The γ-ray flares from Cygnus X-3 detected by AGILE

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on behalf of the AGILE Team

AGILE 9th Science Workshop

“Astrophysics with AGILE:

five years of surprise”

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OUTLINE

- Microquasars in the Cygnus Region: Cygnus X-3, Cygnus X-1.
- The γ-ray flares from Cygnus X-3: brief story of a discovery.
- The AGILE monitoring of Cyg X-3 during the "Pointing" mode:
  - the γ-ray flares in the context of the multiwavelegth emission
  - the γ-ray flaring spectrum detected by the AGILE-*GRID*

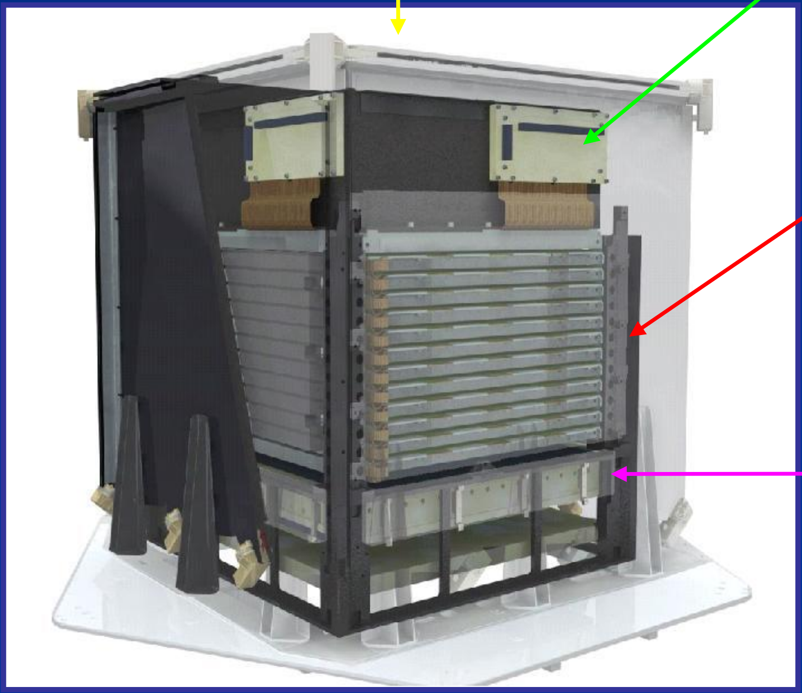
- Spectral modeling of the Cygnus X-3 high-energy SED:
  - leptonic scenario(s)
  - hadronic scenario

- Conclusions

The AGILE Payload

Anticoincidence Shield (AC)
Plastic scintillator + photomultipliers

SuperAGILE (SA)
Silicon strips detector + coded-mask
Energy range: 18 – 60 keV



Silicon Tracker (ST) → (AGILE-*GRID*)
12 trays of tungsten / silicon strips
Energy range: 30 MeV – 30 GeV

MiniCALorimeter (MCAL)
CsI(Tl) bars with photodiodes
Energy range: 0.3 – 100 MeV

Volume : ~ 0.25 m^3 Power Consumption : ~ 60 W Mass : ~ 100 Kg

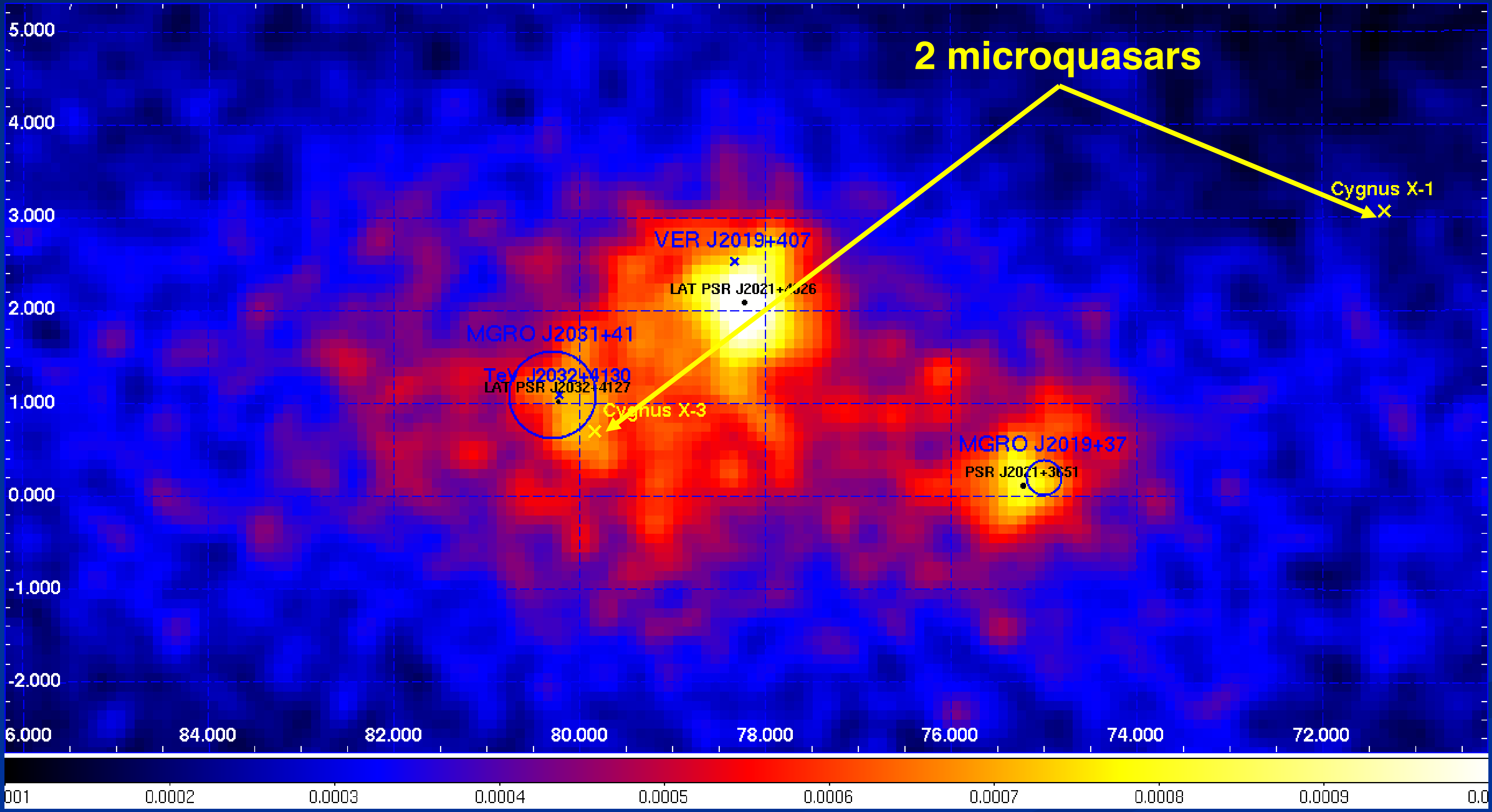
The most compact instrument for high-energy astrophysics

Microquasars in the Cygnus region:

