Multi-messenger analysis of galactic transient sources

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Outline

I. Introduction

> *Transient high-energy sources*

> *X-ray binaries*

II. Multi-wavelength study of (high-mass) X-ray binaries

> *Nature, evolution and particle acceleration*

III. The multi-messenger era

> *How it will revolutionize the study of X-ray binaries and transients in general*

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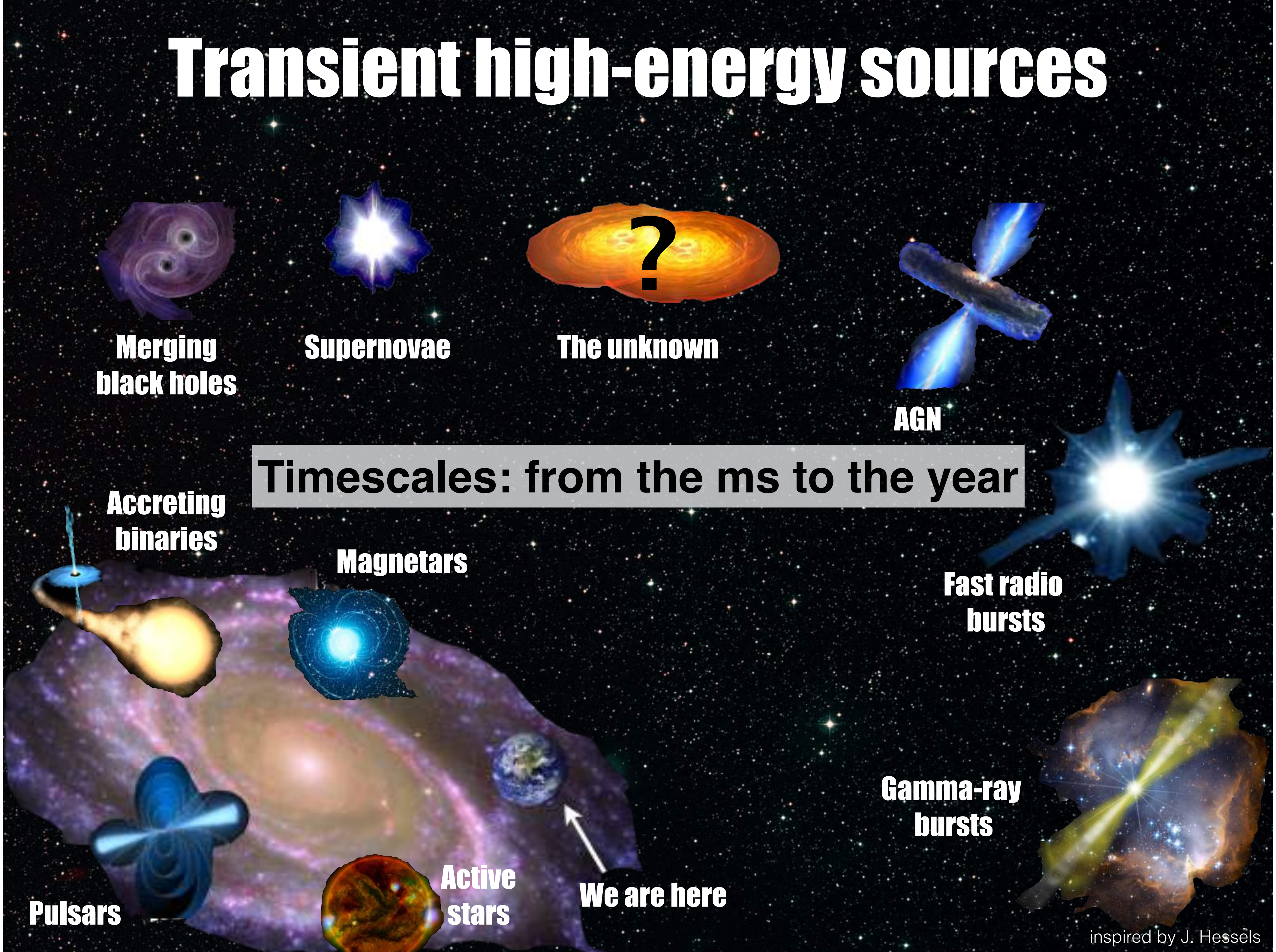
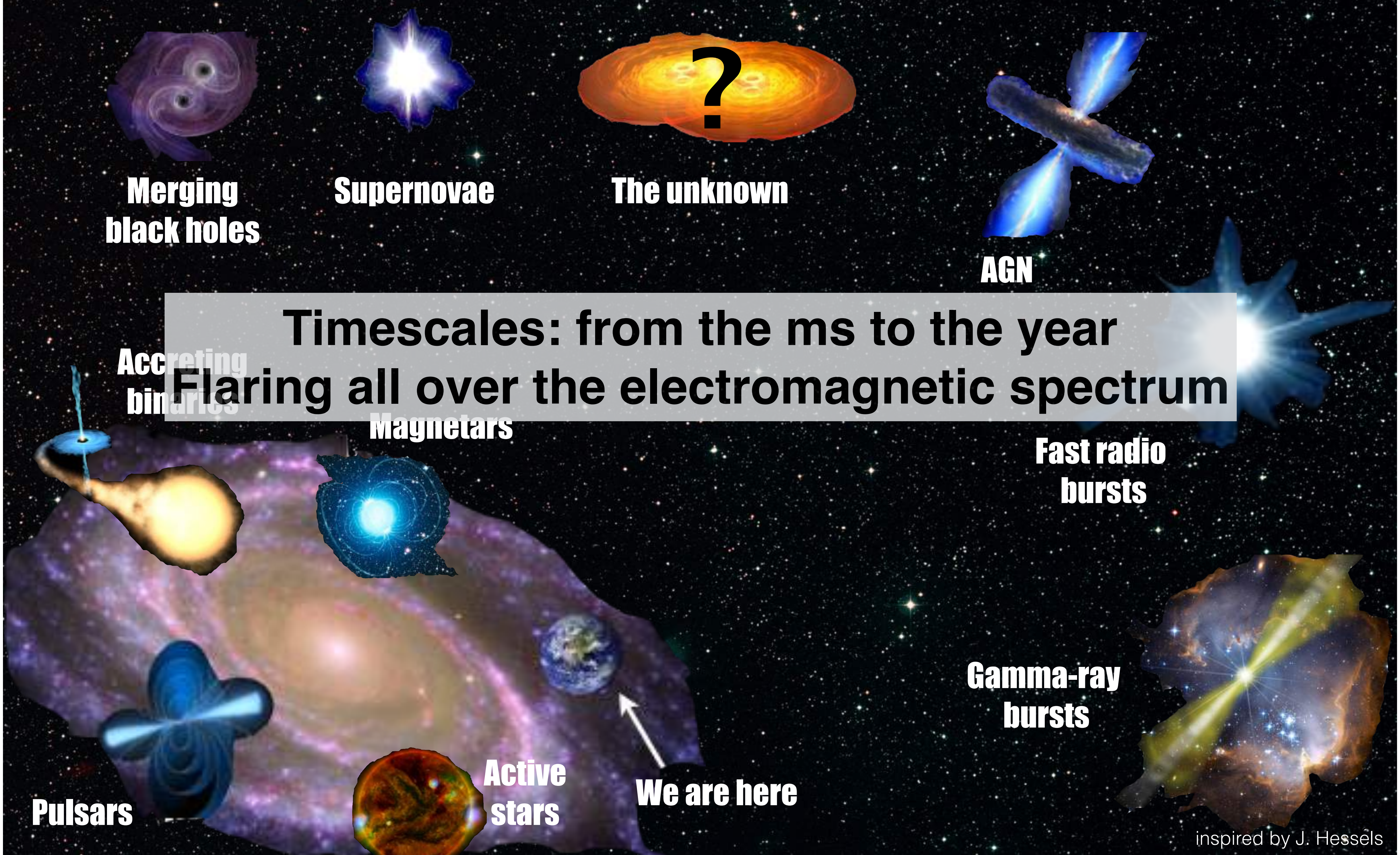
Transient high-energy sources

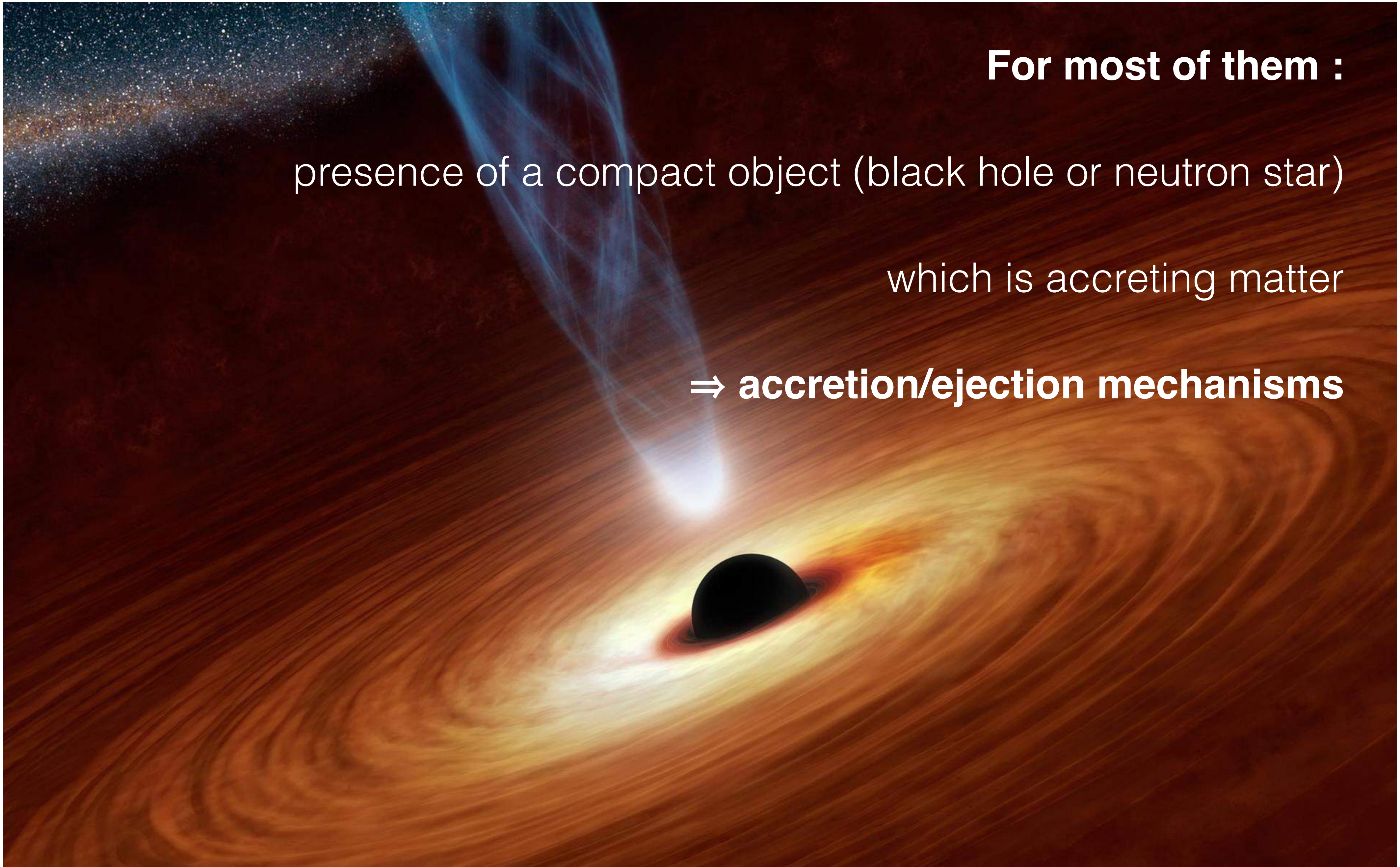

Transient high-energy sources
Merging black holes
Supernovae
?
The unknown
AGN
Timescales: from the ms to the year
Accreting binaries
Magnetars
Fast radio bursts
Gamma-ray bursts
Pulsars
Active stars
We are here
inspired by J. Hessels

Transient high-energy sources

Timescales: from the ms to the year
Flaring all over the electromagnetic spectrum



Transient high-energy sources



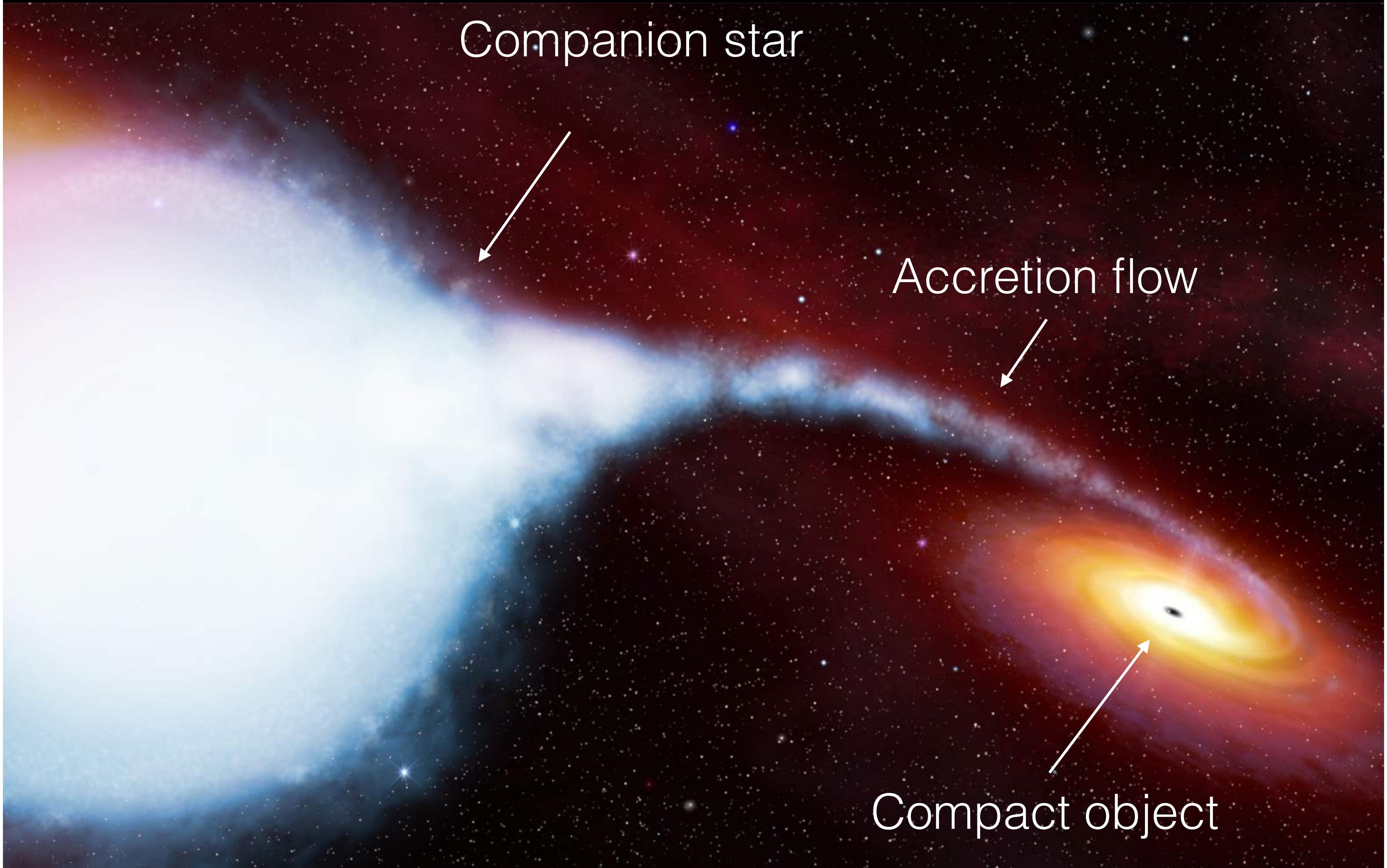
For most of them :

presence of a compact object (black hole or neutron star)

which is accreting matter

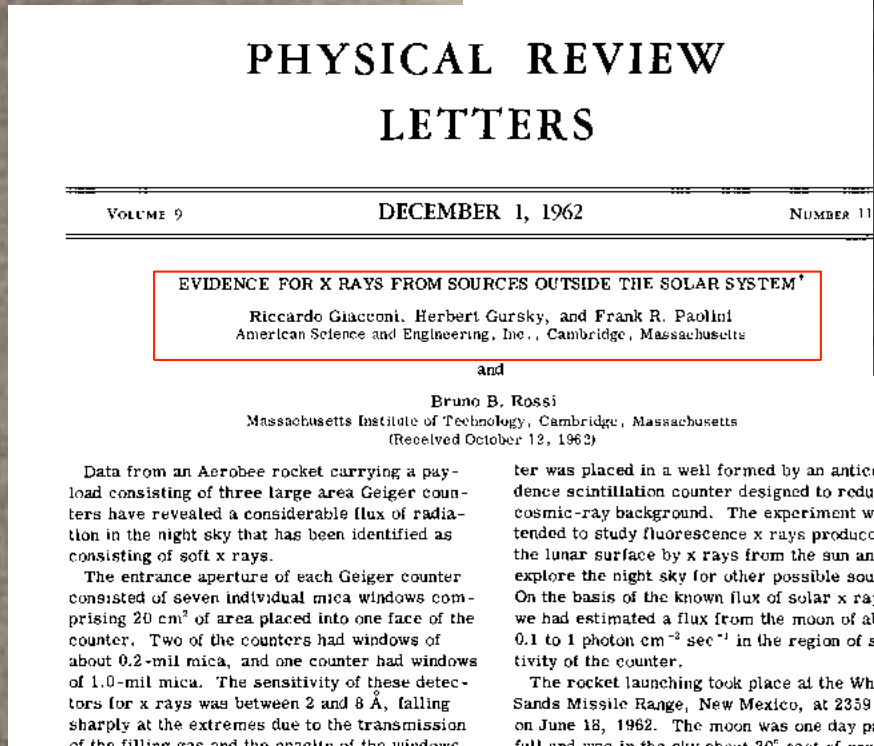
⇒ **accretion/ejection mechanisms**

X-ray binaries



X-ray binaries

19 juin 1962



PHYSICAL REVIEW LETTERS

VOLUME 9 DECEMBER 1, 1962 NUMBER 11

EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

and

Bruno B. Rossi
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received October 12, 1962)

Data from an Aerobee rocket carrying a payload consisting of three large area Geiger counters have revealed a considerable flux of radiation in the night sky that has been identified as consisting of soft x rays.

The entrance aperture of each Geiger counter consisted of seven individual mica windows comprising 20 cm² of area placed into one face of the counter. Two of the counters had windows of about 0.2-mil mica, and one counter had windows of 1.0-mil mica. The sensitivity of these detectors for x rays was between 2 and 8 Å, falling sharply at the extremes due to the transmission

ter was placed in a well formed by an anticoincidence scintillation counter designed to reduce the cosmic-ray background. The experiment was intended to study fluorescence x rays produced on the lunar surface by x rays from the sun and to explore the night sky for other possible sources. On the basis of the known flux of solar x rays, we had estimated a flux from the moon of about 0.1 to 1 photon cm^{-2} sec^{-1} in the region of sensitivity of the counter.

The rocket launching took place at the White Sands Missile Range, New Mexico, at 2359 MST on June 18, 1962. The moon was one day past

X-ray binaries

Sandage et al. 1966

ON THE OPTICAL IDENTIFICATION OF SCO X-1

An optical search has been made of the sky surrounding the new position of Sco X-1 described in the preceding Letter (Gursky, Giacconi, Gorenstein, Waters, Oda, Bradt, Garmire, and Sreekantan 1966*a*). Preliminary results of the measurement were made available to the Tokyo Observatory and to Palomar. The search, which we believe has been successful, was based on these results and on the working hypothesis that the image should (1) appear starlike, (2) be of at least 13th apparent visual magnitude, and (3) have an ultraviolet excess relative to normal stars. The first two requirements are stated in the discussion of Gursky *et al.* (1966*b*) on the measurement of an upper limit of 20″ to the diameter of Sco X-1. The predicted lower limit on the visible magnitude was obtained by extrapolating the energy distribution from the observed range of 1–10 Å into the optical region in the assumption of a spectrum that is flat per unit frequency

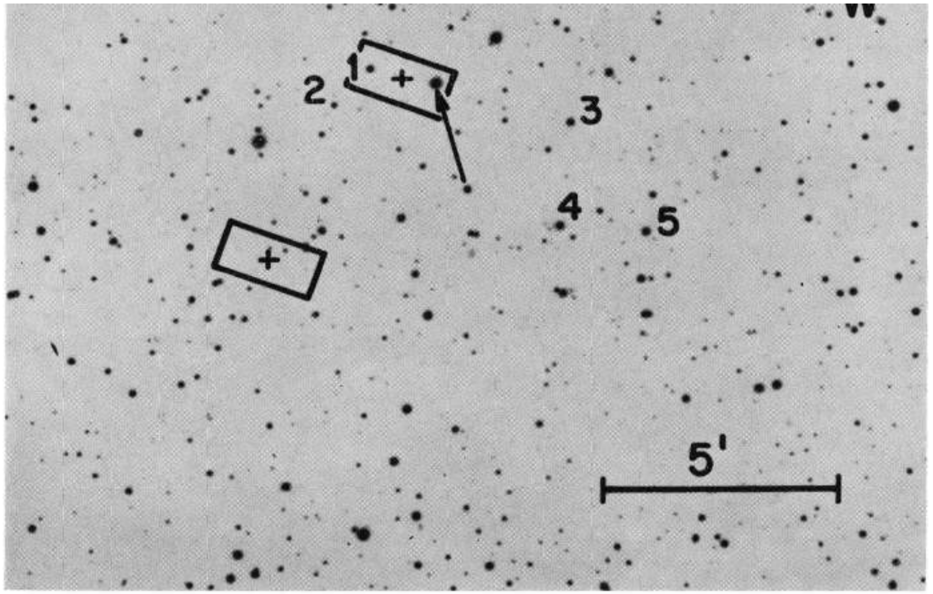
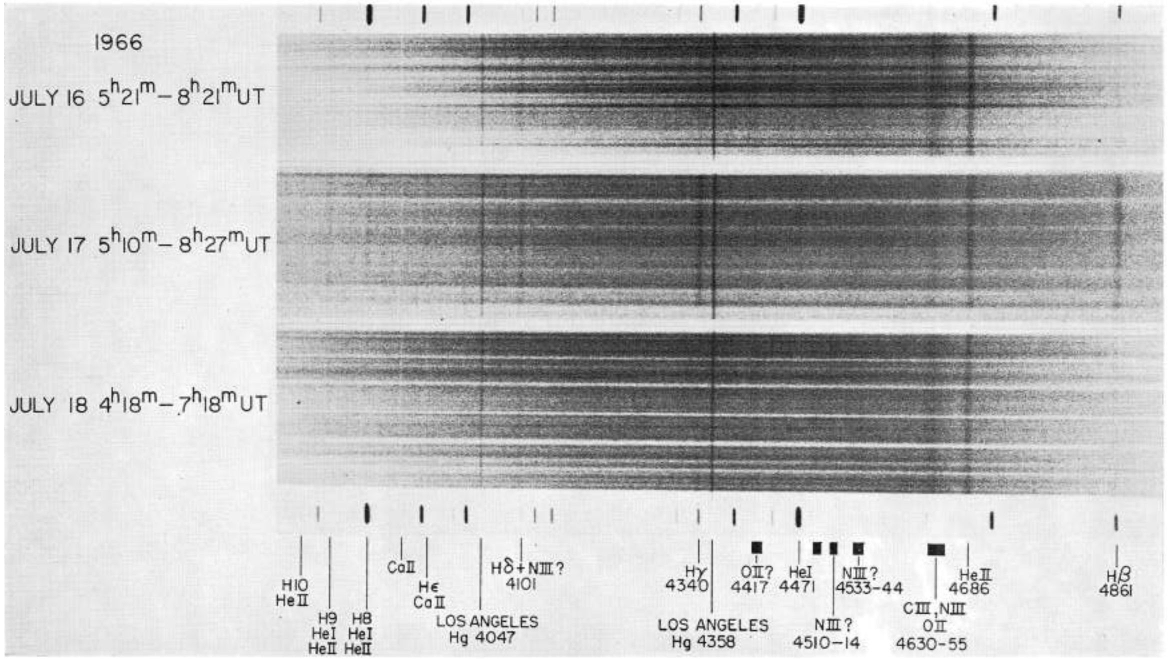


FIG. 1.—Photograph of the region containing the new X-ray position of Sco X-1, reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are marked by crosses surrounded by a rectangle of 1 by 2 arc min. The object described in the text is marked with an arrow. The identifications of other stars for which photoelectric photometry exists are also marked.



