 @ SUPC *(Brocksopp1999,Szstek2007, Gies 2008)*
- SUPERORBITAL MODULATION WITH A 300 d PERIOD *(Rico2008, Zdziarski+2011)*

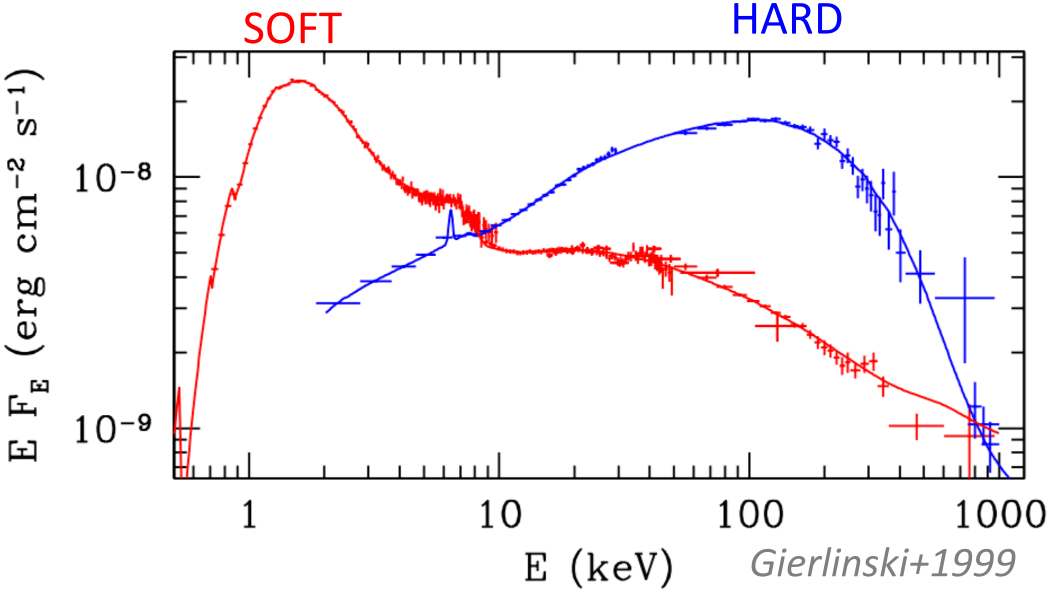


Cygnus X-1: X-ray states

SHOWS THE USUAL SOFT/HARD STATES
(Done+07, Belloni+ 2010)

credits to T. Belloni



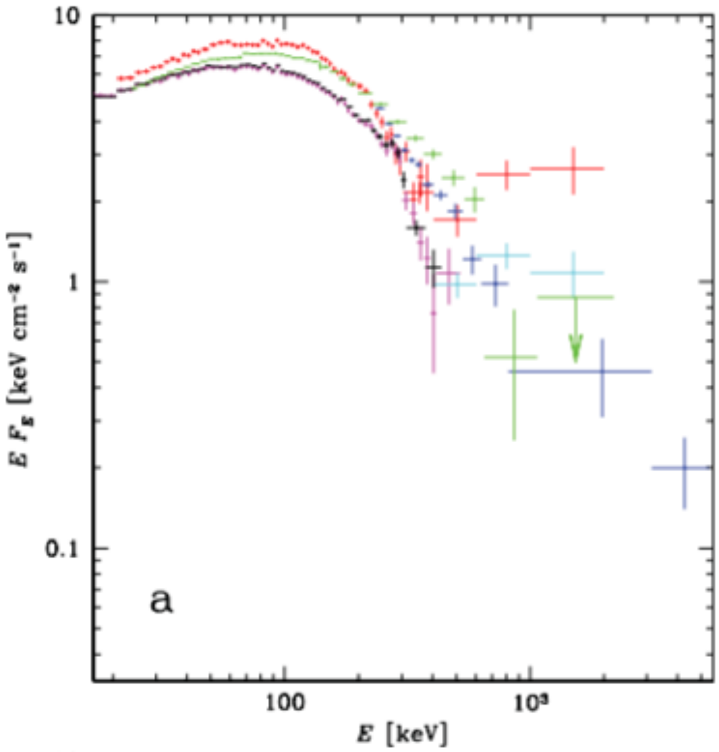


Gierlinski+1999

MOSTLY IN THE HARD STATE (?) AND NEVER IN A FULLY DOMINATED DISK STATE (SS)
(Gringberg+13)

Cygnus X-1: an extra-tail

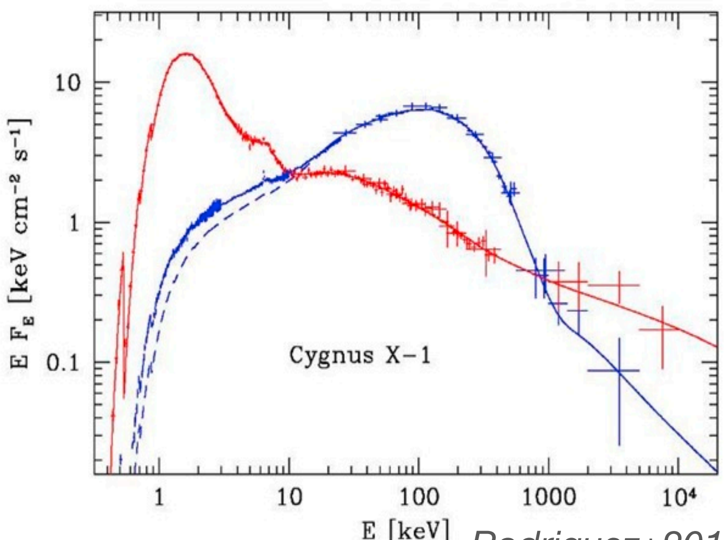
Zdzizarski+2012



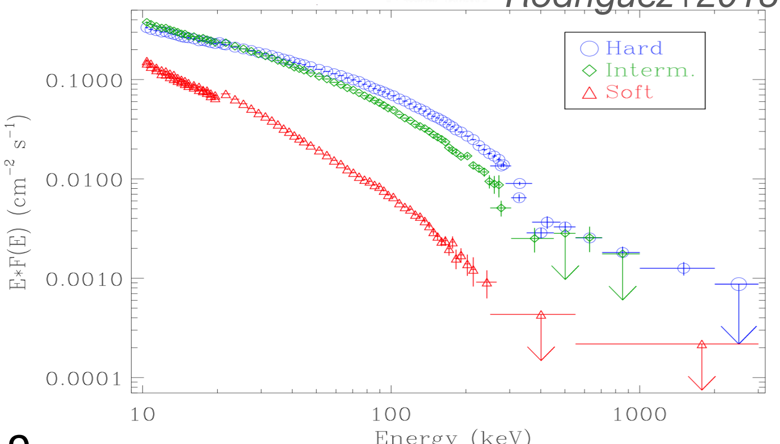
EXPERIMENTALLY
SOME SPECTRAL DISCREPANCES BETWEEN
DIFFERENT INSTRUMENT RESULTS

Cygnus X-1: an extra-tail

McConnell+2002



Rodriguez+2015

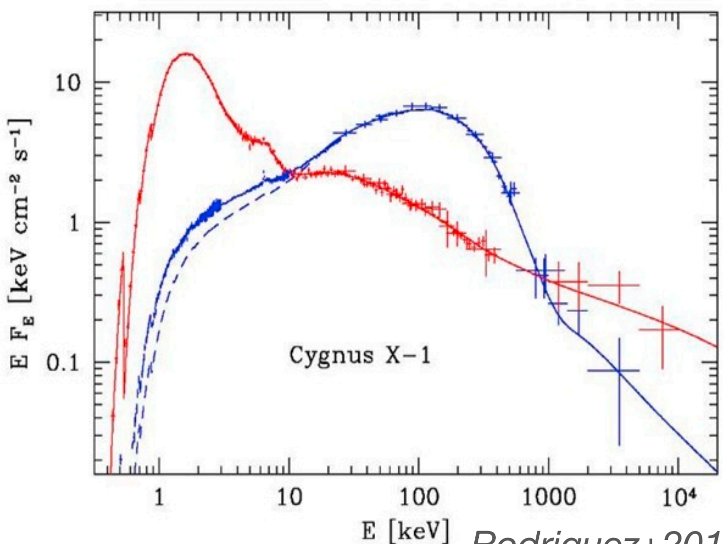


EXPERIMENTALLY
SOME SPECTRAL DISCREPANCES BETWEEN
DIFFERENT INSTRUMENT RESULTS

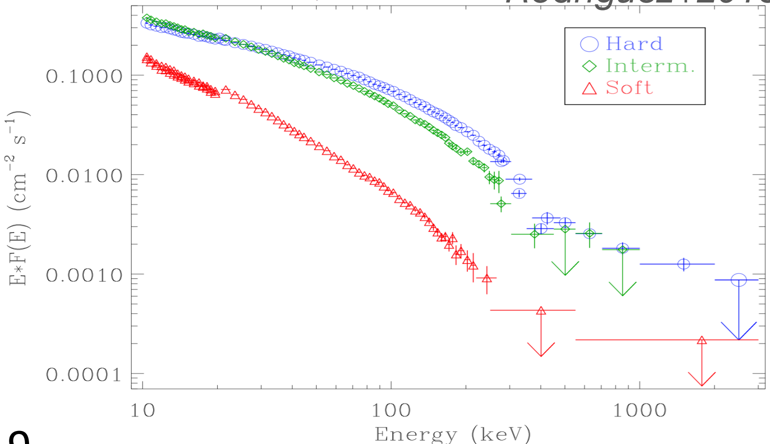
BOTH IN THE HS OR IN THE SS? VARIABLE?
(McConnell+02,Zdzizarski+12,Rodriguez+15)

Cygnus X-1: an extra-tail

McConnell+2002



Rodriguez+2015



EXPERIMENTALLY
SOME SPECTRAL DISCREPANCES BETWEEN
DIFFERENT INSTRUMENT RESULTS

ONLY IN THE HS OR ALSO IN THE SS?
(McConnell+02,Zdzizarski+12,Rodriguez+15)

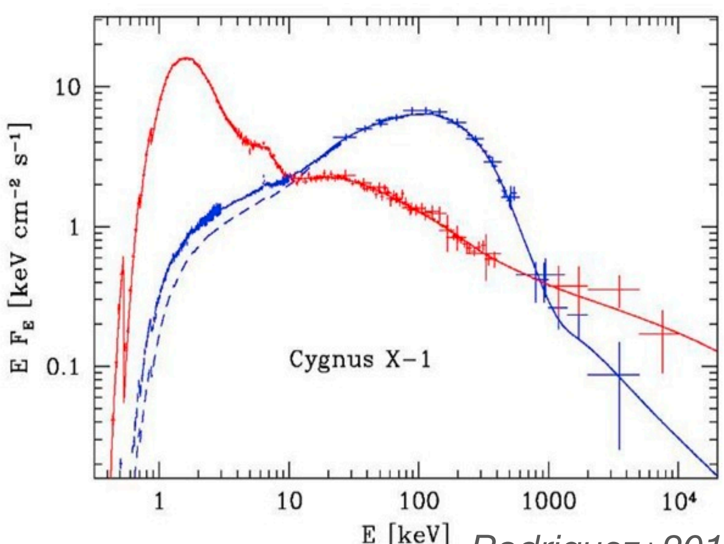
THE **ORIGIN OF THE TAIL** IS NOT CLEAR:

1. **SYNCHROTRON EMISSION FROM THE JET**
2. **HYBRID COMPTONIZATION**

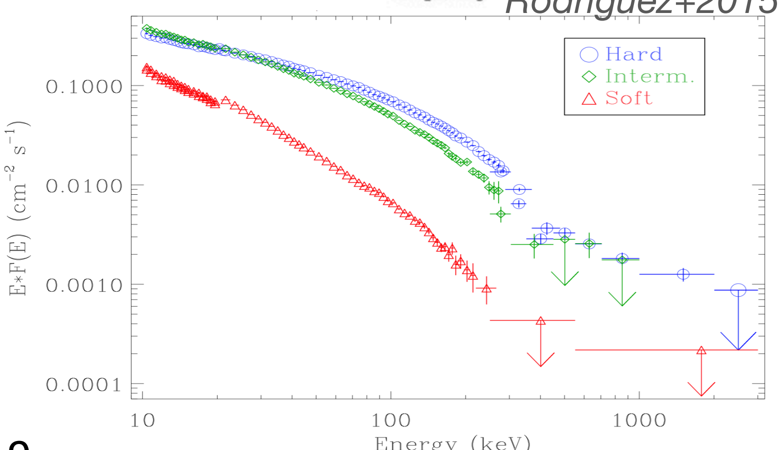
(Zdziarski+12,Laurent+12, Romero14)

Cygnus X-1: an extra-tail

McConnell+2002



Rodriguez+2015



STRONGLY POLARIZED > 400 keV
PF= 75±16%
PA = 42°±3°
(Laurent+11, Jourdain+12)
→ JET SYNCHROTRON

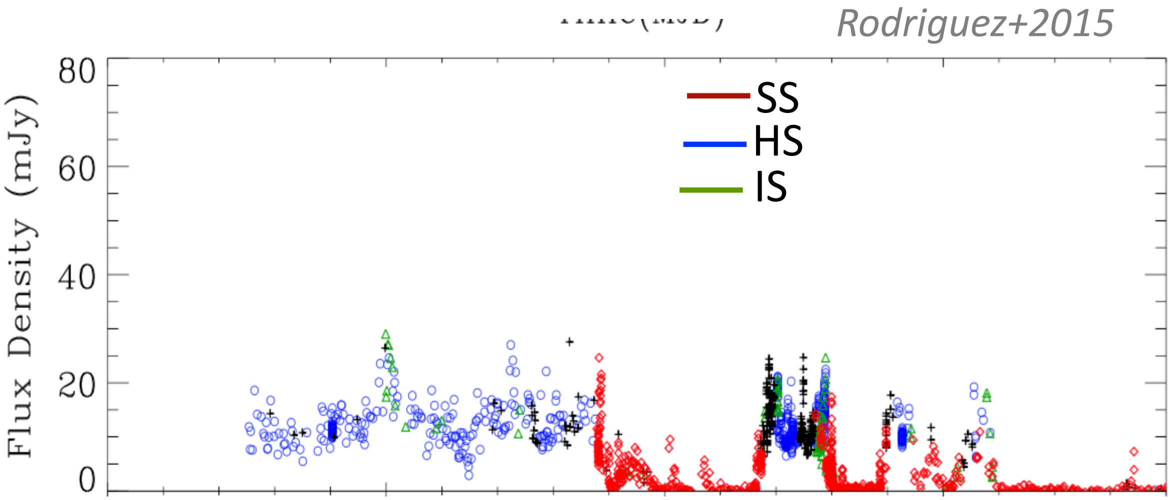
SYNCHROTRON FROM THE JET ONLY UNDER VERY EFFICIENT ACCELERATION (flat electron spectrum) & B ABOVE THE EQUIPARTITION LEVEL
(Zdziarski+14)