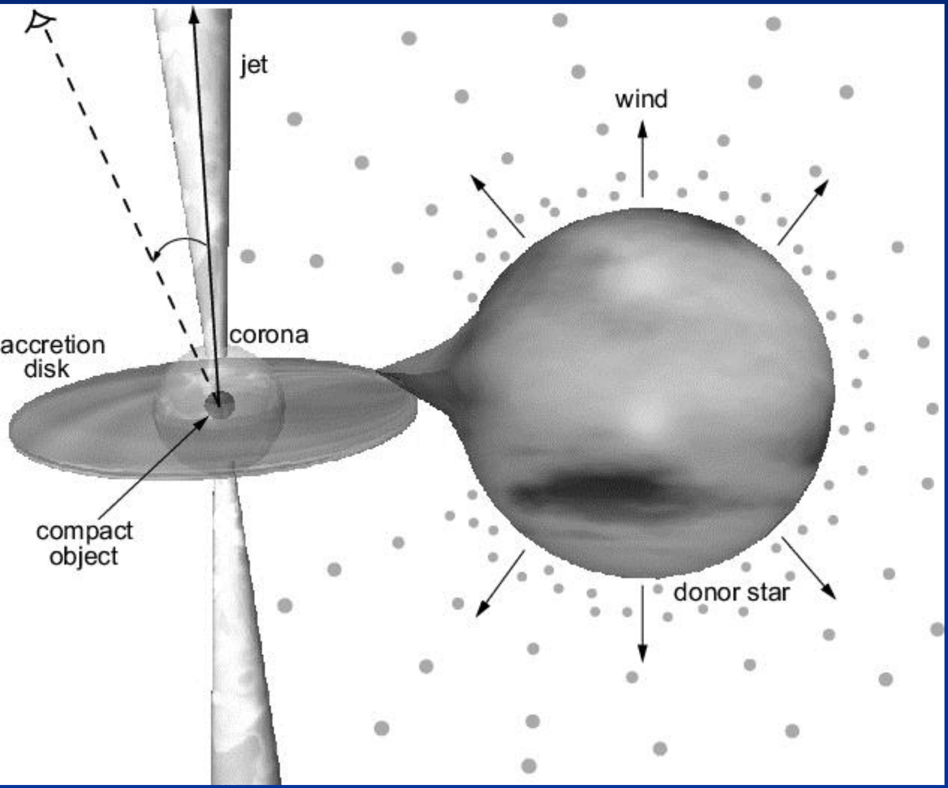
AGILE-*GRID* INTENSITY MAP (100 MeV-10 GeV)

"Pointing" Mode: November 2007 – July 2009,

~275 days, ~11 Ms net exposure time



Microquasars



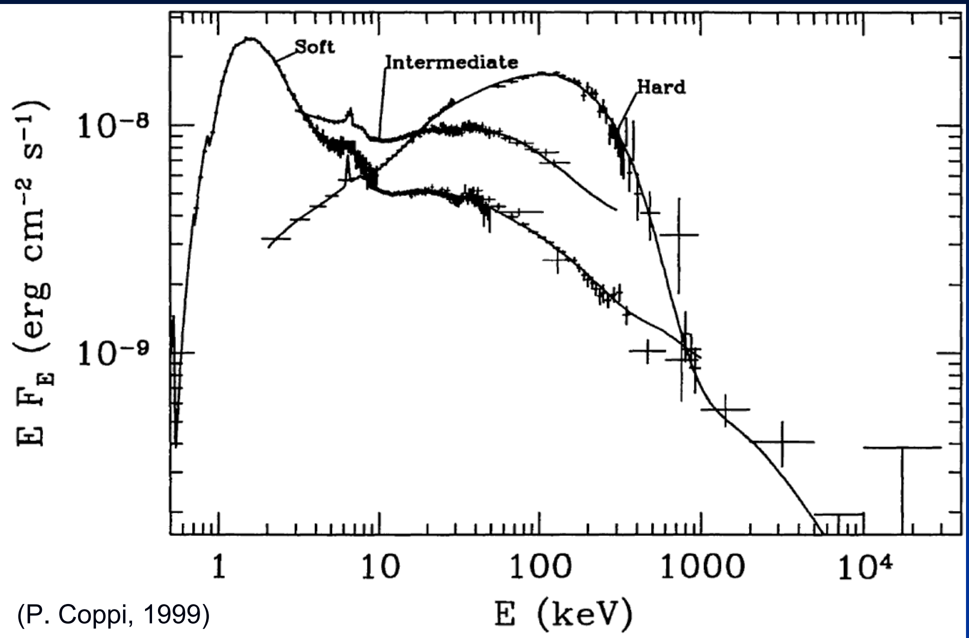
Open questions (pre-AGILE):

- **can jet formation accelerate relativistic particles?**
- **can the jet emit γ-rays above 100 MeV?**

The discovery of the γ-ray activity from Cygnus X-3 is the proof of extreme particle acceleration in microquasars.

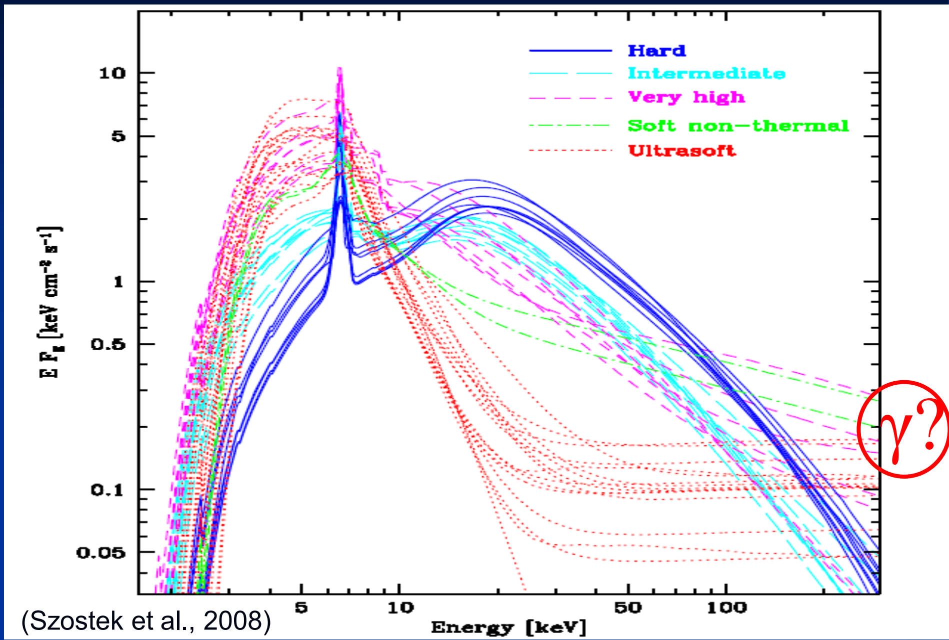
Typical X-ray spectra of a microquasar

Cygnus X-1



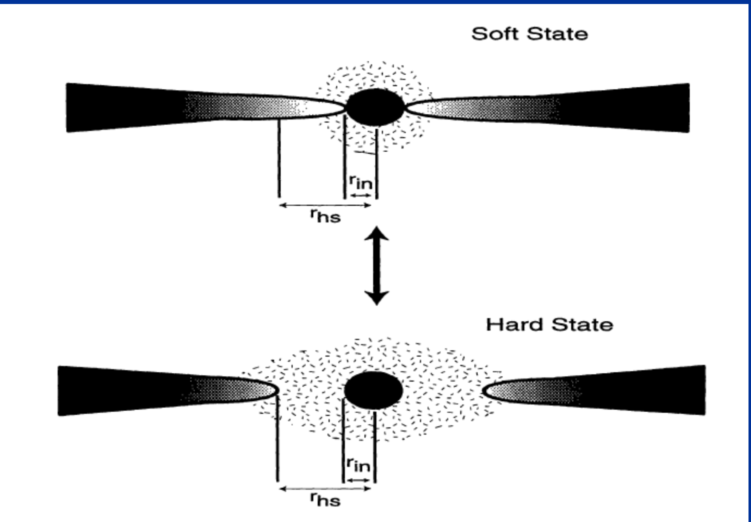
(P. Coppi, 1999)