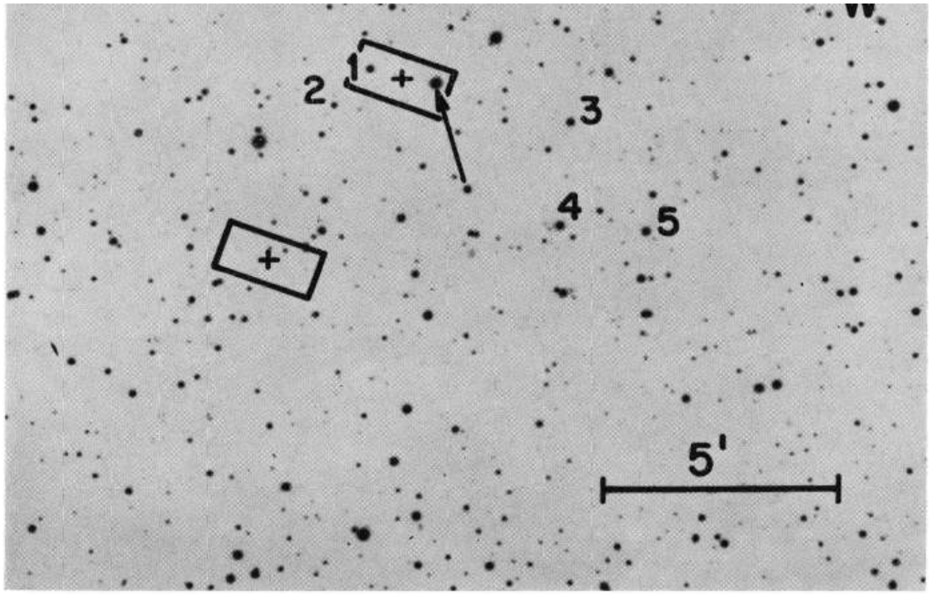
Sandage et al. (1966)

X-ray binaries

Sandage et al. 1966

ON THE OPTICAL IDENTIFICATION OF SCO X-1

We shall not attempt here to discuss the physics of this system any further except to note that the objects which are categorized as old novae appear to possess disk structures which emit variable, blue continuous radiation by optical bremsstrahlung and by bound-free transitions of H and He. The excitation mechanism and the kinetic temperature of the gas is unknown. If, in this particular object, parts of the gas have $T \simeq 5 \times 10^7\,°$ K, the bremsstrahlung process could produce the observed X-rays. We do not yet know if all old novae are X-ray sources at some power level. It may be that only a fraction of these explosive stars have kinetic temperatures in their external gaseous component which are high enough to emit X-radiation. The distribution of known old novae is con-



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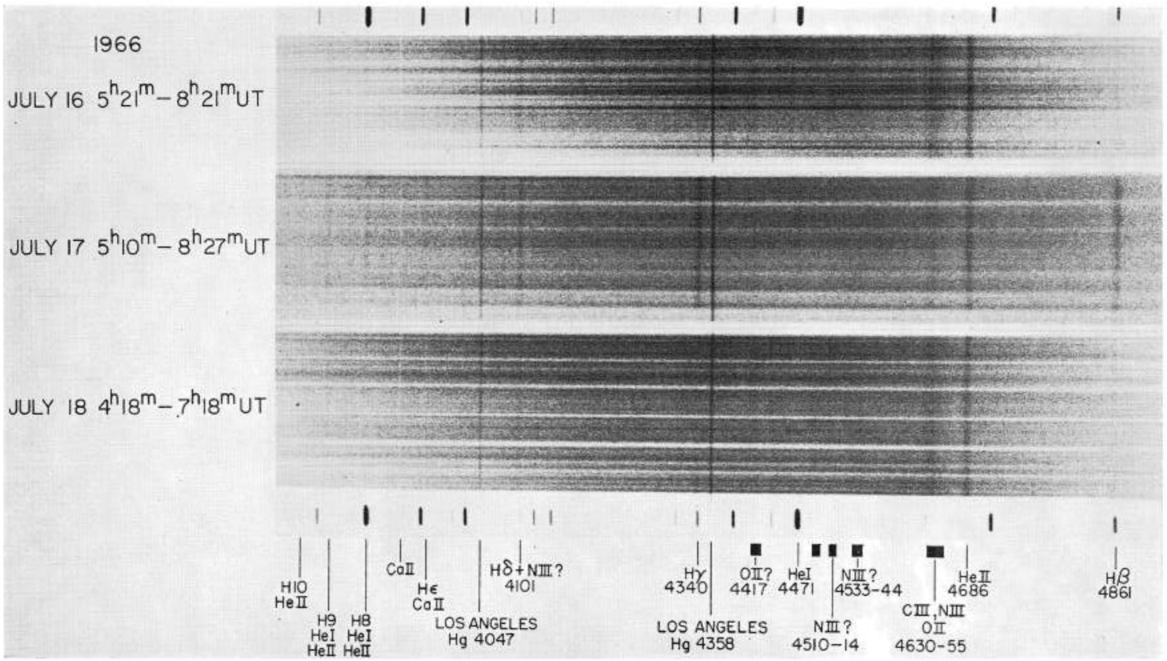


Sandage et al. (1966)

X-ray binaries

Shklovsky 1967 “Sco X-1 is a neutron star accreting matter from a companion”

Birth of X-ray binary concept
but theoretically hard to understand !

Van den Heuvel & Heinse, 1972
Tutukov & Yngelson, 1973

Existence due to a substantial mass transfer between the two objects

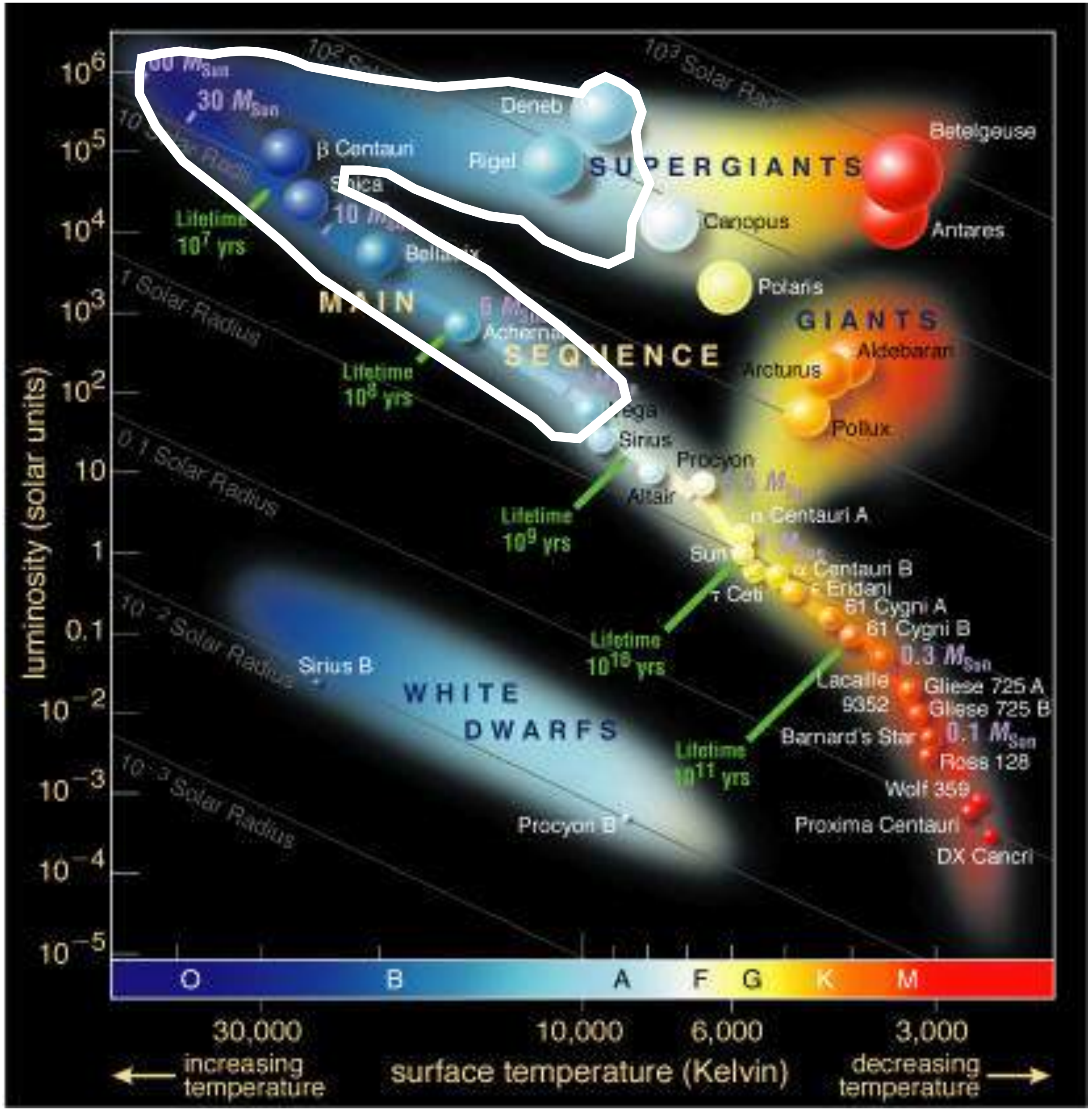
Low-Mass X-ray Binaries vs High-Mass X-ray Binaries

Massive stars

- O/B spectral type
- High mass (>8 M⊙)
- High temperature (>10 000 K)
- High luminosity (>25 L⊙)
- Short lifetime (10-100Myr)
- Mass loss plays a critical role

Sana et al. (2012)

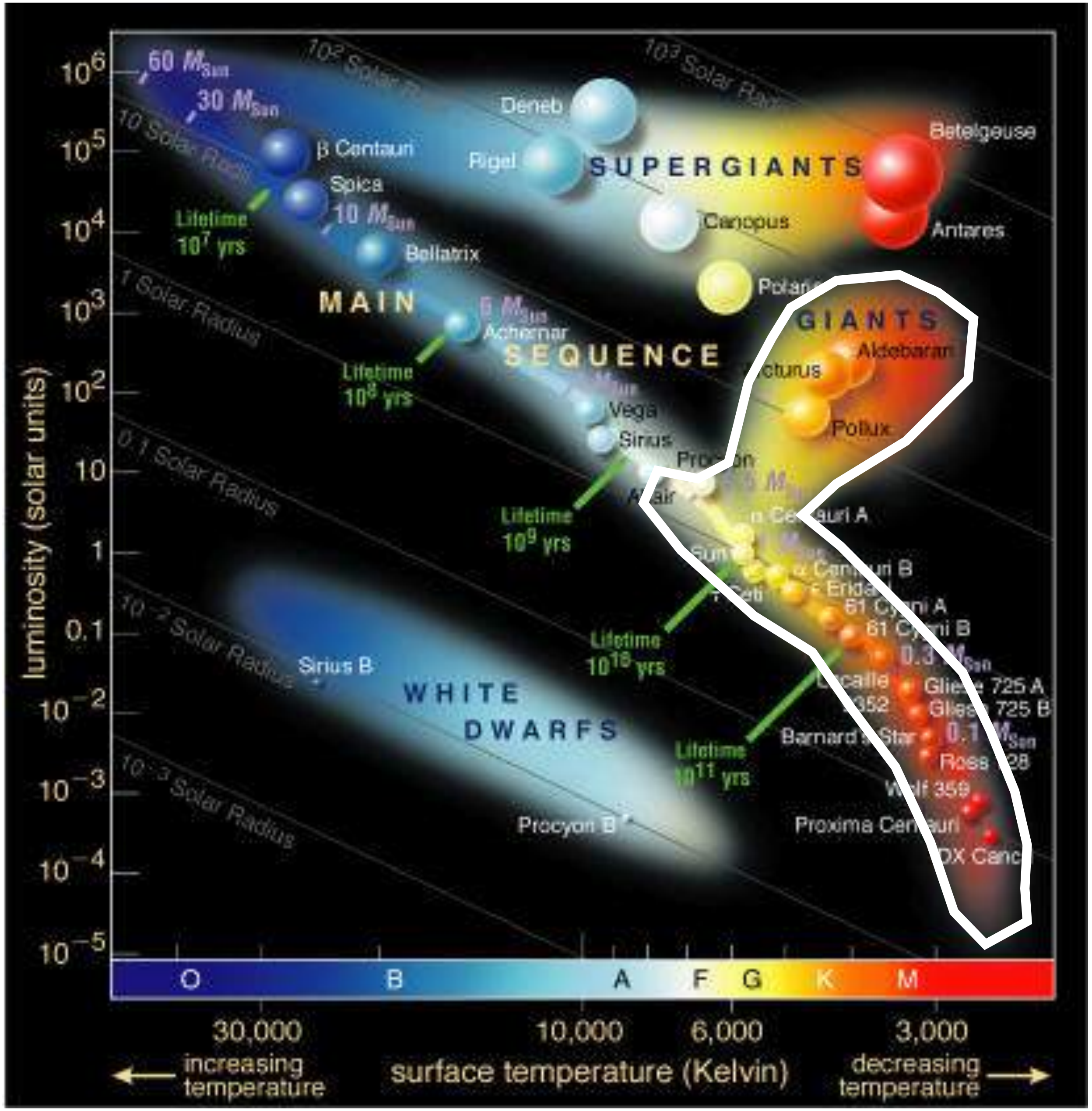
More than 70% of massive stars do not live alone and experience mass transfer…



Low-Mass X-ray Binaries vs High-Mass X-ray Binaries

Low mass stars

- G/K/M spectral type
- Low mass (<8 M☉)
- Low temperature (< 7000 K)
- Low luminosity (<5 L☉)
- Long lifetime (> 1 Gyr)



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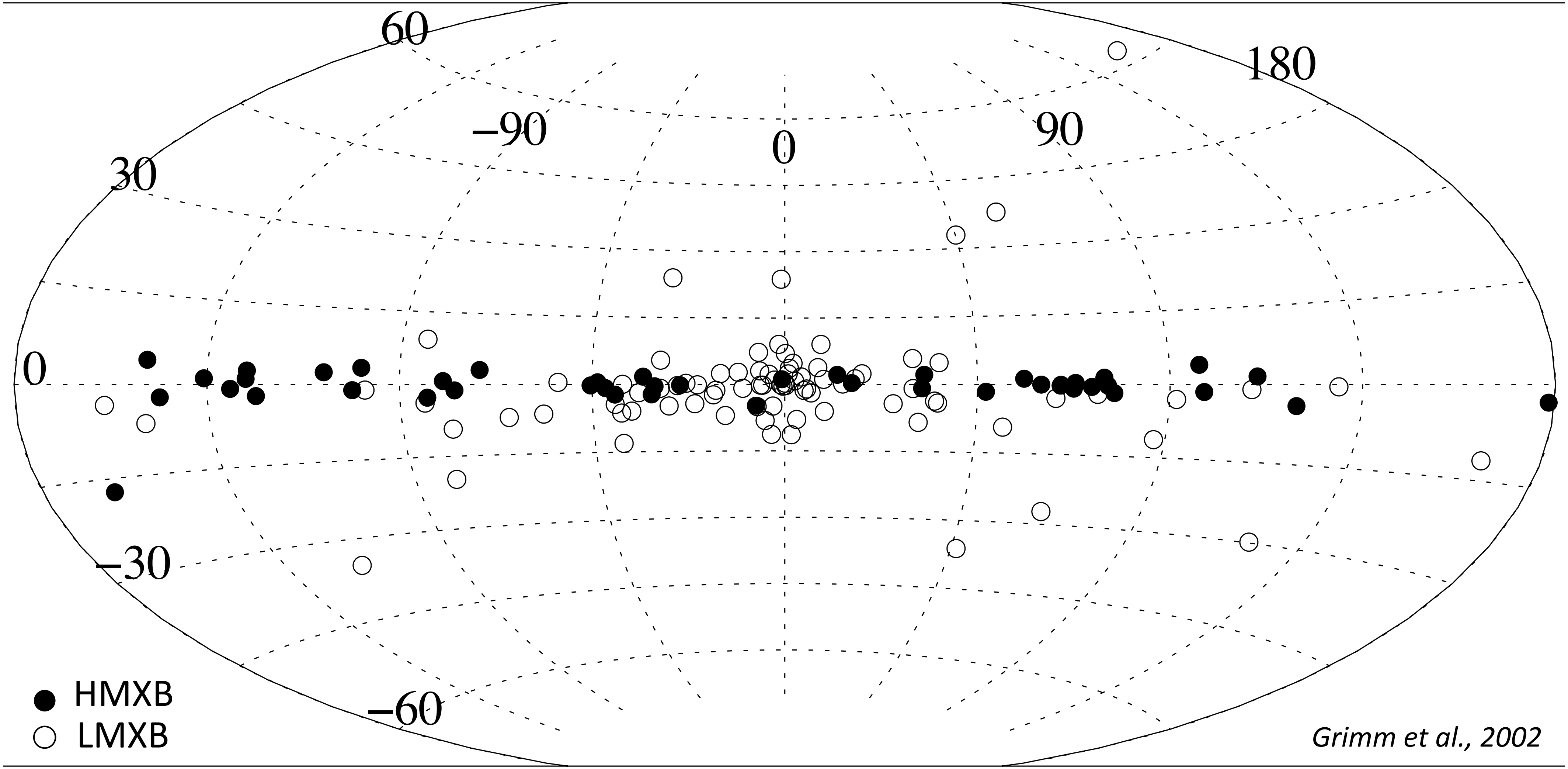
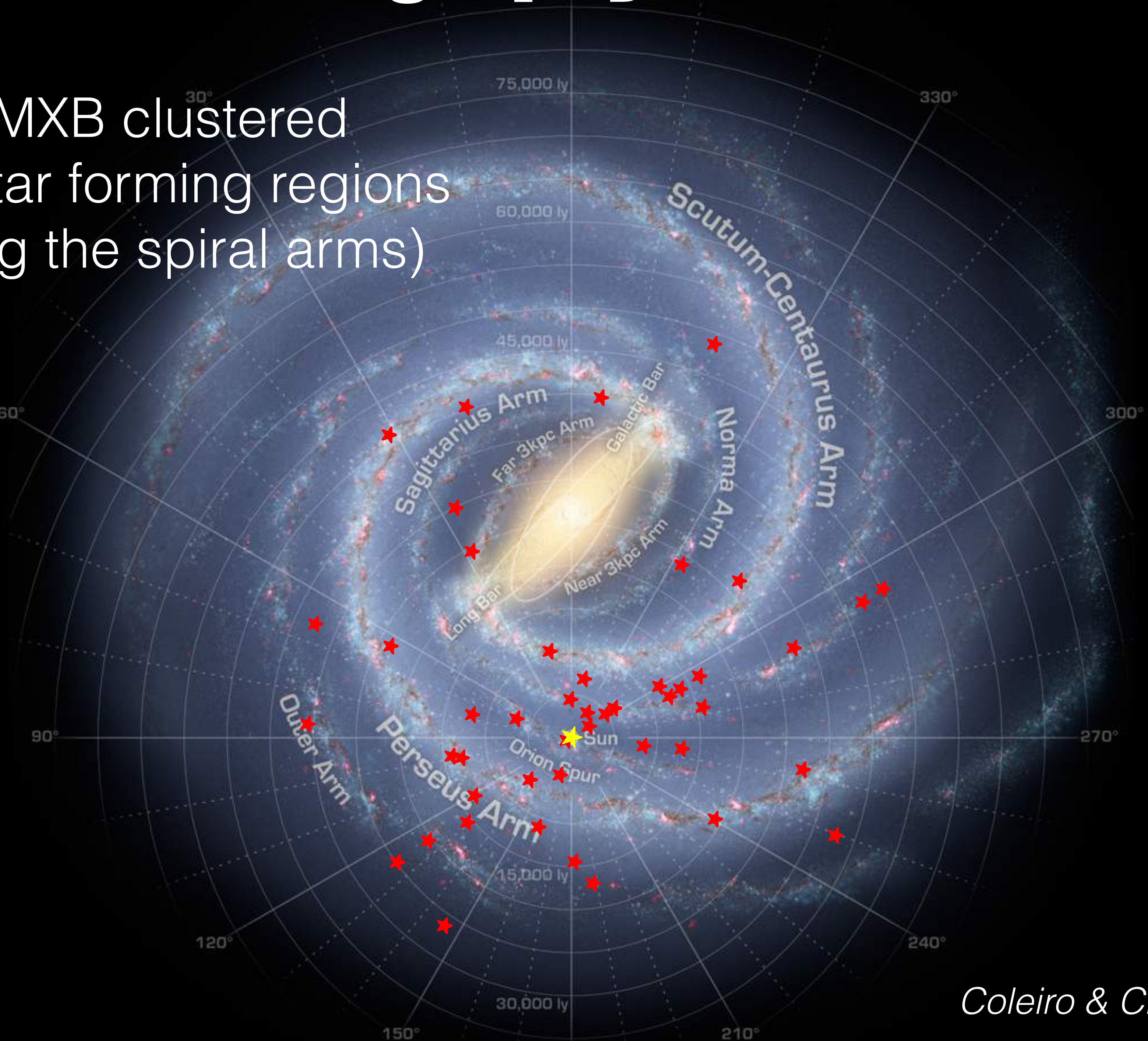


Grimm et al., 2002

Cartography of HMXB

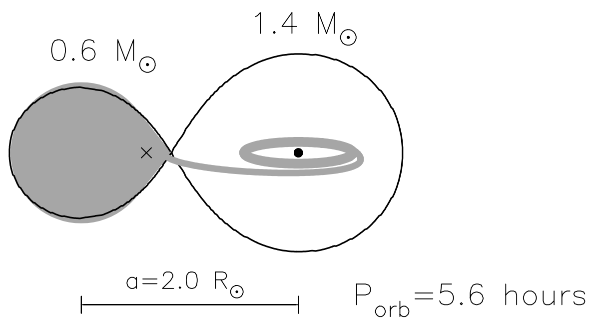
HMXB clustered
with star forming regions
(along the spiral arms)