THE ORIGIN IS STILL AN OPEN QUESTION

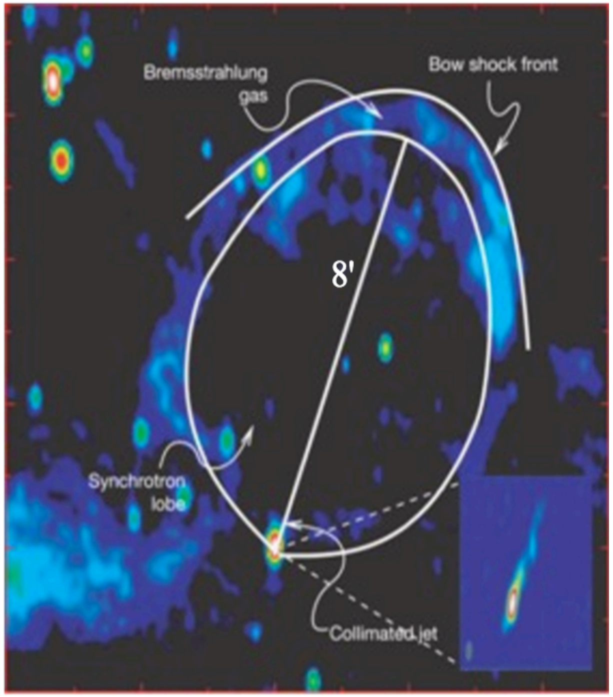
Cygnus X-1 jets

JET POWER: 10^{37} erg/s *(Stirling 2001)*
POWERS A BOW SHOCK NEBULA AT 10^{19} cm *(Gallo+2005)*

Rodriguez+2015



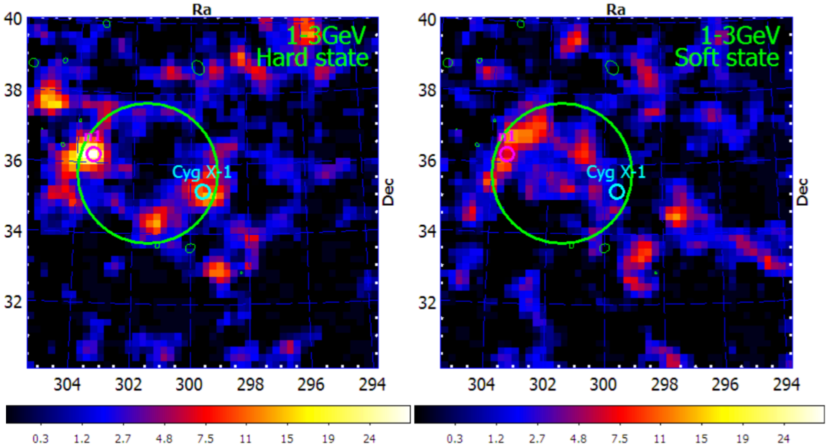
Gallo+2005



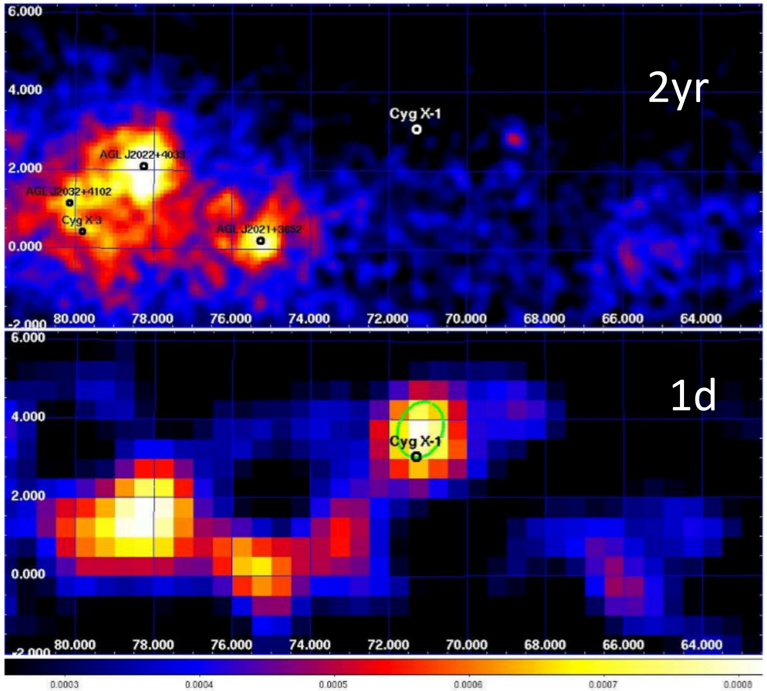
LESS THAN 10% POLARIZATION IN RADIO
(Stirling 2001)

Cygnus X-1 at high energies

HINT OF SIGNAL IN **3.5yr**
Fermi/LAT DATA
(Malyshev+13)



(Sabatini+2010)



THREE 1-2 DAY LONG FLARES HINTED BY AGILE with a F(>100MeV) =2×10^{-6} ph/cm^2/s
(Sabatini+10, Bulagarelli+13)

3σ 1-day FLARES in Fermi/LAT
(Bodaghee+13)

Cygnus X-1 at high energies

HINT OF SIGNAL IN **3.5yr** *Fermi*/LAT DATA

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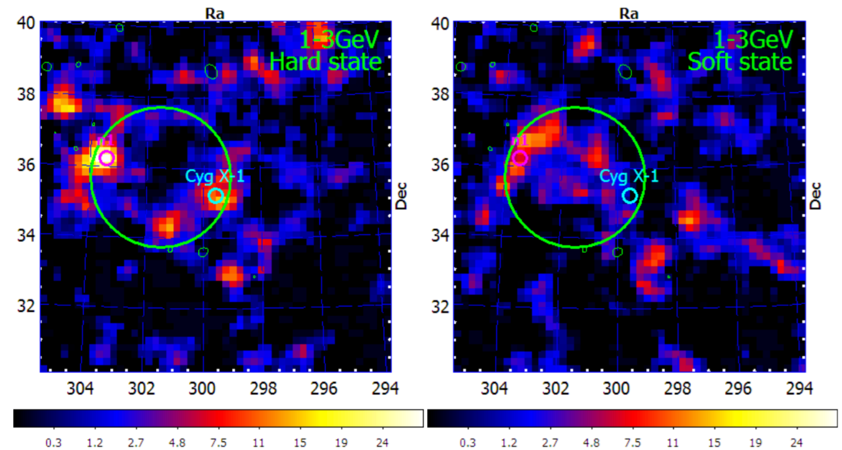
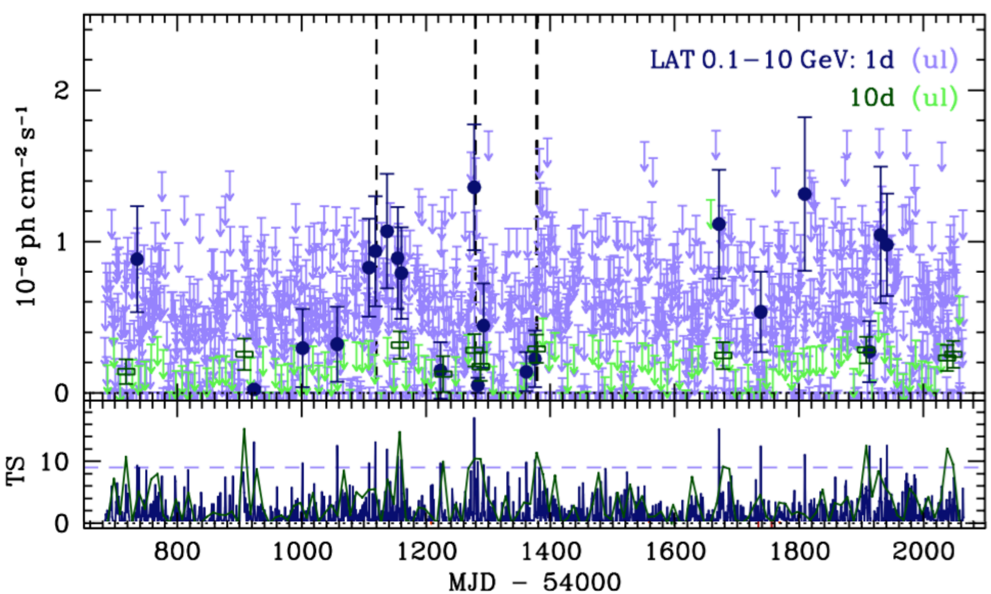


(Bodaghee+2013)



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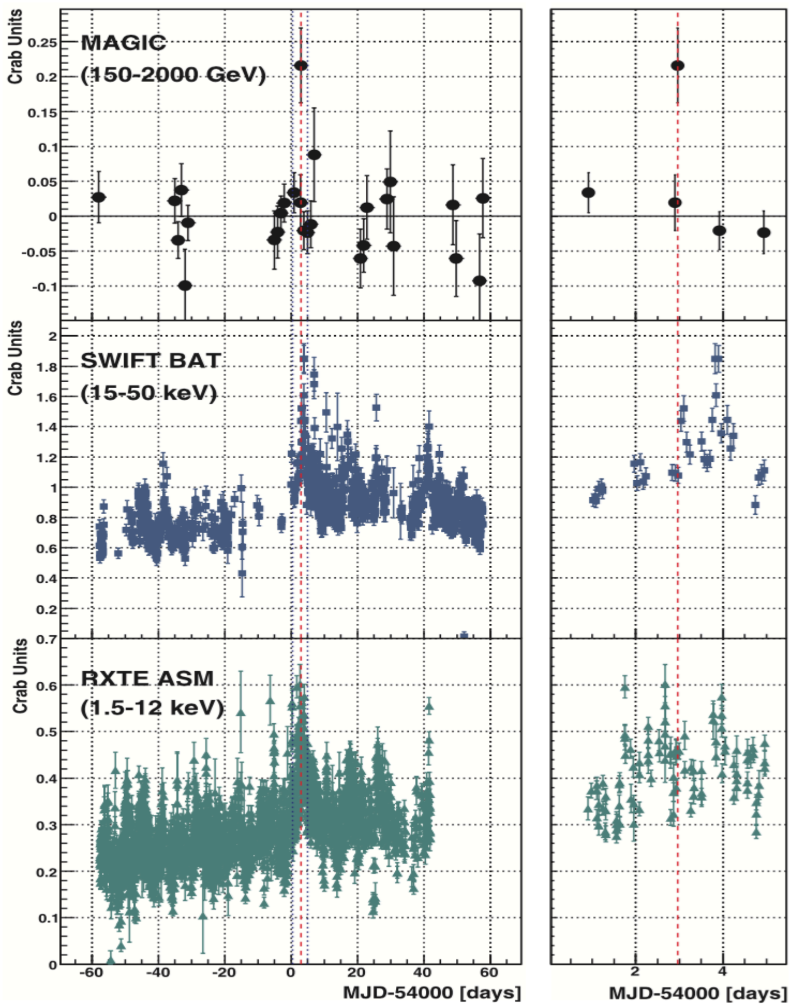
3σ 1-day FLARES in Fermi/LAT

(Bodaghee+13)

Cygnus X-1 at VHE

- **4σ** POST-TRAIAL **80’ ON 2006.09.24** ABOVE 150 GeV *(MAGIC 2007)*
- IN THE **HS**
- **ONE DAY BEFORE A FLARE DETECTED BY INTEGRAL** *(Malzac+2008)*
- **3.2 POWER LAW SPECTRUM** *(MAGIC 2007)*

(MAGIC 2007)