Cygnus X-3



(Szostek et al., 2008)

Comptonization of soft thermal photons from disk by a hybrid population of electrons (thermal + non-thermal) in the corona.



2 main X-ray spectral states:

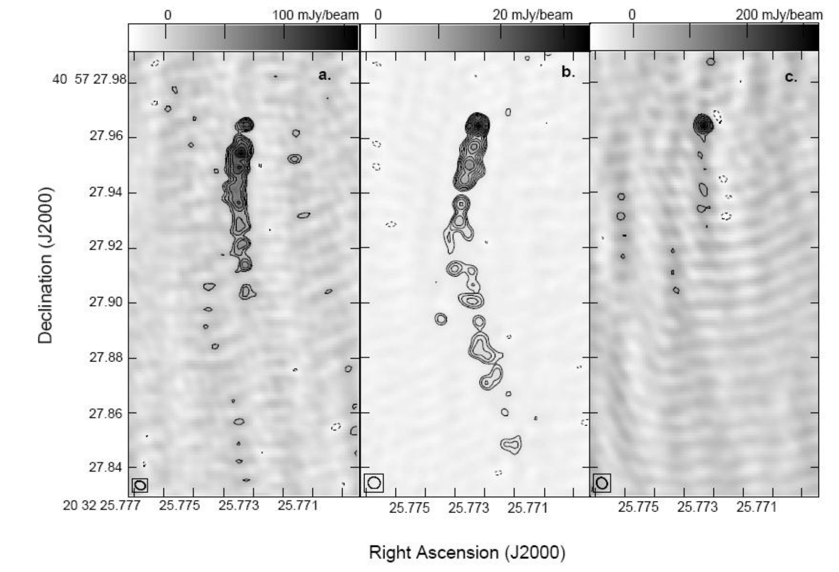
Soft → thermal emission (BB) from disk
+ Comptonization by cold thermal electrons (Soft Excess)
+ Comptonization by non-thermal high-energy electrons (power-law tail)

Hard→ Comptonized emission by hot quasi-thermal population of electrons

Cygnus X-3

- distance → 7-10 kpc
- donor Star → Wolf-Rayet star with strong stellar wind (mass loss ~ 10^{-5} $M_\odot$ y^{-1}, v_{wind} ~ 1000 km s^{-1})
- compact object → UNKNOWN. Published results range: from a *Neutron Star* of 1.4 $M_\odot$ to a *Black Hole* of a mass of up to 10 $M_\odot$.
- orbital period (X-ray, Infrared, γ-ray): 4.8 hr (very tight orbit!!!).
- strong radio outbursts (up to 20 Jy) with jet morphology at milliarcsec scale (expansion speed of 0.3-0.7c.)
- complex and repetitive pattern of emission in radio/X-ray during *Major Flares* (hysteresis curve)
- **γ-ray emission** expected and claimed (at PeV and TeV energies) in the 70's and 80's, but **never confirmed**

Feb. 6, 1997 Feb. 8 Feb. 11



Cyg X-3 radio jets
(Mioduszewski, Rupen, Hjellming, Pooley, Waltman, 2001)

until…

The γ-ray detection of Cygnus X-3:
brief story of a discovery

- December 2, 2009:

  The AGILE-*GRID* detects 4 γ-ray flares from Cygnu

  ("*Extreme particle acceleration in the microquasar Cygnus X-3*", Tavani e

  - γ-ray flaring-fluxes greater than 1 order of magnitude with r
  - coincident with **prominent minima** of the hard X-ray flux
  - a few days before major radio flares

- December 11, 2009:

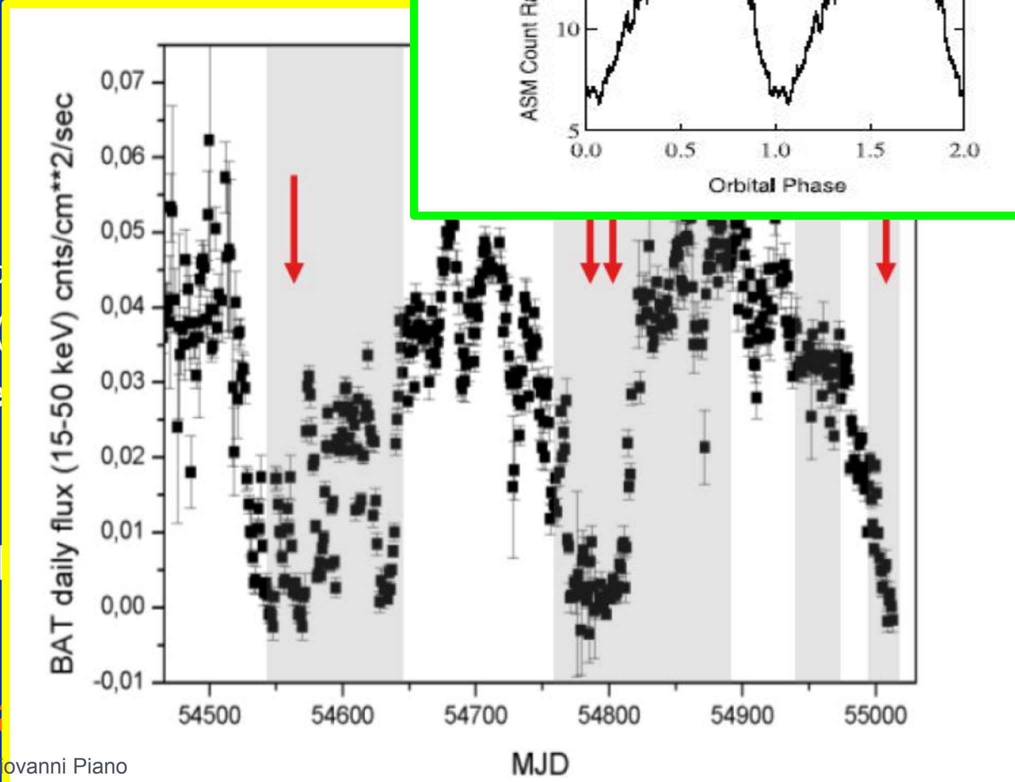
  Fermi-LAT confirms our detection

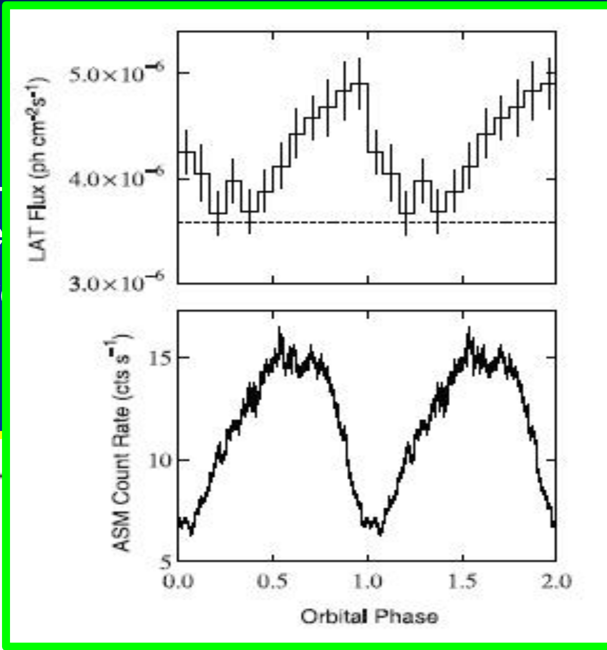
  ("*Modulated High-Energy Gamma-Ray Emission fro*

  - γ-ray detection of the **orbital period** (
  - γ-ray flaring fluxes consistent with the

In 9 days a long-lasting myste

Cygnus X-3 is able to accelerat
energies and to emit γ-rays





The AGILE monitoring of Cygnus X-3 during the "Pointing" Mode

November 2007 → July 2009

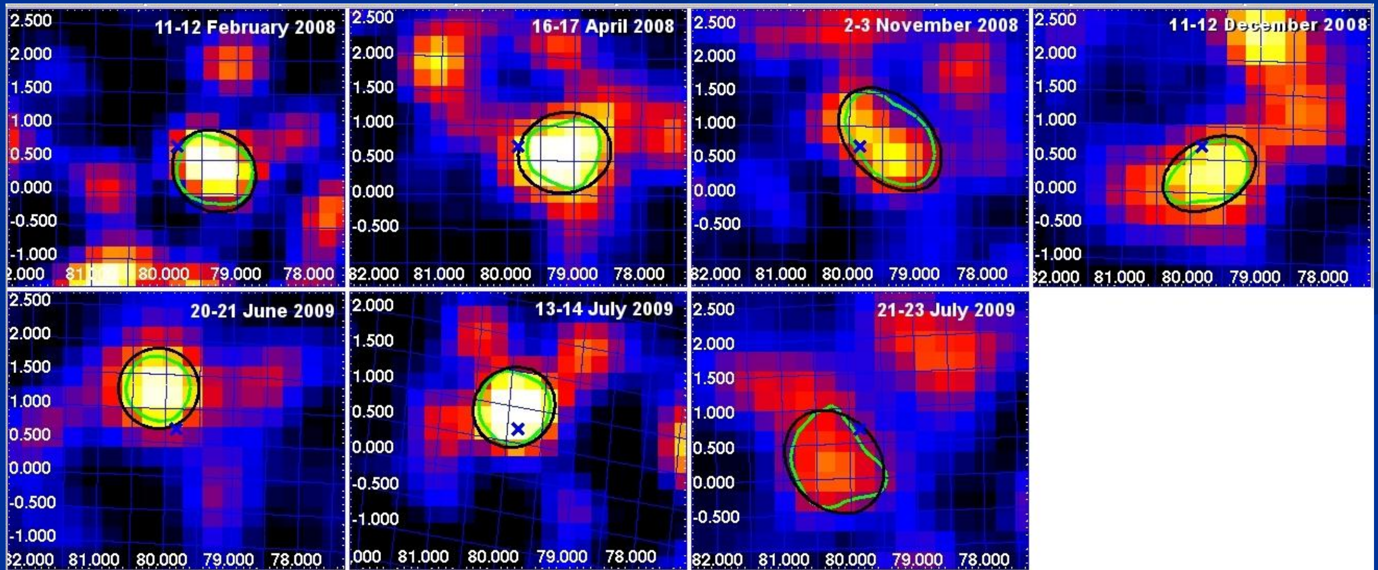
7 major flaring episodes

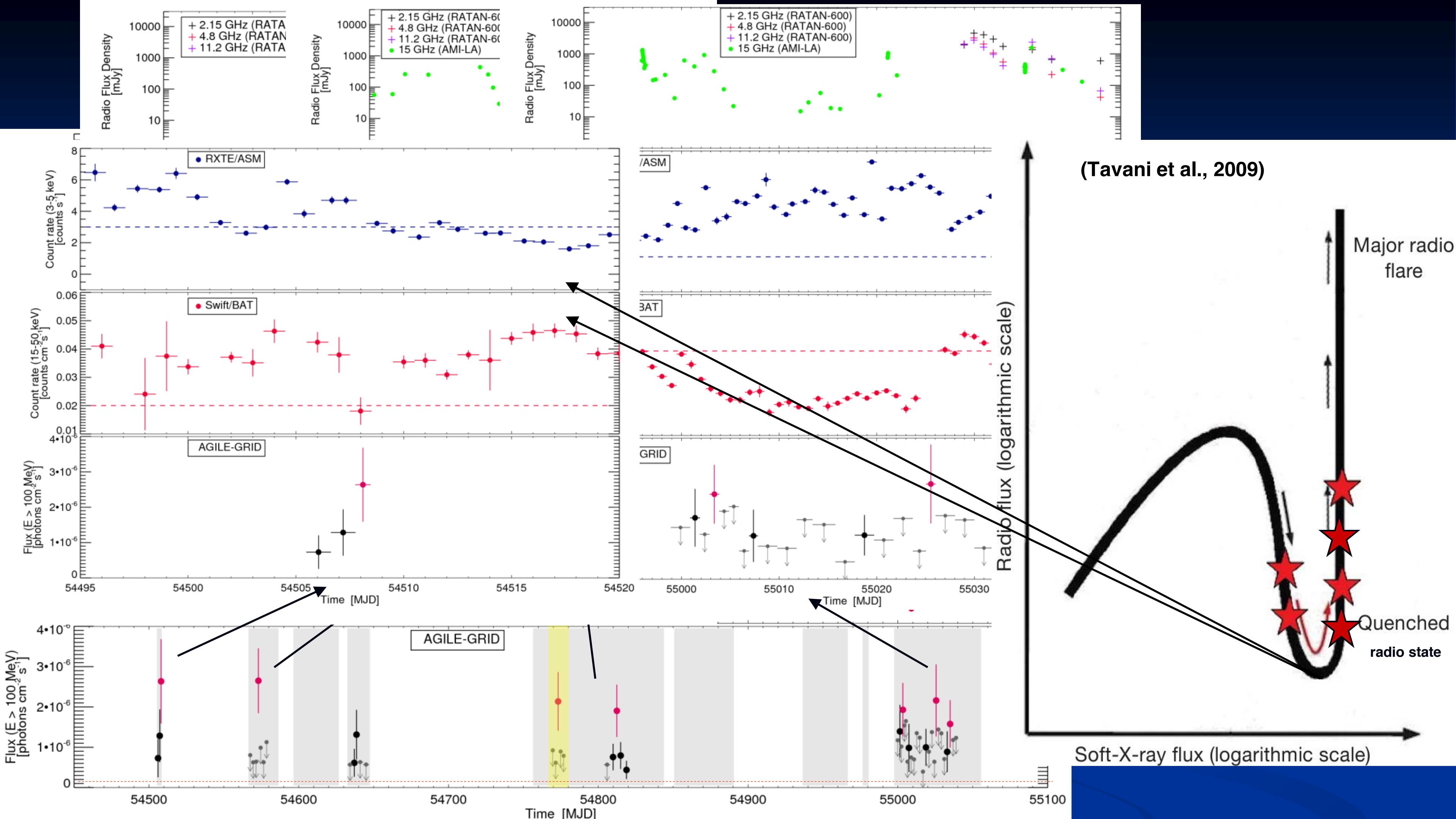
lasting 1-2 days:

- ➢ significance ≥ 3σ;
- ➢ flaring fluxes ≥ 1 order of magnitude greater than the steady flux.

