Transient γ-ray emission from Cygnus X-3: AGILE observations and spectral constraints

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OUTLINE

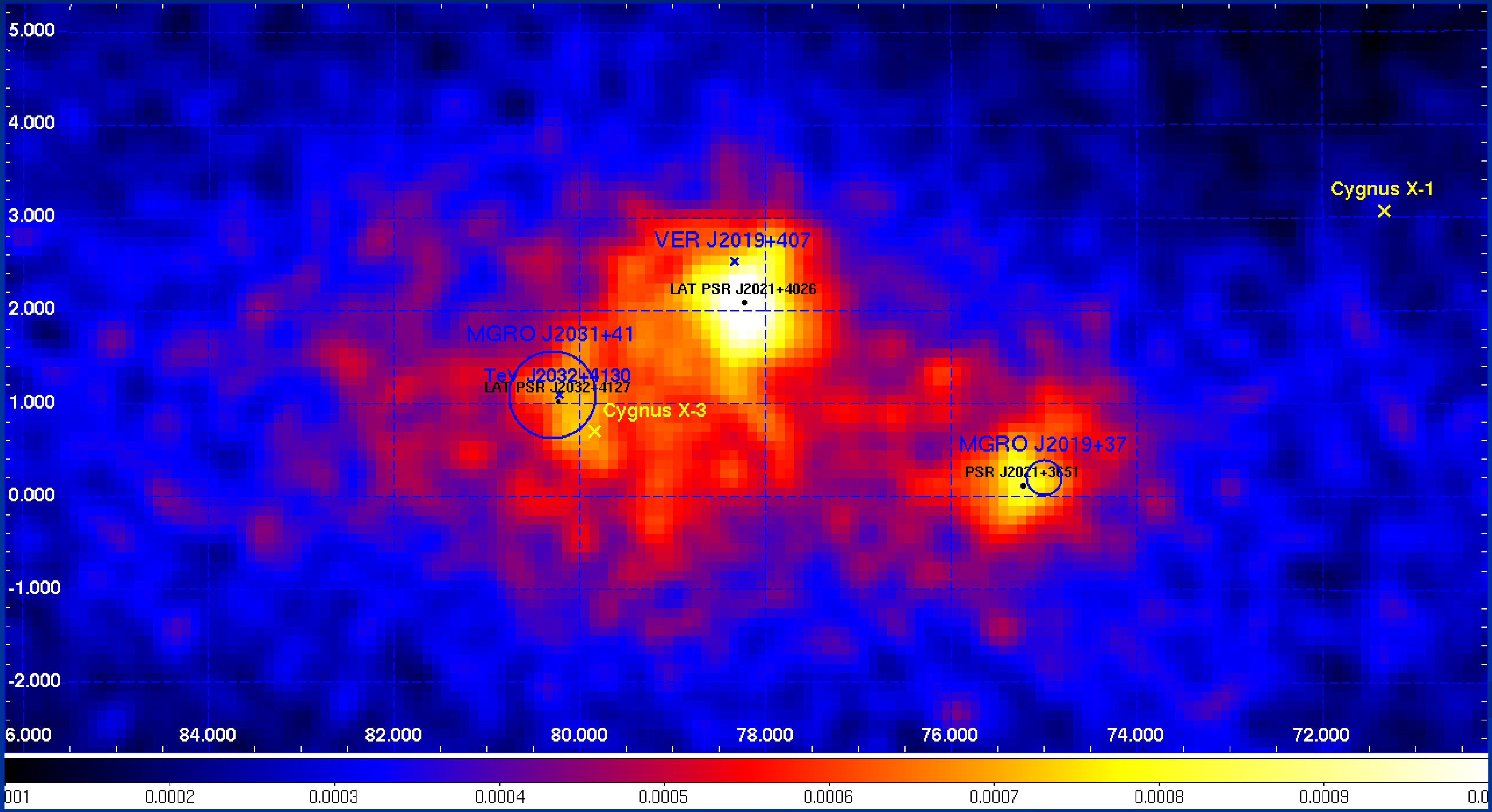
- The AGILE monitoring of Cygnus X-3
  (November 2007 → July 2009):
  - the γ-ray activity in the context of the multi-wavelength emission
  - the γ-ray spectrum detected by AGILE

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

- Conclusions

Microquasars in the Cygnus region:

AGILE-*GRID* INTENSITY MAP (100 MeV-10 GeV)
November 2007 – July 2009,
~275 days, ~11 Ms net exposure time



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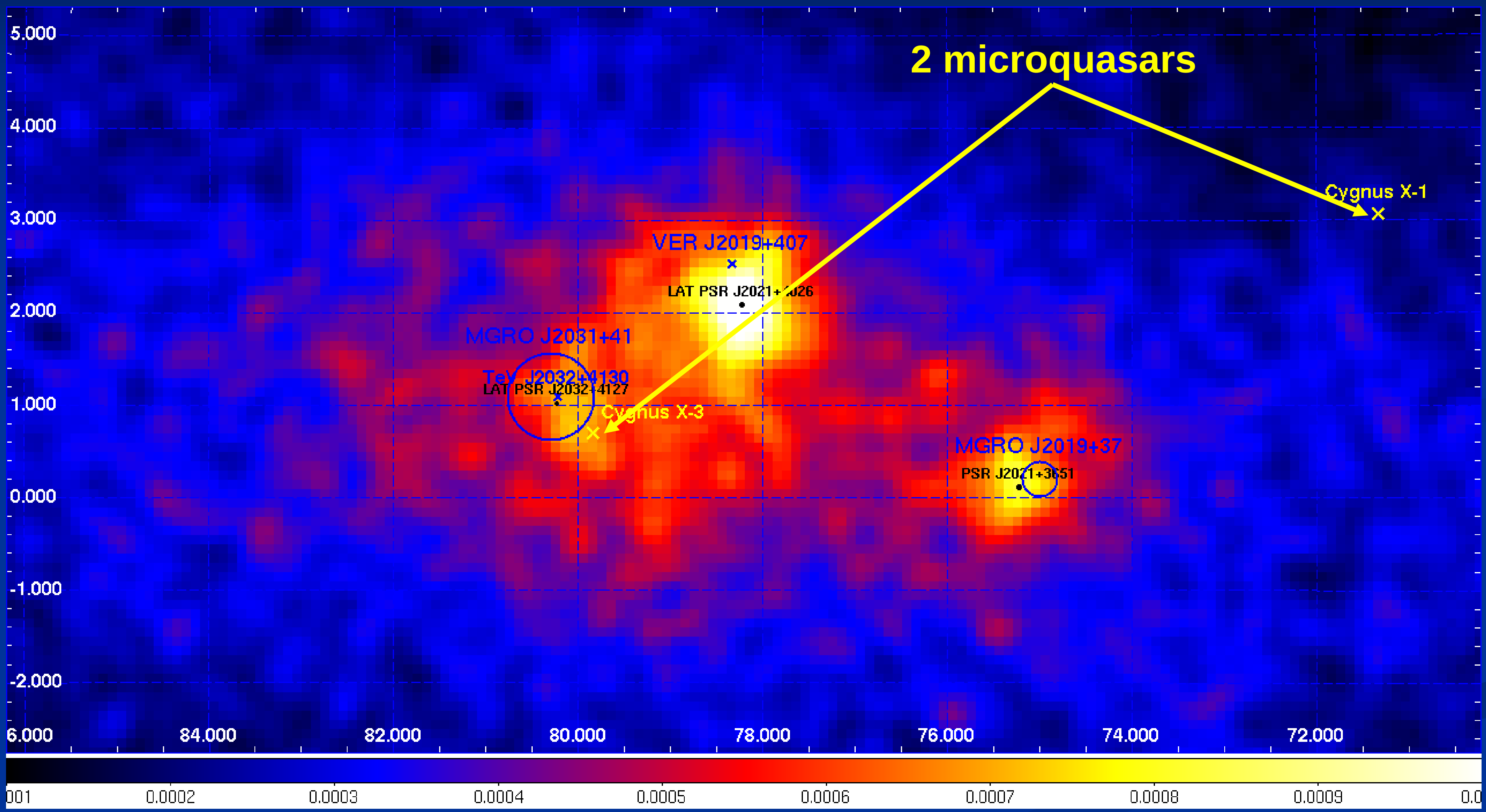
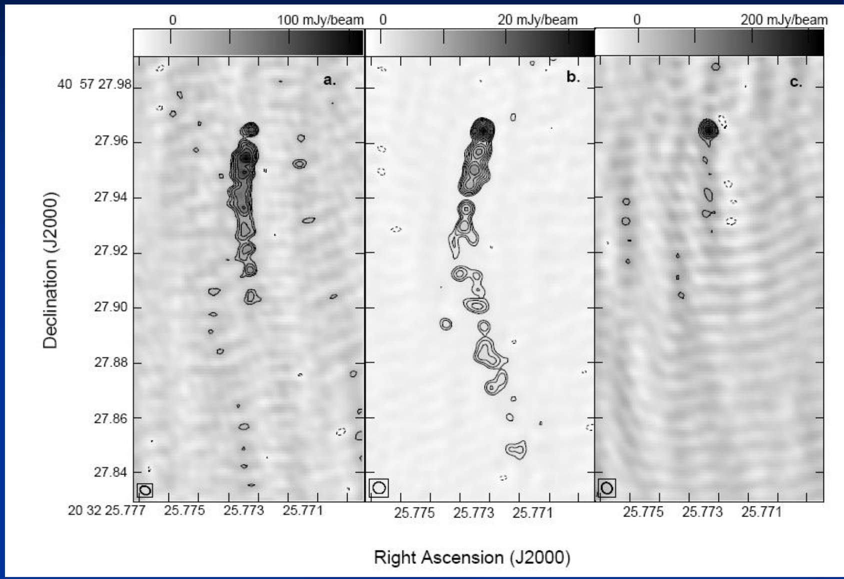