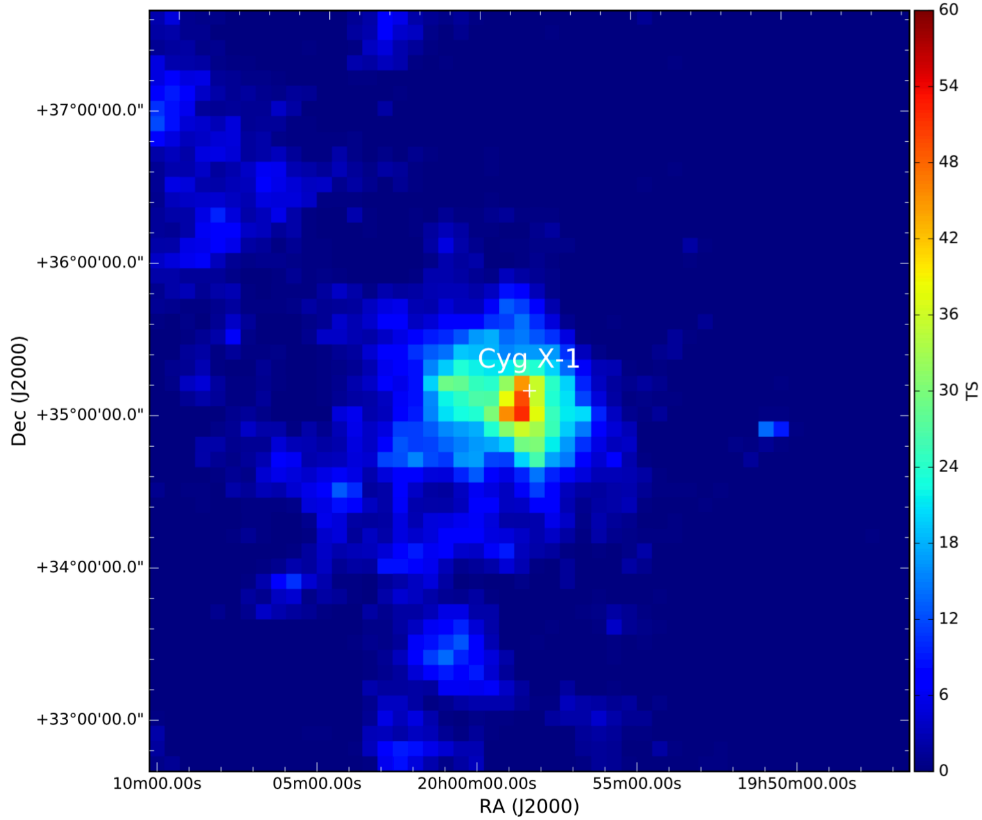


PASS8 Fermi/LAT analysis

7.5yr PASS8 *Fermi*/LAT data
from 20-60 MeV to 500 GeV

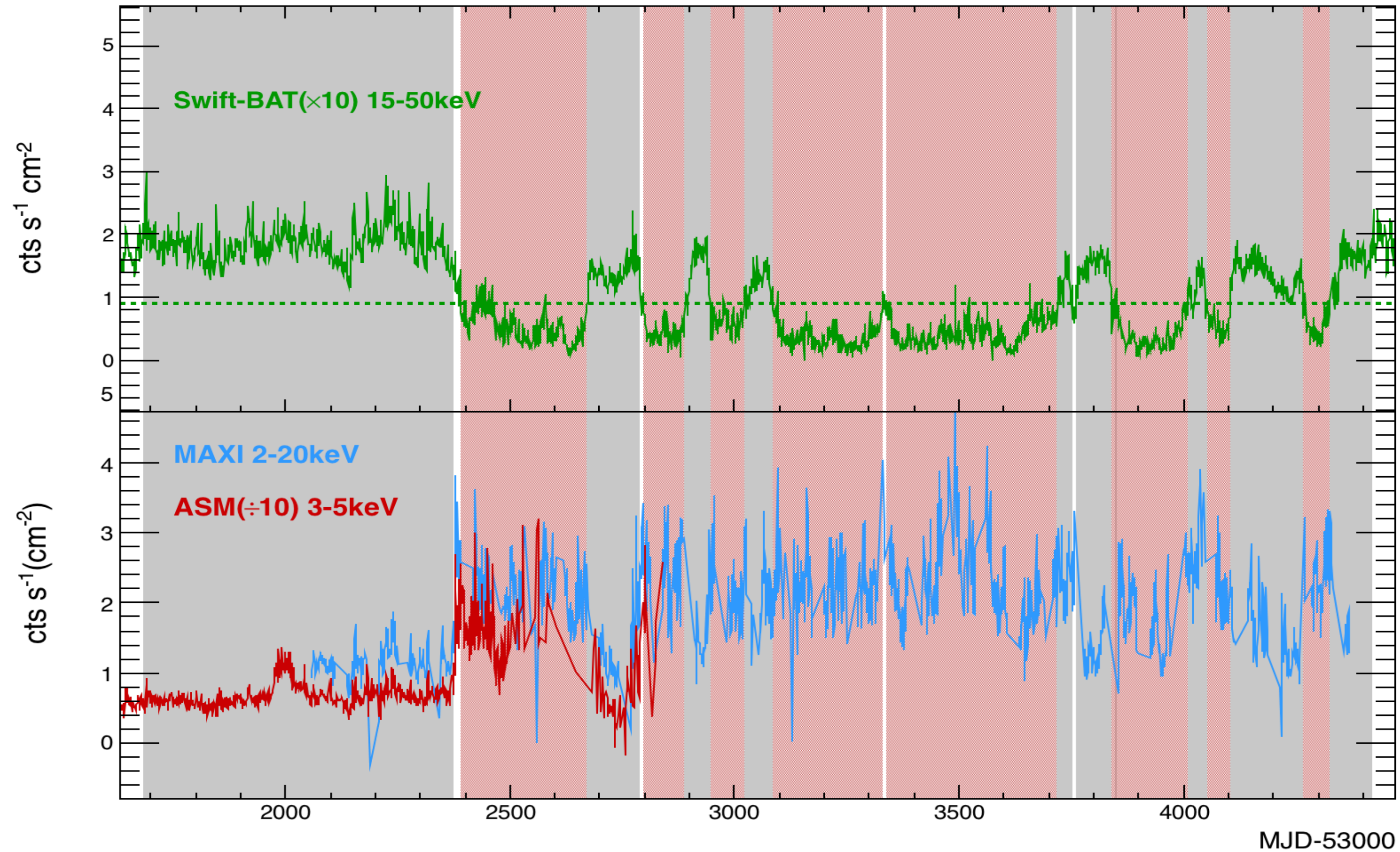
TS=53 @ CygX-1 NOMINAL POSITION
(Zanin+16, Zdziarski+ in arxiv 1607.05059)

(Zanin+ 2016)



Simultaneous X-ray flux

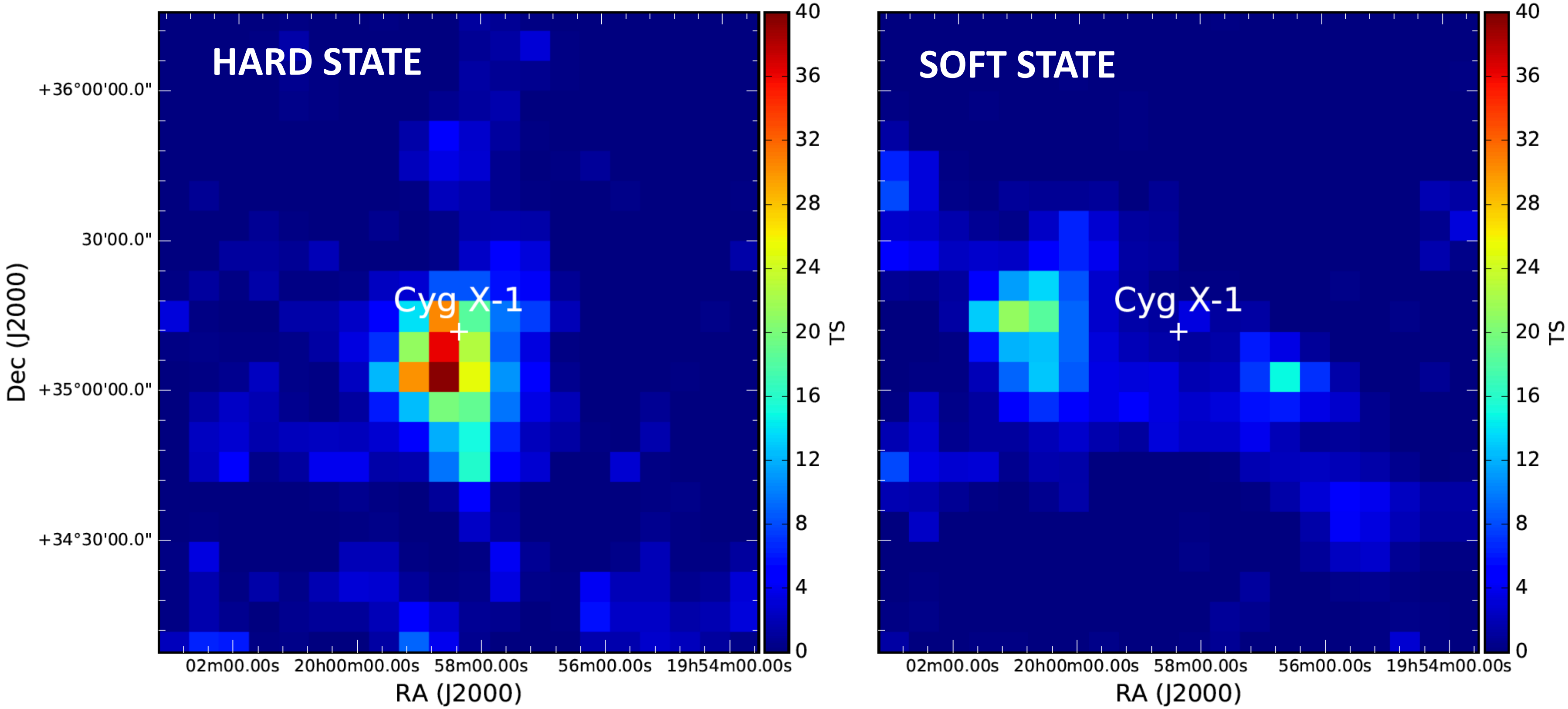
(Zanin+ 2016)



THRESHOLD TO SEPARATE HS(+IS) FROM SS:
***SWIFT*/BAT 0.09 cts/cm^2/s** *(Gringberg+13)*

HS and SS states

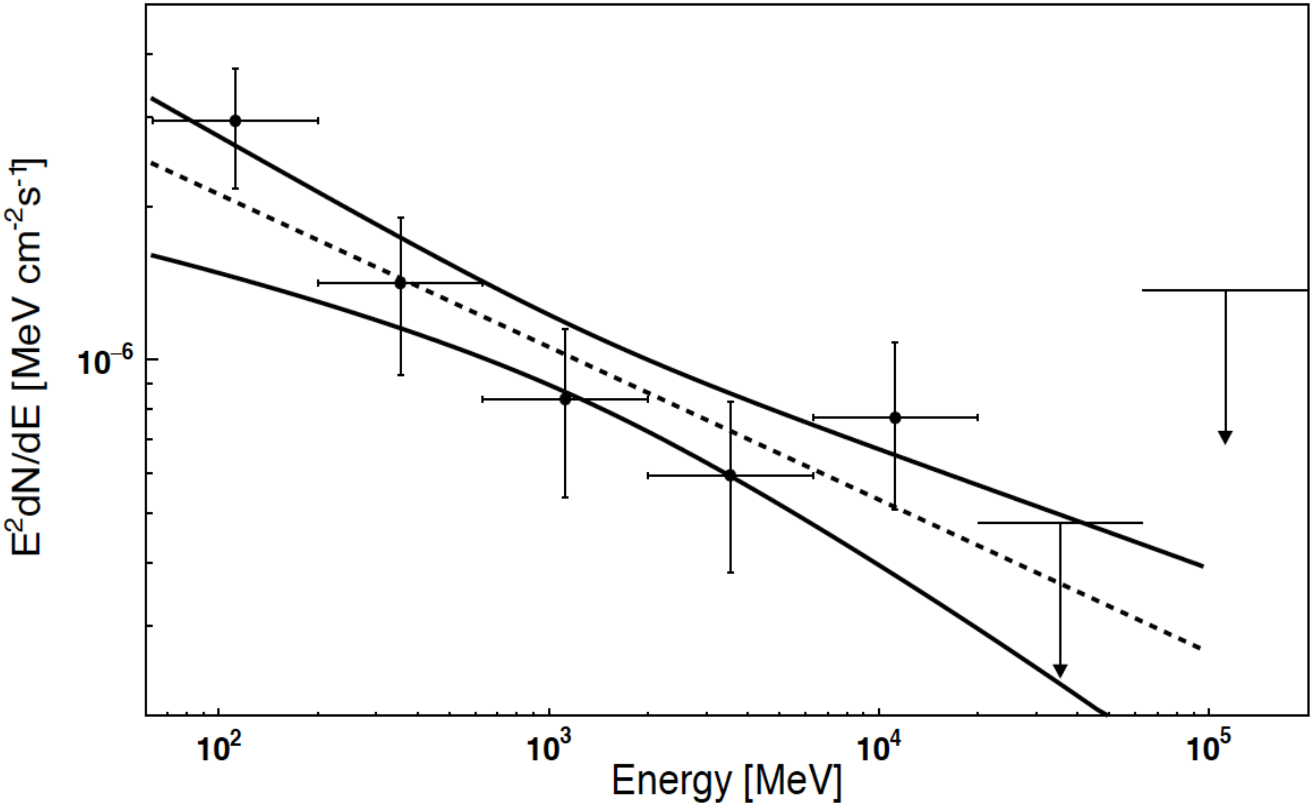
49% obs. time *(Zanin+ 2016)* **48% obs. time**



Spectral energy distribution

ONLY HS

(Zanin+ 2016)



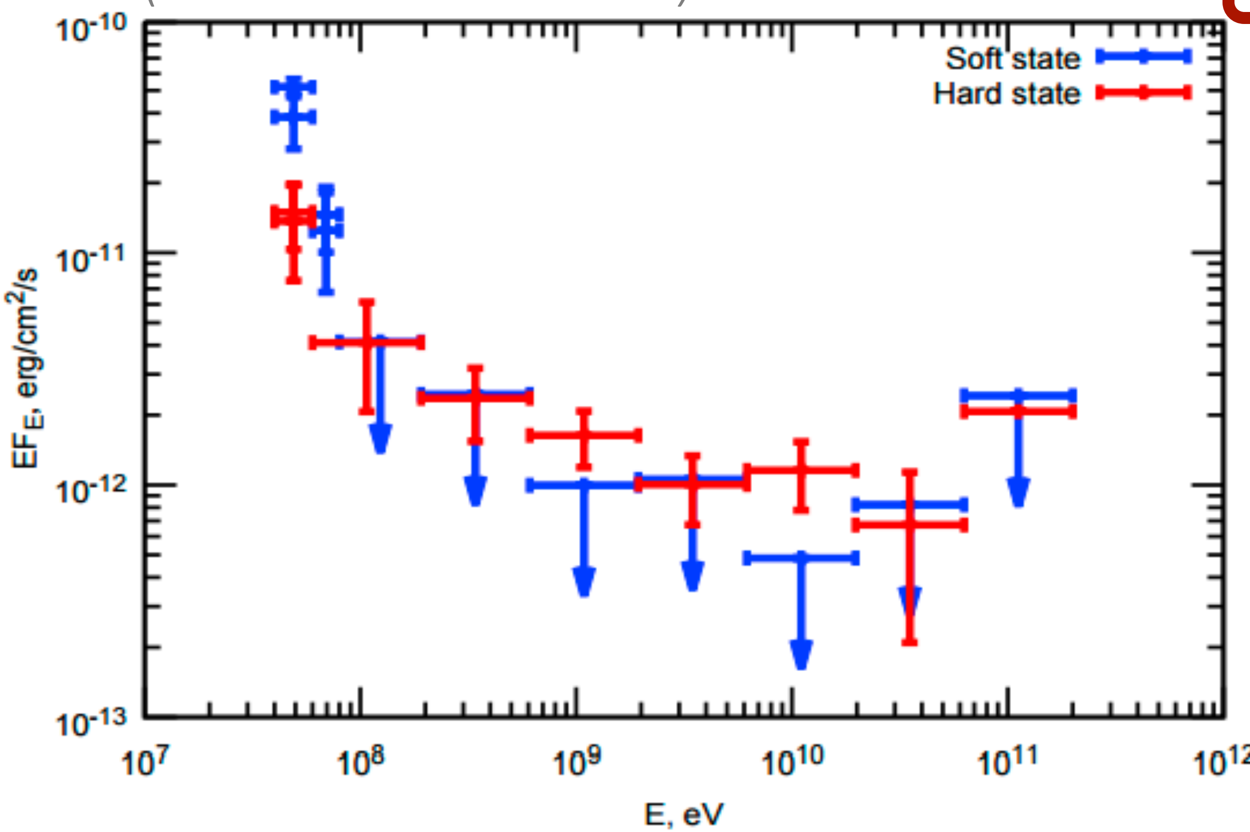
BROKEN PL NO IMPROVEMENT WRT TO THE PL
ΔTS<2

Γ= (2.3±0.1) $N_{0(@1.3GeV)}$=(5.8±0.9)x10^{-13} $MeV^{-1}cm^{-2}s^{-1}$

Spectral energy distribution

DOWN TO 40 MeV

(Zdziarski+ in arxiv 1607.05059)