Tavani et al., *Nature*, 2009

Period	MJD	$\sqrt{TS}$	Flux $[10^{-8}$ photons cm^{-2} $s^{-1}]$	Filter
2008-02-11 (18:07:28) - 2008-02-12 (11:07:44)	54507.76 - 54508.46	3.66	264 ± 104 (stat) ± 10% (syst)	FM
2008-04-16 (13:59:12) - 2008-04-17 (13:48:00)	54572.58 - 54573.58	4.48	265 ± 80 (stat) ± 10% (syst)	FM
2008-11-02 (13:01:05) - 2008-11-03 (19:01:05)	54772.54 - 54773.79	3.92	214 ± 73 (stat) ± 10% (syst)	FT
2008-12-11 (19:50:40) - 2008-12-12 (23:02:40)	54811.83 - 54812.96	3.98	190 ± 65 (stat) ± 10% (syst)	FM
2009-06-20 (21:04:48) - 2009-06-21 (20:53:04)	55002.88 - 55003.87	3.84	193 ± 67 (stat) ± 10% (syst)	FM
2009-07-13 (01:11:60) - 2009-07-14 (00:59:44)	55025.05 - 55026.04	3.23	216 ± 89 (stat) ± 10% (syst)	FM
2009-07-21 (21:07:12) - 2009-07-23 (21:07:12)	55033.88 - 55035.88	3.62	158 ± 59 (stat) ± 10% (syst)	FM





Repetitive multi-frequency emission pattern:

- **STRONG ANTICORRELATION** between hard X-ray and γ-ray emission: every local minimum in the hard X-ray light curve (*Swift*-BAT count rate ≤ 0.02 counts cm^{-2} s^{-1}) is associated with a γ-ray flare detected by the AGILE-*GRID* and (vice versa) every γ-ray flare is associated with a hard X-ray local minimum
- γ-ray flares associated with soft spectral states (RXTE/ASM count rate ≥ 3 counts s^{-1})
- γ-ray flares a few days before major radio flares

Cygnus X-3 γ-ray "flaring" spectrum

By integrating all flaring data:

(E ≥ 100 MeV)

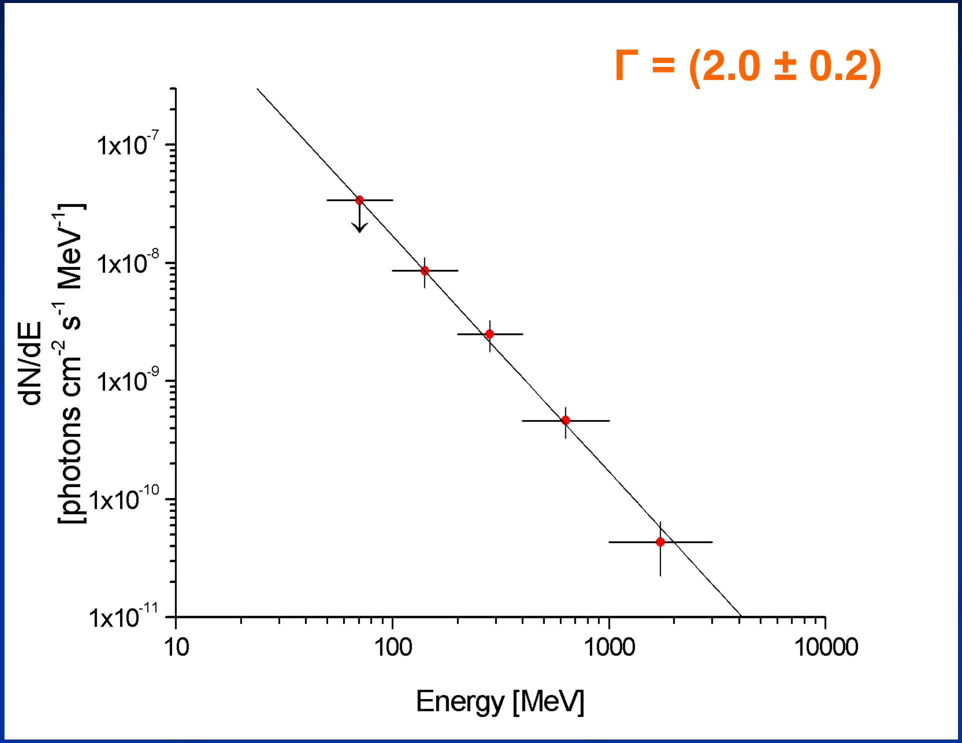
6.7σ pre-trial

5.5σ post-trial

(79.7, 0.9) ± 0.4° (stat.) ± 0.1° (syst.),

F = (158 ± 29) x 10^{-8} ph cm^{-2} s^{-1}

[F_{steady} = (14 ± 3) x 10^{-8} ph cm^{-2} s^{-1}]