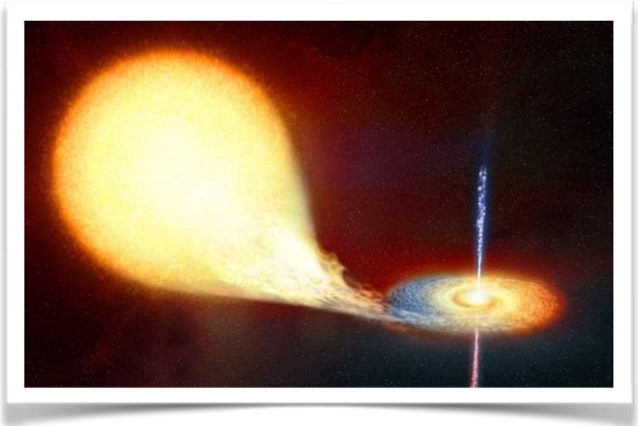


Coleiro & Chaty, 2013

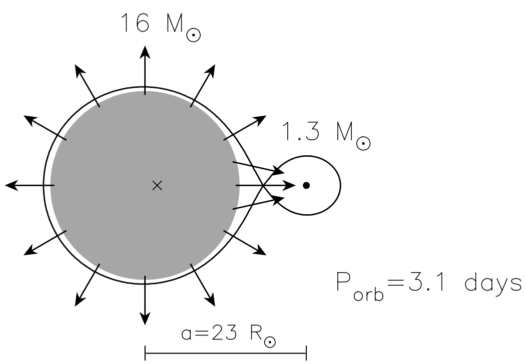
Different ways of accreting matter

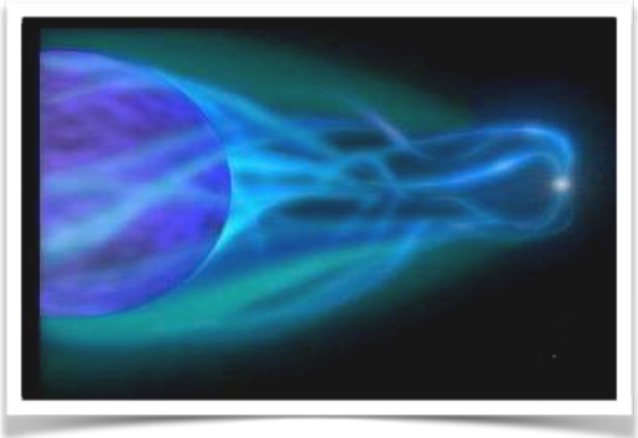
Accretion disc
Roche Lobe overflow
(for LMXB mainly)



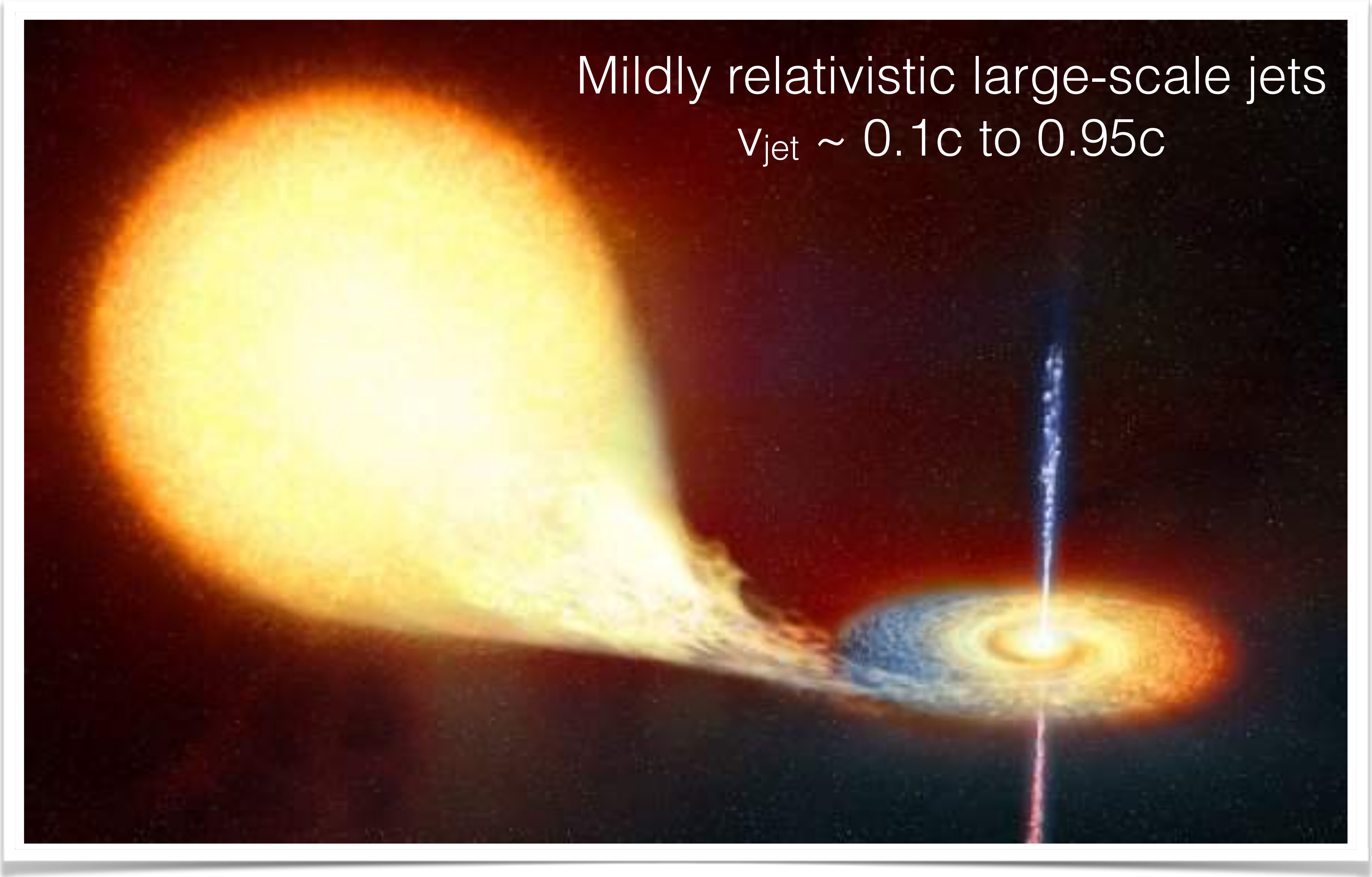


Stellar wind accretion
for HMXB (in majority)



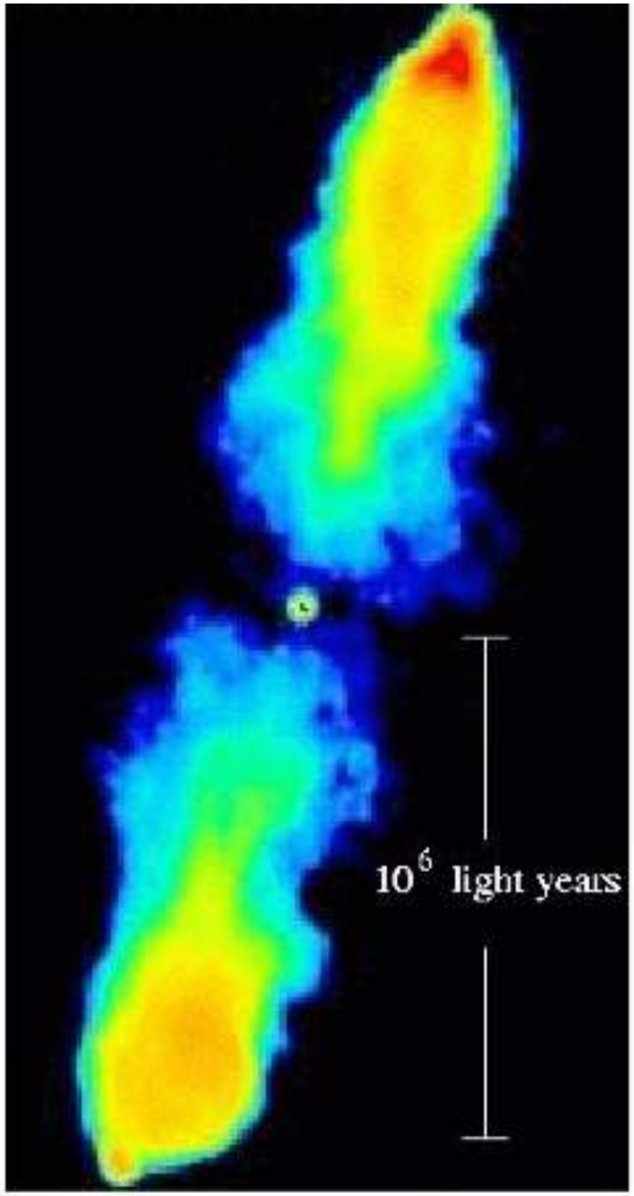


Microquasars



quasar/microquasar analogy

quasar 3C 223



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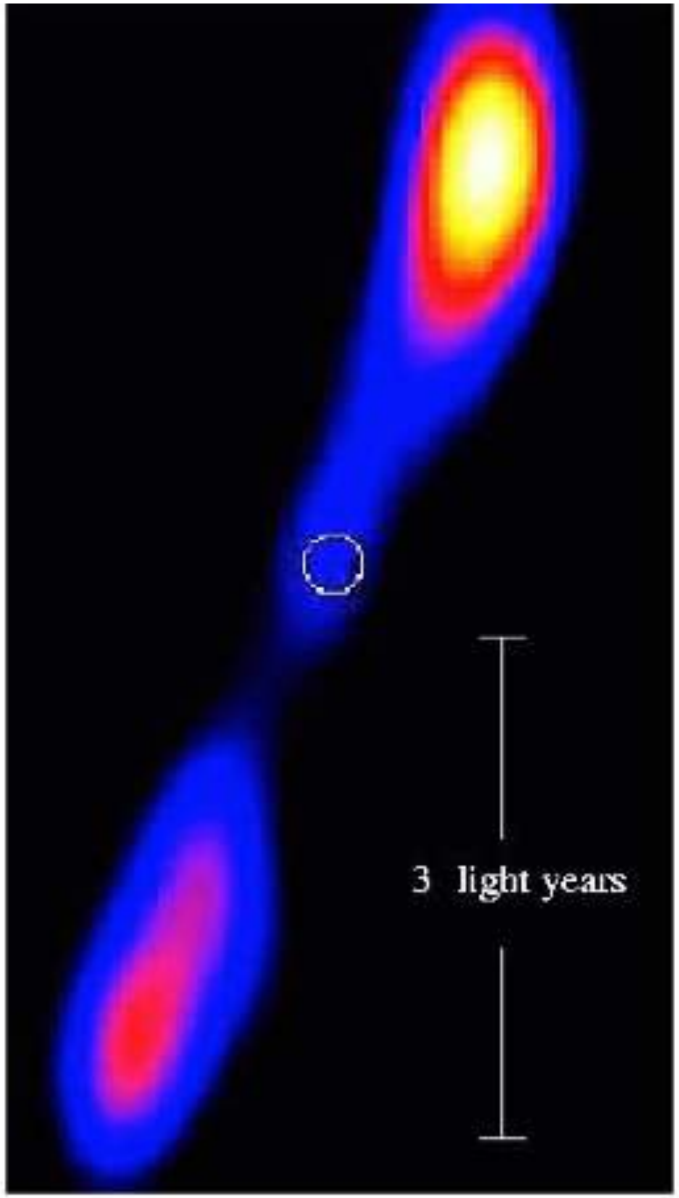
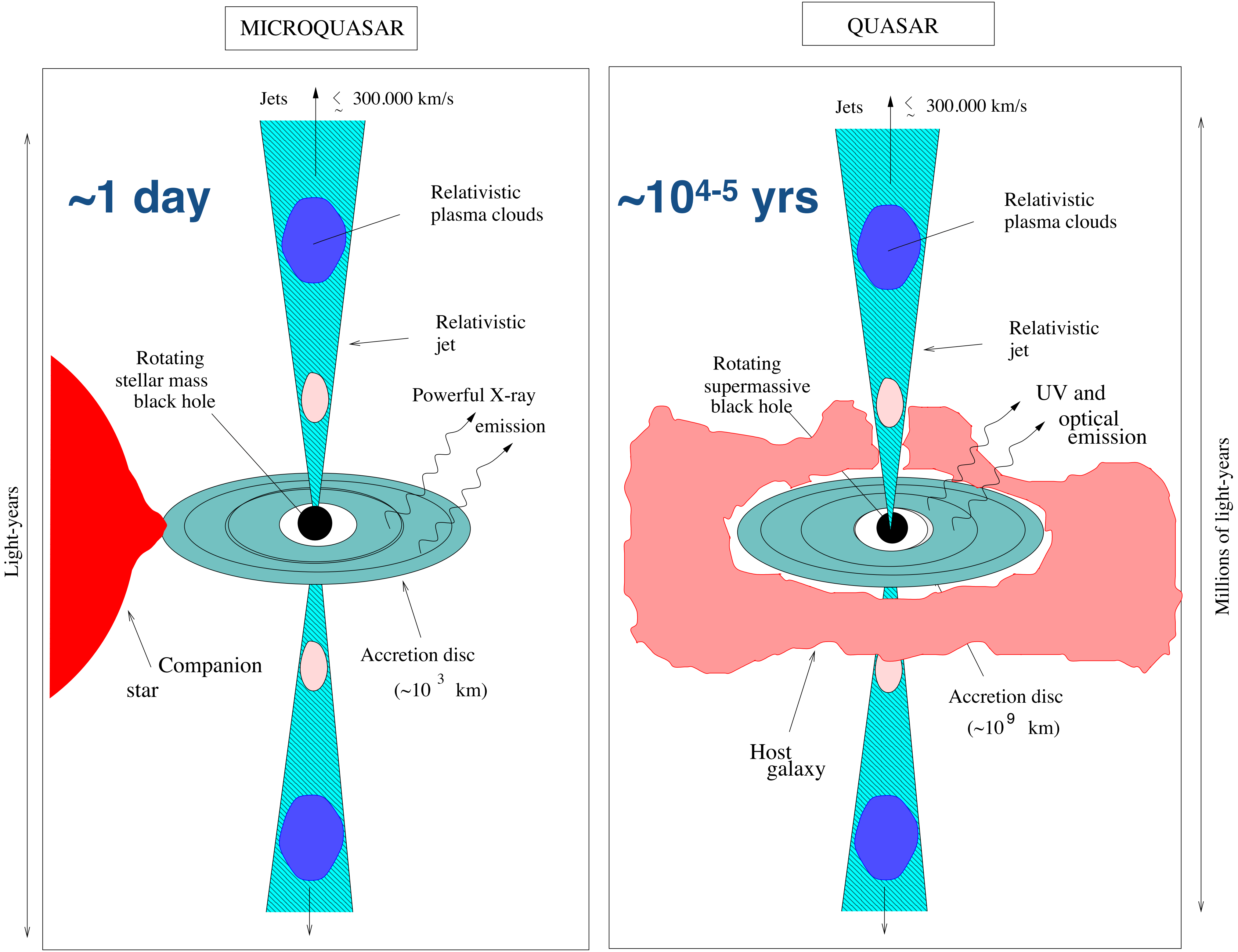
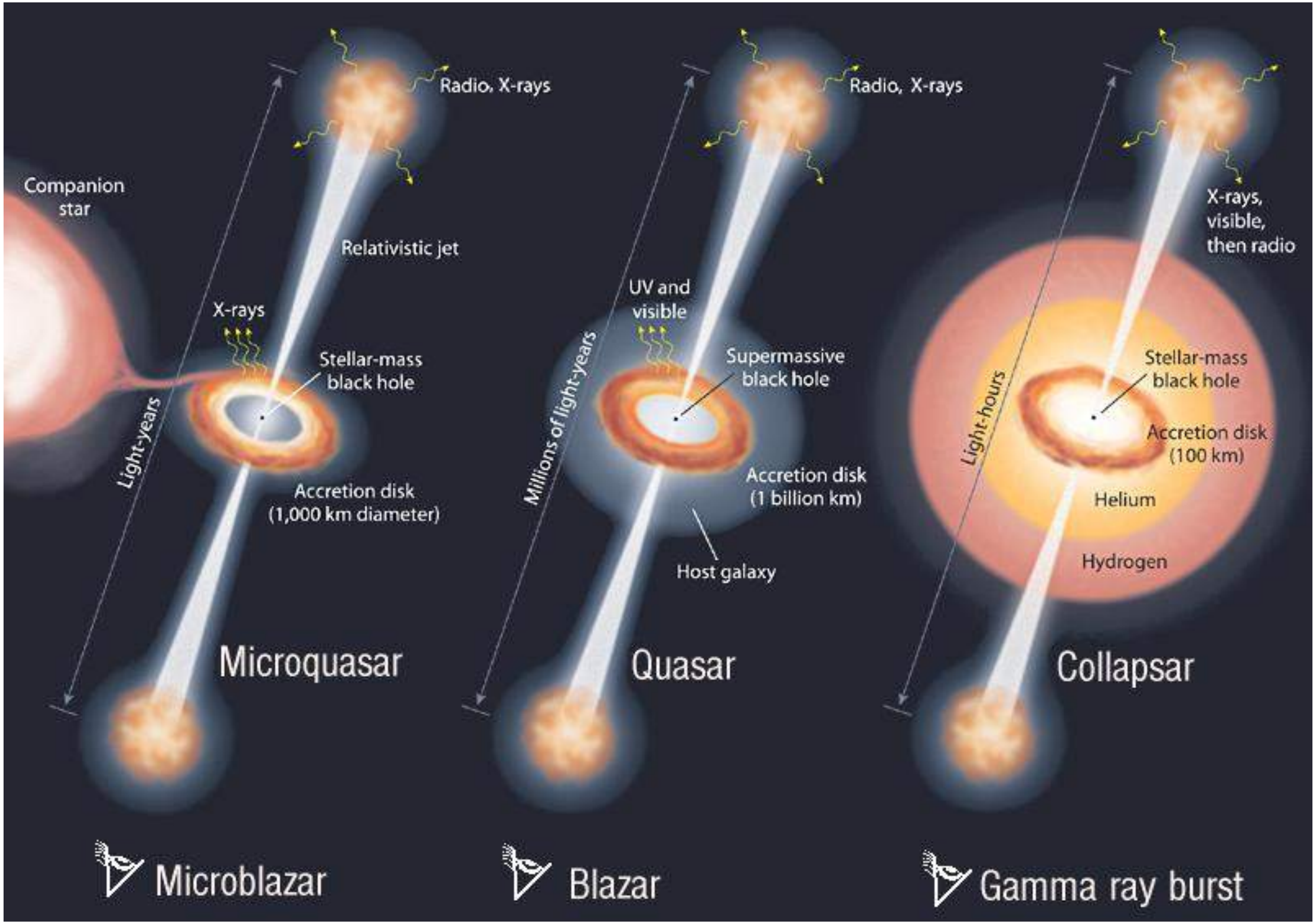
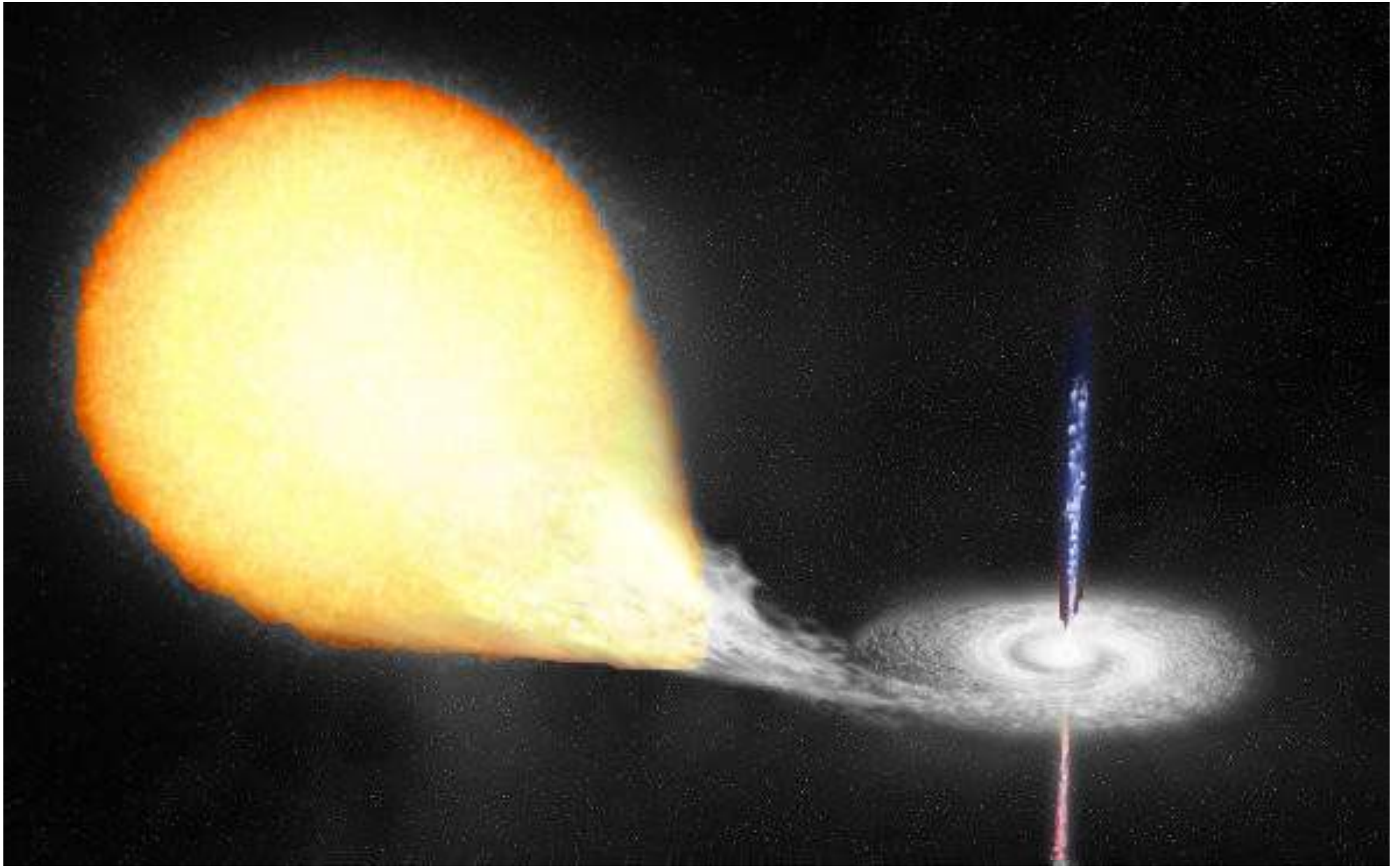



MICROQUASAR
QUASAR
Jets
≲ 300.000 km/s
~1 day
Relativistic
plasma clouds
Relativistic
jet
Rotating
stellar mass
black hole
Powerful X-ray
emission
Companion
star
Accretion disc
(~10 3 km)
Light-years
Jets
≲ 300.000 km/s
~10^4-5 yrs
Relativistic
plasma clouds
Relativistic
jet
Rotating
supermassive
black hole
UV and
optical
emission
Accretion disc
(~10 9 km)
Host
galaxy
Millions of light-years

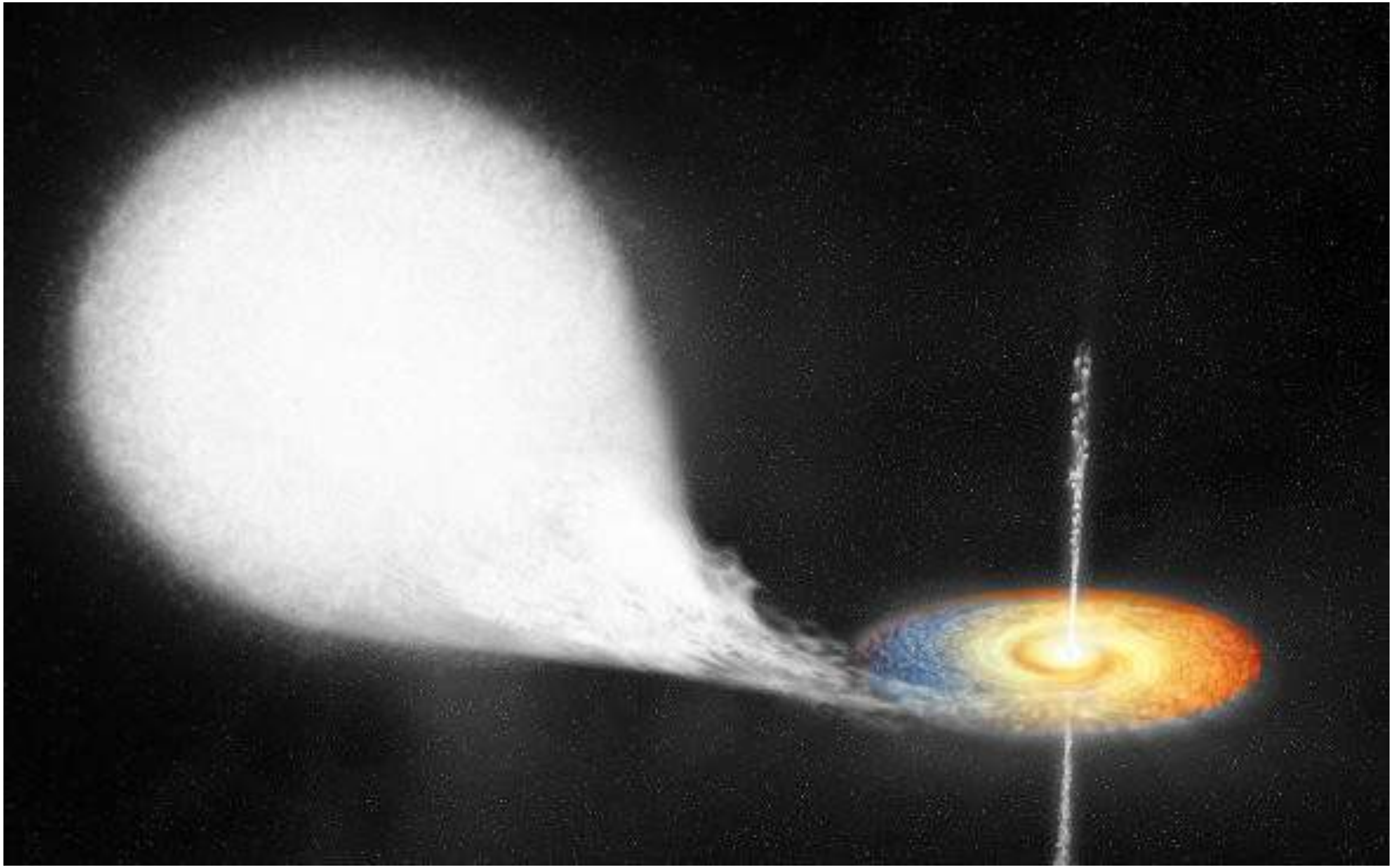
Why studying them ?