Cygnus X-3

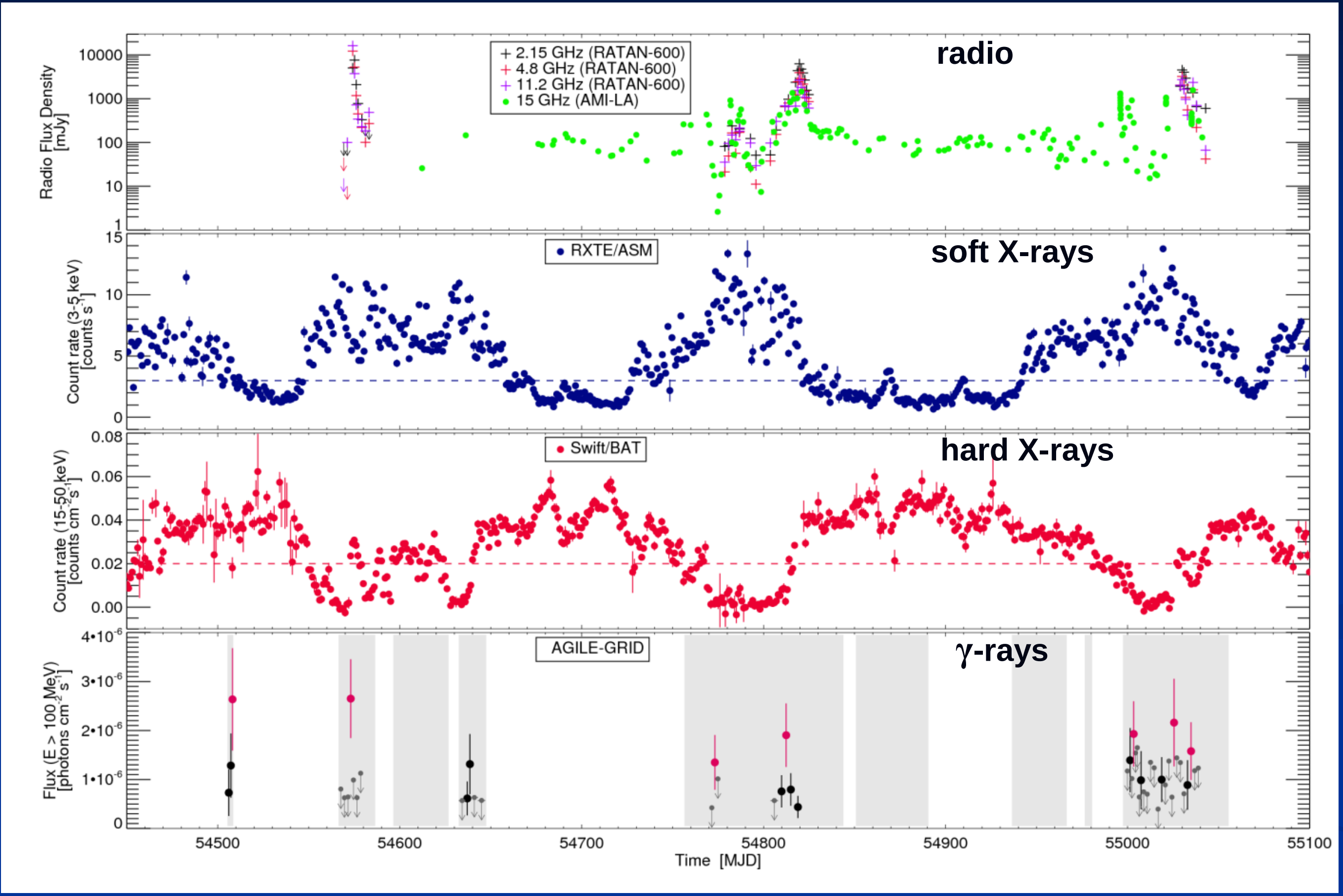
- distance → 7-10 kpc
- donor Star → Wolf-Rayet star with strong stellar wind (mass loss ~ 10^{-5} $M_\odot$ y^{-1}, v_{wind} ~ 1000 km s^{-1})
- compact object → UNKNOWN. Published results range: from a *Neutron Star* of 1.4 $M_\odot$ to a *Black Hole* of a mass of up to 10 $M_\odot$.
- orbital period (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 correlations between radio and X-ray emissions during *Major Flares* (hysteresis curve)
- **transient γ-ray emission above 100 MeV (detected by AGILE and Fermi)**

Feb. 6, 1997 Feb. 8 Feb. 11



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

γ-ray activity detected by AGILE (November 2007 → July 2009) in the context of the multi-wavelength emission



Repetitive multi-frequency emission pattern:

- **STRONG ANTICORRELATION** between hard X-ray and γ-ray emission: γ-ray activity associated with sharp/local minima in the hard X-ray light curve (*Swift*/BAT count rate ≤ 0.02 counts cm^{-2} s^{-1})
- γ-ray flares coincident with soft spectral states (*RXTE*/ASM count rate ≥ 3 counts s^{-1})