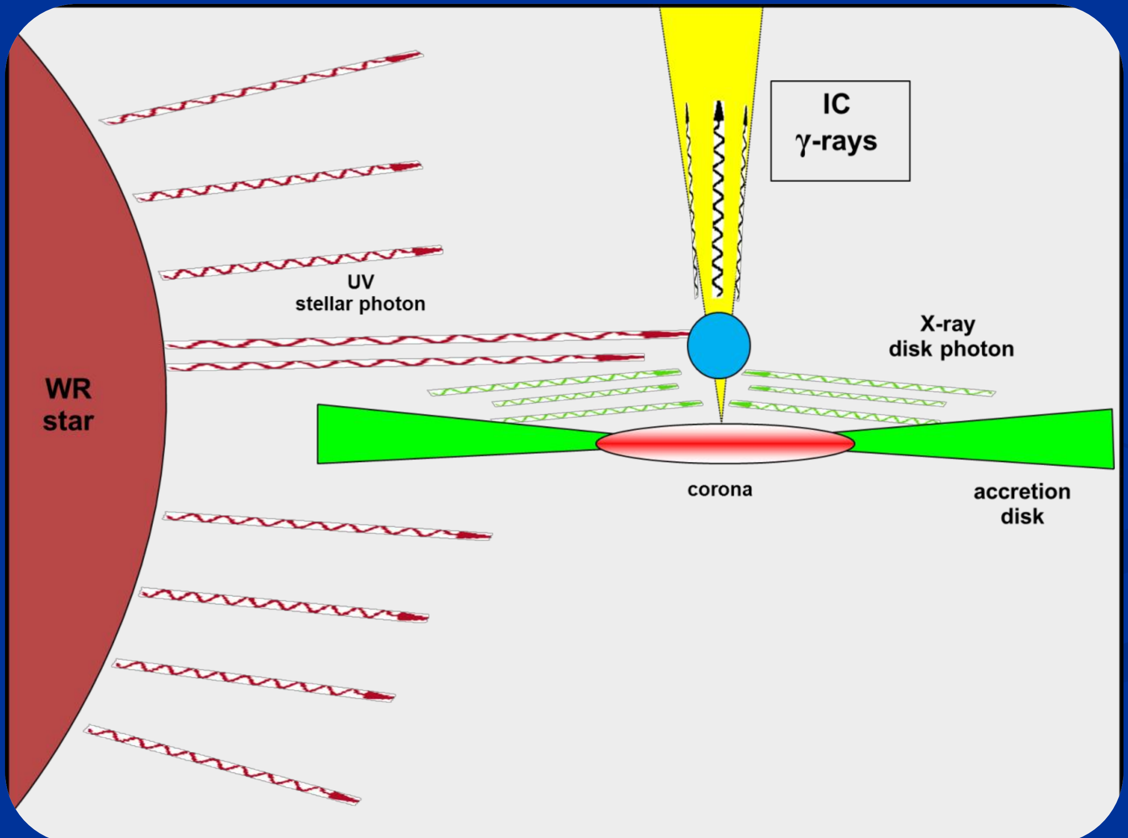
Modeling the spectrum:

- AGILE γ-ray flaring spectrum
- typical X-ray spectrum of the quenched state → Hypersoft State (Koljonen et al., 2010)
- (MAGIC ULs during soft spectral state)

γ-ray emission from Cygnus X-3

A LEPTONIC model:

- corona “evacuation”
- injection of a spherical plasmoid of relativistic electrons/positrons scattering off soft photons from the disk and from the wind of the WR star
- γ-rays from IC processes in the jet



Cygnus X-3 multi-wavelength spectrum (model "A")

Star:
L ~ 10^{39} erg/s

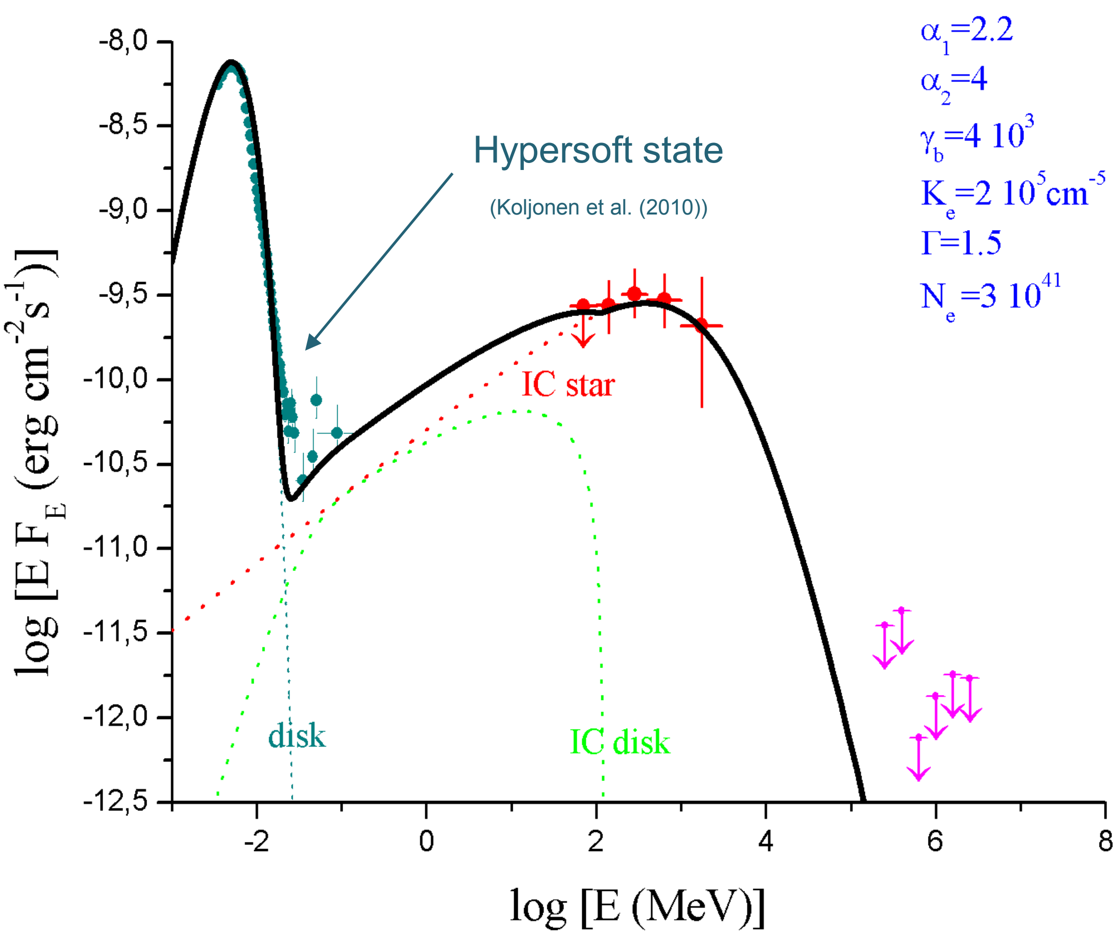
Disk:
T_{bb} ~ 1.3 keV

Spherical plasmoid:
R~ $3\cdot10^{10}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e \gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \qquad [\alpha_1 < \alpha_2]$$

(Piano et al., 2012, Submitted to A&A)



Geometry of the interaction:

(d ≡ orbital distance)

(D ≡ star-blob distance)

(H ≡ disk-blob distance)

H ~ $3\cdot10^{10}$ cm

D ~ d ~ $3\cdot10^{11}$ cm

(plasmoid close to the disk)

electron density ~ $3\cdot10^{9}$ cm^{-3}

Cygnus X-3 multi-wavelength spectrum (model "B")

Star:

L ~ 10^{39} erg/s

Disk:

T_{bb} ~ 1.3 keV

Spherical plasmoid:

R~ $3\cdot10^{10}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e\,\gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \qquad [\alpha_1 < \alpha_2]$$