Studying stellar evolution



Studying high-energy phenomena



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HMXB in particular (stellar evolution)

III. The multi-messenger era

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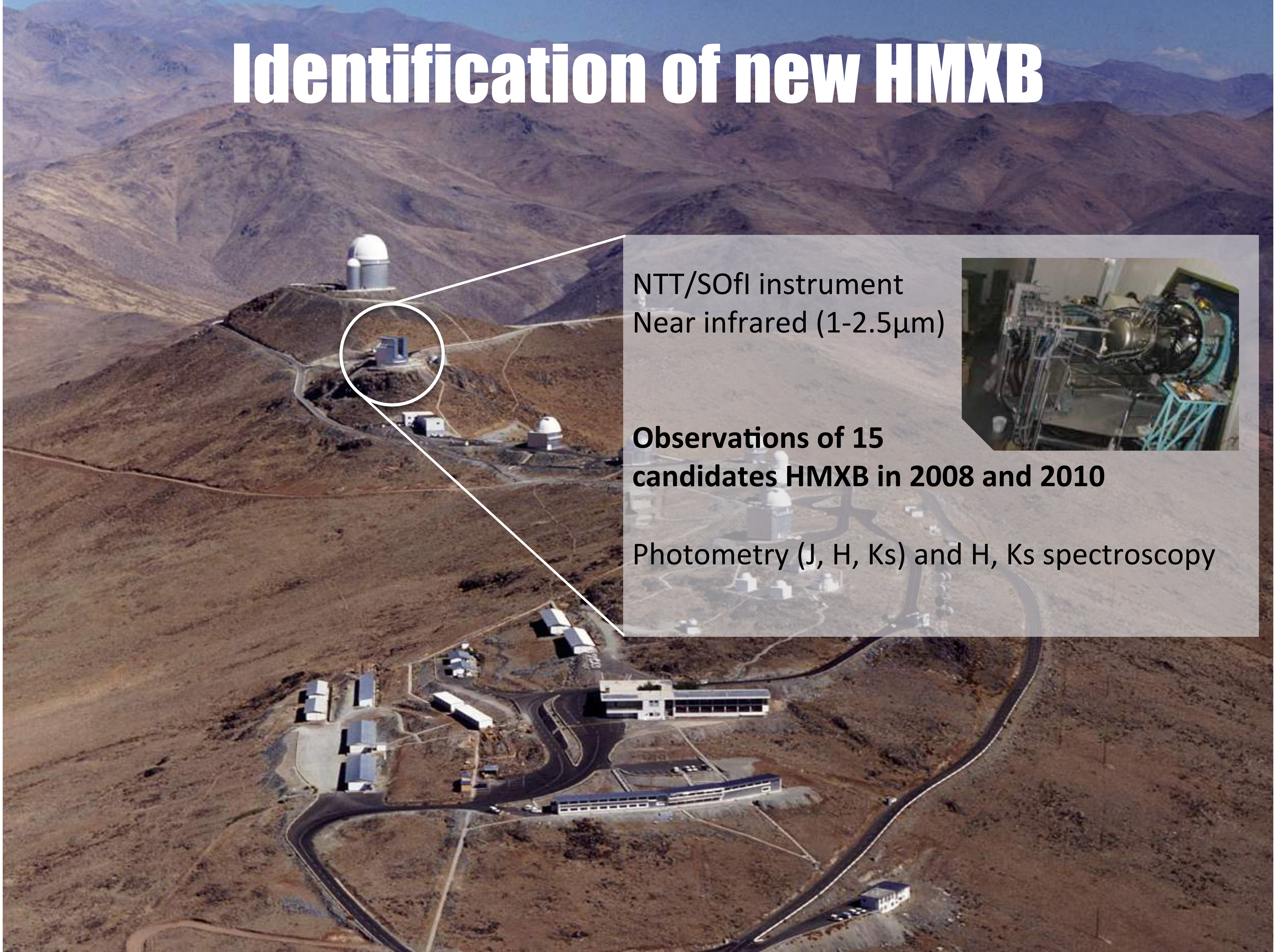
Identification of new HMXB

Only a multi-wavelength approach enables to accurately identify X-ray binaries

In the Galactic plane → high extinction → need infrared observations

Identification of new HMXB

Identification of new HMXB



NTT/SOfI instrument
Near infrared (1-2.5µm)

Observations of 15 candidates HMXB in 2008 and 2010

Photometry (J, H, Ks) and H, Ks spectroscopy

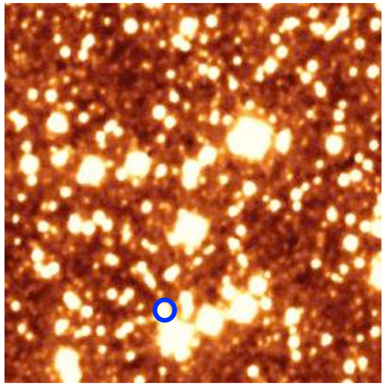
Identification of new HMXB

Observing constraints

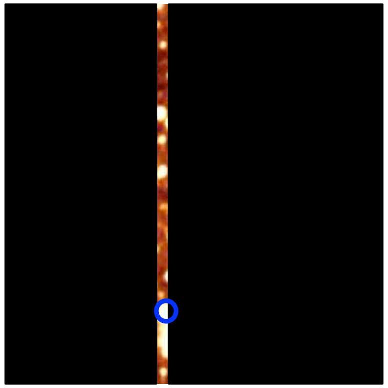
- uncertainty on position
- Galactic plane location
- high density of sources
- low luminosity sources

Spectra extraction

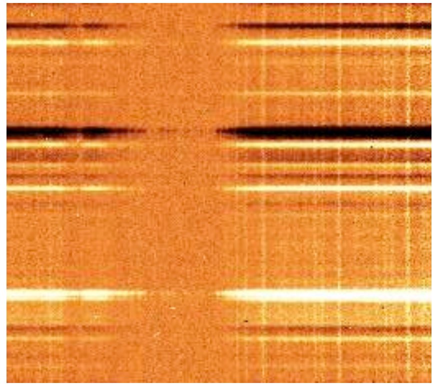
- low signal-to-noise ratio
- IR sky emission
- telluric absorption

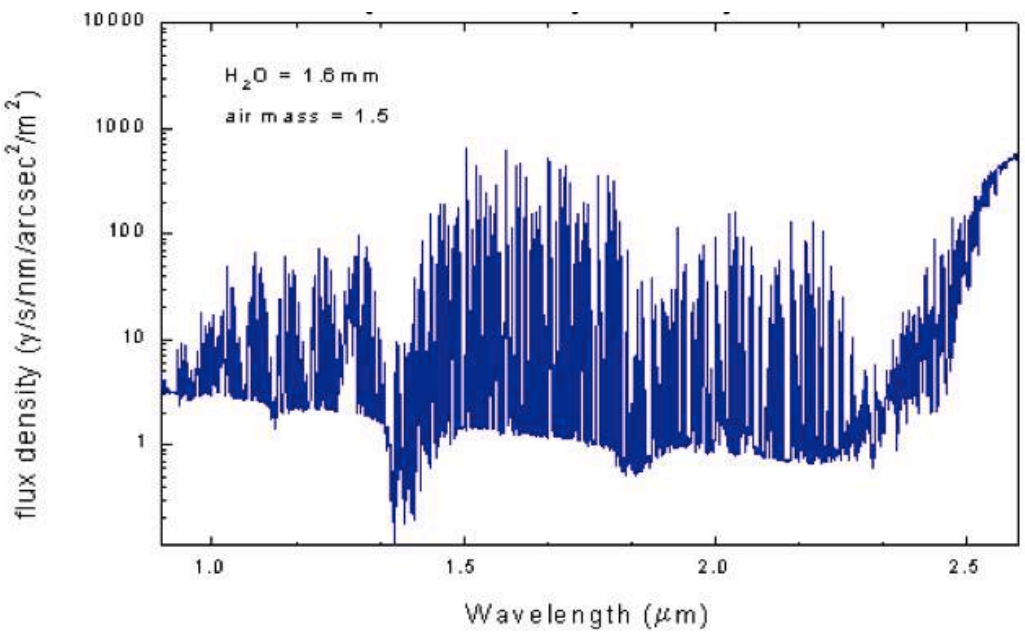


~ 1.8 arcmin



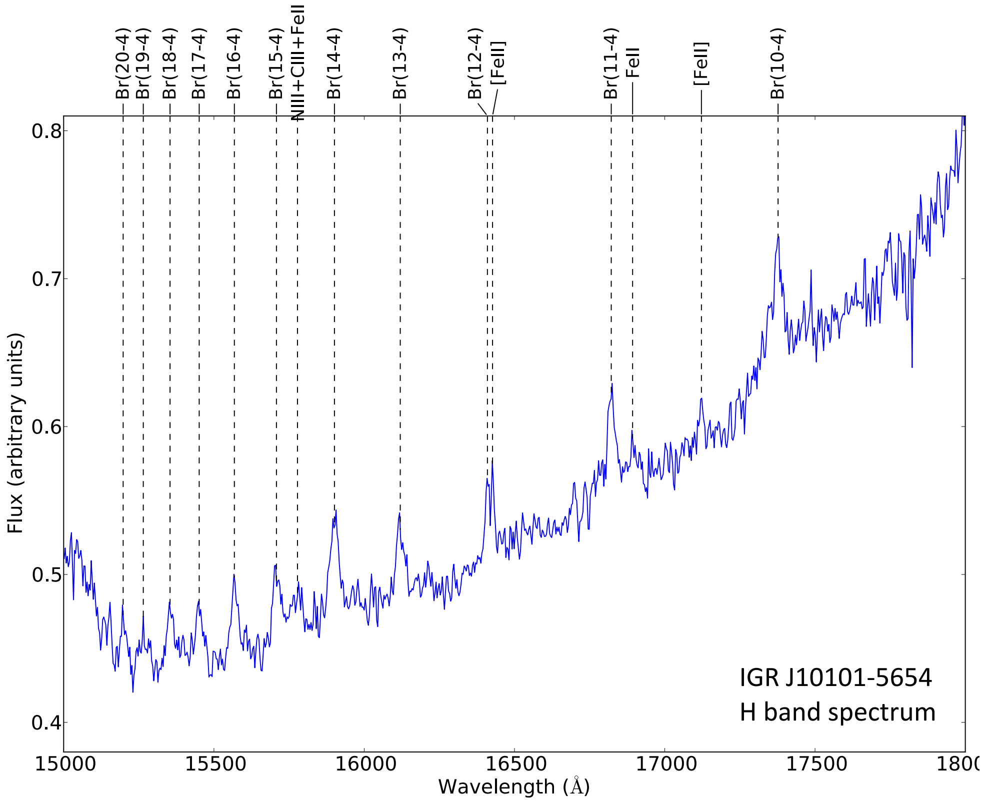
Slit width = 1 arcsec



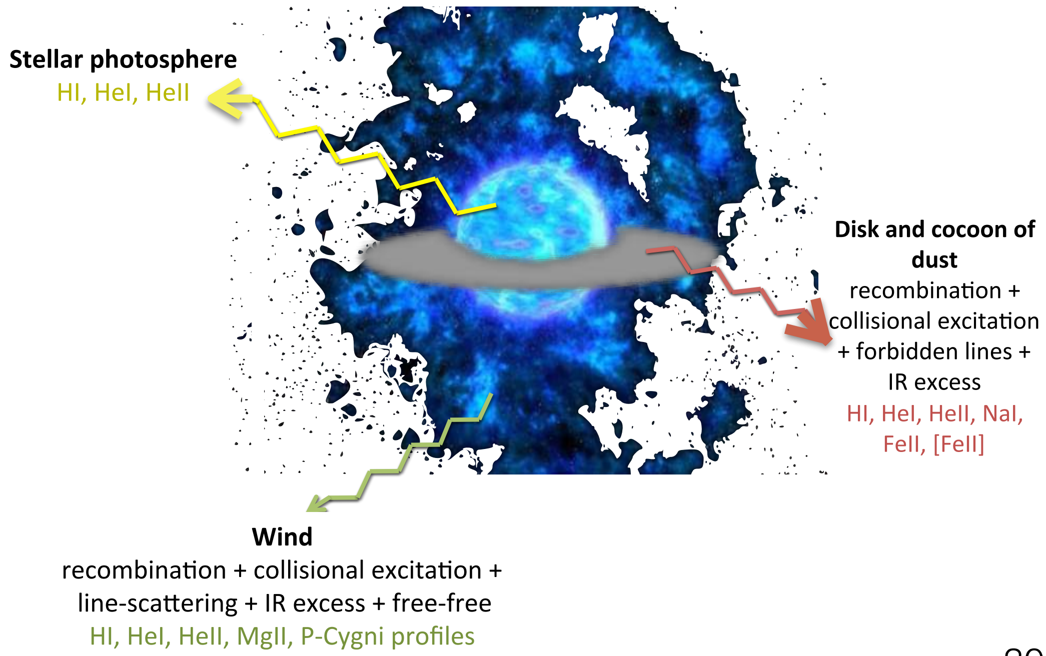


Identification of new HMXB

Spectra example: IGR J10101-5654



nIR (1 – 2.5 µm) → detection of the companion and its environment



Identification of new HMXB

Main results (Coleiro et al., 2013):

- 6 sgHMXB

- 3 BeHMXB

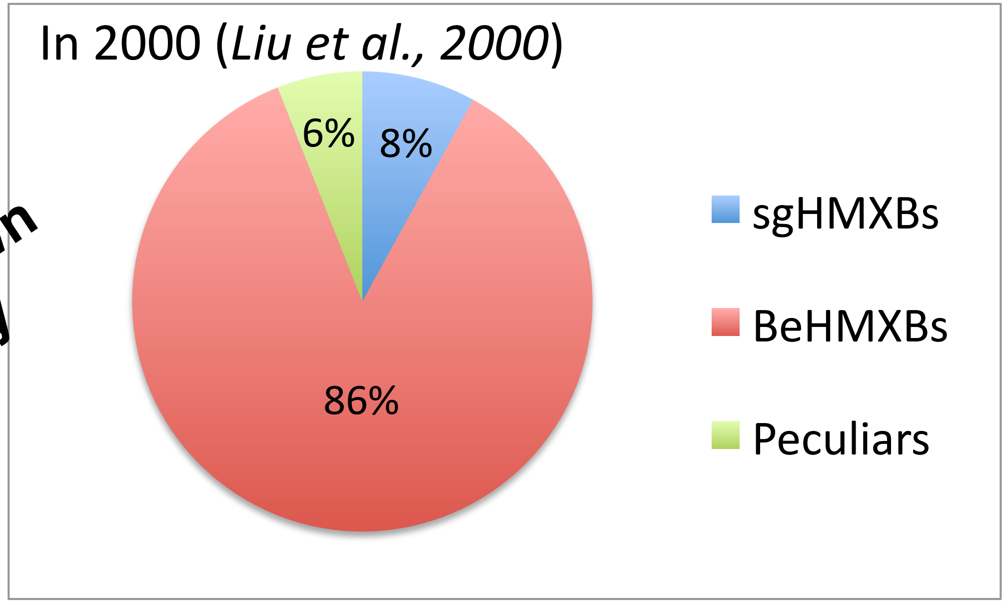
- 2 sgB[e] HMXB

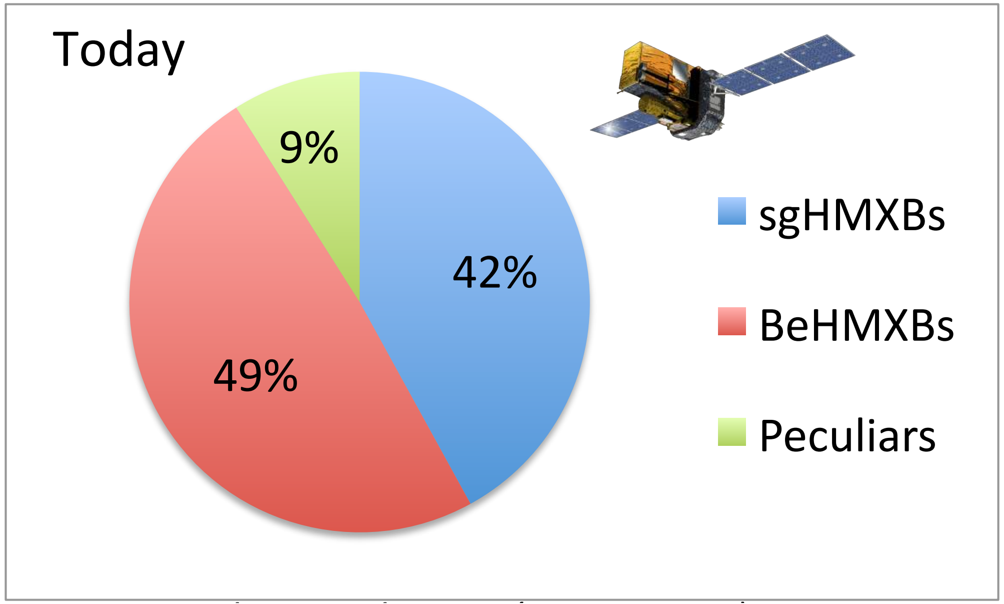
- 3 unknown

114 were known previously

→ the number of sgHMXB has quintupled with *INTEGRAL*

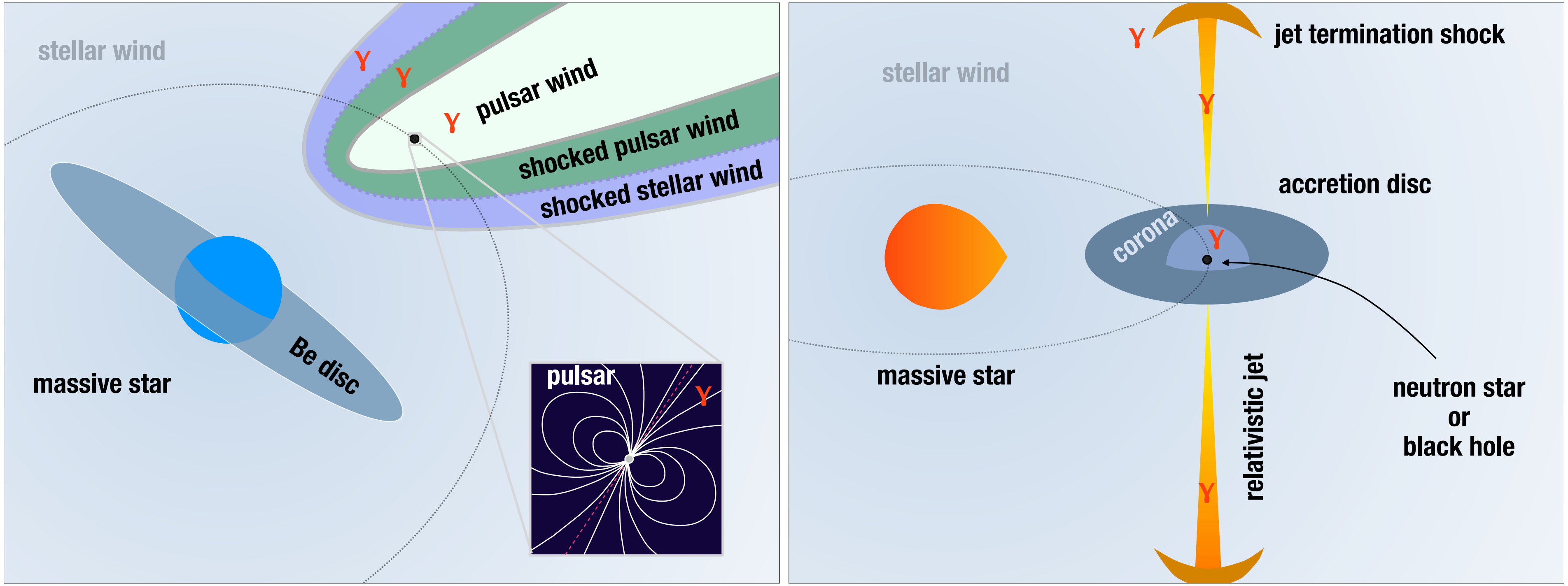
Need to be taken into account in population synthesis models !