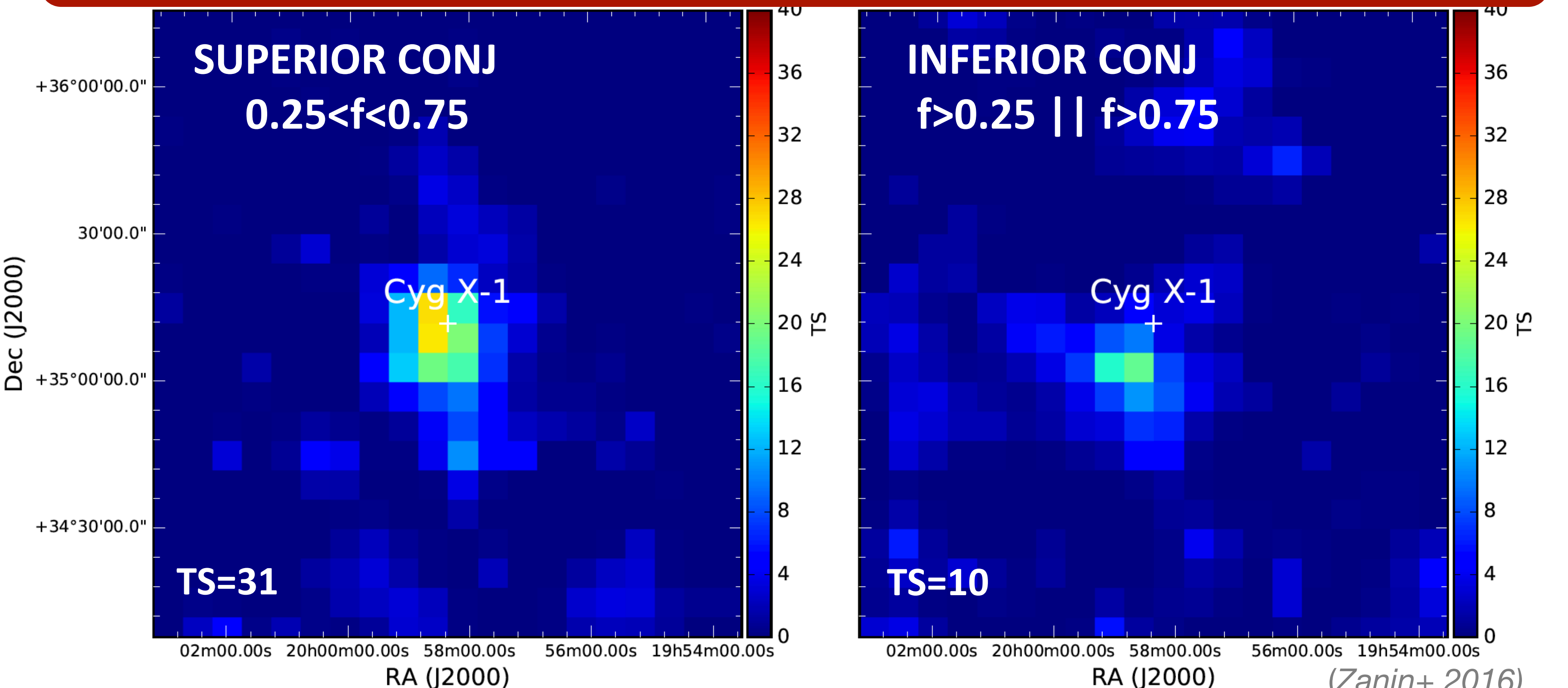
IN THE HS ONE EXTRA SPECTRAL POINT

IN THE SS 2 EXTRA SPECTRAL POINTS

IN 0.1-10 GeV RANGE THE HS SPECTRUM IS A PL Γ= (2.4±0.2)
(compatible with the previous one)

Orbital variability

NO PERIODICITY FOUND, BUT WHEN DIVIDING THE SAMPLE INTO 2 PHASE BINS....

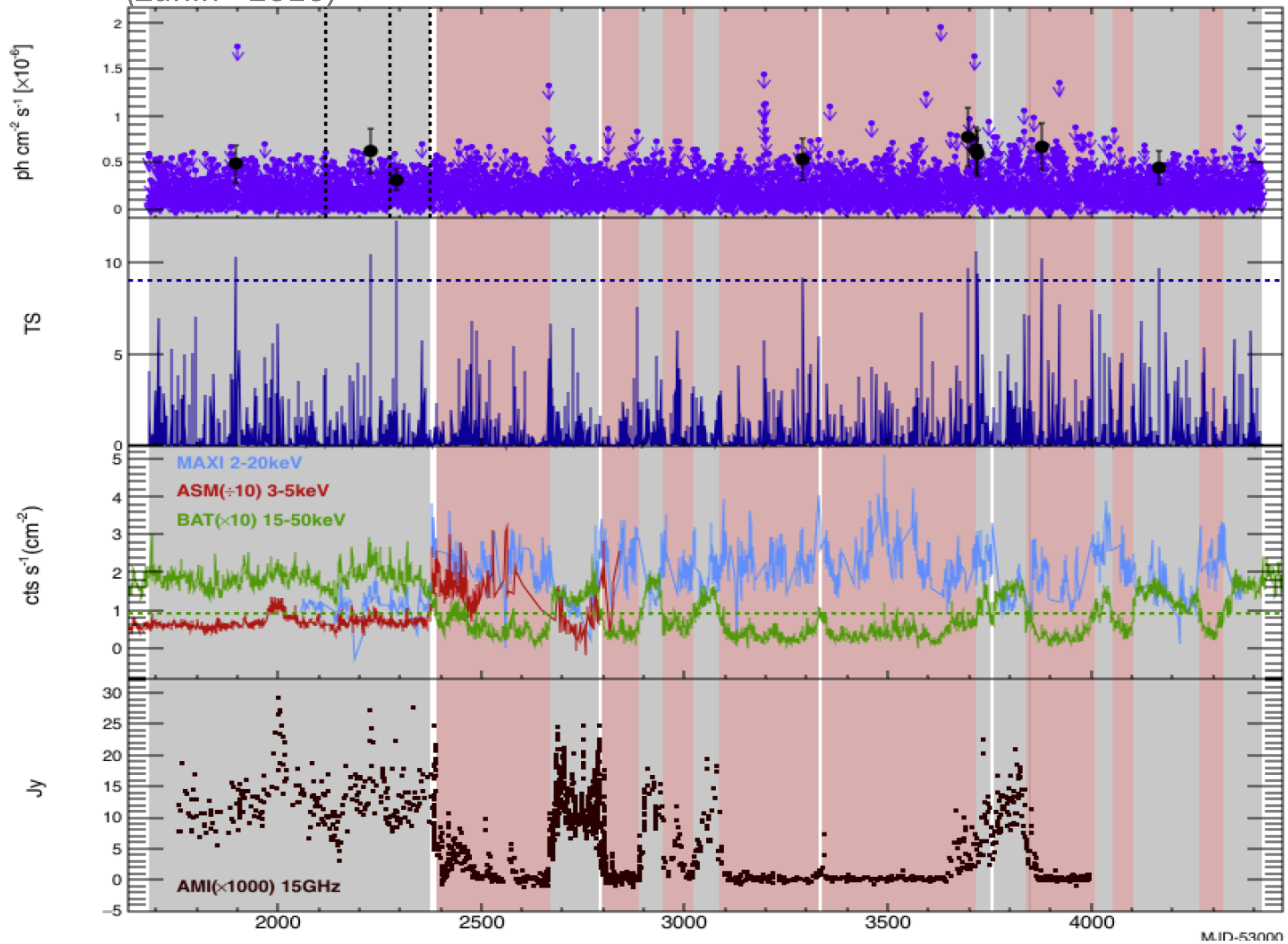


(Zanin+ 2016)

... CAN BE TAKEN AS A HINT OF ORBITAL MODULATION
PHOTON INDEX COMPATIBLE WITHIN 1s WITH THE OVERALL 2.3

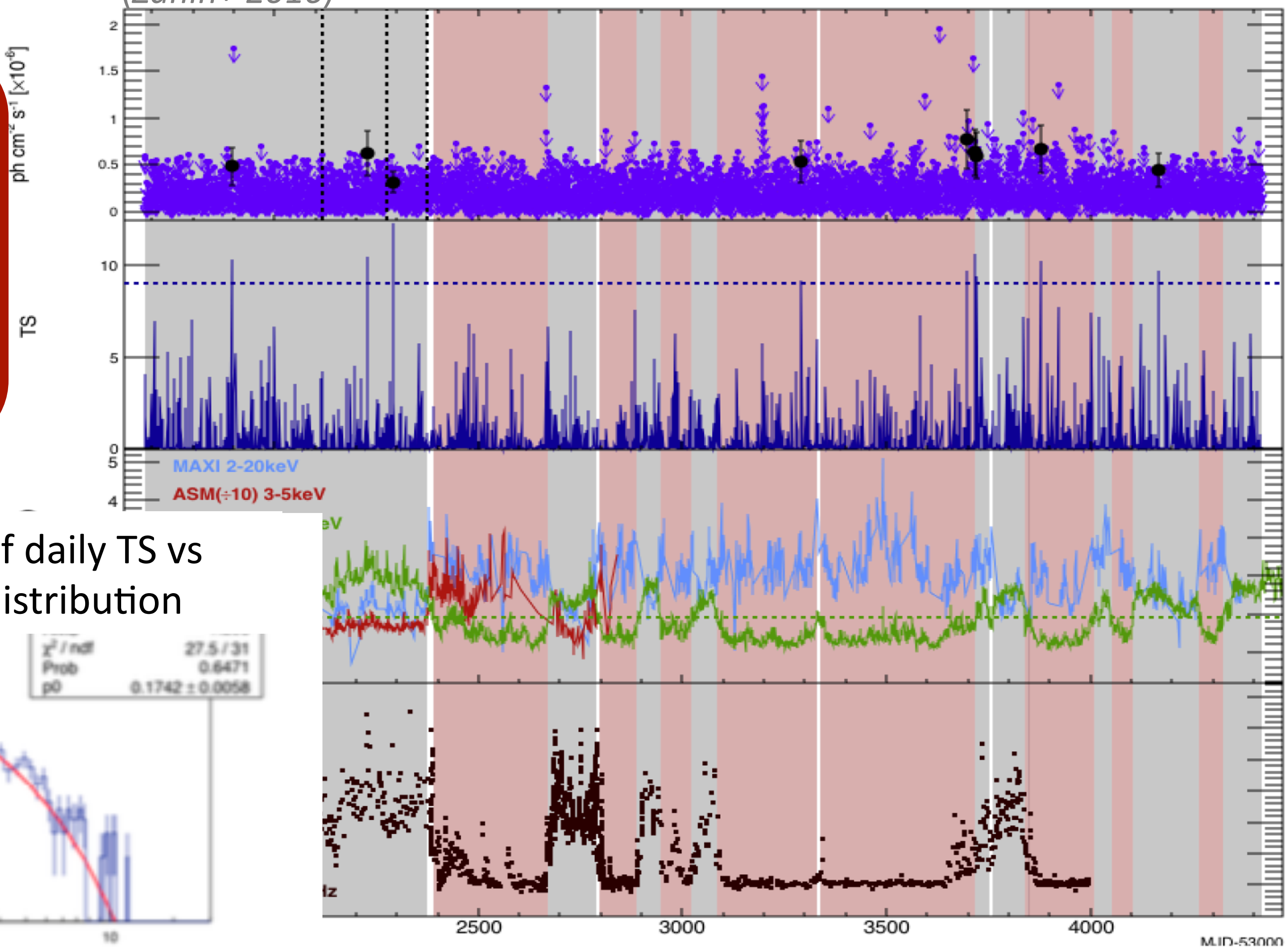
Flux variability

(Zanin+ 2016)

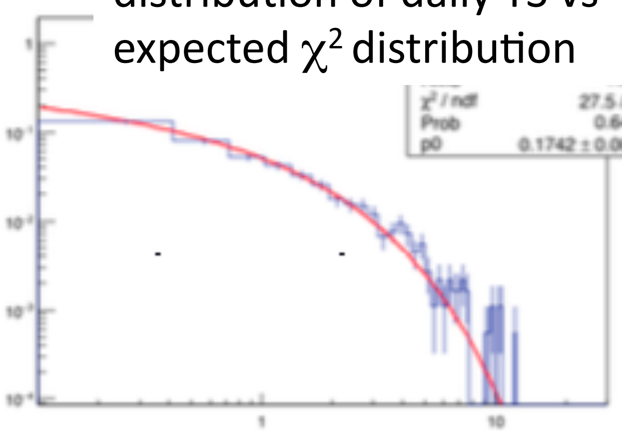


Flux variability

9 DAYS WITH TS>9 NOT CLUSTERED AROUND ANY PREVIOUS CLAIM



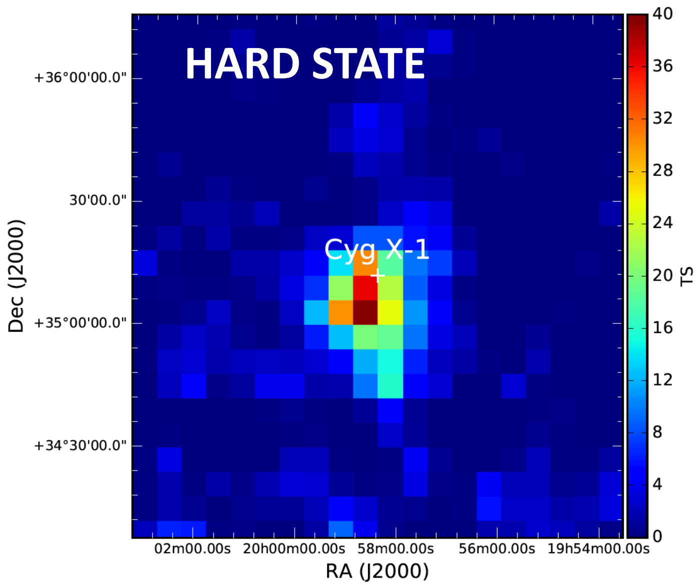
distribution of daily TS vs expected χ^2 distribution