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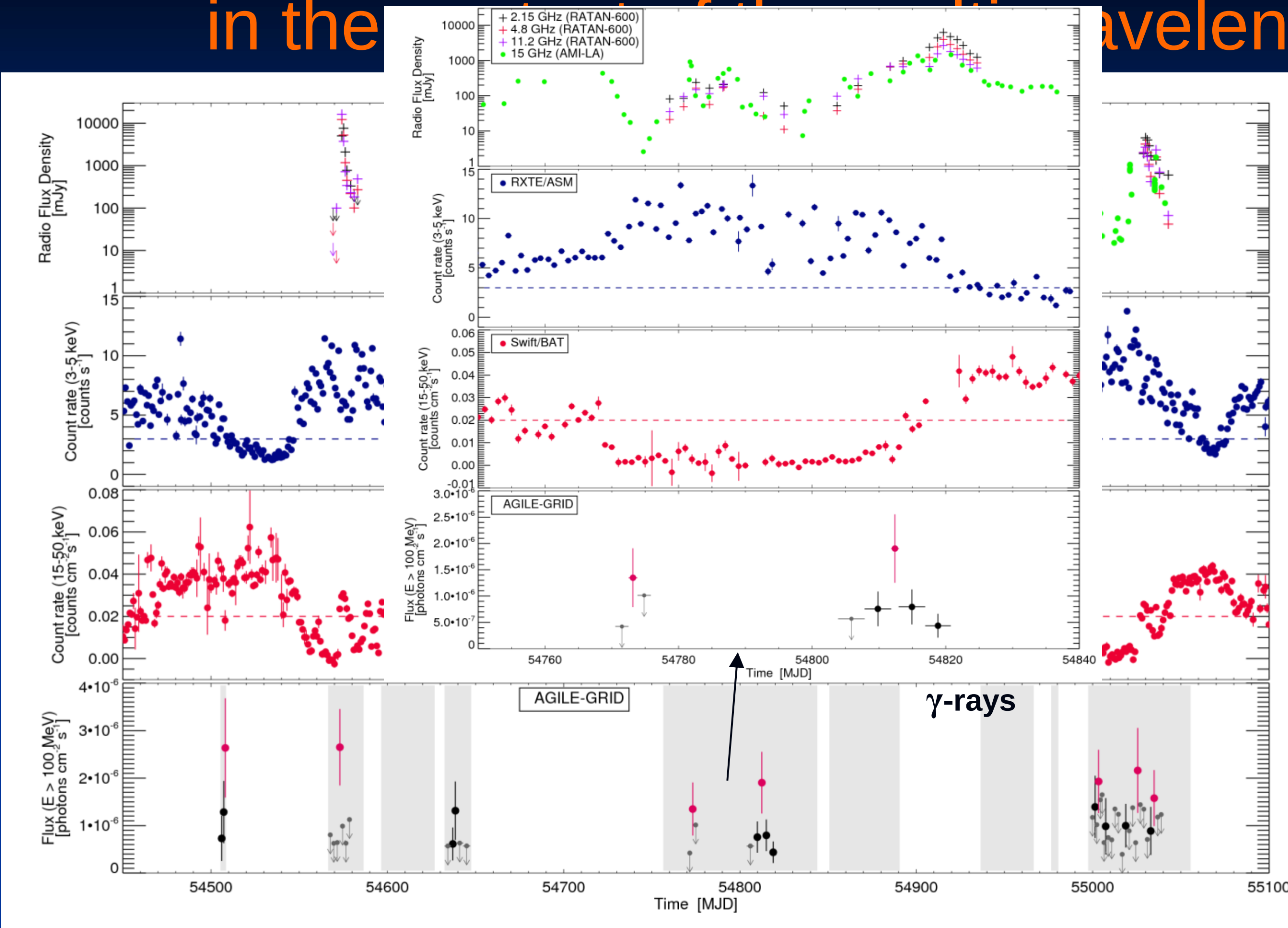

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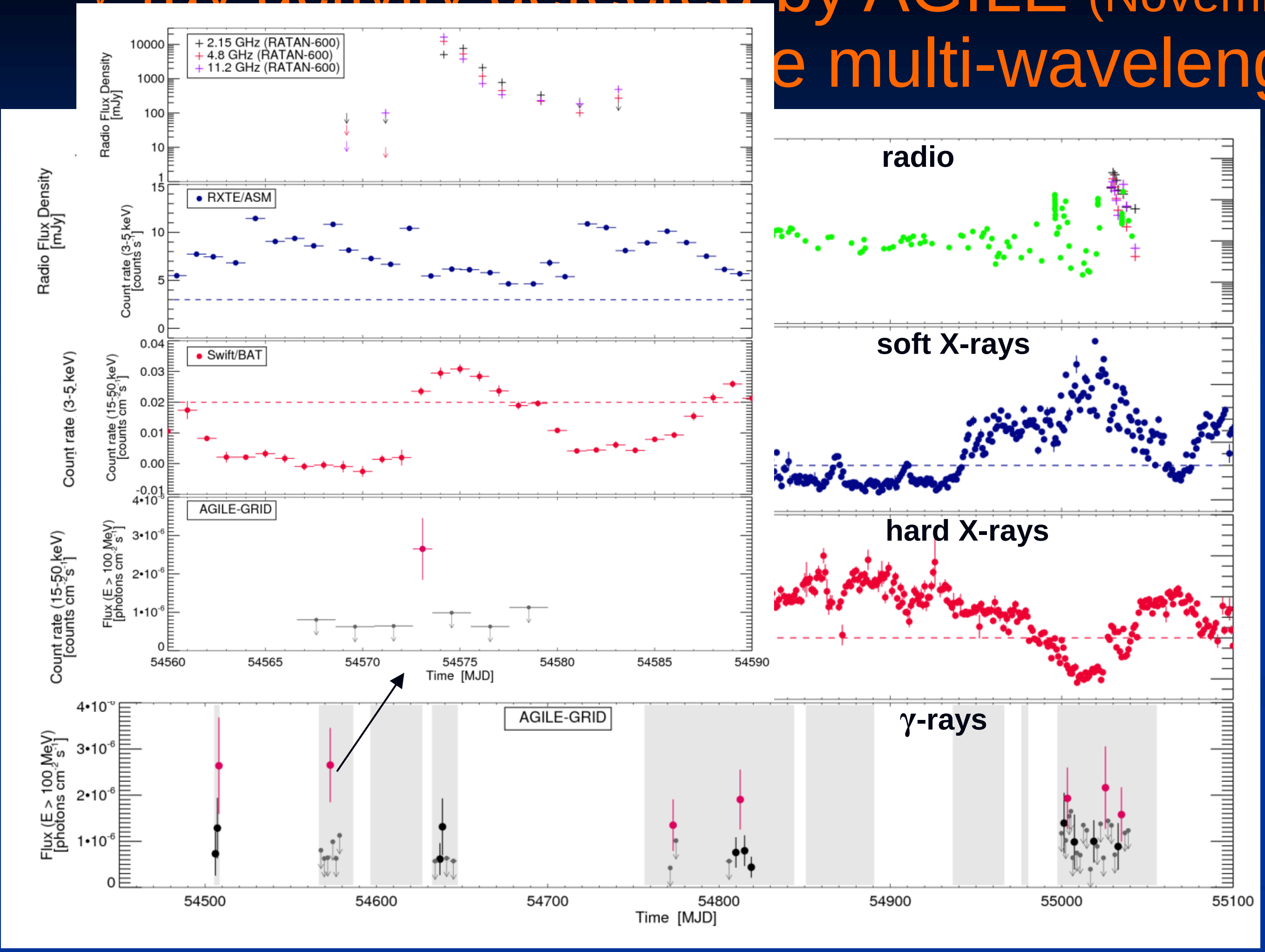