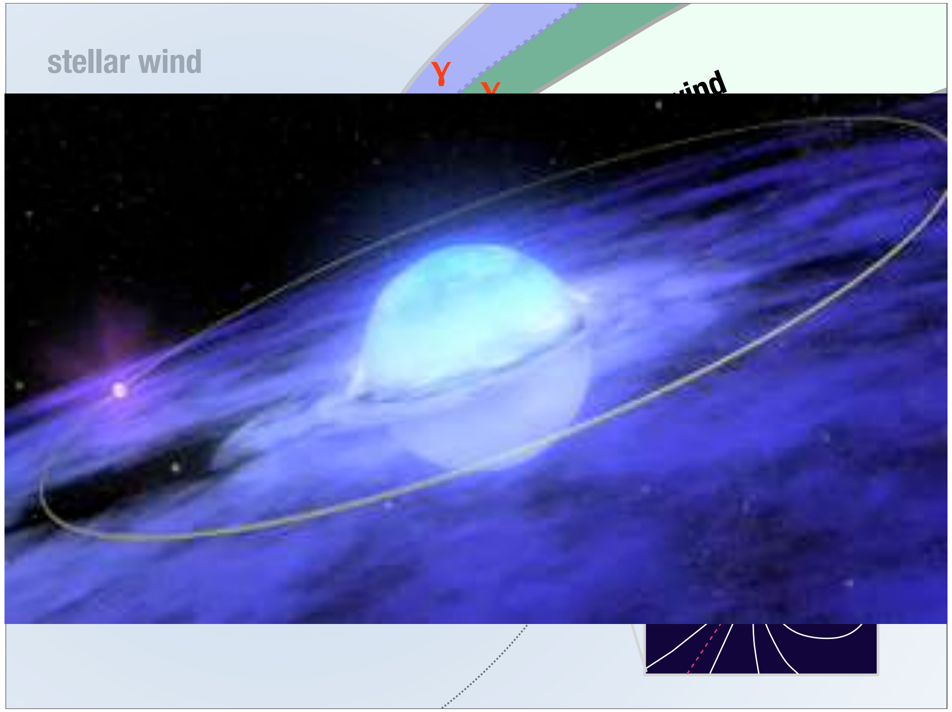
Coleiro et al., 2013

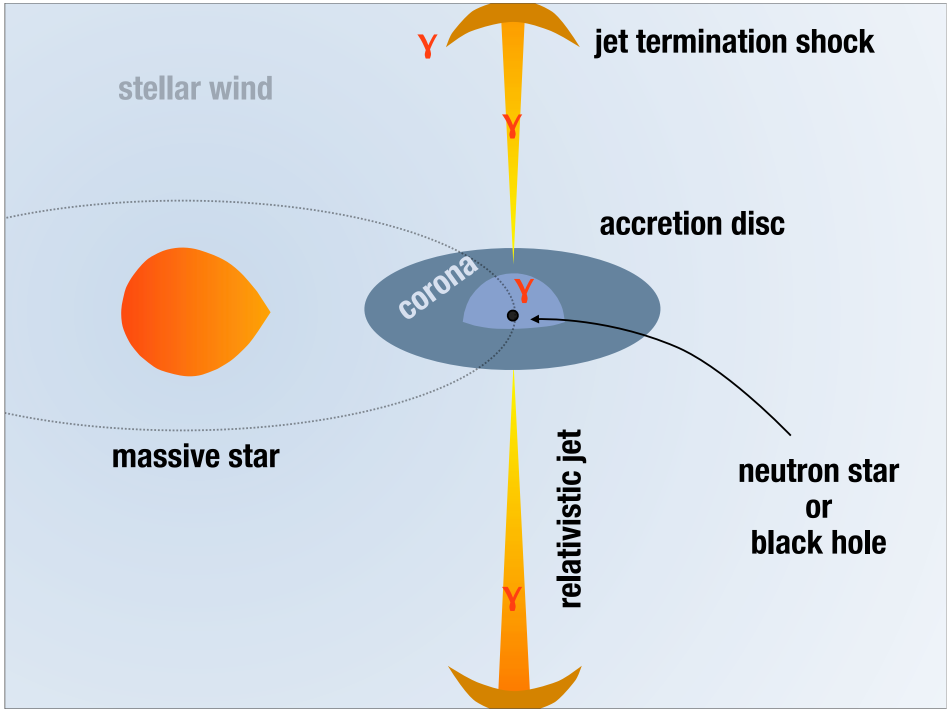
Gamma-ray binaries



Radiate mainly beyond 1 MeV (**detected from GeV to TeV**)
What are the main differences between these sources and the « common » HMXB ?

Gamma-ray binaries





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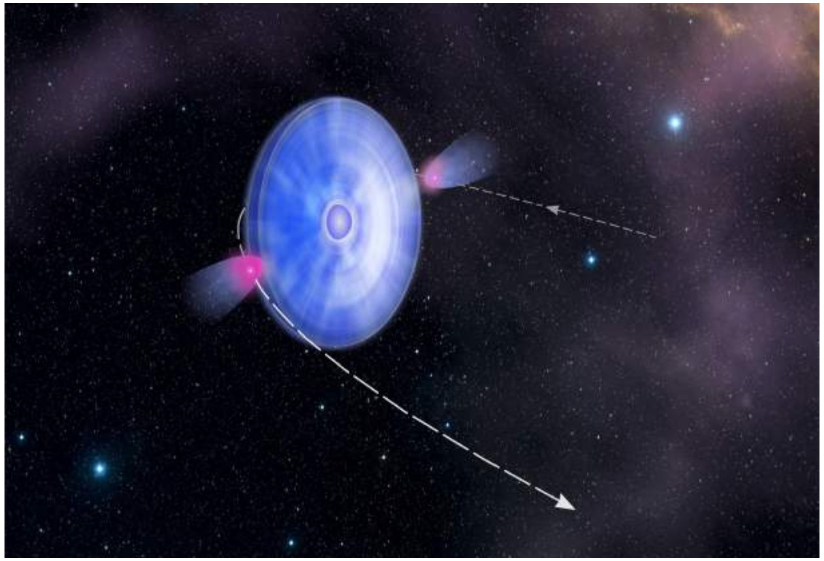
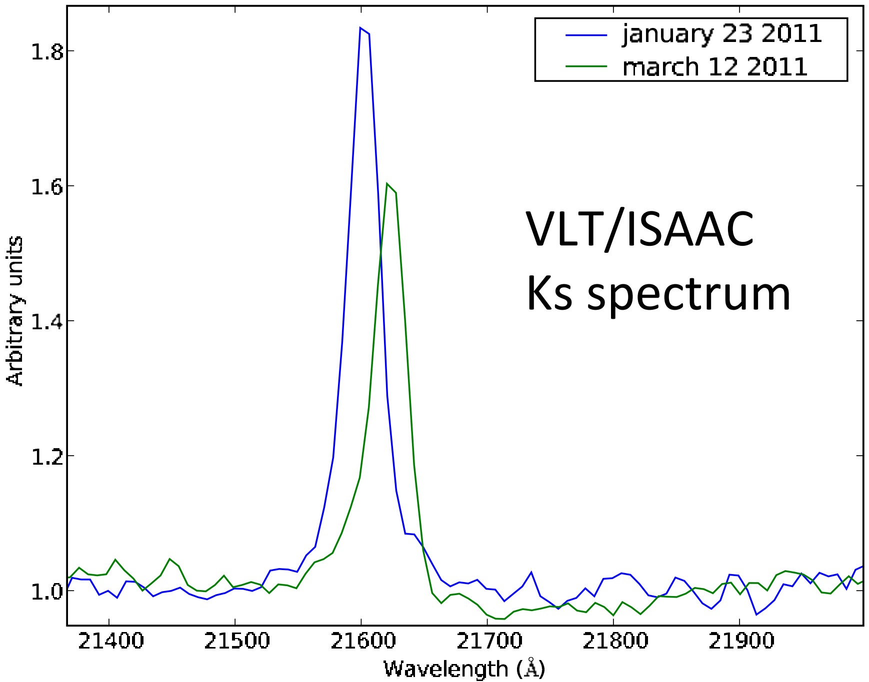
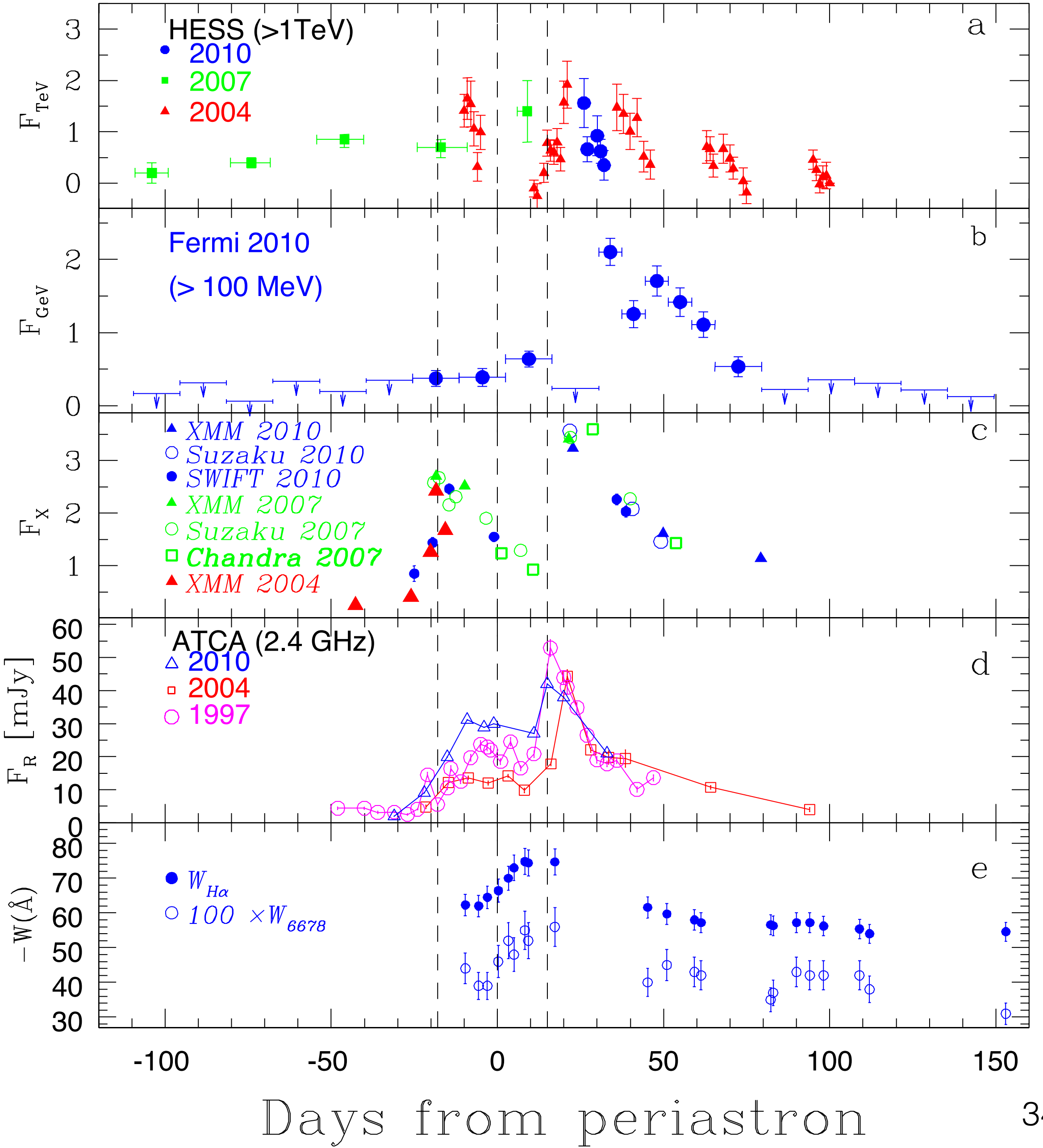
Gamma-ray binaries

> PSR B1259-63

Chernyakova et al. (Coleiro), 2014







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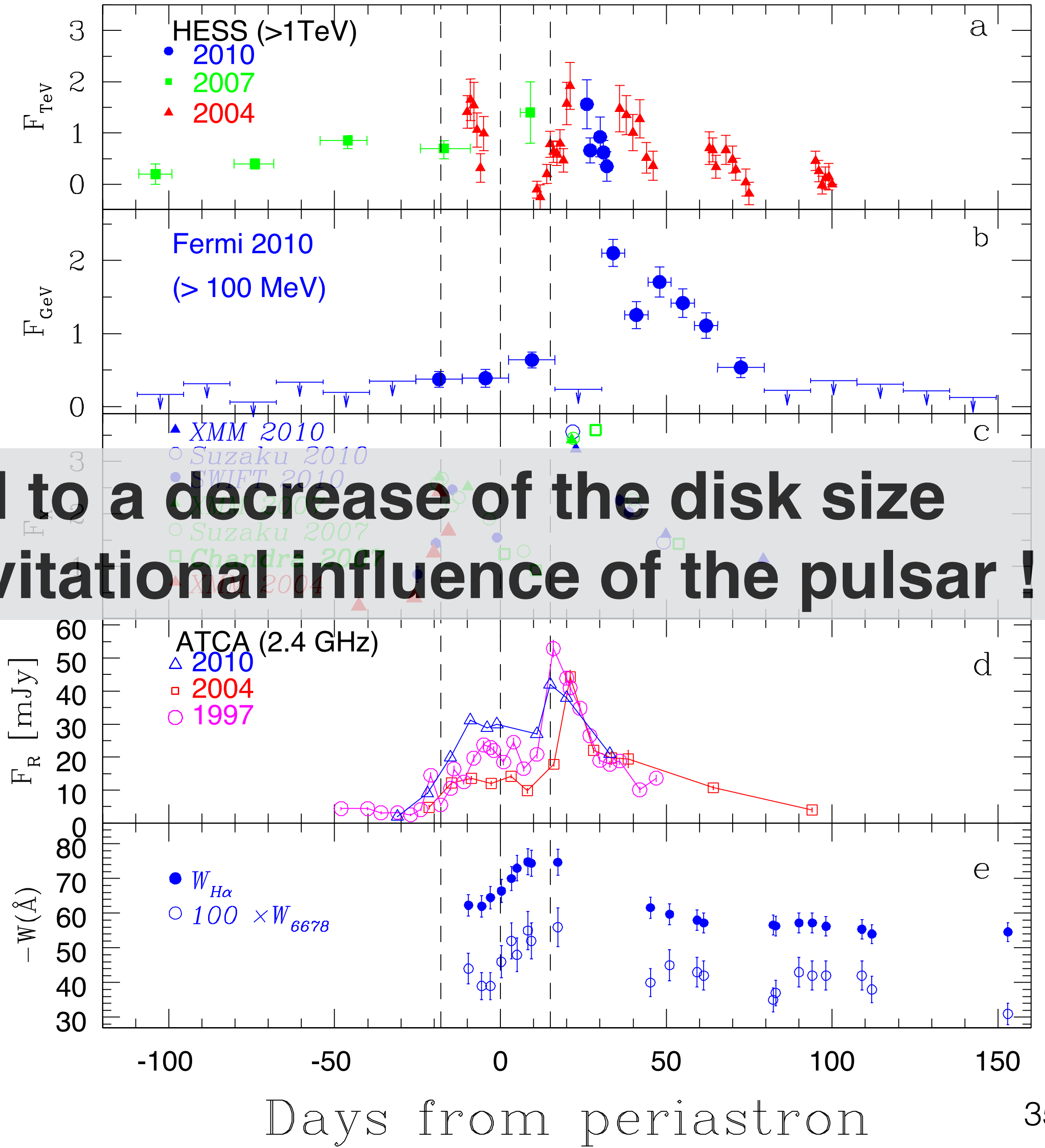
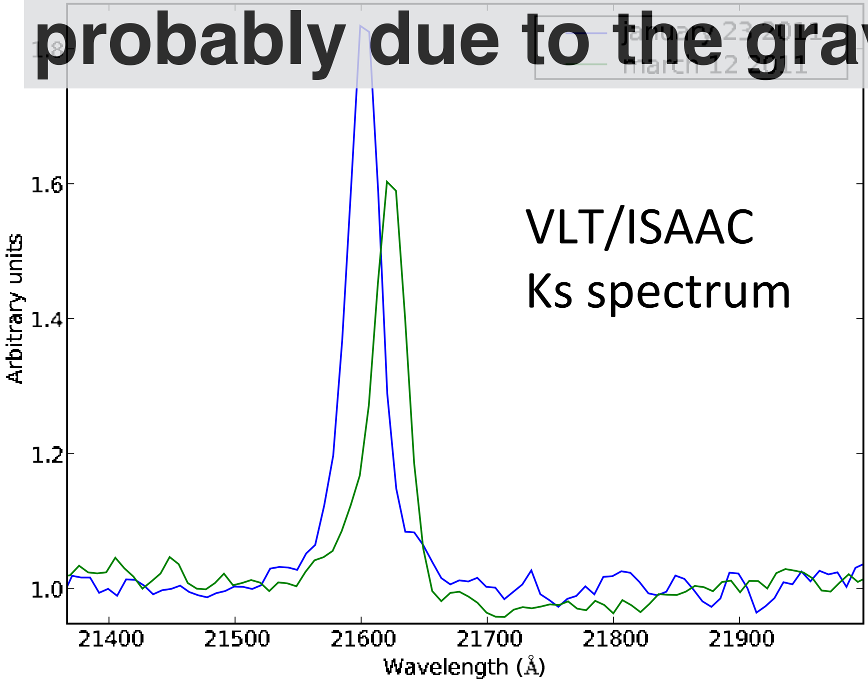
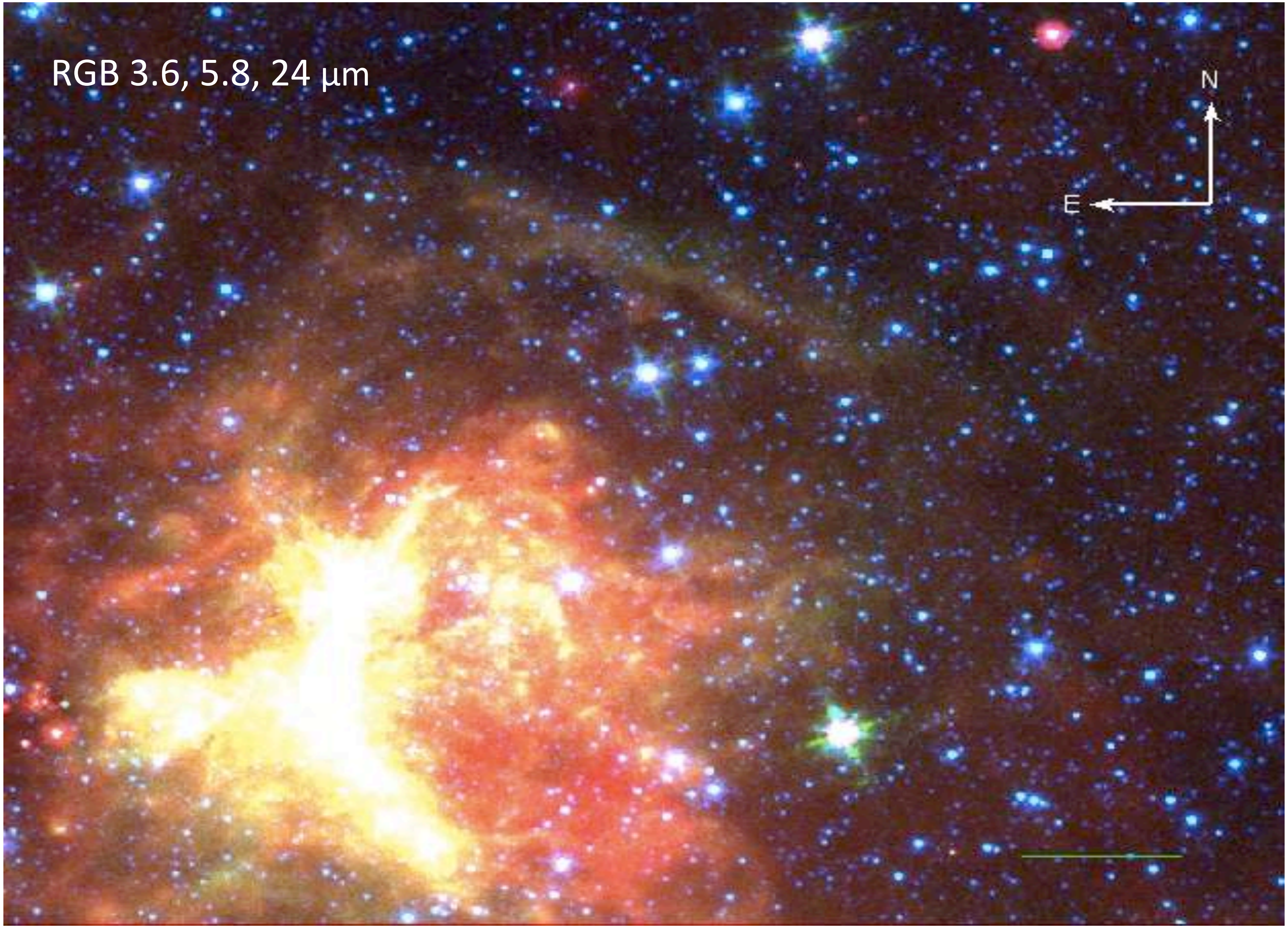


GeV emission related to a decrease of the disk size probably due to the gravitational influence of the pulsar !



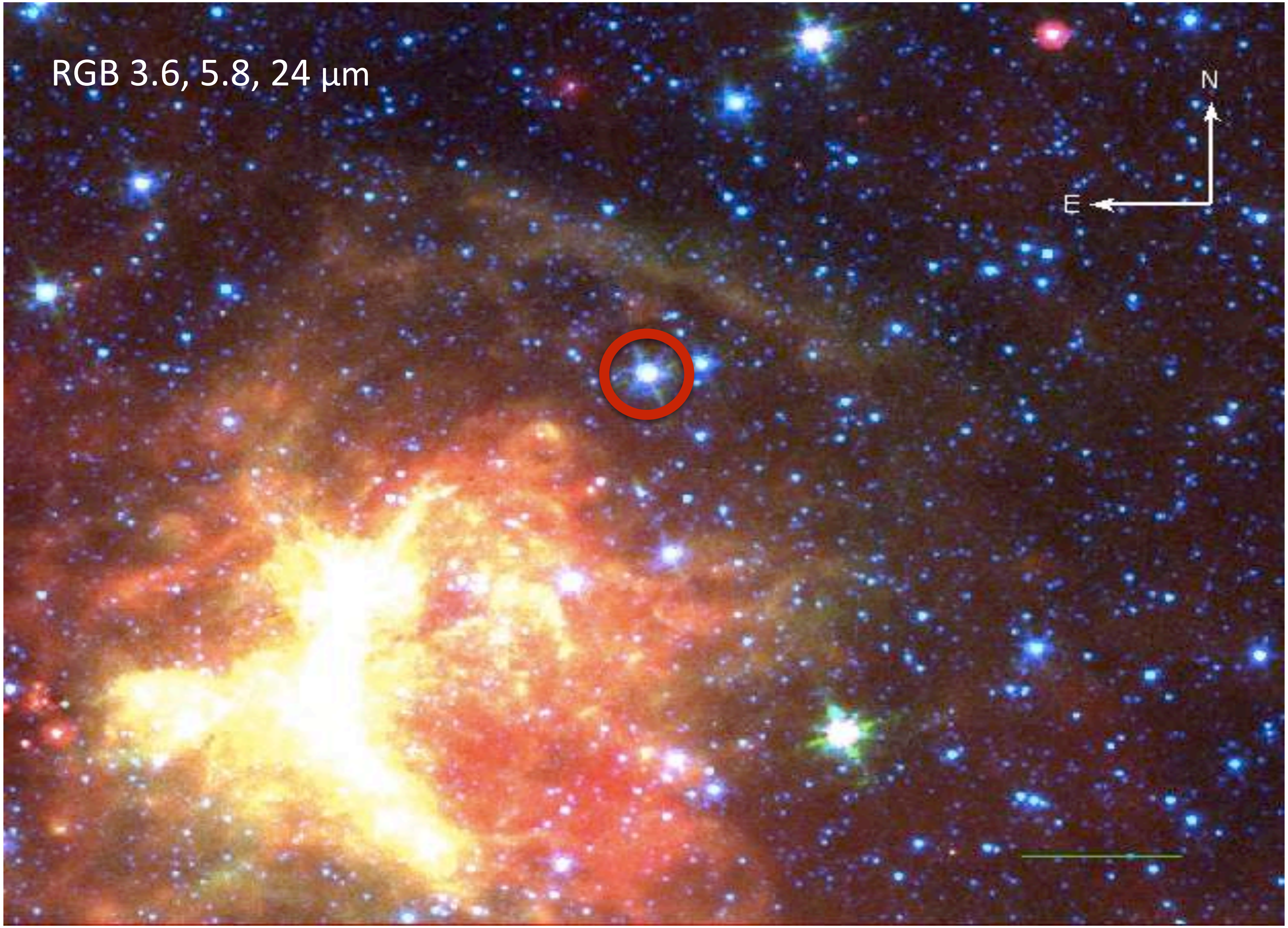
Impact on their environment

GX 301-2



Impact on their environment

GX 301-2



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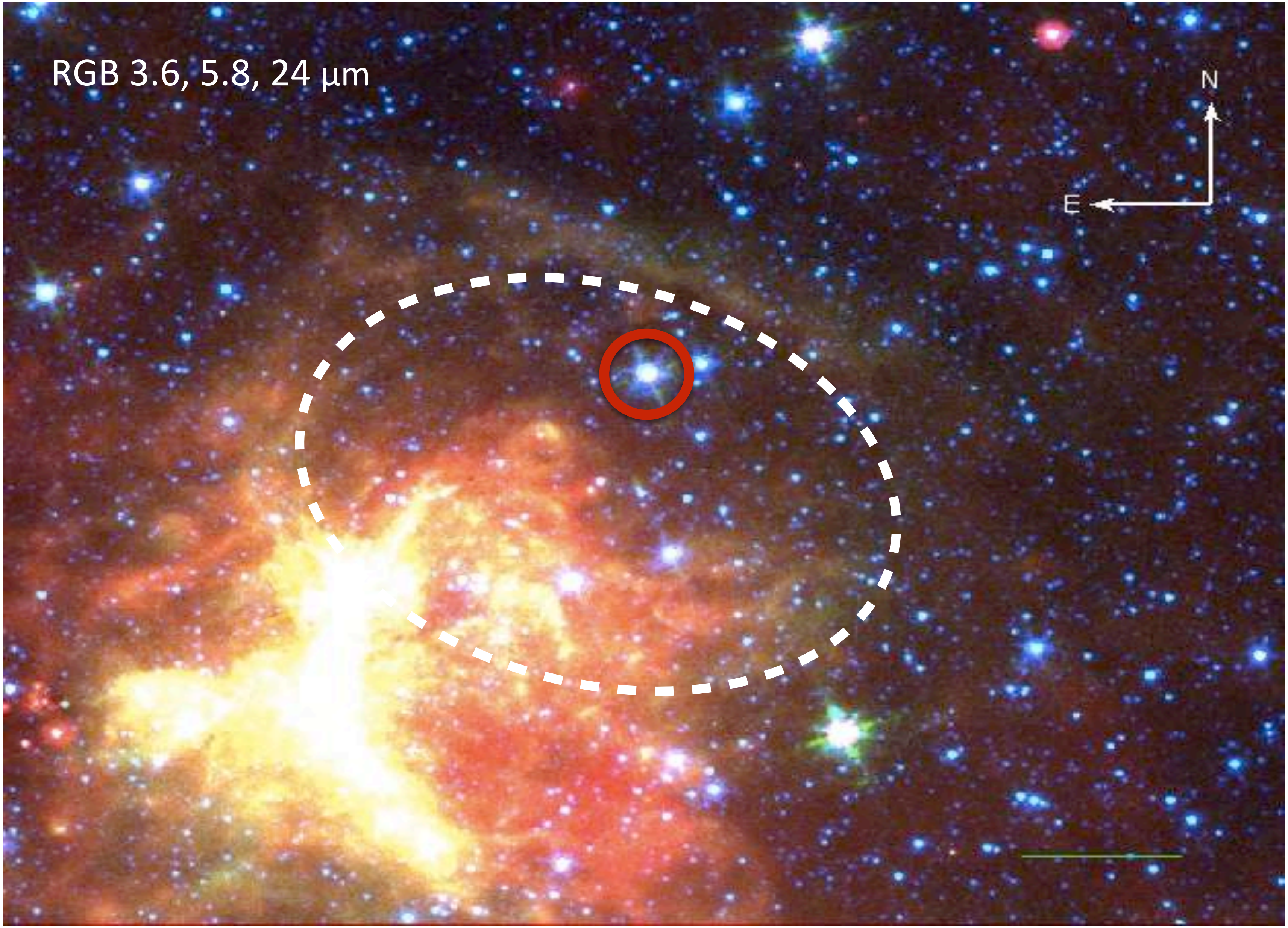