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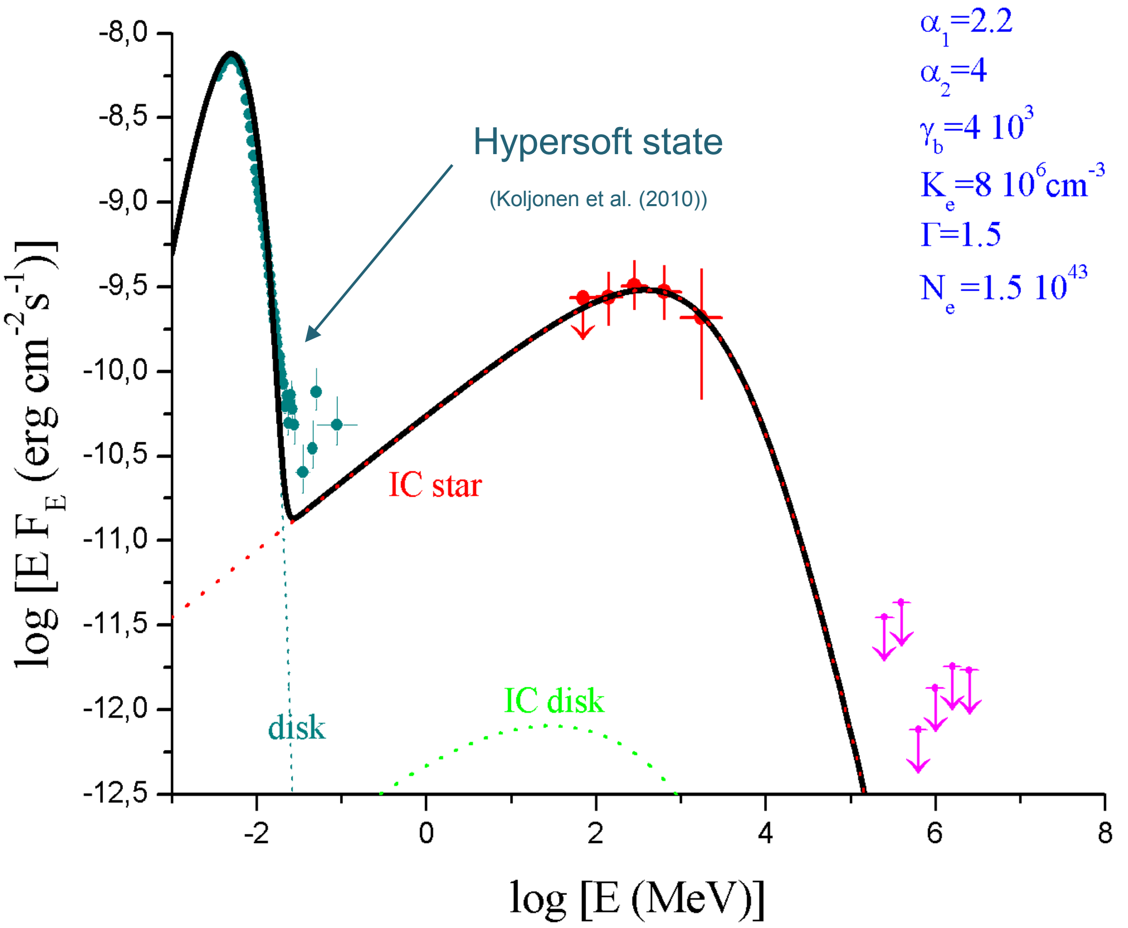


Geometry of the interaction:

(d ≡ orbital distance)

(D ≡ star-blob distance)

(H ≡ disk-blob distance)

H ~ $3\cdot10^{12}$ cm ~ 10 d

D ~ H ~ $3\cdot10^{12}$ cm

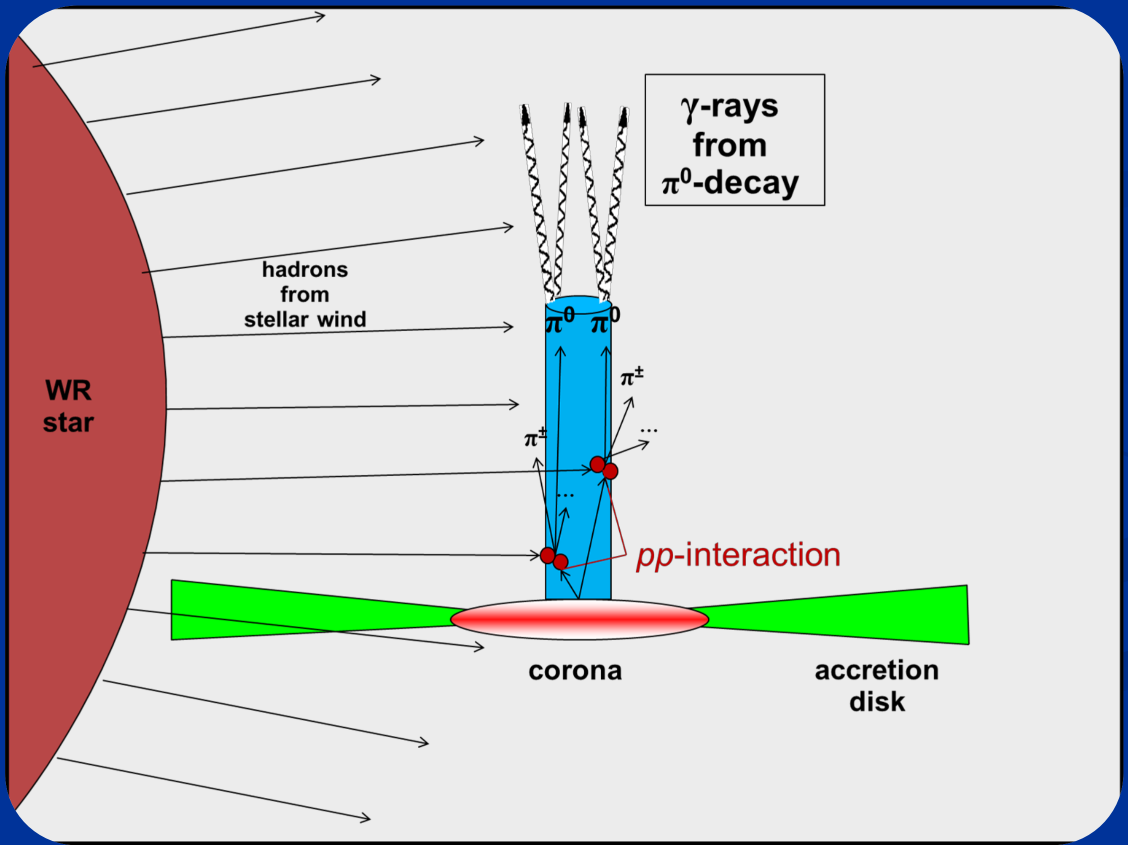
(plasmoid far away from the disk)

electron density ~ $1.5\cdot10^{11}$ cm^{-3}

γ-ray emission from Cygnus X-3

A HADRONIC model:

- injection of mildly relativistic protons
- interaction with the gas of the WR strong wind along a cylindrical column of matter (radius $R \sim 3 \cdot 10^{10}$ cm, height $H \sim 3 \cdot 10^{12}$ cm)
- inelastic scatterings: $p + p \rightarrow \pi^0 + \ldots$; $\pi^0 \rightarrow \gamma + \gamma$



A hadronic model

Strong stellar wind:

$v_{wind} \sim 1000 \text{ km s}^{-1}$

$\dot{M} \sim 10^{-5} M_{\odot} \text{yr}^{-1}$

Geometry of the interaction:

injected proton interact with the hadronic matter of the wind along a cylinder

R~ $3 \cdot 10^{10}$ cm

H~ $3 \cdot 10^{12}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e \gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \quad [\alpha_1 < \alpha_2]$$