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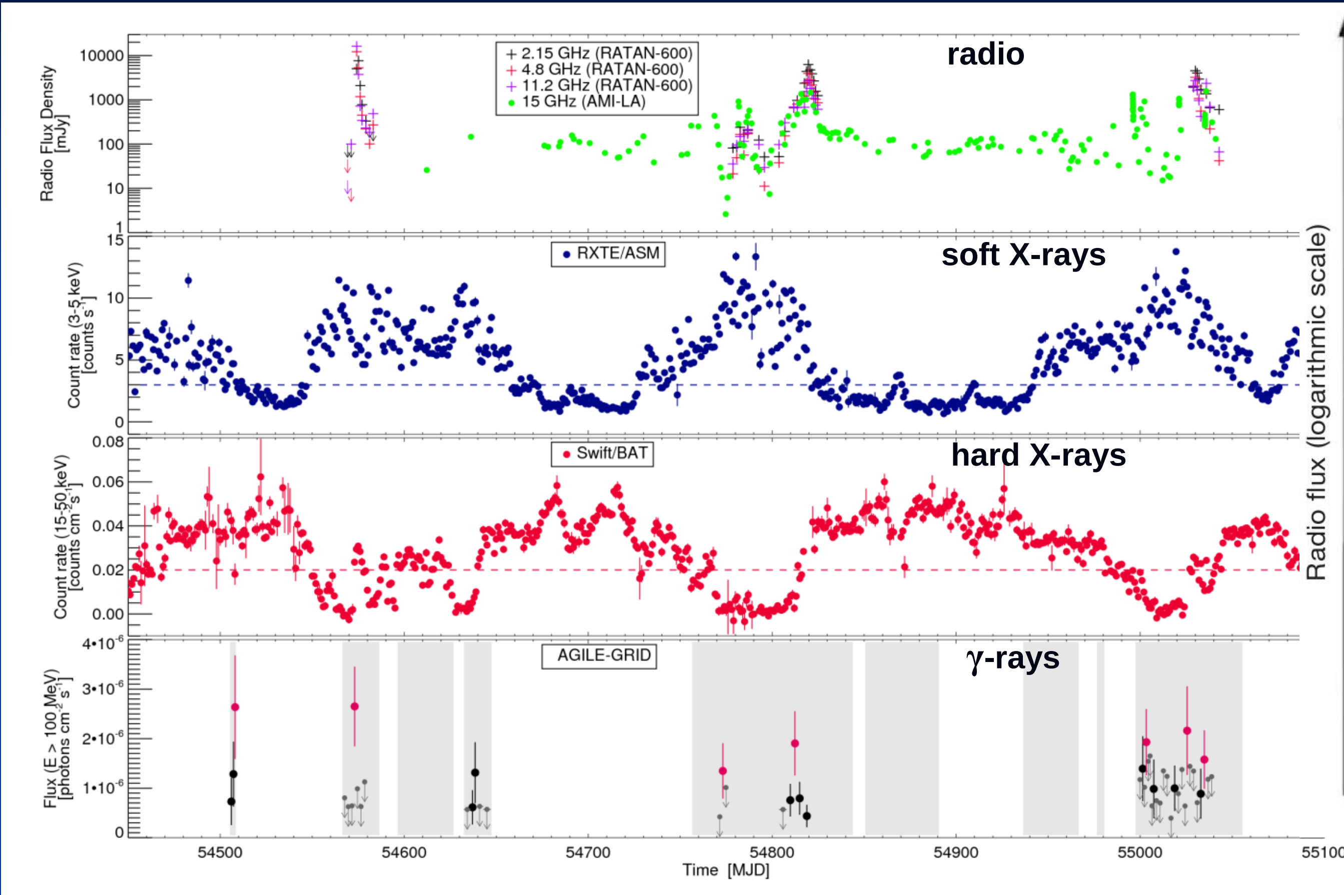

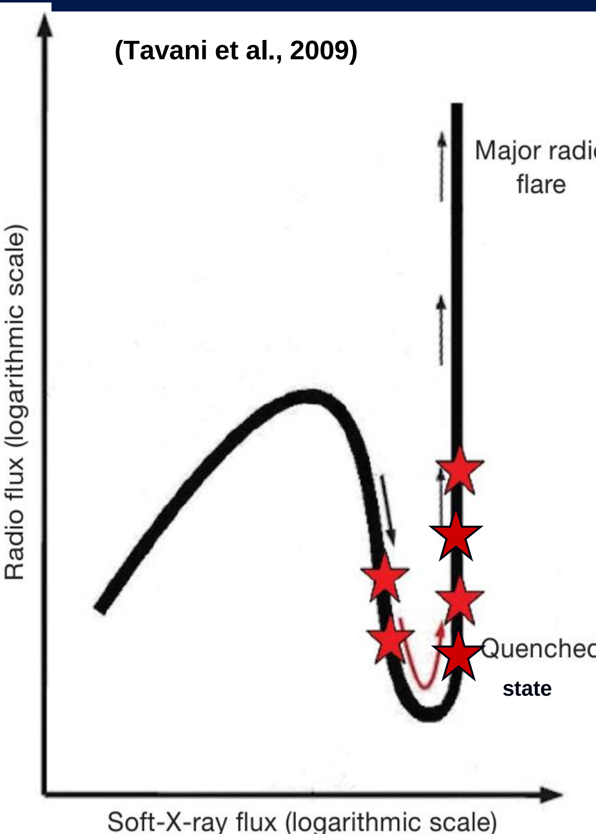

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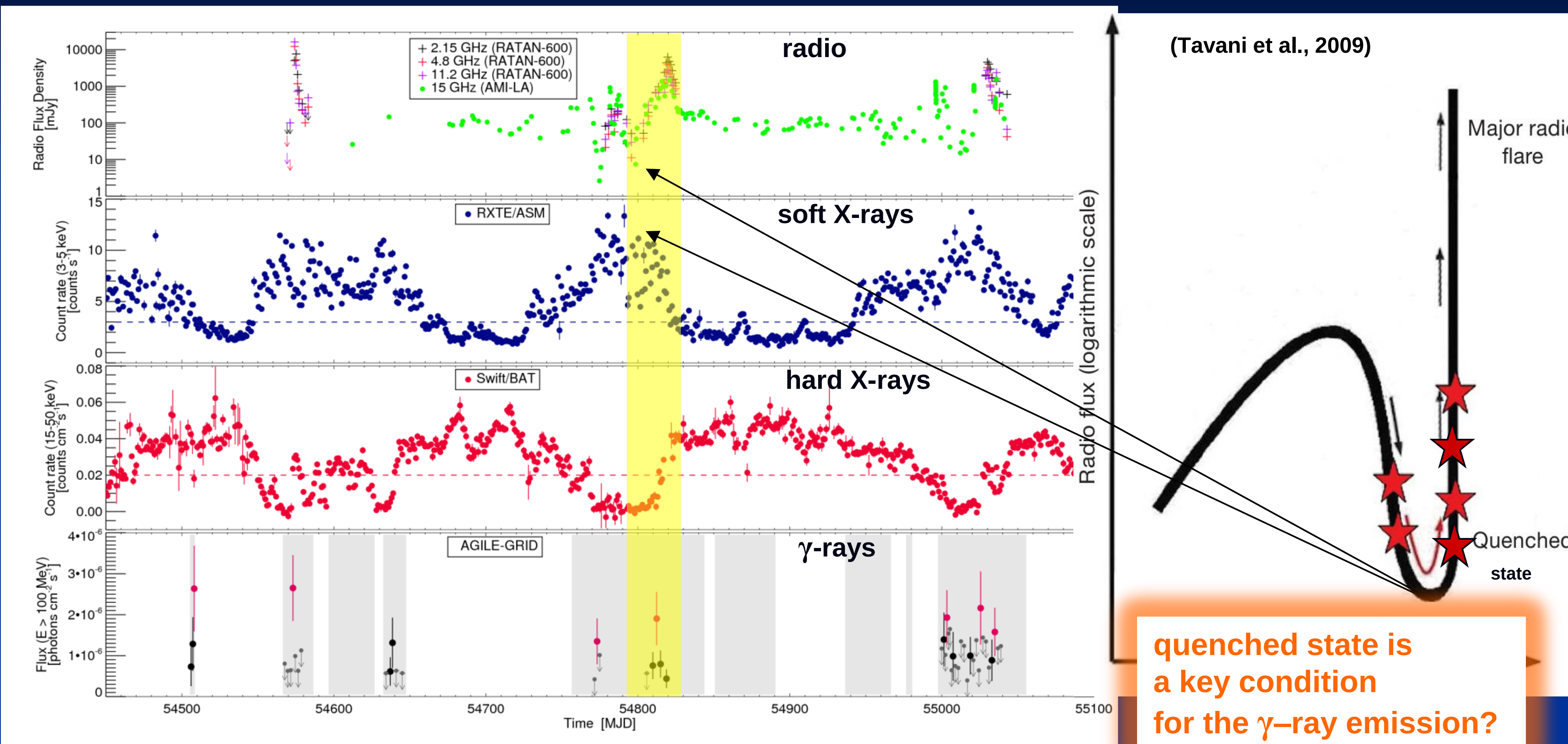