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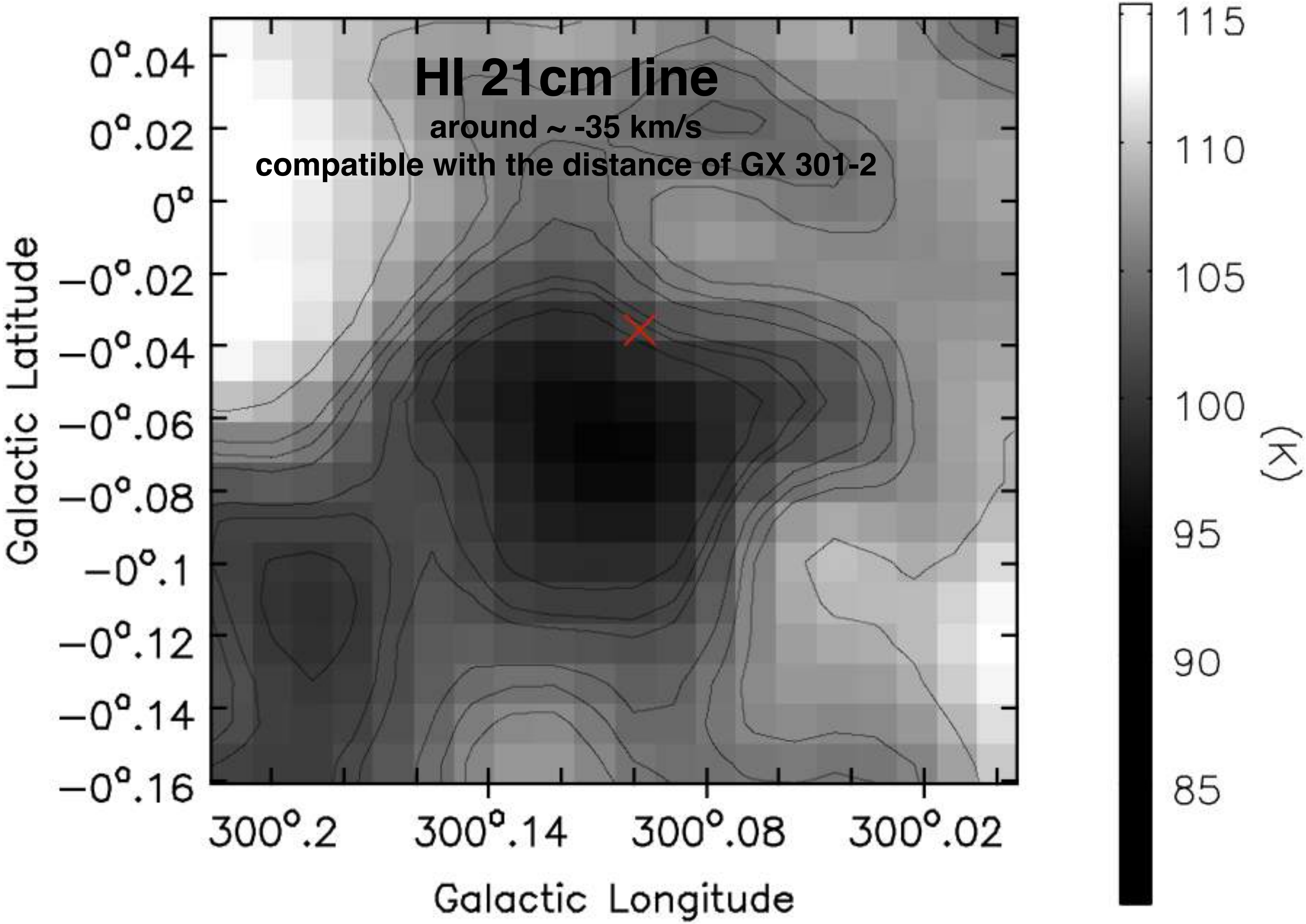

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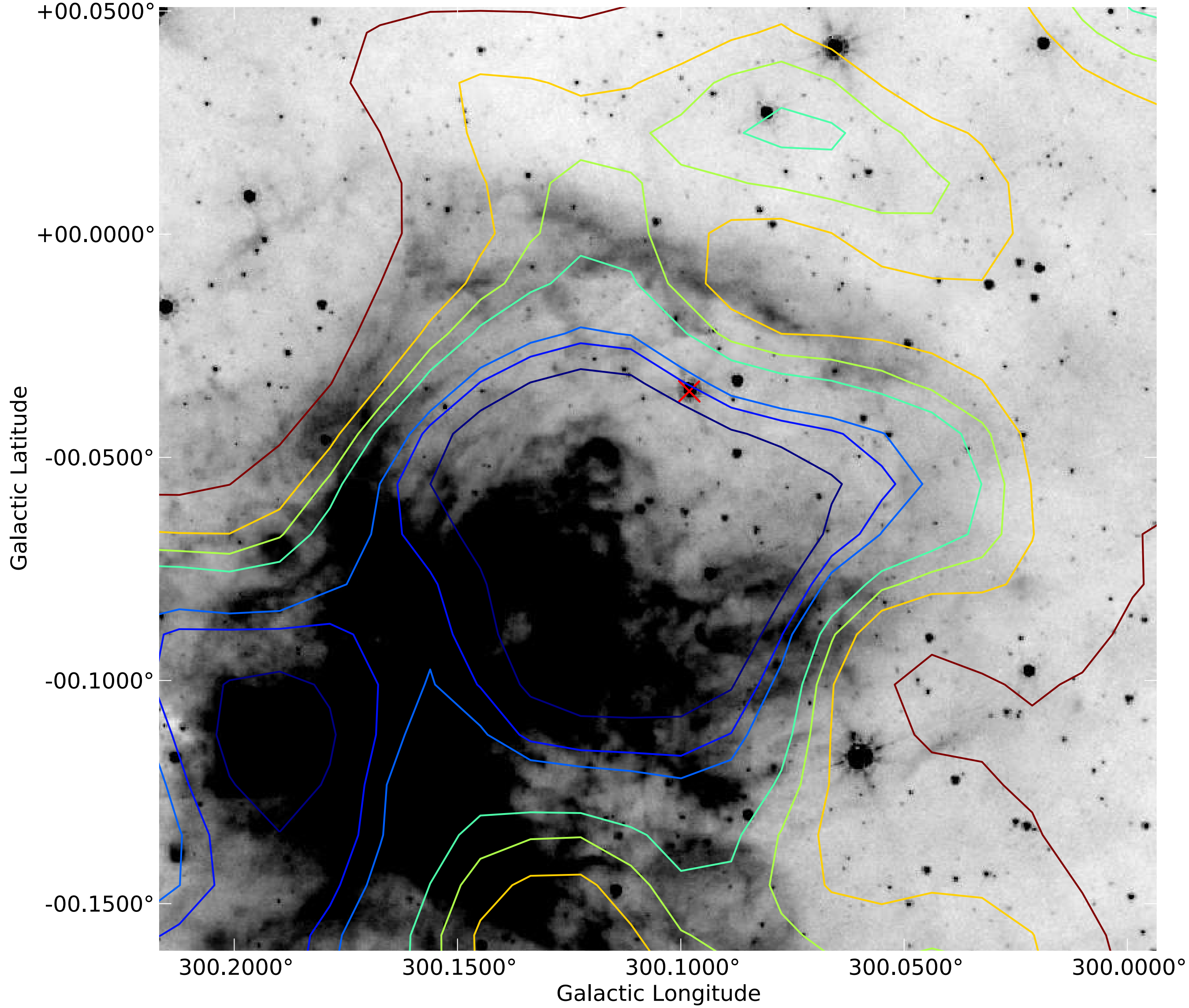
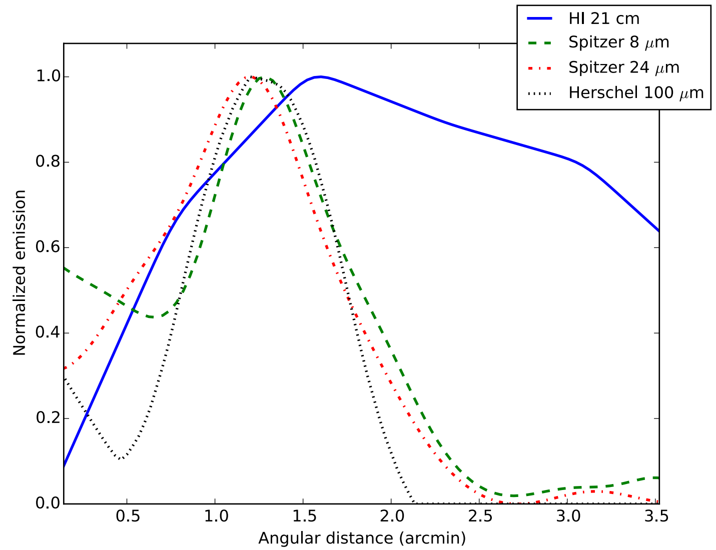
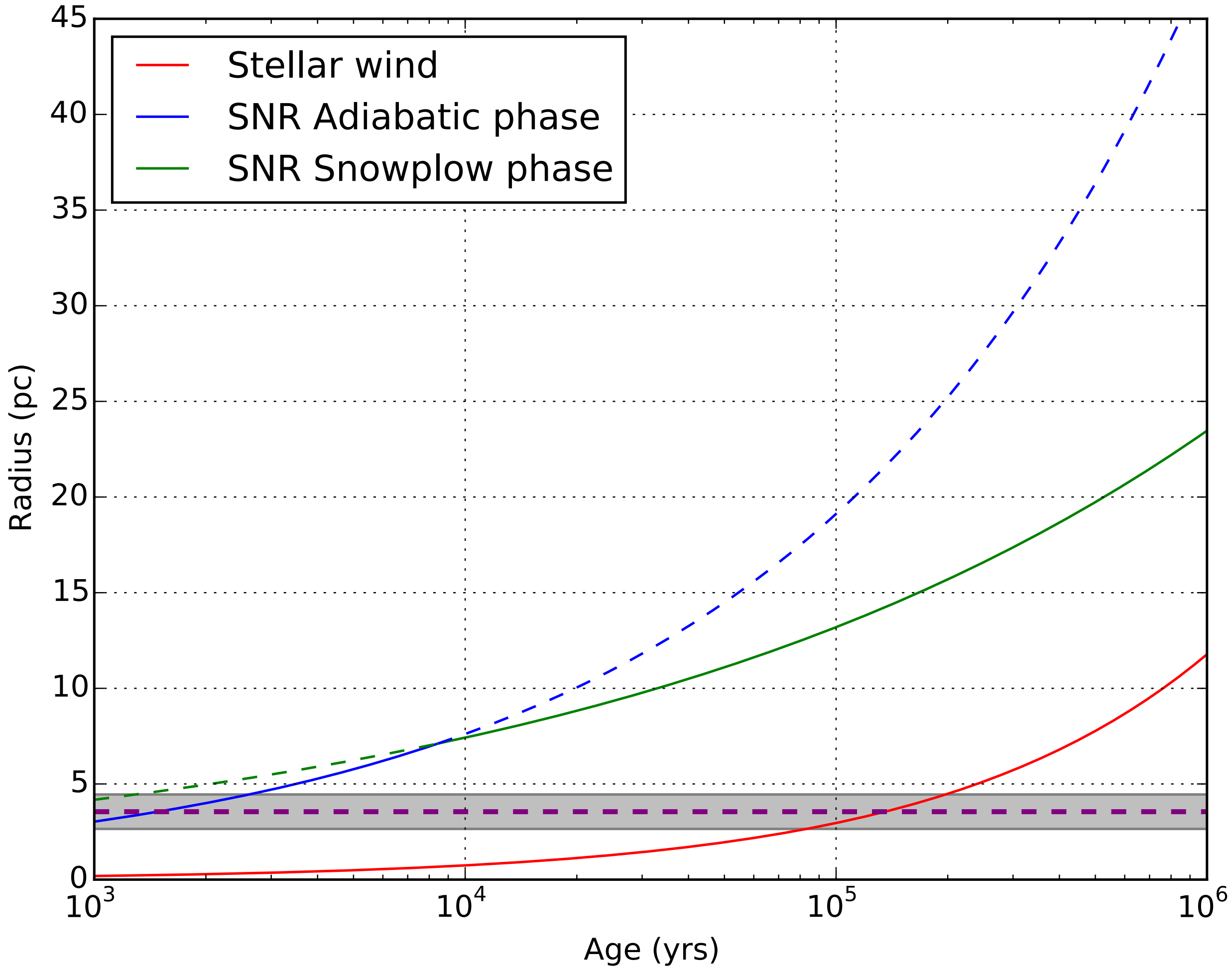




Coleiro et al., MNRAS, subm.

Impact on their environment

The cavity might have been formed by the SN or the stellar wind of the massive star(s)



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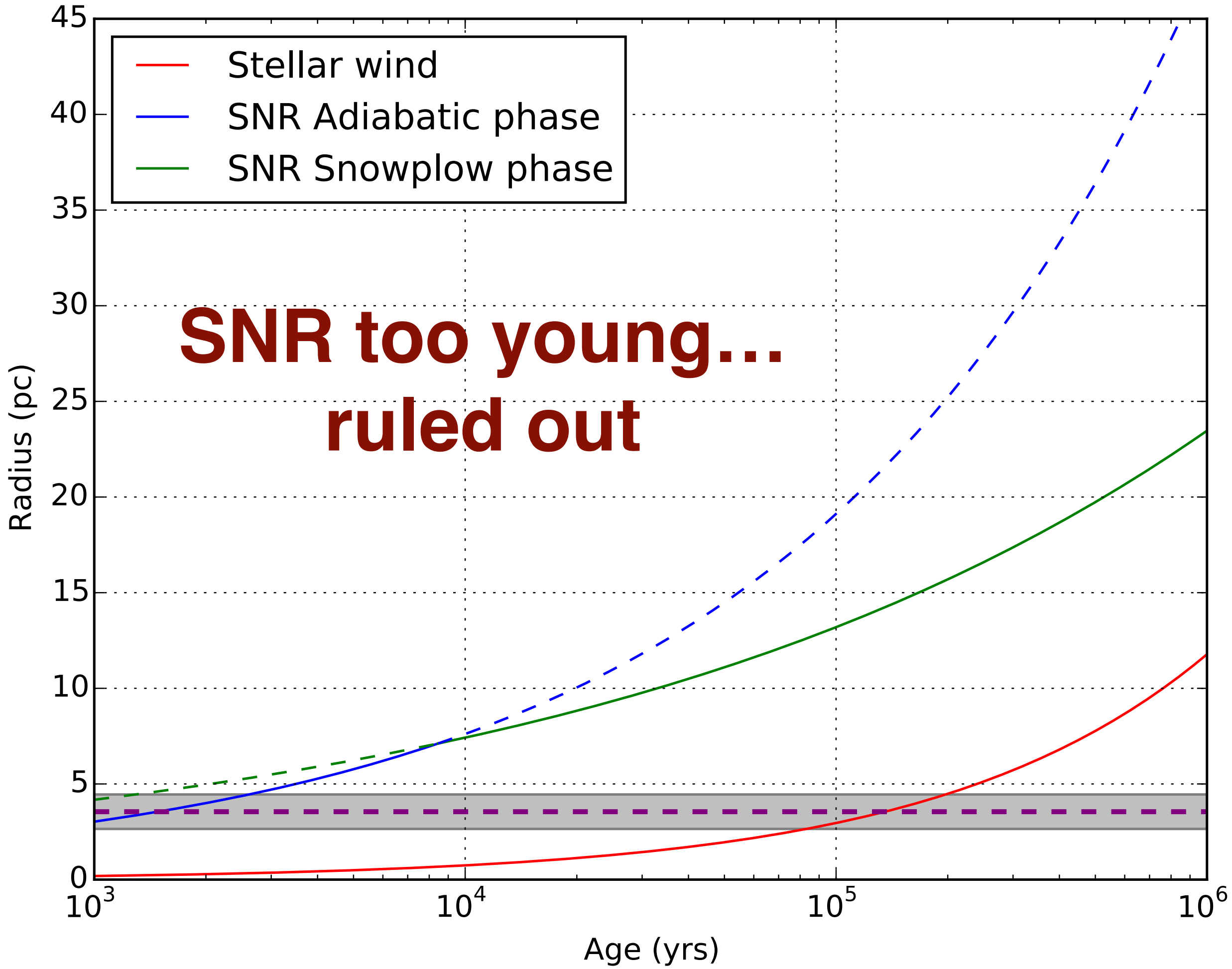

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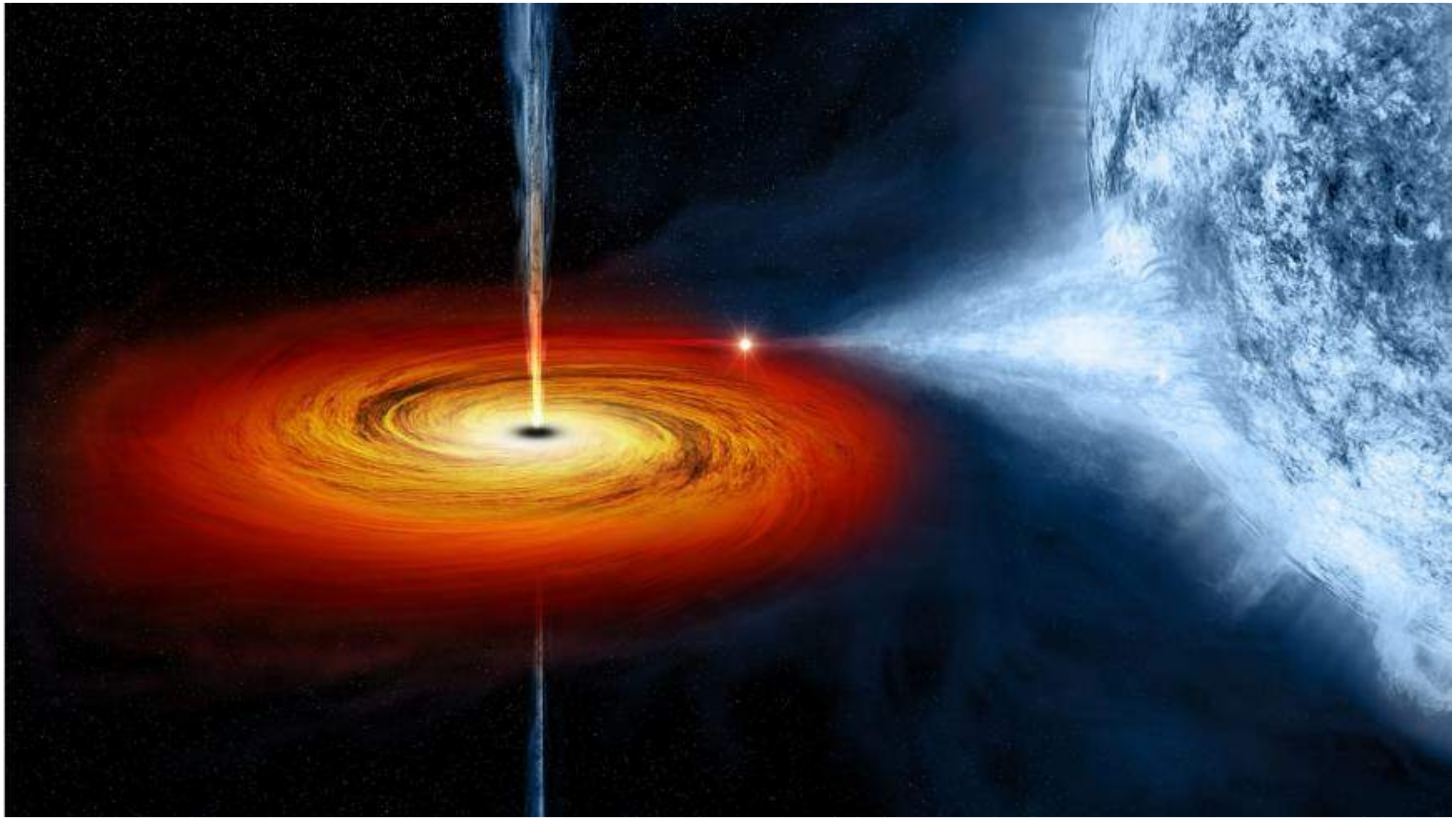
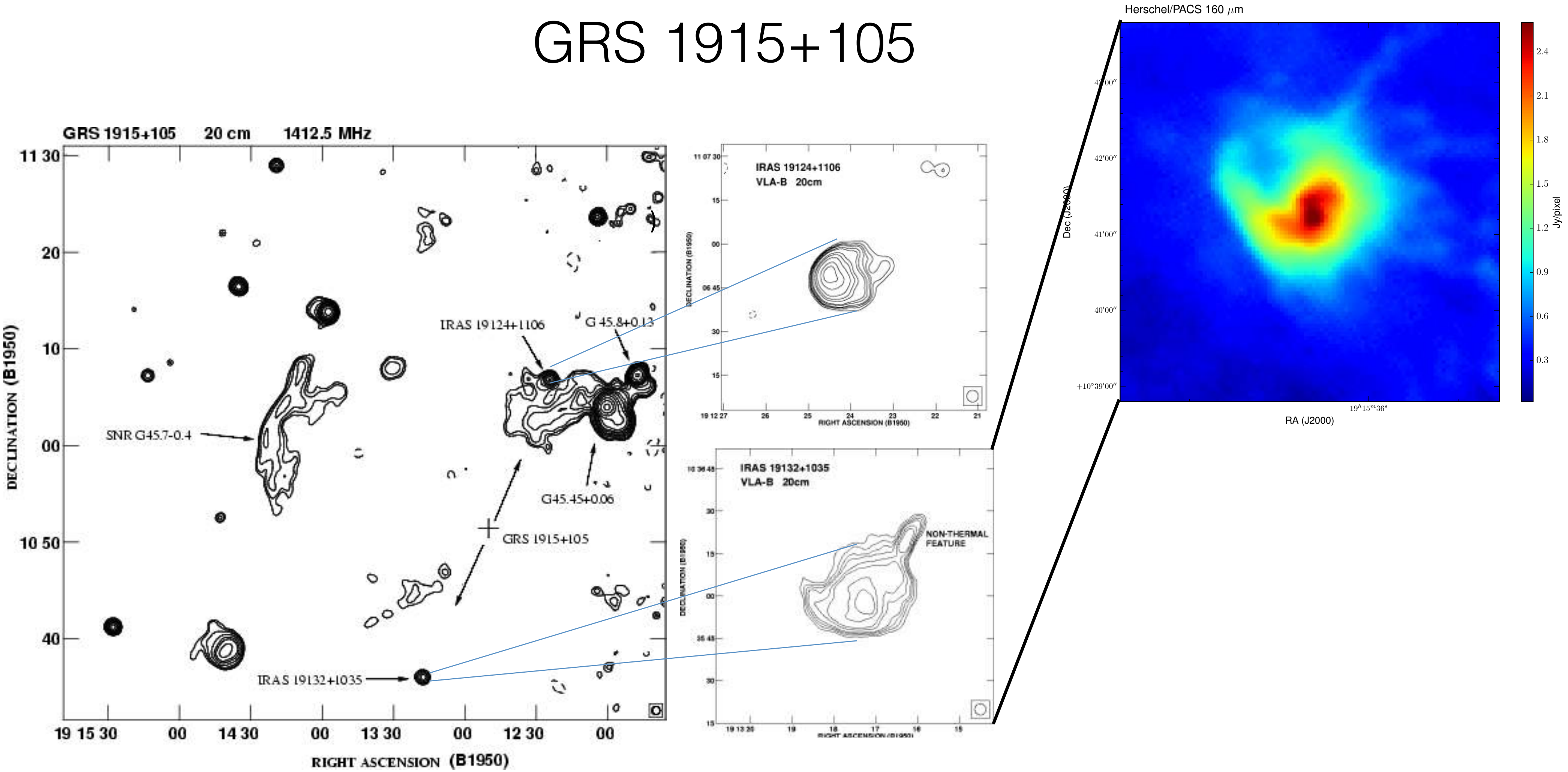