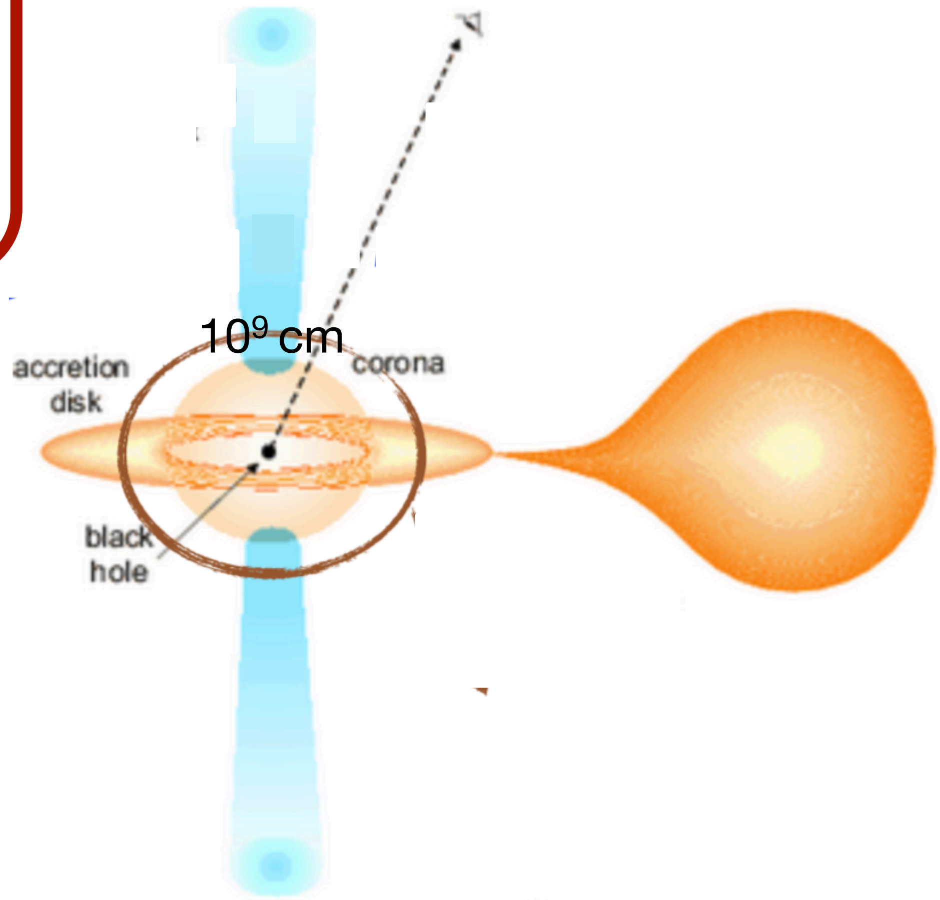


The origin of the HE emission

ABSORPTION ON THE CORONA
→ EMISSION COMES FROM $r > 10^9$cm

EMISSION FROM THE JETS





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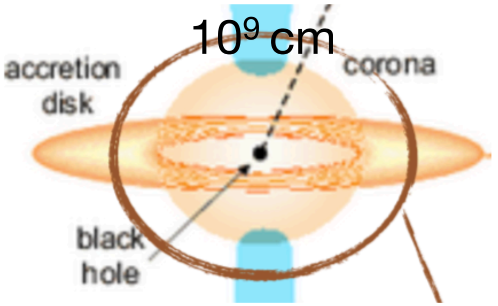
EMISSION FROM THE JETS

IN LEPTONIC SCENARIO,
INVERSE CONPTON ON:
- **THERMAL ACCRETION** PHOTONS



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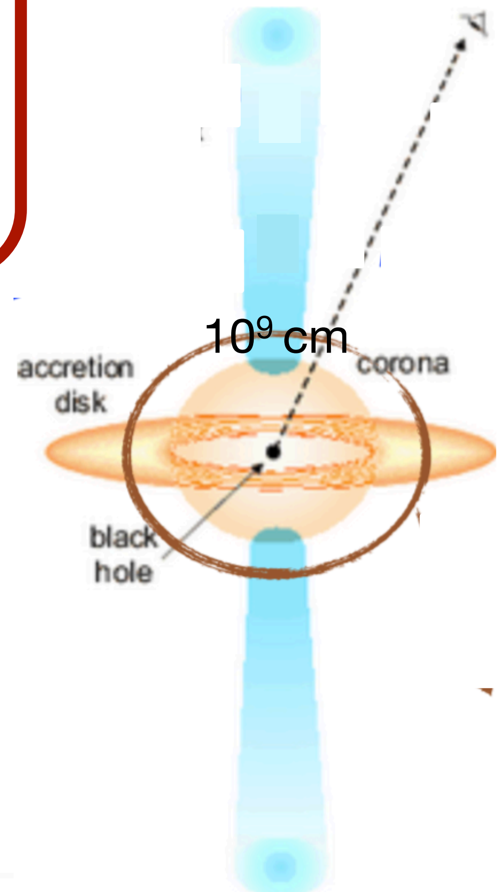

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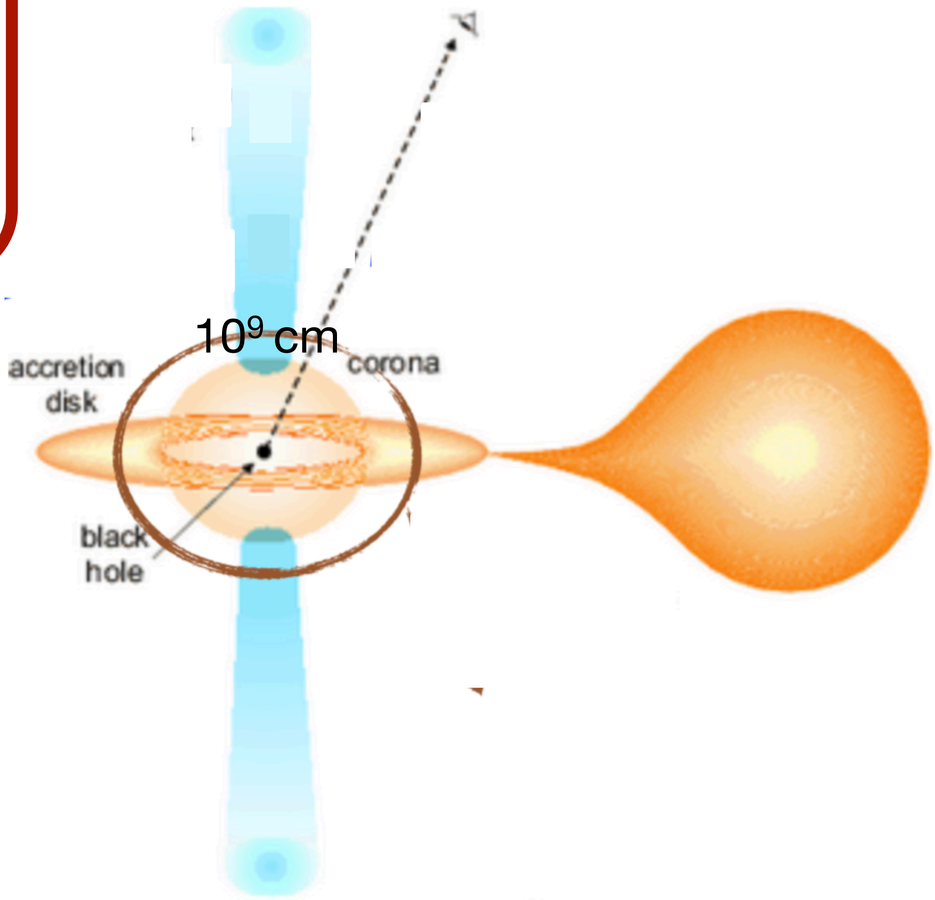

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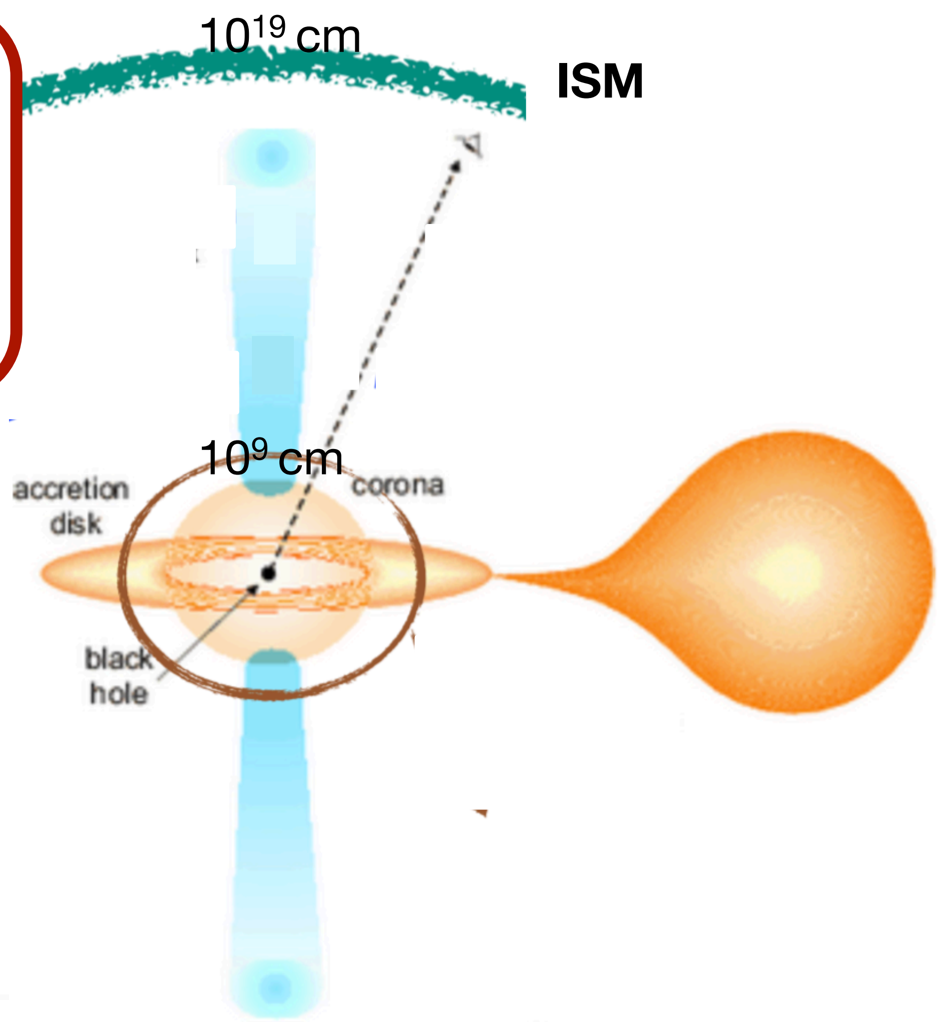

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- **STELLEAR** PHOTONS
- **ISM** PHOTONS

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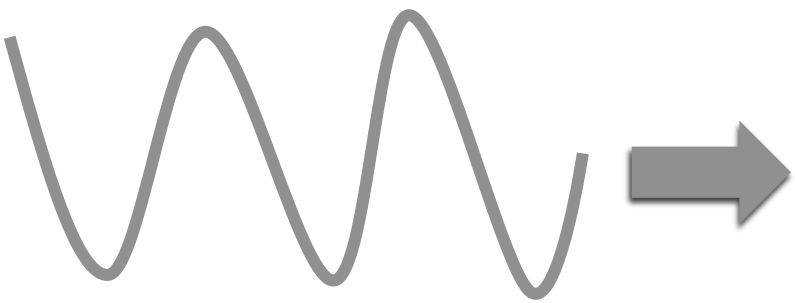

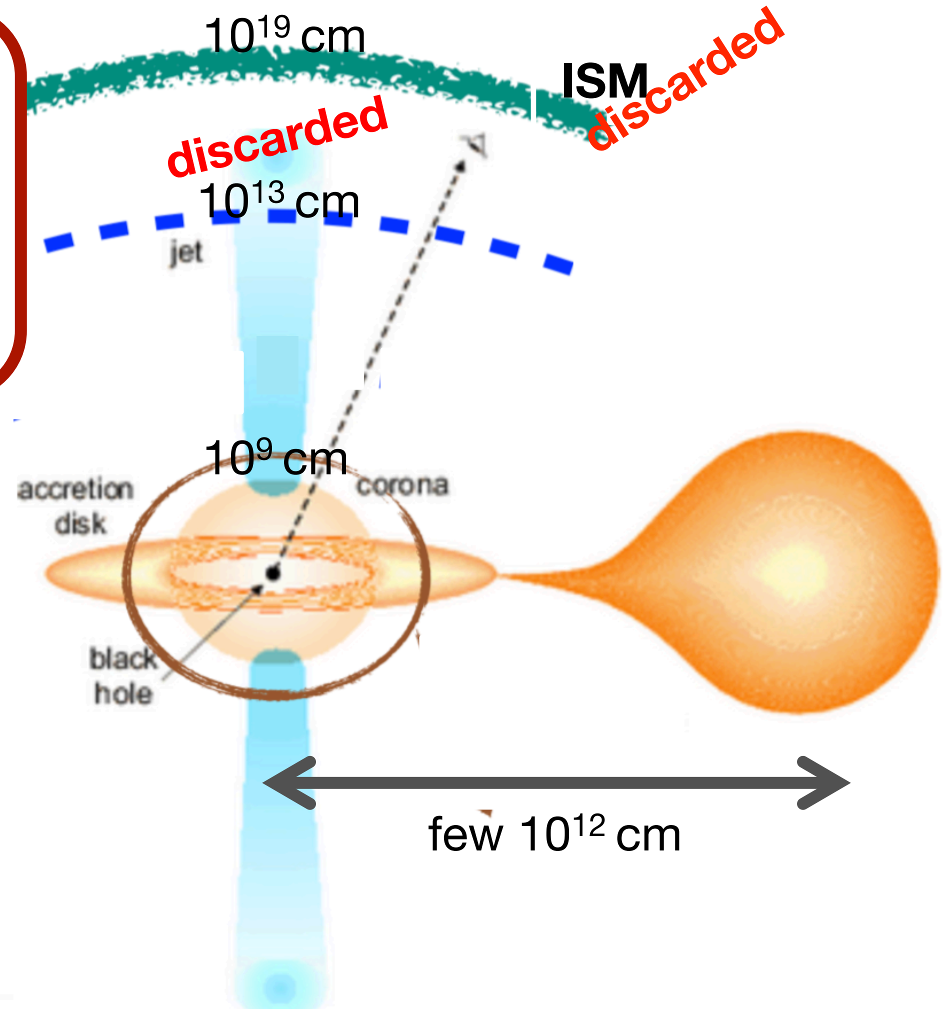

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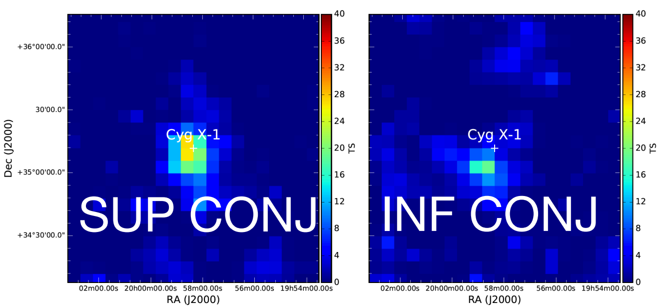
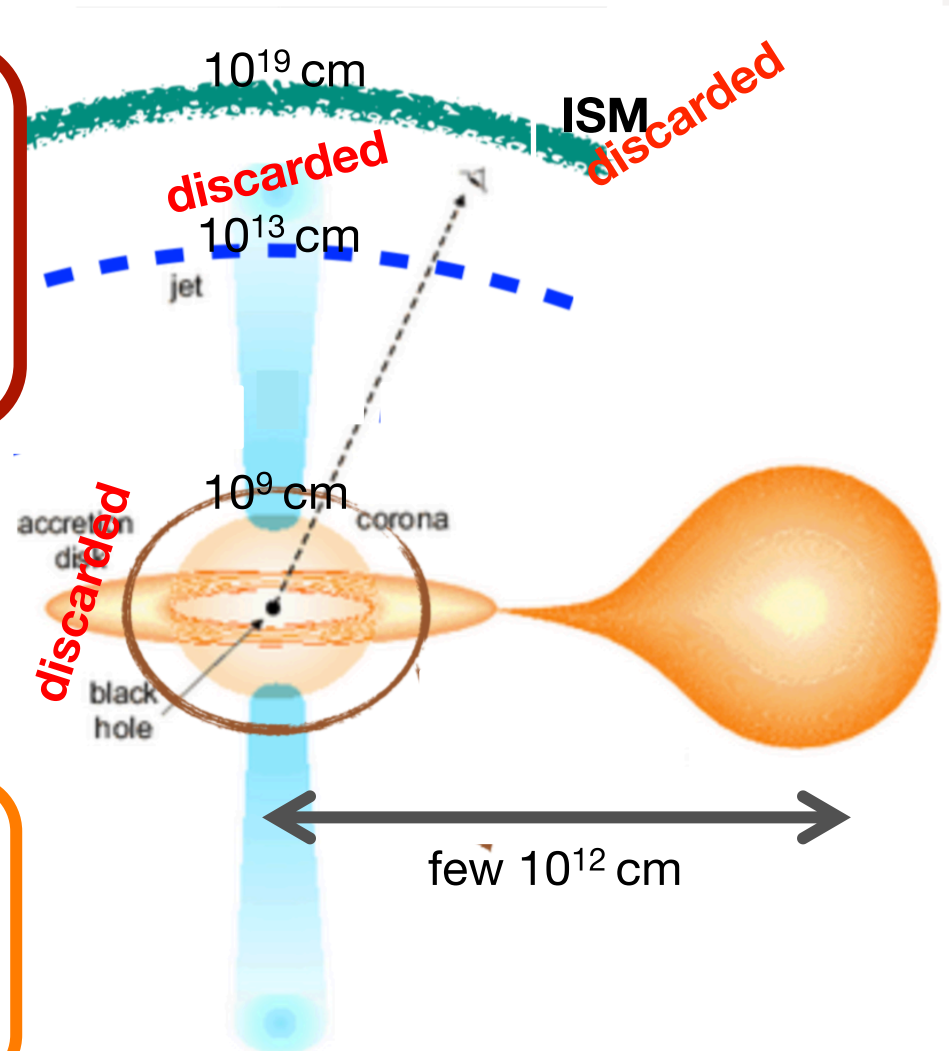