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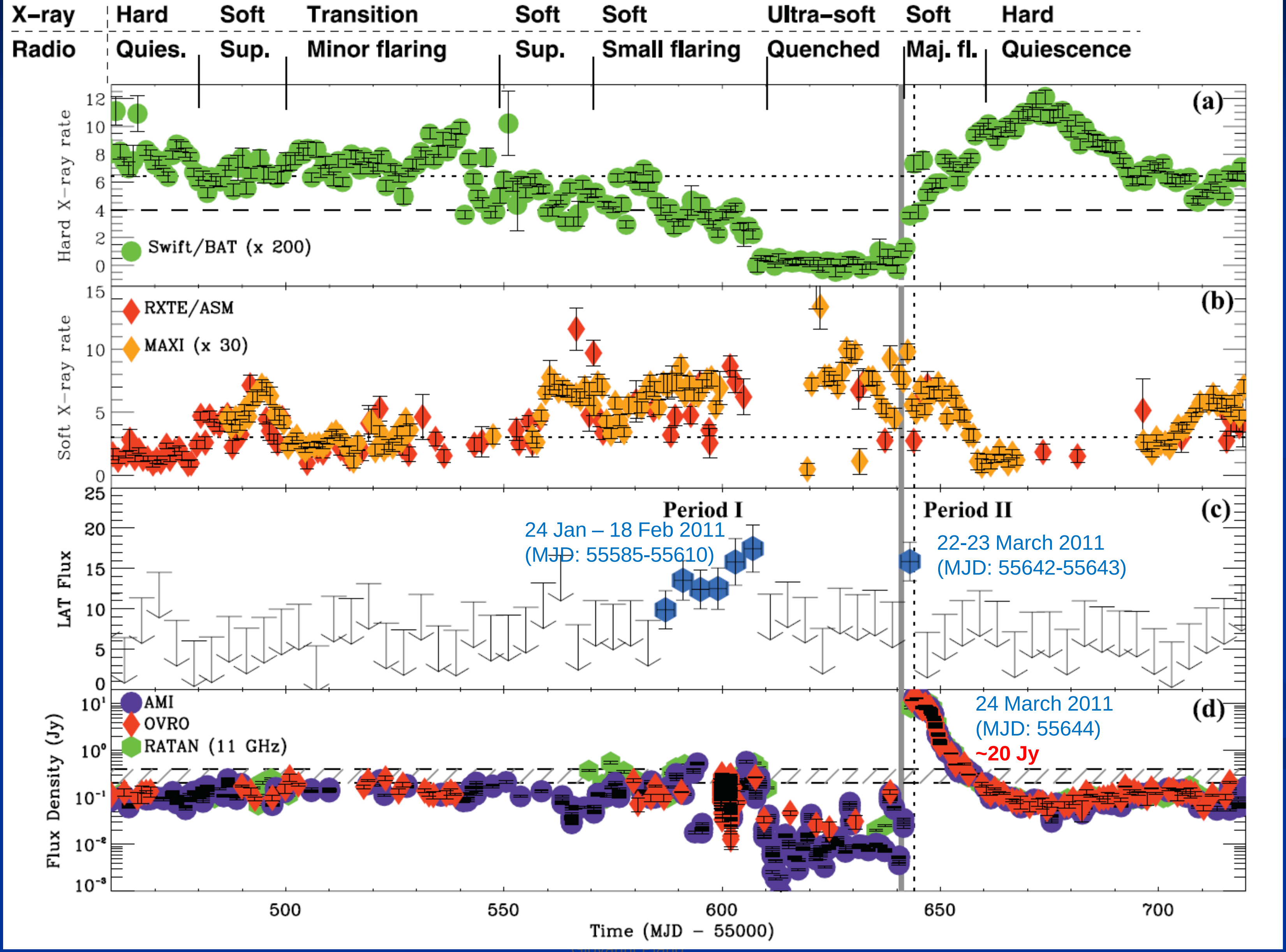
γ-ray activity detected by *Fermi*-LAT before a giant radio flare (Corbel et al., 2012)



Cygnus X-3 γ-ray spectrum

By integrating the 7 γ-ray flares:

(E ≥ 100 MeV)

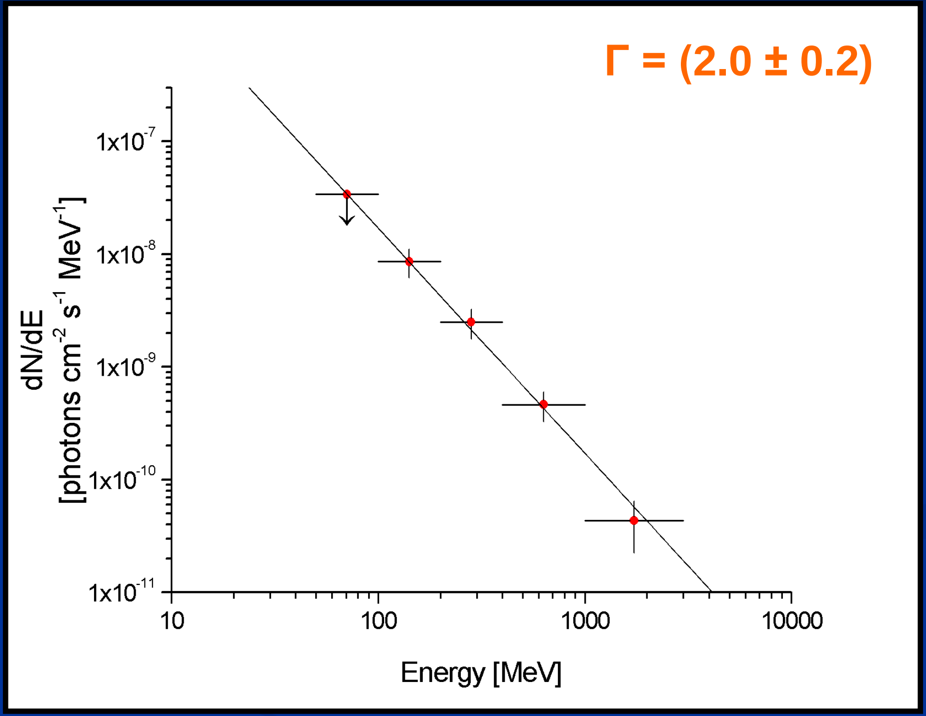
6.7σ pre-trial

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}]