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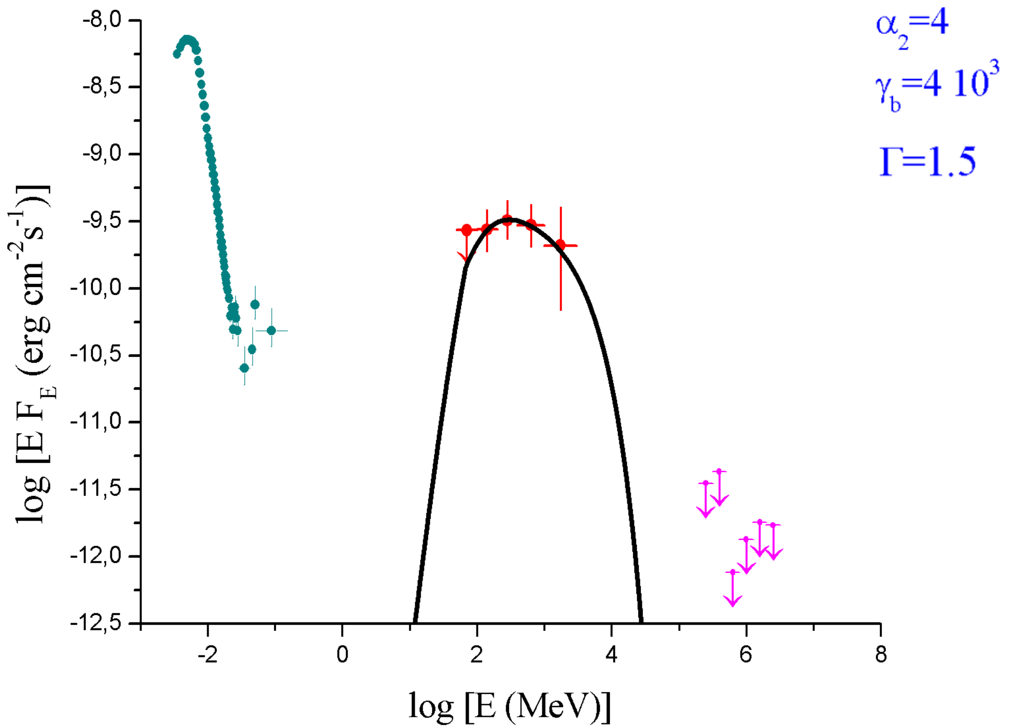


Results from modeling:

$N_{p,wind} \approx 3.7 \times 10^{45}$

$N_{p,jet} \approx 2 \times 10^{45}$

$\dot{N}_{p,jet} \approx 1.4 \times 10^{43}$ protons s^{-1}

$L_{kin,\ p} \approx 3 \times 10^{40}$ erg s^{-1}

Jet kinetic luminosity exceeds:

- Disk luminosity of the Hypersoft state (L_{HYS}~10^{38} erg s^{-1})
- Eddington accretion limit (L_{Edd}~10^{39} erg s^{-1})

Spectral modeling:
discussion

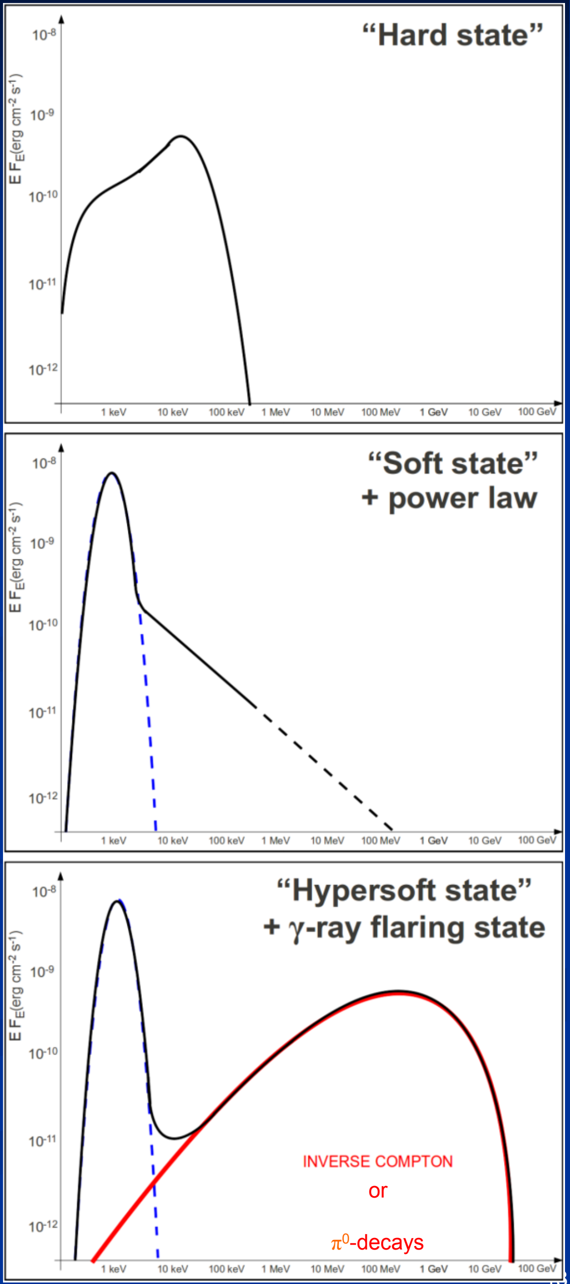
Both leptonic and hadronic models might account for the γ-ray flaring spectrum of Cygnus X-3 detected by the AGILE-*GRID*, but…

- Hadronic model requires very high jet kinetic power ($L_{kin,\,p} > L_{Edd}$)
  (Does Cygnus X-3 emit hadronic jet outflows in a super-Eddington regime, like SS433?)
- Leptonic models
  - ✓ γ-ray modulation (Dubus et al, 2010; Zdziarski et al., 2012)
  - ✓ time delay between γ-ray and radio outflows
    (Is the same population of electrons that emits in the γ-ray and in the radio band ?)
  - ✓ low jet kinetic power:
    $L^{A}_{kin,\,e} \approx 2 \times 10^{35}\ \mathrm{erg\ s^{-1}}$ $L^{B}_{kin,\,e} \approx 10^{37}\ \mathrm{erg\ s^{-1}}$
  - ✓ **Model "A" → spectral link between the hard X-ray tail and the γ-ray spectrum.**

Leptonic scenario is favorable

Cygnus X-3 detected by the AGILE-*GRID*

conclusions



Major γ-ray flares:

⇨ **when?**

- ✓ during soft states, a few days before strong radio outbursts
- ✓ the system is moving into or out of the quenched state

  ("spectral signature" of the γ-ray emission in Cygnus X-3)

⇨ **where?**

- ✓ in the **jet**
  - ➢IC γ-rays by relativistic leptons
  - ➢γ-rays from π^0-decays (by relativistic protons)

  (evidence of extreme particle acceleration)

⇨ **implications:**

- ✓ new component in the multiwavelength spectrum
- ✓ spectral link between X-ray and γ-ray spectra (leptonic model)
- ✓ new constraints in the high-energy emission model

(Piano et al., 2012, Submitted to A&A)

Thank you!