ANISOTROPIC IC
ON STELLAR PHOTONS



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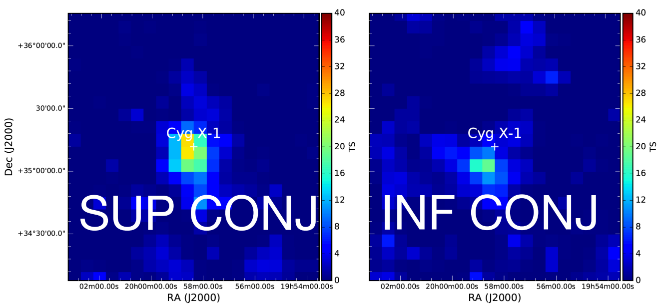
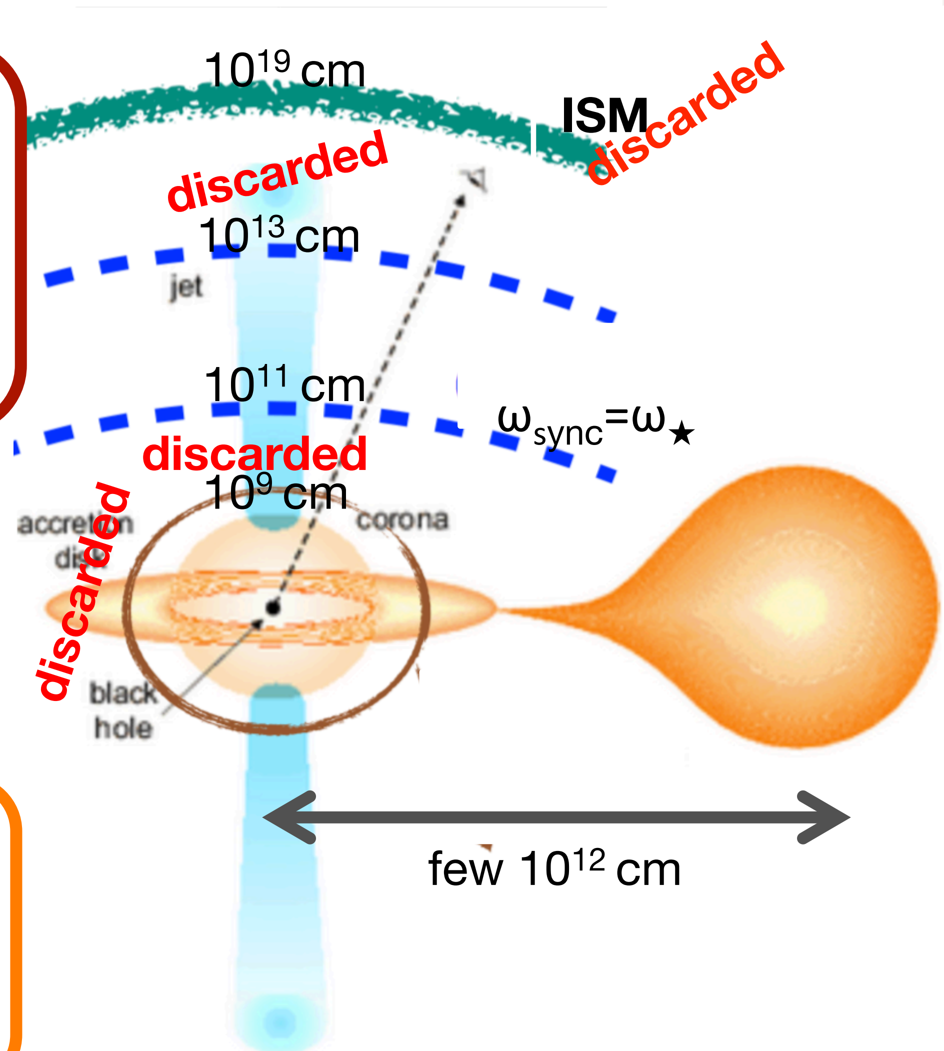




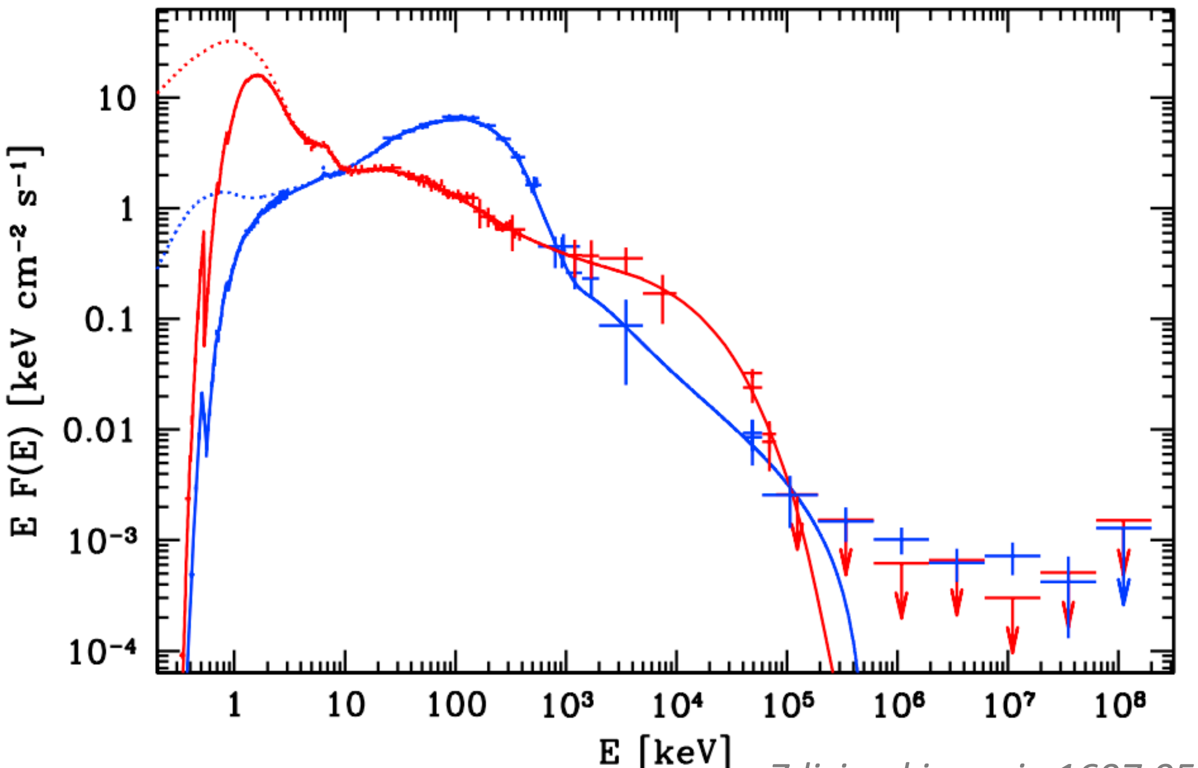
ANISOTROPIC IC ON STELLAR PHOTONS

→ **$10^{11}<z<10^{13}$ cm**

The origin of the E<100MeV emission

THE TWO SPECTRAL POINTS 40-100 MeV AS THE TAIL OF THE MeV POWER LAW

(Zdzizarski+ arxiv:1607.05059)



Zdiziarski+ arxiv:1607.05059

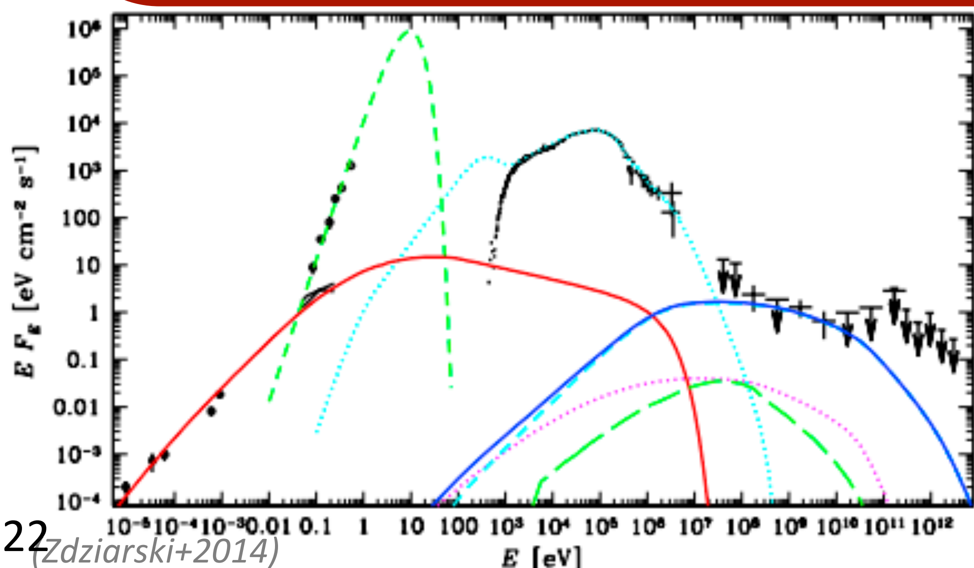
Theoretical expectations at VHE

- BOTH LEPTONIC & HADRONIC SCENARIOS:
  - **LEPTONIC: IC ON THERMAL, STELLAR, ISM PHOTONS**
    (Khangulyan+2008,Bosch-Ramon+2008, Zdziarski+12, 14)

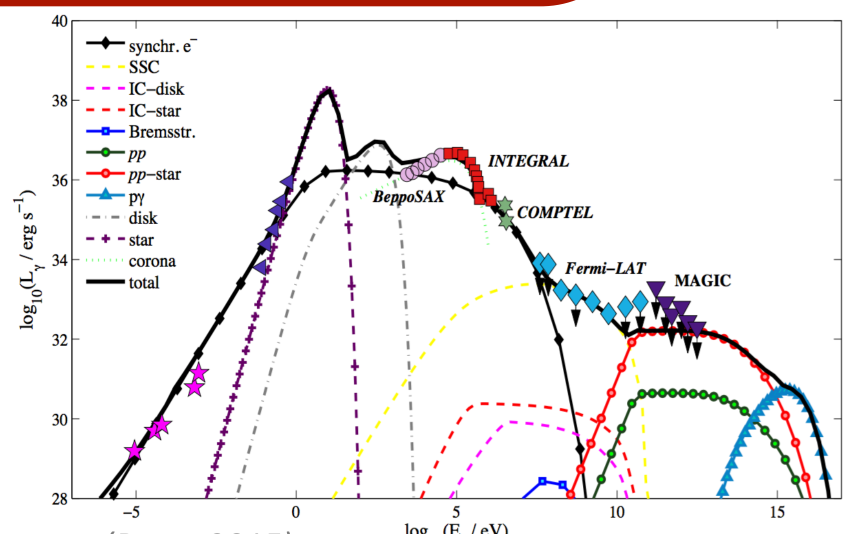
LEPTONS ACCELERATED UP TO TeV ENERGIES

  - **HADRONIC: p_{jet}-p_{jet} p_{jet}-$p_{\star}$ & p-γ**
    with γ either stellar or synchrotron *(Romero2003,2008, Vila+2012)*

PROTRONS ACCELERATED UP TO 10^{15} eV



(Zdziarski+2014)



(Pepe+2015)

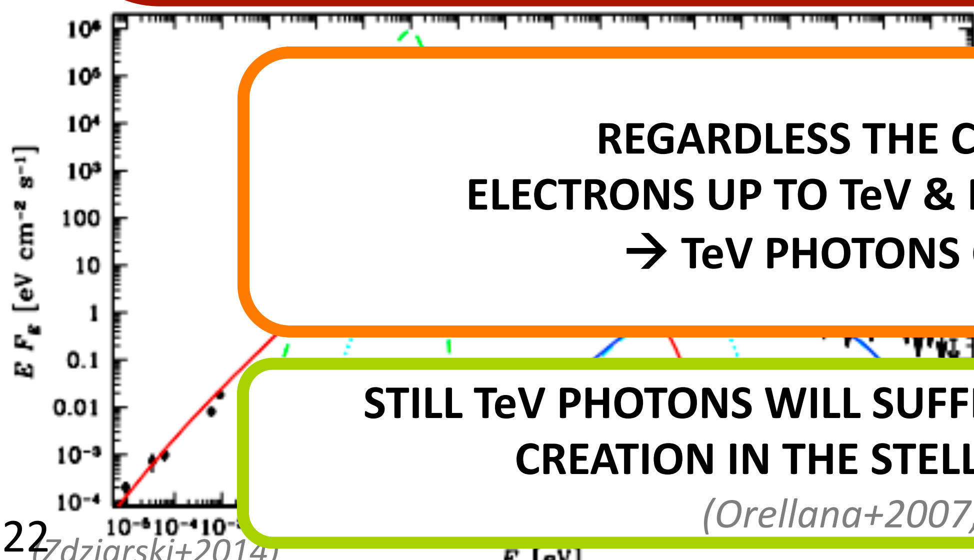
Theoretical expectations at VHE

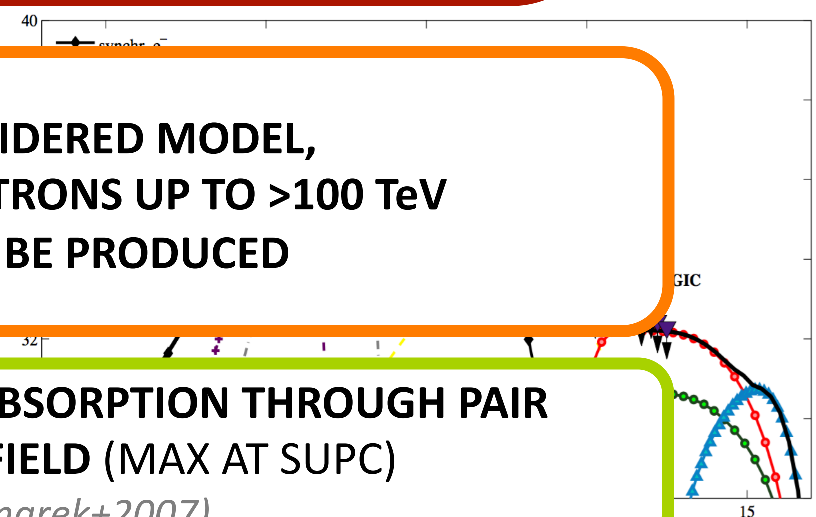
- BOTH LEPTONIC & HADRONIC SCENARIOS:
  - **LEPTONIC: IC ON THERMAL, STELLAR, ISM PHOTONS** *(Bosch-Ramon+2008, Zdziarski+12, 14, Pepe+15)*