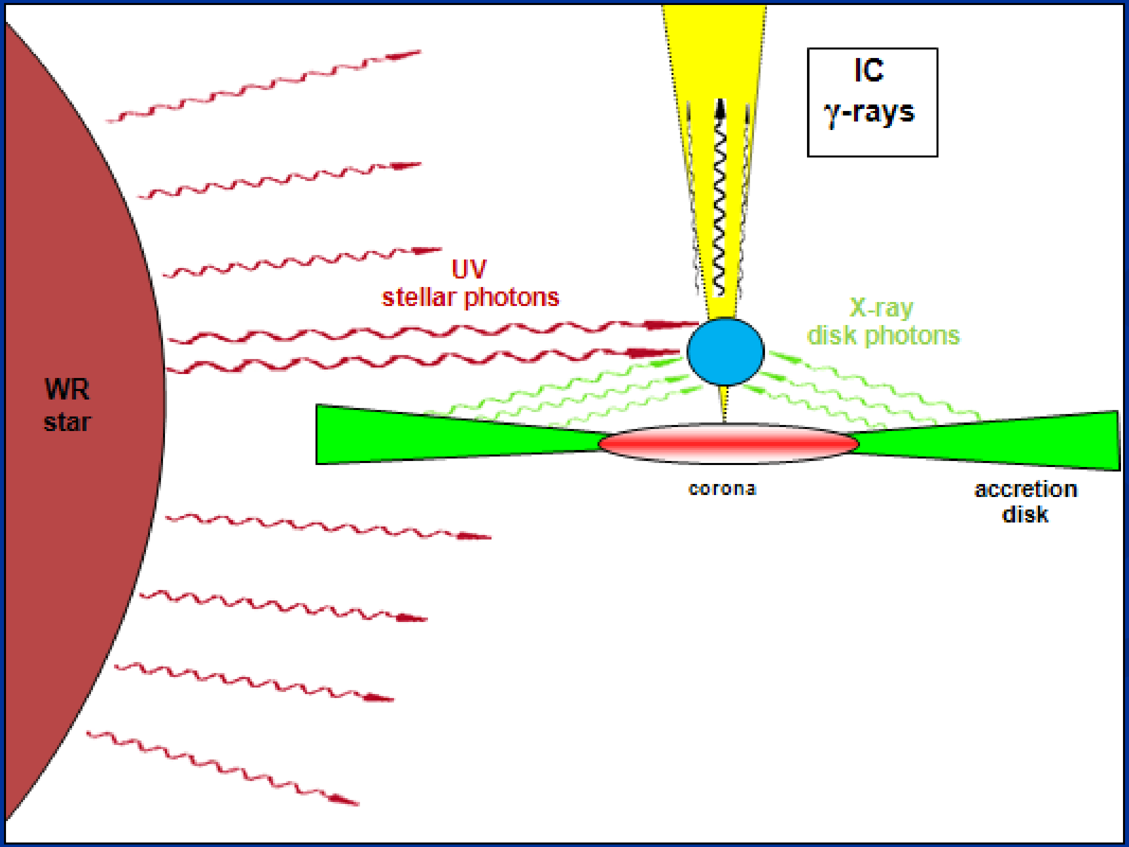
Modeling the spectrum:

- AGILE γ-ray spectrum [50 MeV – 3 GeV]
- typical X-ray spectrum of the quenched state → Hypersoft Spectrum (Koljonen et al., 2010)
- (MAGIC ULs during soft spectral state)

γ-ray emission from Cygnus X-3

A LEPTONIC model:

- corona "evacuation" (→ Hypersoft State)
- injection of a spherical plasmoid of relativistic electrons/positrons scattering off soft photons from both the disk and 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 ~ $3{\cdot}10^{10}$ cm

Broken power-law:

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

Geometry of the interaction:

(d ≡ orbital distance)

(R ≡ star-blob distance)

(H ≡ disk-blob distance)

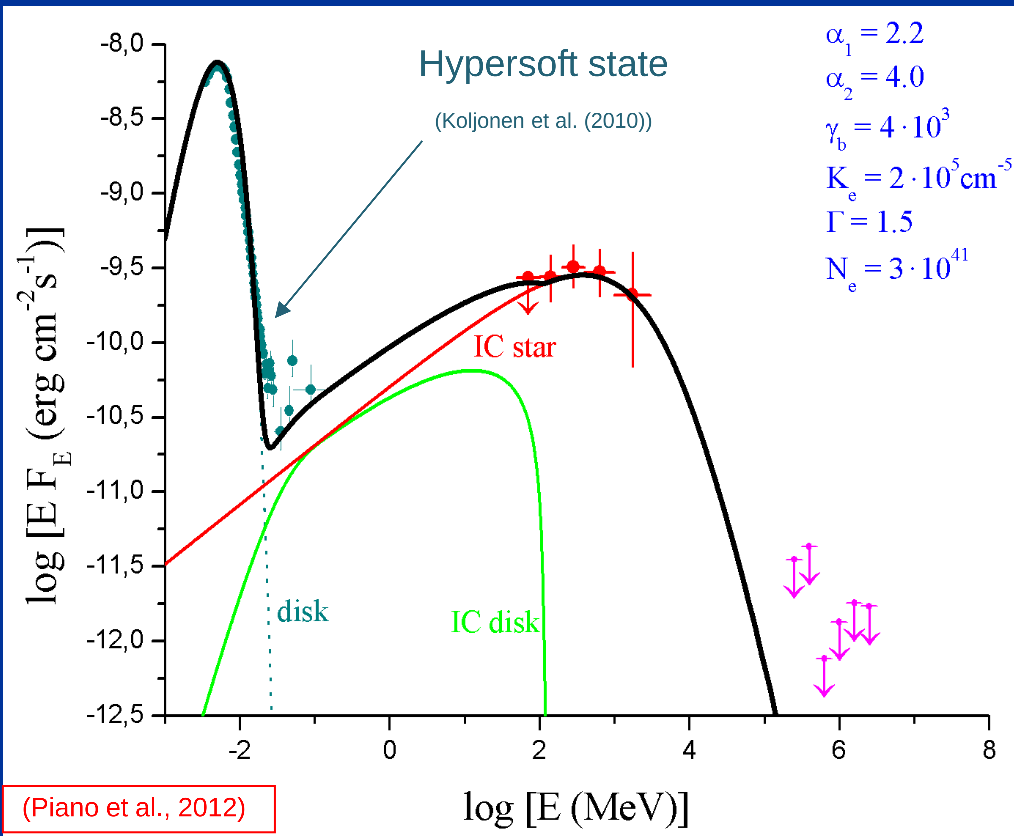
H ~ $3{\cdot}10^{10}$ cm ~ 10^{-1} d

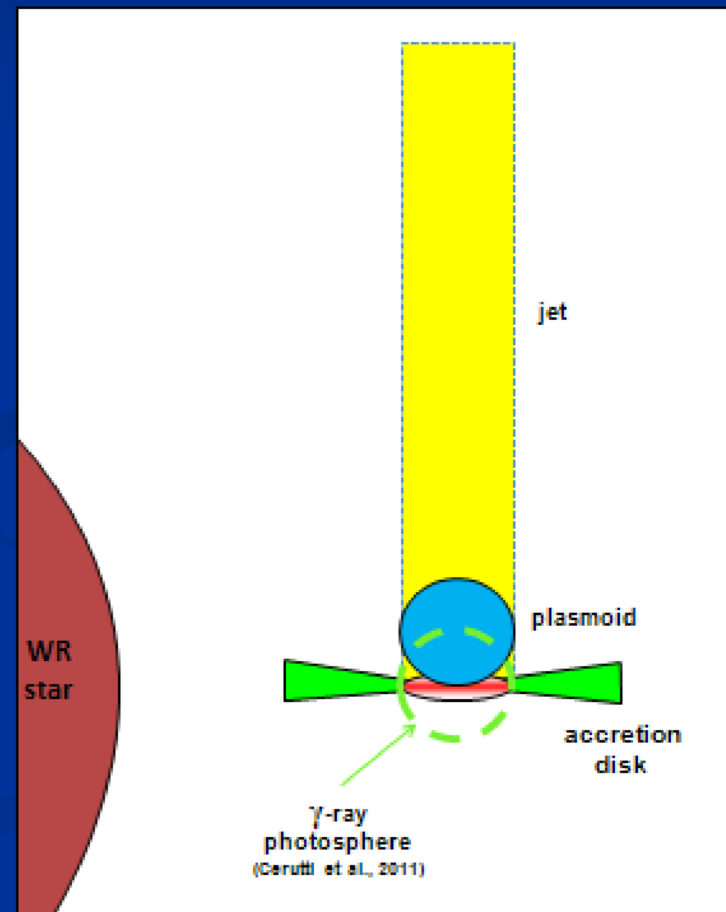
R ~ d ~ $3{\cdot}10^{11}$ cm

(plasmoid close to the disk)

i = 14°

electron density ~ $3{\cdot}10^{9}$ cm^{-3}





$$L^{A}_{kin,\,e} \approx 2 \times 10^{35}\ \mathrm{erg\ s^{-1}}$$

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

Star:

$L \sim 10^{39}$ erg/s

Disk:

$T_{bb} \sim 1.3$ keV

Spherical plasmoid:

$r \sim 3{\cdot}10^{10}$ cm

Broken power-law:

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

Geometry of the interaction:

(d ≡ orbital distance)

(R ≡ star-blob distance)

(H ≡ disk-blob distance)