Impact on their environment

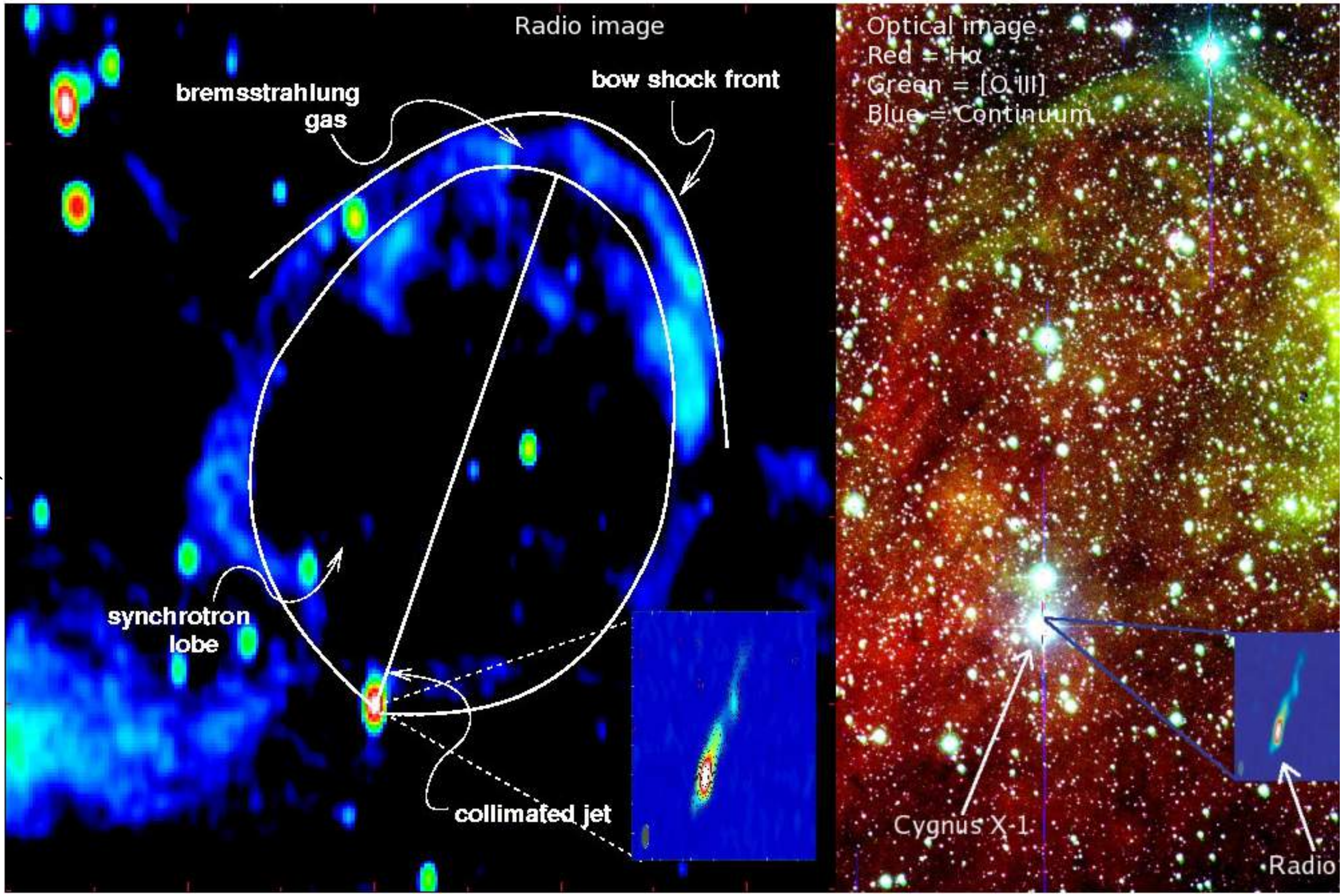
GRS 1915+105



Mirabel et al., 2015

Impact on their environment

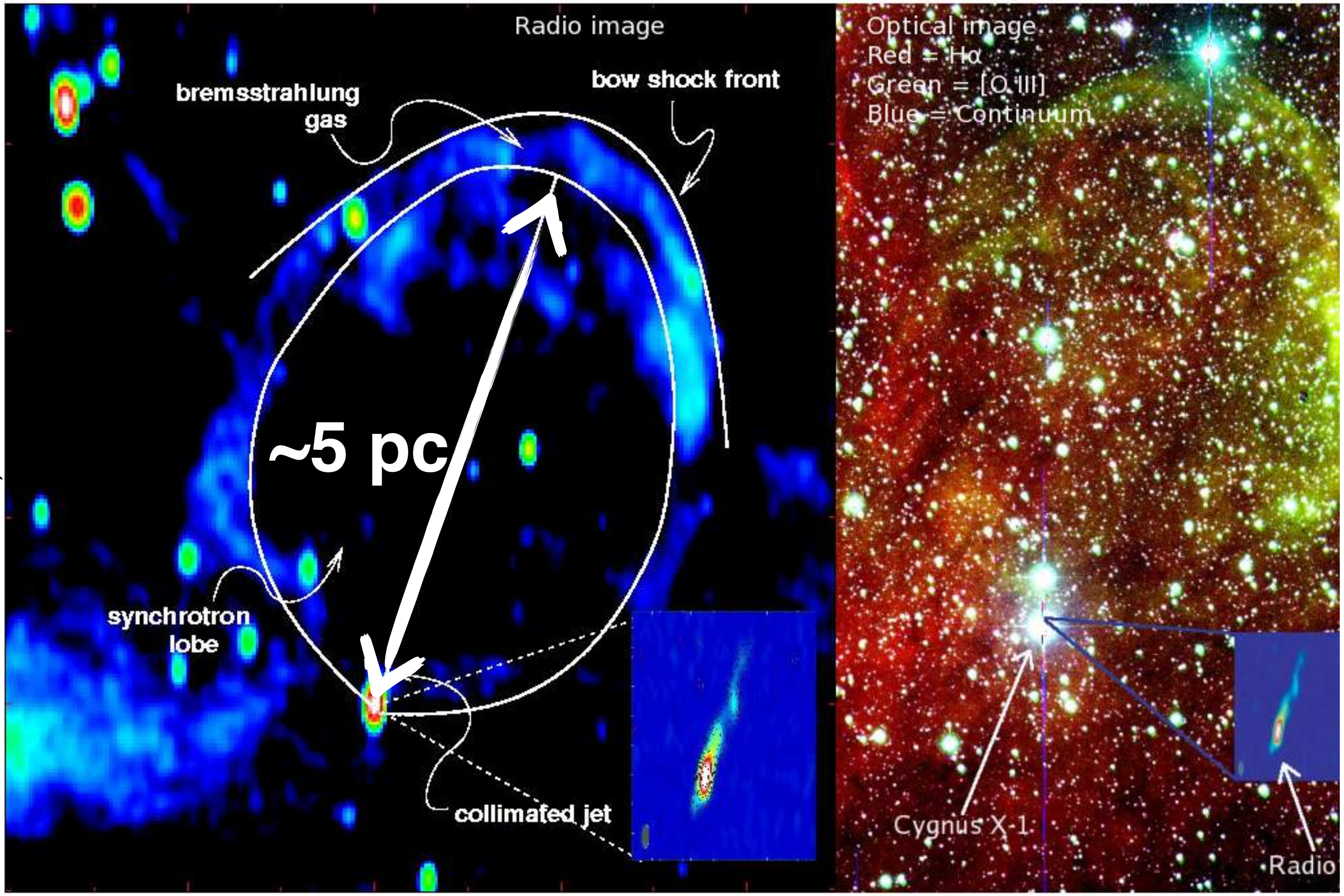
Gallo et al., 2005



- Radio ring inflated by the inner radio jet
- Bremsstrahlung emission from the shock where the collimated jet strikes the ISM
- **ISM = effective jet calorimeter ⇒ estimate jet power !!**

- Ratio of jet power to X-ray luminosity in the range 0.06 to 1.0 ($8.10^{35}<P_{jet}<10^{37}$ erg/s)
- Accretion energy may be released through dark jets (=radiatively inefficient)

Impact on their environment



Gallo et al., 2005

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I. Introduction

> *Transient high-energy sources*

> *X-ray binaries*

II. Multi-wavelength study of (high-mass) X-ray binaries

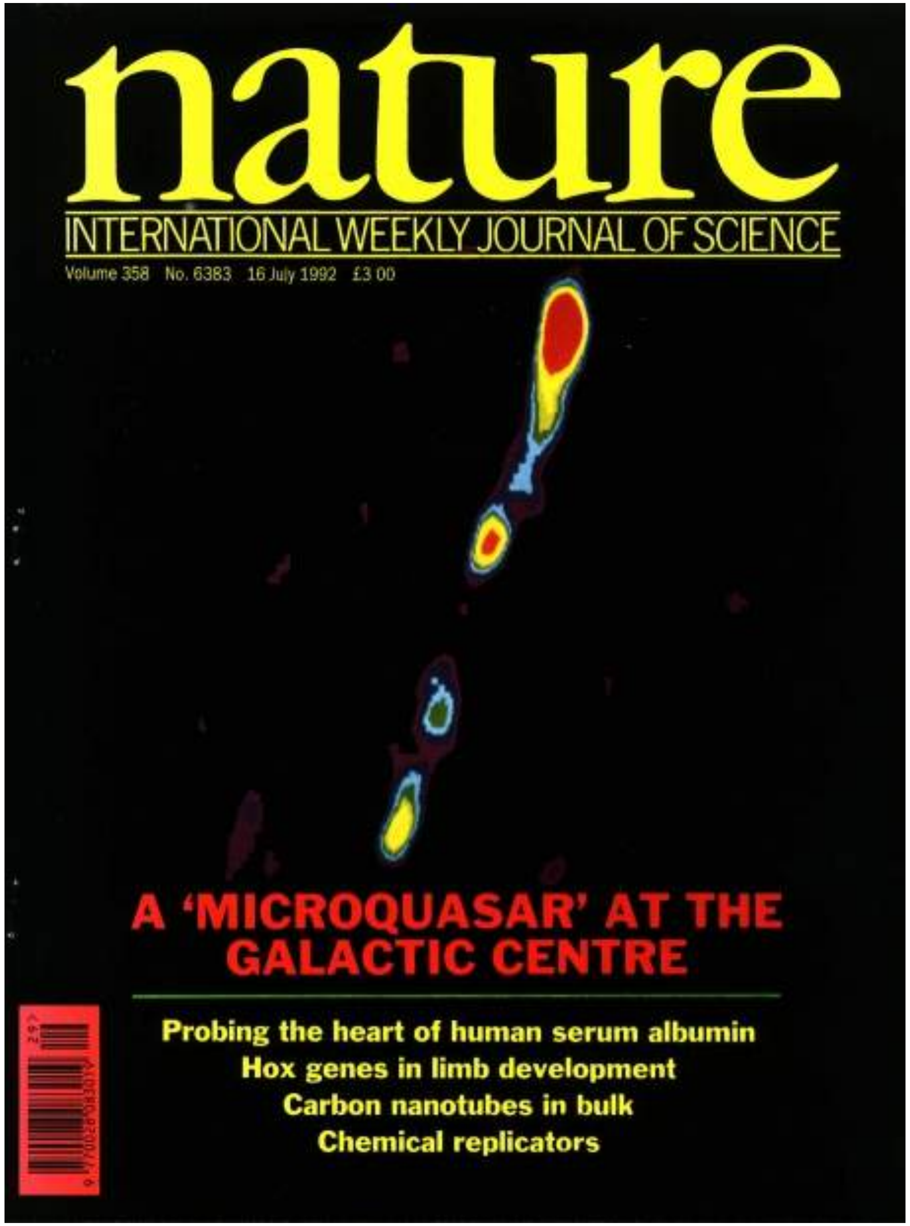
> *Nature, evolution and particle acceleration*

Microquasars (LMXB and HMXB)

III. The multi-messenger era

> *How it will revolutionize the study of X-ray binaries and transients in general*

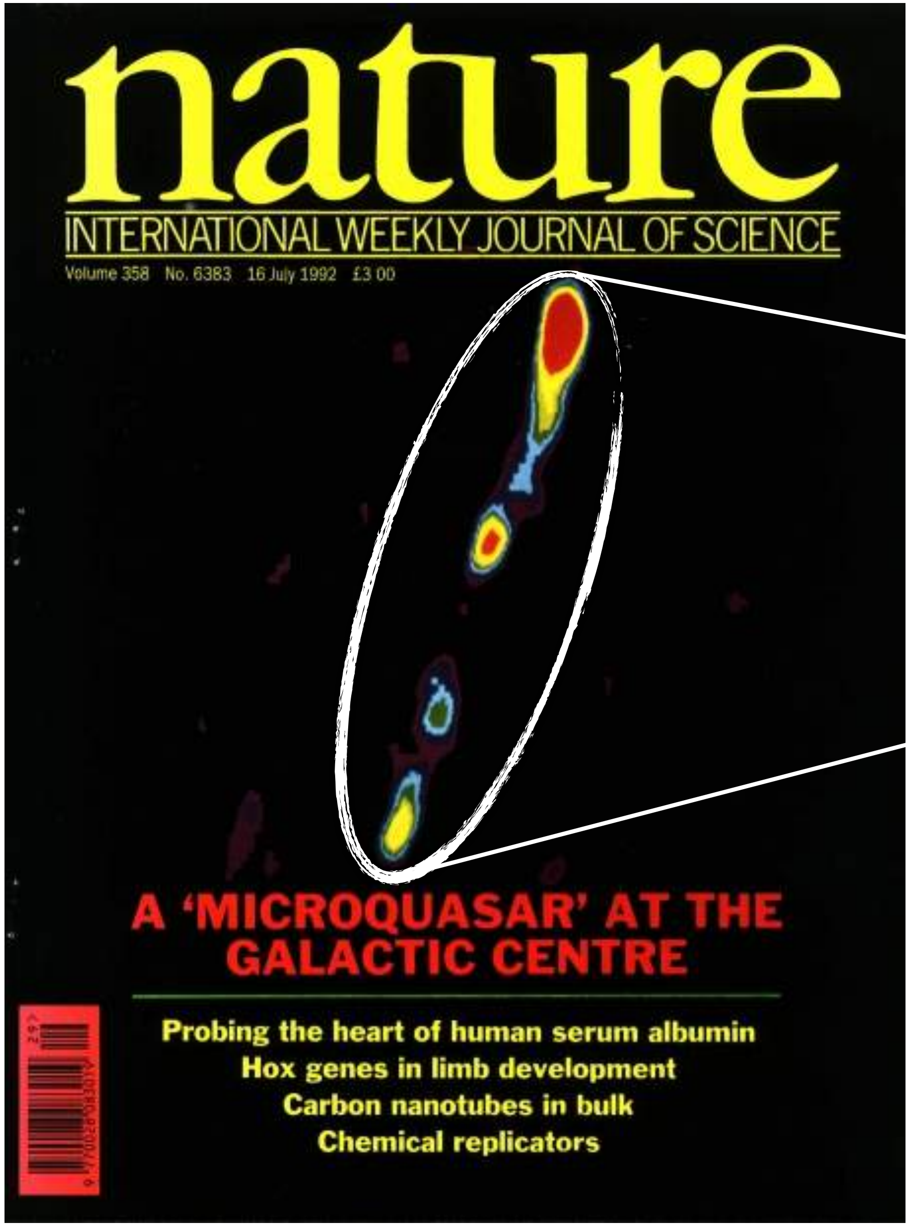
Microquasar discovery

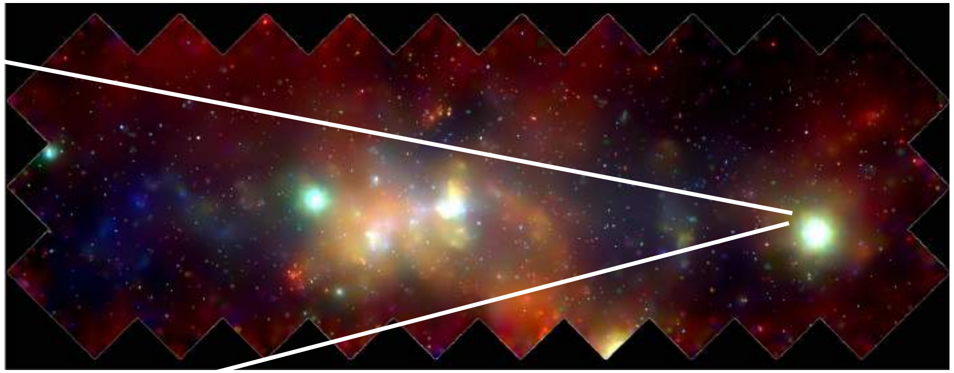


Mirabel et al., 1992

NASA/UMass/D.Wang et al.

Microquasar discovery





NASA/UMass/D.Wang et al.

Mirabel et al., 1992

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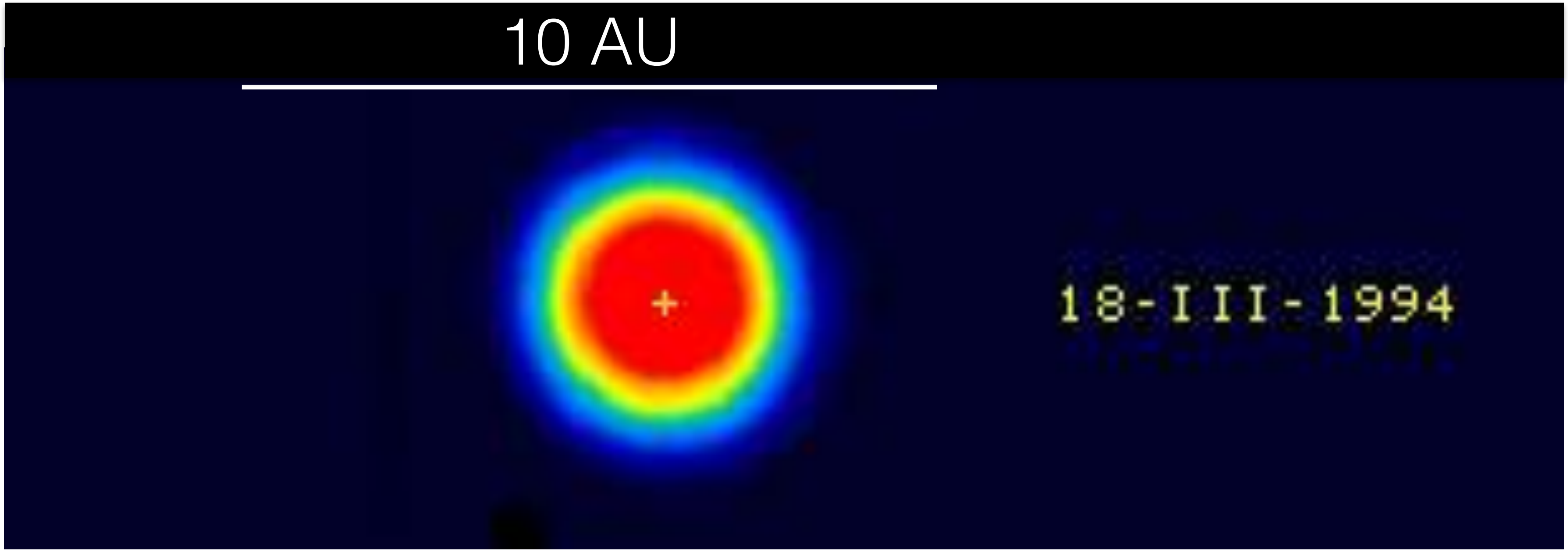
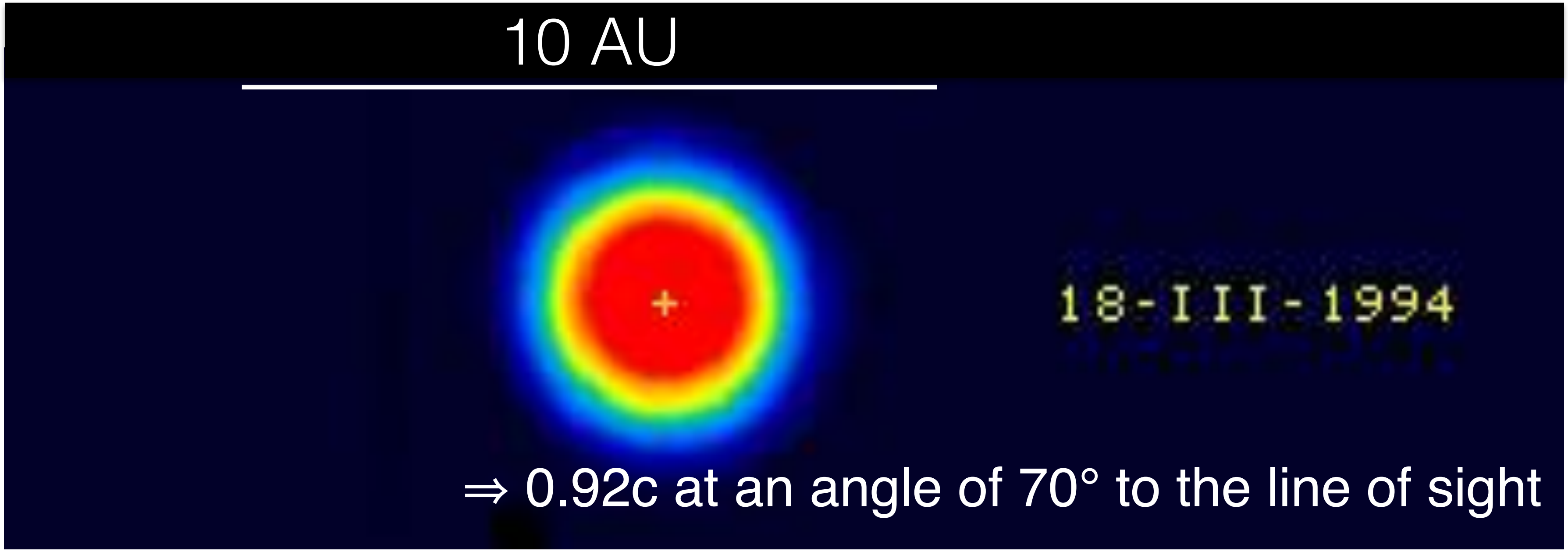