  LEPTONS ACCELERATED UP TO TeV ENERGIES

  - **HADRONIC: p_{jet}-p_{jet} p_{jet}-$p_{\star}$ & p-γ** with γ either stellar or synchrotron *(Romero2003,2008, Vila+2012)*

  PROTRONS ACCELERATED UP TO 10^{15} eV





REGARDLESS THE CONSIDERED MODEL,
ELECTRONS UP TO TeV & PROTRONS UP TO >100 TeV
→ TeV PHOTONS CAN BE PRODUCED

STILL TeV PHOTONS WILL SUFFER ABSORPTION THROUGH PAIR CREATION IN THE STELLAR FIELD (MAX AT SUPC)
(Orellana+2007, Bednarek+2007)

(Zdziarski+2014)

(Pepe+2015)

VHE observations

(*MAGIC, submitted to MNRAS*)

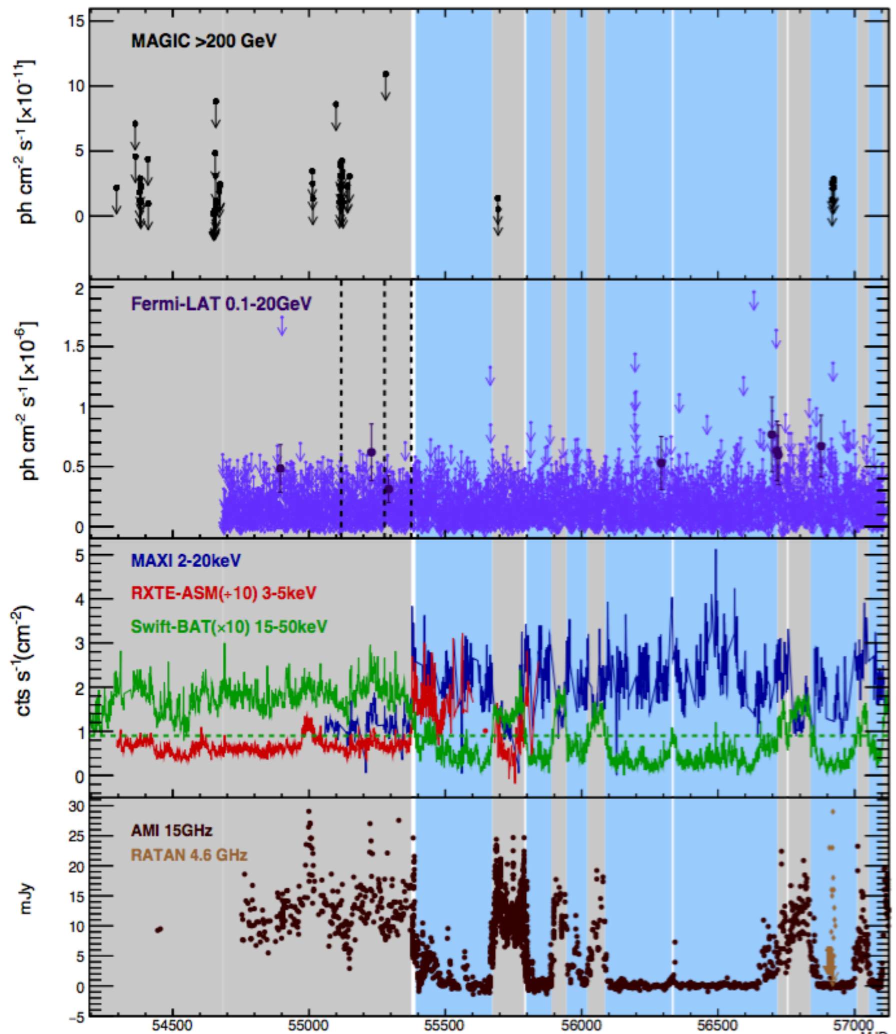
~100 hr OF OBSERVATION
WITH MAGIC > 100 GeV COVERING
BOTH HS & SS

NO STEADY SIGNAL IN ANY X-RAY STATE

NO ORBITAL MODULATION

NO SHORT-TERM FLUX VARIABILITY

→ ALTHOUGH NO OBSERVATION SIMULATNEOUS TO A HARD X-RAY STATE (same condition as 2007)



The VHE non-detection

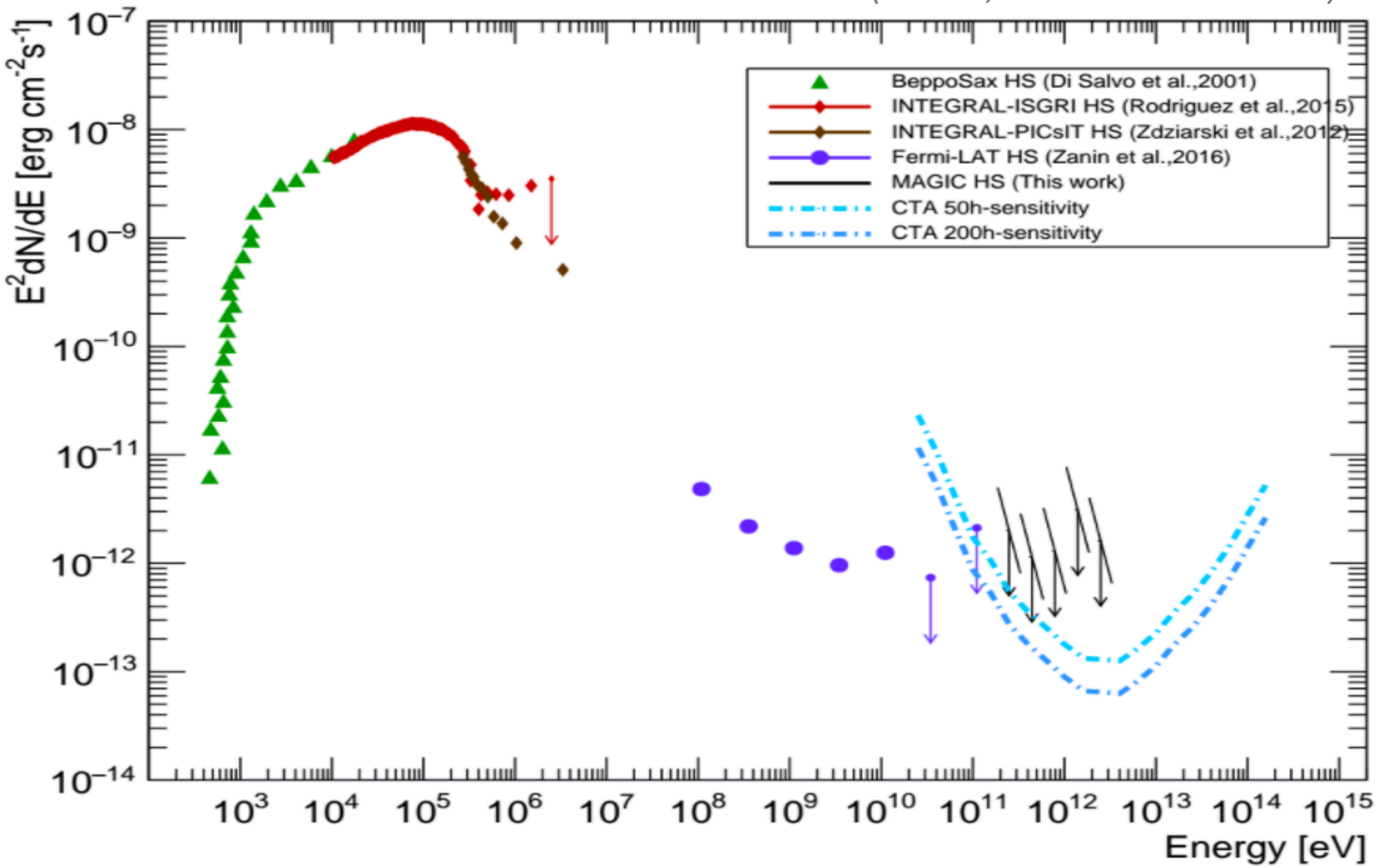
EMISSION FROM JET-ISM INTERACTION EXCLUDED BELOW $6x10^{32}$ erg/s LEVEL
(MAGIC submitted to MNRAS)
ON BINARY SCALES LESS CONCLUSIVE BECAUSE OF ABSORPTION

TRANSIENT EMISSION AS THE ONE HINTED IN 2006 IS STILL A POSSIBILITY.

IF REAL, THIS OCCURRED
*** IN SUPC** (MAX ABSORPTION) **THUS EMITTED AT z >= 10^{13} cm** *(MAGIC 2007)*
(UNLESS EXTENDED PAIR CASCADING IS CONSIDERED, *BoschRamon+2008, Zdziarski+14***)**
*** SIMULTANEOUS TO HARD X-RAY FLUX INCREASE** *(Malzac+2008)*
→ CHANGE AT THE BASE OF THE JET

Perspectives for the future

(MAGIC, submitted to MNRAS)



Conclusions

Cygnus X-1, the prototype BH microquasar. With many peculiarities:

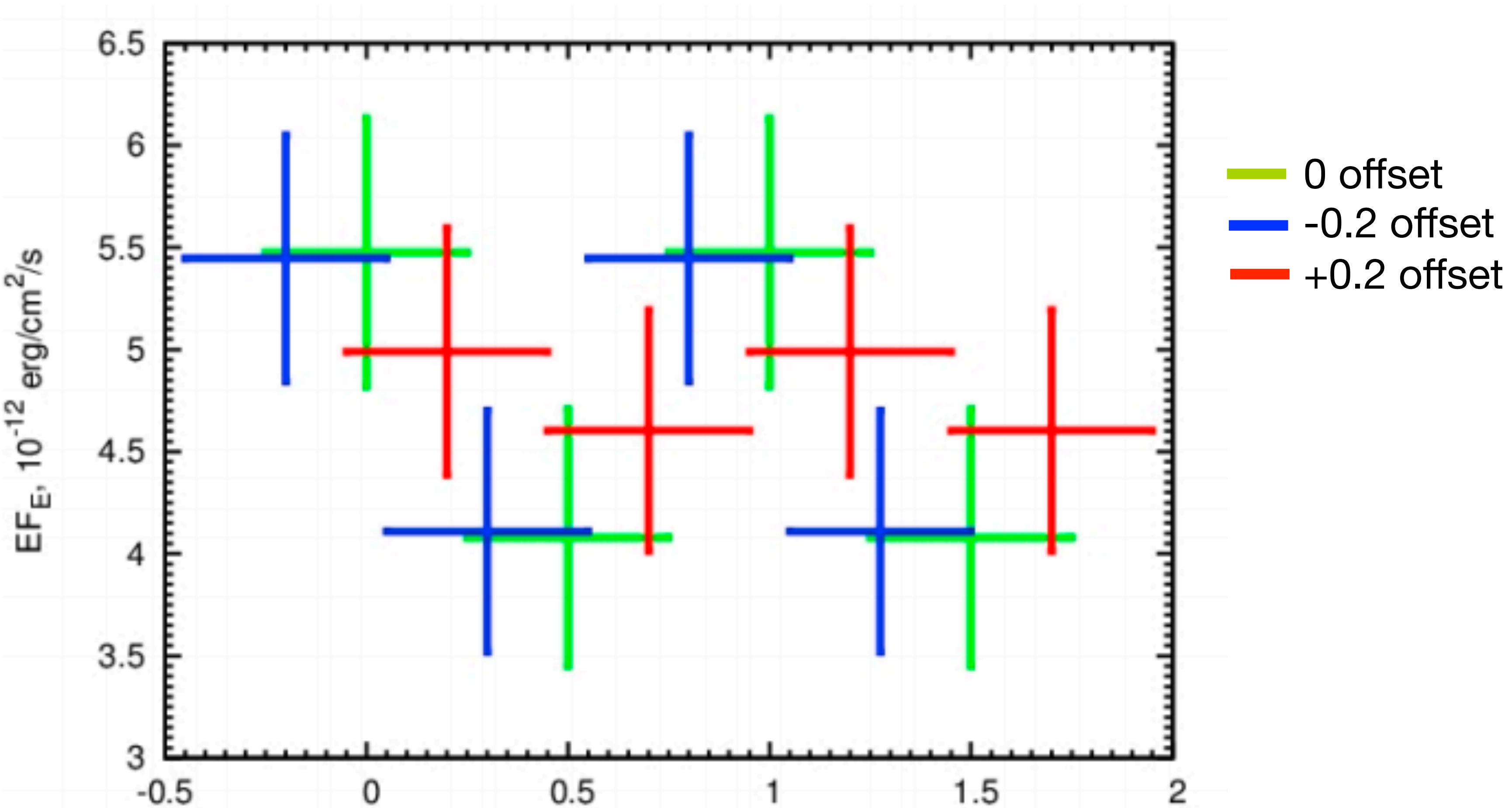
- Persistent X-ray source: CORONA emission always present
- MeV tail. If highly polarized synchrotron from the jet and produced in a different region than radio, but not established.
- Gamma-rays most likely produced by **anisotropic inverse Compton on stellar photons by electrons accelerated in the jets**
- **At VHE perspectives to detect the cutoff of the steady emission are really poor. Transient emission cannot be ruled out.**
  MWL is needed to understand the origin.