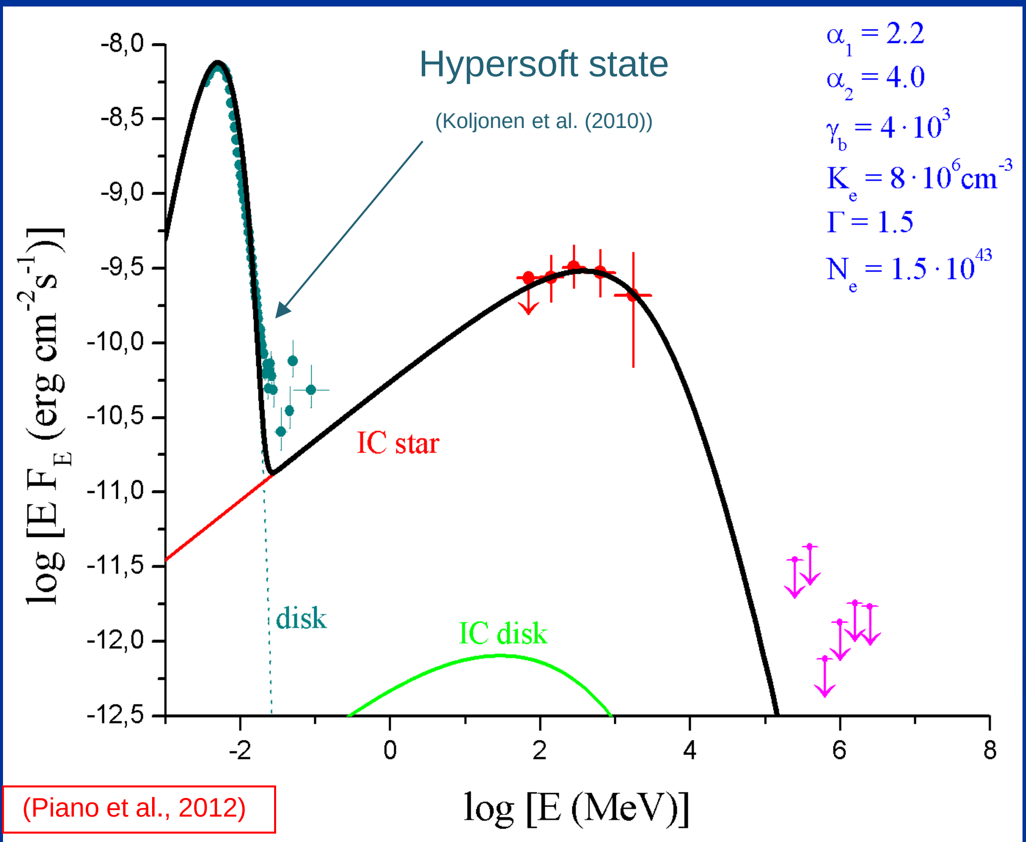
$H \sim 3{\cdot}10^{12}$ cm ~ 10 d

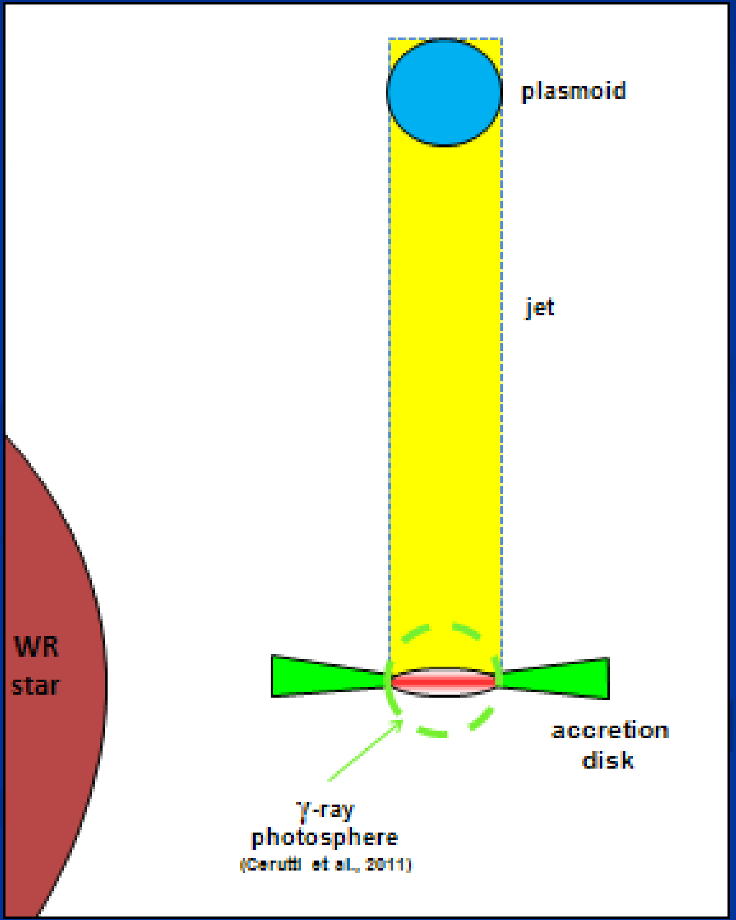
$R \sim H \sim 3{\cdot}10^{12}$ cm

(plasmoid far away from the disk)

$i = 14°$

electron density $\sim 1.5{\cdot}10^{11}$ cm^{-3}



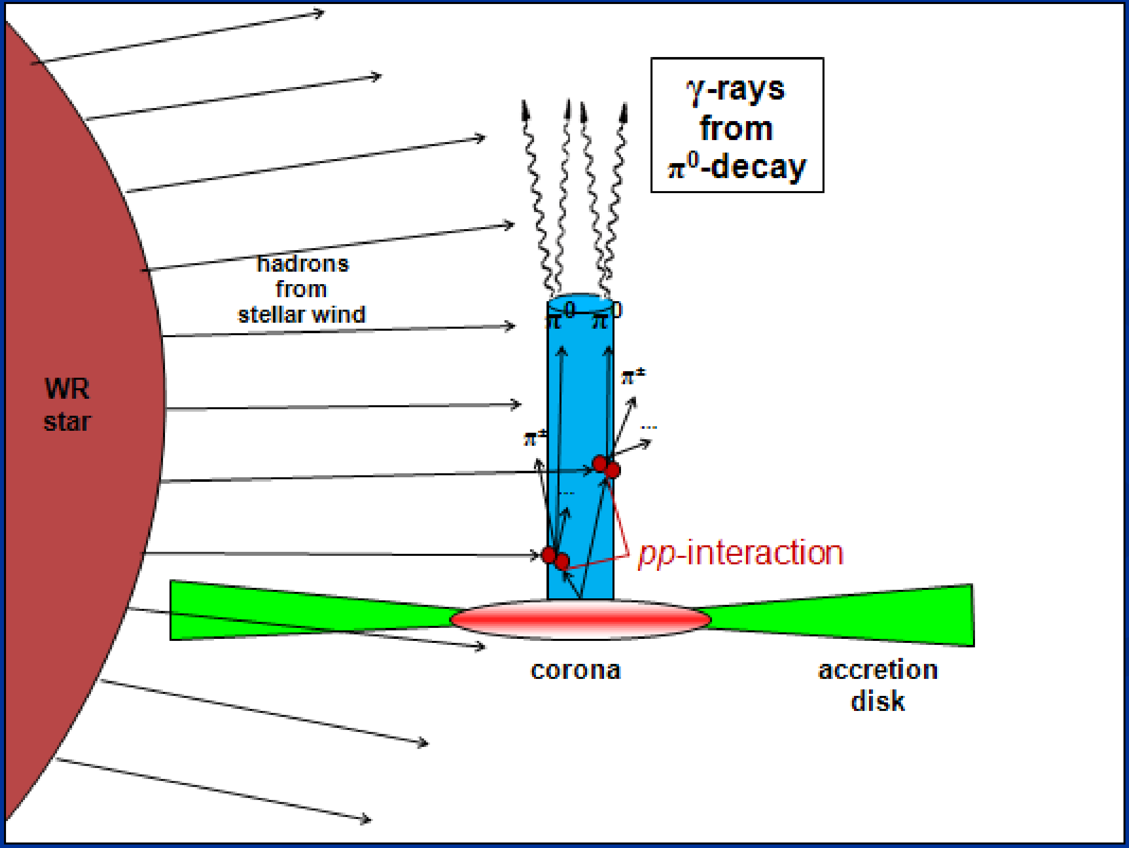


$$L^{B}_{kin,\, e} \approx 10^{37} \text{ erg s}^{-1}$$

γ-ray emission from Cygnus X-3

A HADRONIC model:

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



A hadronic model

Stellar wind:

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

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

homogeneous (not clumpy)

Geometry of the interaction:

jet protons interact with the hadronic matter of the wind along a cylinder:

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

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

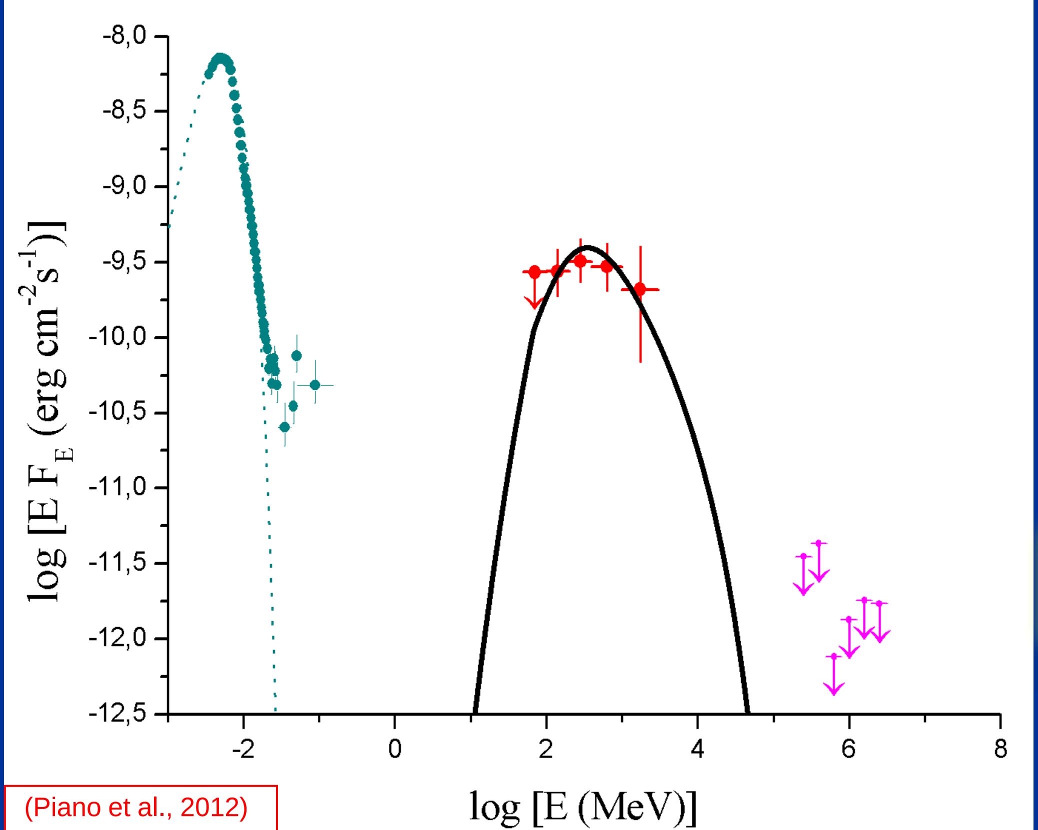
$i = 14°$

proton distribution:

power-law with high-energy cut-off

$$\frac{dN}{d\gamma dV} = K_p \gamma^{-\alpha} \exp(-\gamma/\gamma_c) \qquad [\gamma \geqslant \gamma_{min}]$$

$\alpha = 3, \gamma_{min} = 1, \text{ and } \gamma_c = 100$



(Piano et al., 2012)

Results from the modeling:

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

$N_{p,jet} \approx 9.0 \times 10^{42}$

$\dot{N}_{p,jet} \approx 6.7 \times 10^{40}$

$L_{kin,\ p} \approx 1.5 \times 10^{38} \text{ erg s}^{-1}$

- Disk luminosity of the Hypersoft state ($L_{HYS} \sim 10^{38}$ erg s^{-1})
- Eddington accretion limit ($L_{Edd} \sim 10^{39}$ erg s^{-1}) [$M_x = 10\ M_{\odot}$]

Cygnus X-3 detected by AGILE

conclusions (I)

Phenomenology of the transient γ-ray activity:

- **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)

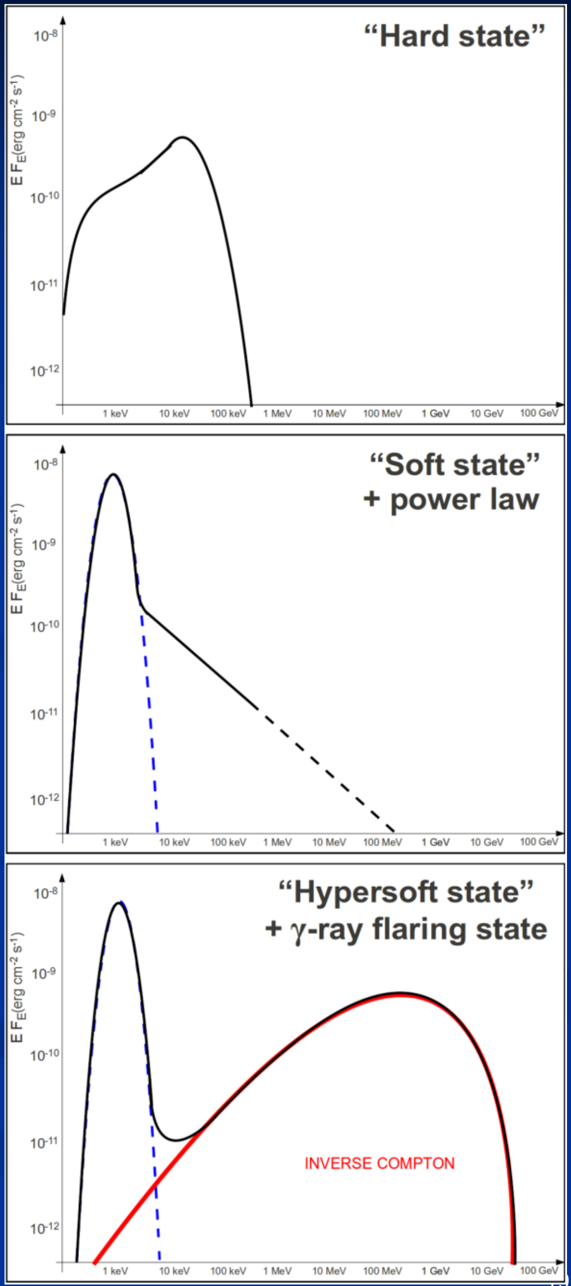
Cygnus X-3 detected by AGILE
conclusions (II)

Emission models:

- **Leptonic scenario**
  - ✓ spectral link with hard X-ray emission
    - lowest part of the jet [up to ~10^{10} cm] → 100 keV
    - farthest part of the jet [above ~10^{10} cm] → >100 MeV
  - ✓ low jet kinetic power
  - ✓ temporal link with major radio flares

    (electrons are the main emitters)
  - ✓ consistent with the γ-ray modulation (*Fermi*-LAT)

    (Dubus et al., 2010, Zdziarski et al., 2012)
- **Hadronic scenario**
  - ✓ physically reasonable
    - consistent with the spectral shape detected by AGILE
    - energetics: sub-Eddington jet kinetic power



(Piano et al., 2012, A&A 545 A110)

Thank you!