Thank you

2017 February 16

The Tulip and Cygnus X-1
Image Credit & Copyright: Ivan Eder

Orbital variability



hint of offset of the peak modulation towards negative values

Cygnus X-1 versus Cygnus X-3

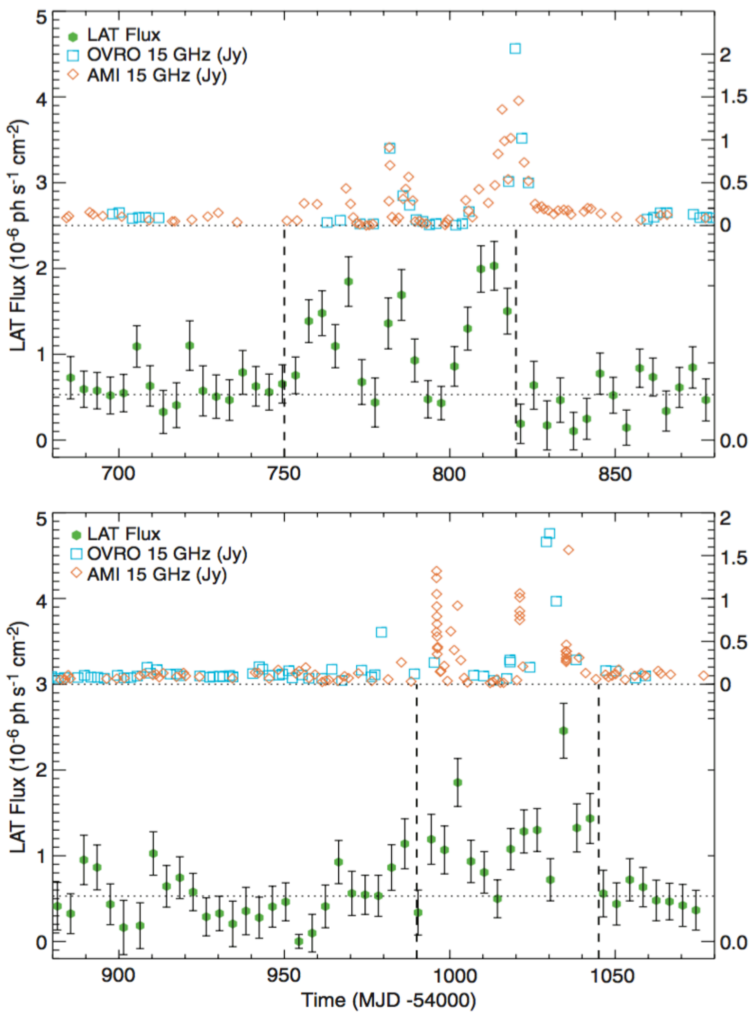
CYGNUS X-1

- 15 $M_{\odot}$ BH
- 09.7Iab **supergiant**
- 1.86 kpc
- orbital period: **5.6 d**
- persistent X-ray source: never fully disk-dominated

CYGNUS X-3

- unknown compact object, most probably BH
- **Wolf Rayet**
- ~7 kpc
- Orbital period: **4.8 h**
- bright radio source

Cygnus X-3 at high energies



(Tavani+2009,Abdo+2009,Piano+2012,Corbel+2012)

- **7 flaring events** from 2009 to 2016 (each **~30σ**)
- orbital periodicity found
- lasting **10-20 days**
- flux peaks 1-2 days long
- in the **SS**
- **correlated with radio**

triggering condition is:

- minimum 0.2-0.4Jy radio
- raising radio emission

- **PL with 2.7 index**

Cygnus X-1 versus Cygnus X-3

CYGNUS X-1

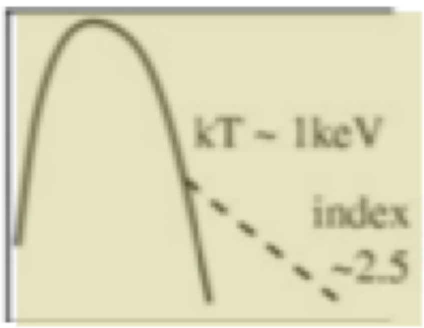
- steady emission
- persistent jets
- emission inside the binary system
- anisotropic IC on stellar photons

CYGNUS X-3

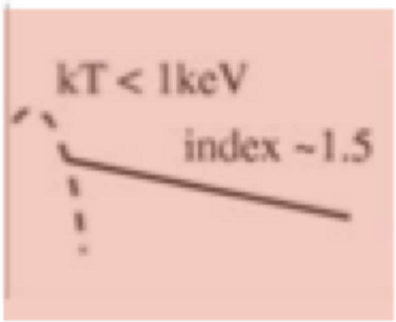
- flaring activity correlated with radio
- discrete jets
- emission inside the system
- anisotropic IC on stellar photons

The X-ray spectral states

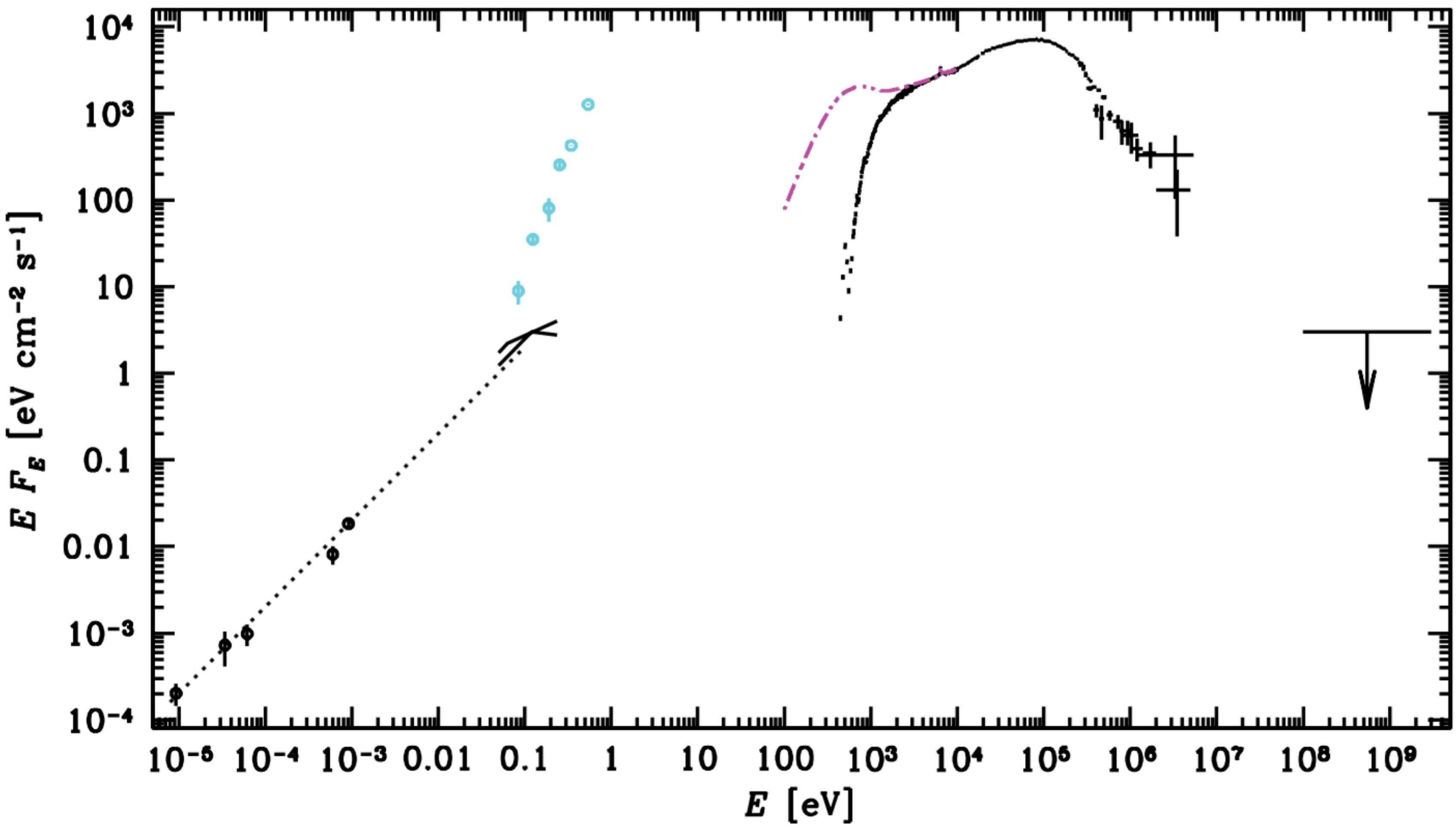
SOFT



HARD



OUTDATED DEFINITION
at beginning measurements only
in the 2-10 keV→ $F_{SOFT}>5*F_{HARD}$
but
bolometric luminosity is comparable
(Gierlinski+99)
LET'S USE THE DEFINITION BASED ON SPECTRA

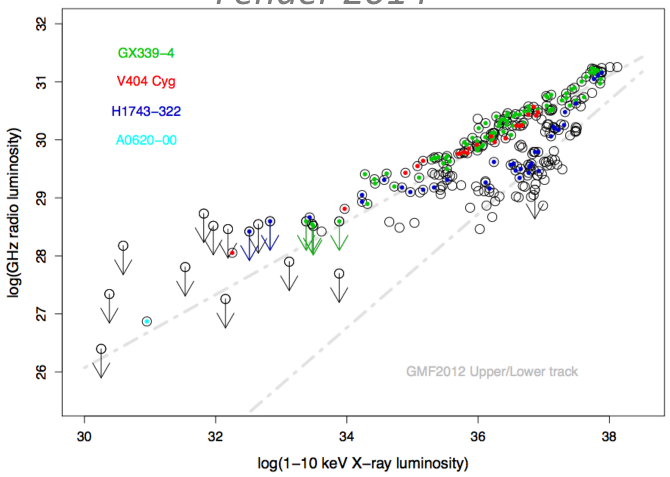


10^4
10^3
100
10
1
0.1
0.01
10^{-3}
10^{-4}
$E F_E$ [eV cm^{-2} s^{-1}]
10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 100 10^3 10^4 10^5 10^6 10^7 10^8 10^9
E [eV]

Disk-jet coupling

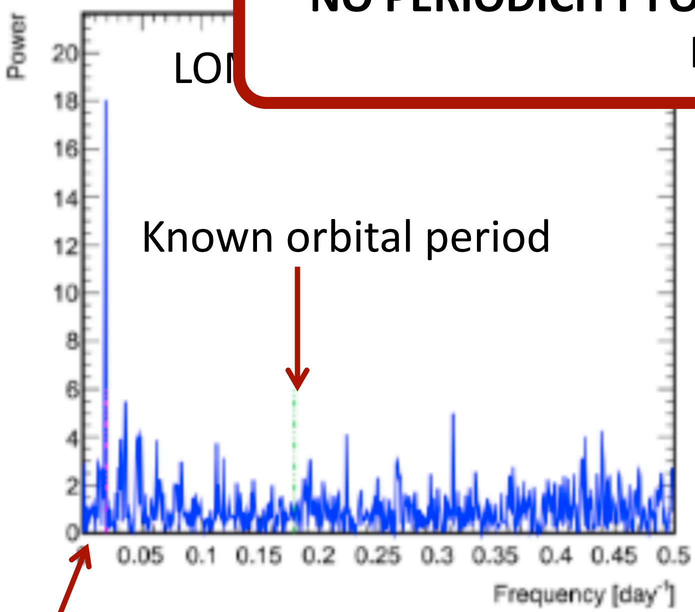
L_X-L_{radio} CORRELATION POWERFUL
TOOL TO TEST THE DISK-JET COUPLING
NOT CONCLUSIVE
(Corbel+2013,Gallo+2003,2013)

Fender 2014



Orbital variability

NO PERIODICITY FOUND, BUT WHEN DIVIDING THE SAMPLE INTO 2 PHASE BINS....

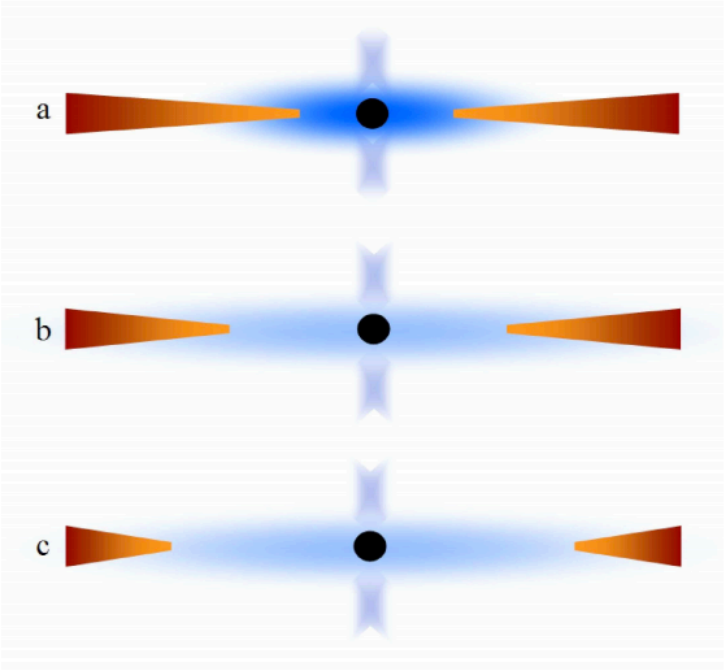


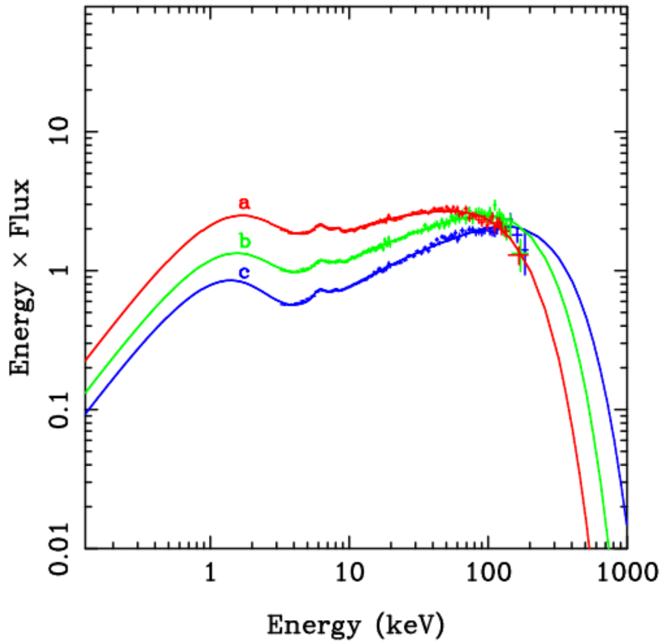
Known orbital period

spacecraft period

WHEN DIVIDING THE SAMPLE INTO 2 PHASE BINS....

Cygnus X-1: the HARD state





L/L_{Edd} ~ 0.01-0.02
CUTOFF at 200-300 KeV → THERMAL/NON-THERMAL (HYBRID) COMPTONIZATION
Disk spectrum at 0.2-0.5 keV
()

Cygnus X-1: new results at HE

7.5yr PASS8 *Fermi*/LAT data from 20-60 MeV to 500 GeV

(Zanin+ 2016)