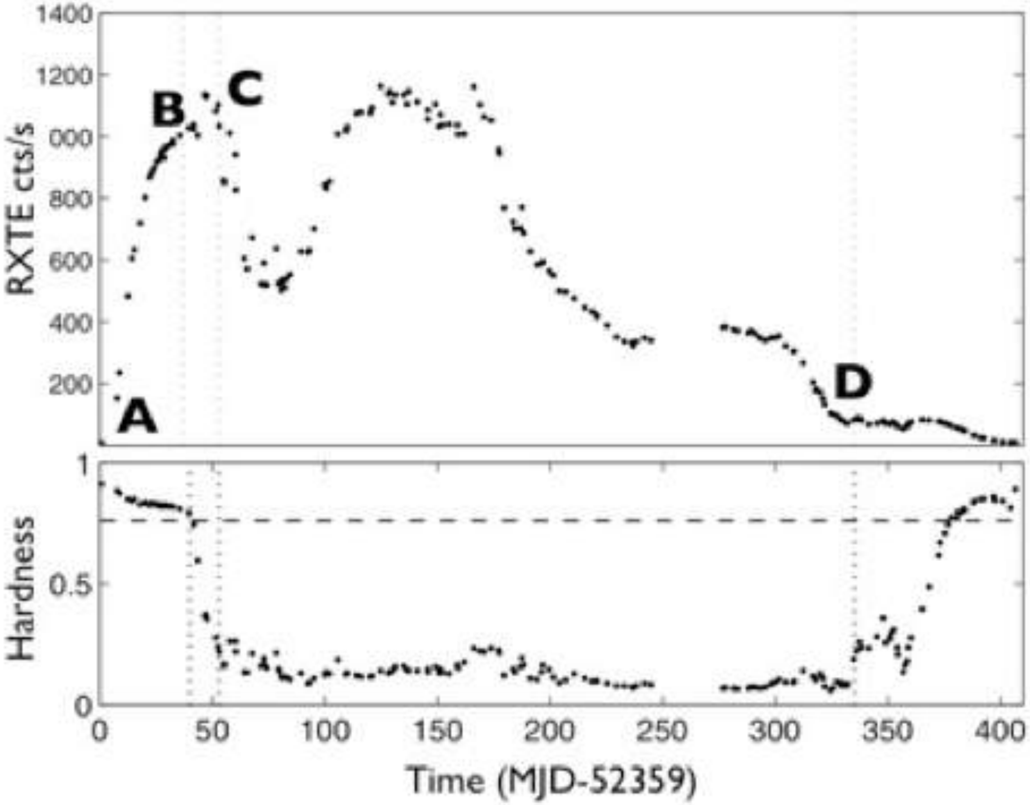
Mirabel et Rodriguez, 1994

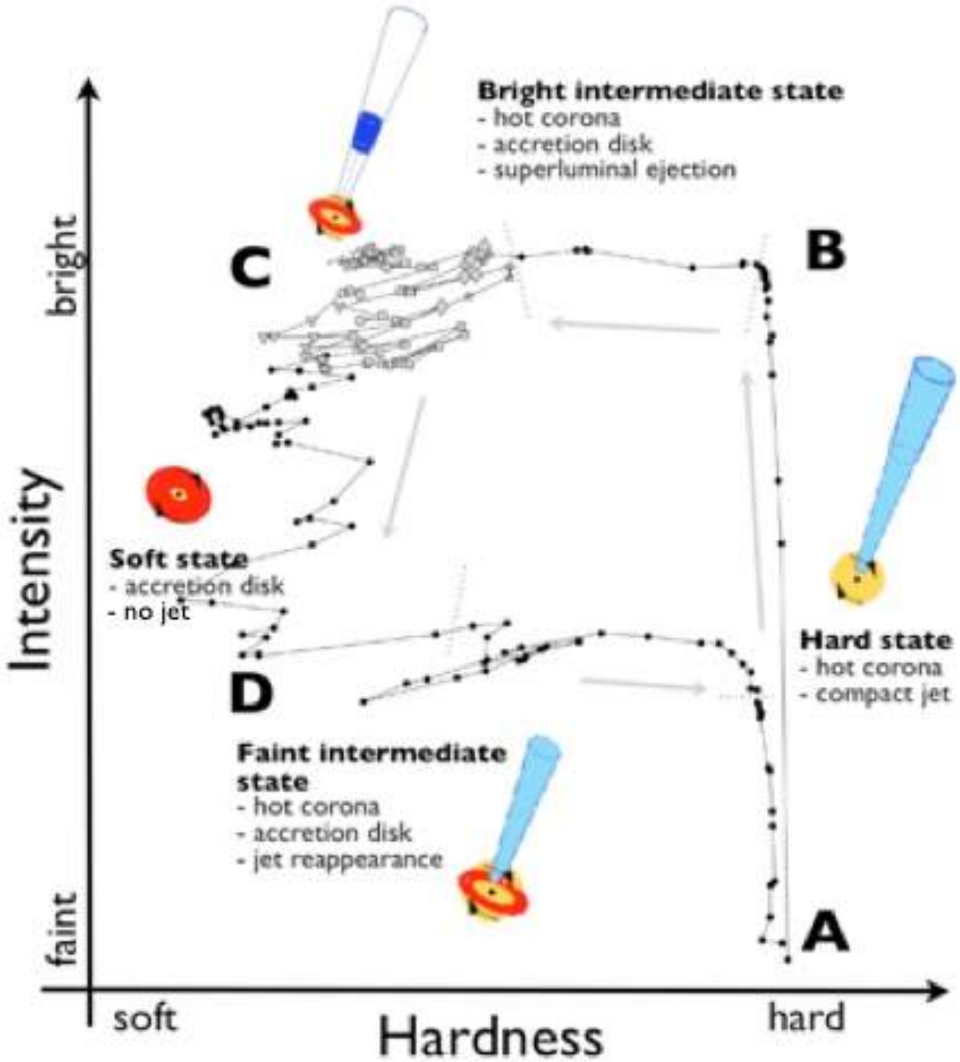
Microquasar discovery



Mirabel et Rodriguez, 1994

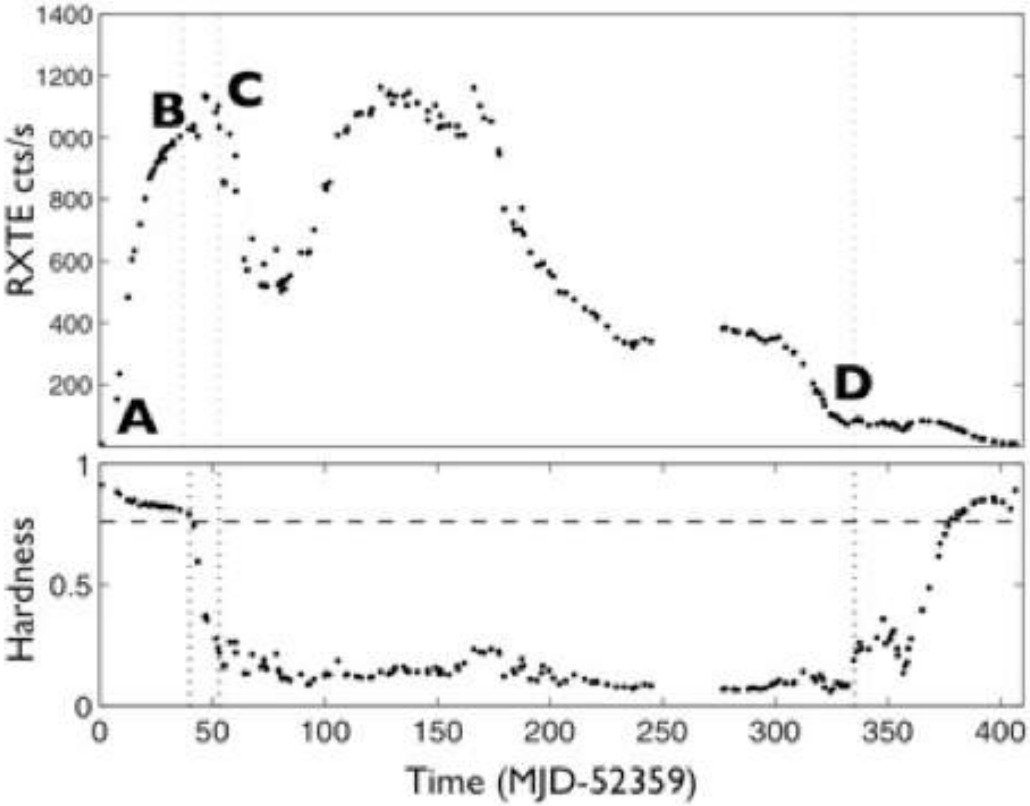
Microquasar X-ray states

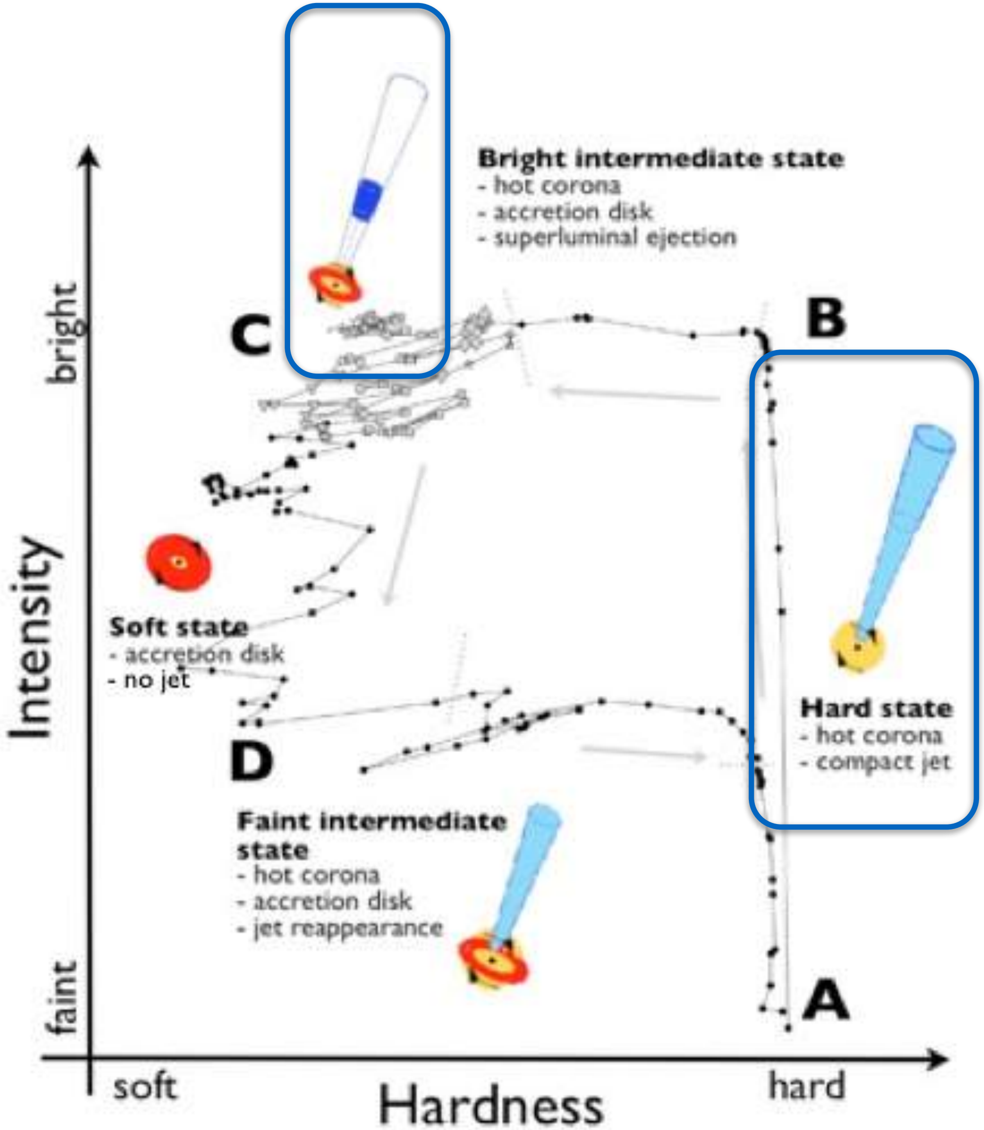




Microquasar X-ray states

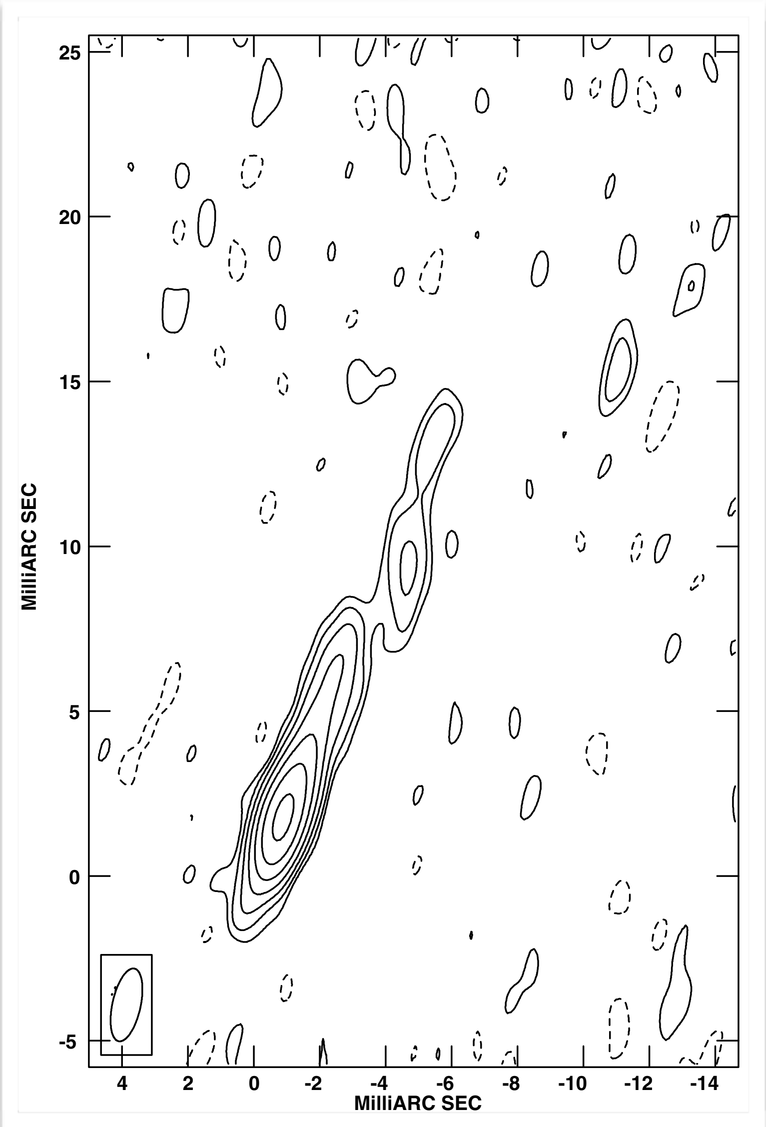
2 types of jets





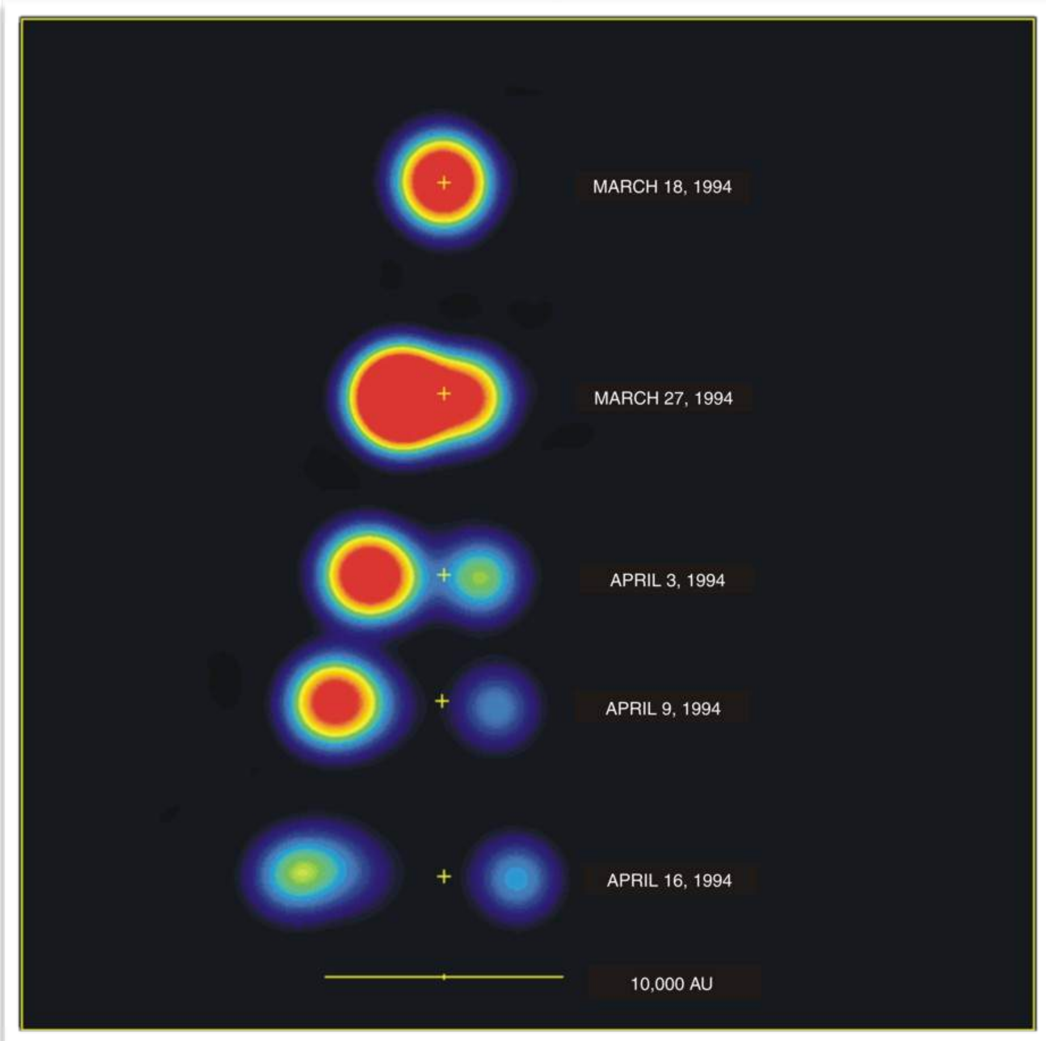
2 types of jets

Compact jets: tens of AU found in low/hard X-ray state



Stirling et al., 2001

Discrete jets: large scale - up to parsecs, produced at state transitions

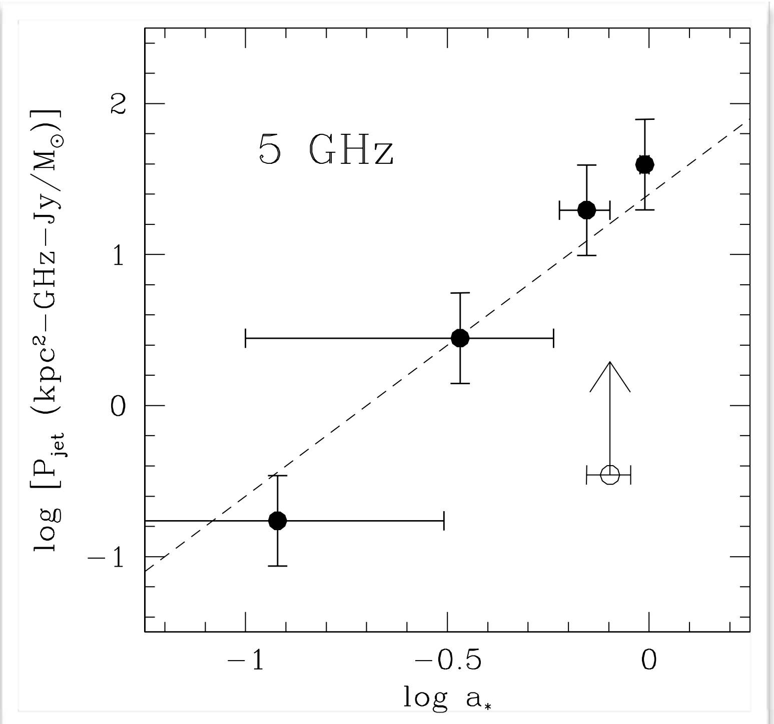


Mirabel et Rodriguez, 1994

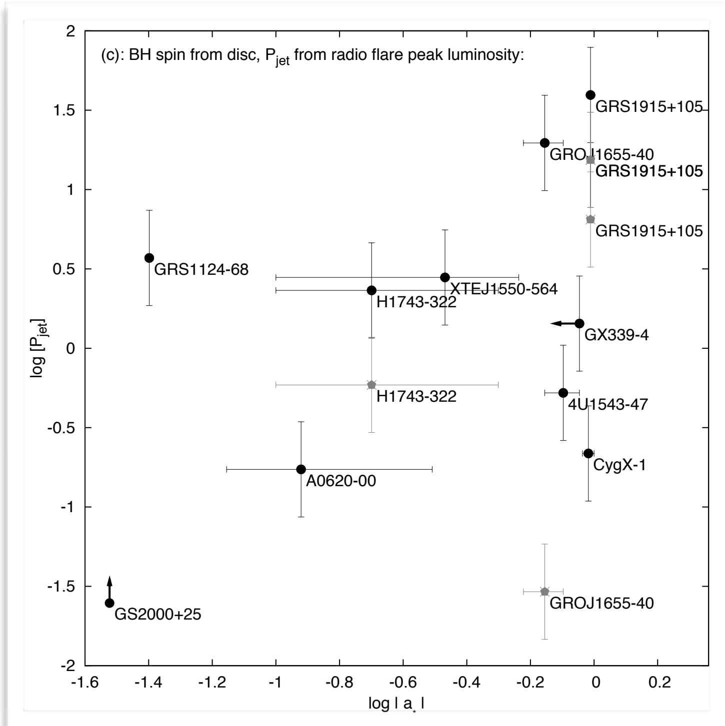
Jet power and composition

Jet formation mechanism not established yet
Find observational signatures to distinguish between:

-accretion disc rotation model (Blandford & Payne 1982)
-black hole spin model (Blandford & Znajek 1977) : based on the birth of a dense, relativistic pair plasma in a strongly magnetized region



Narayan & McClintock, 2012



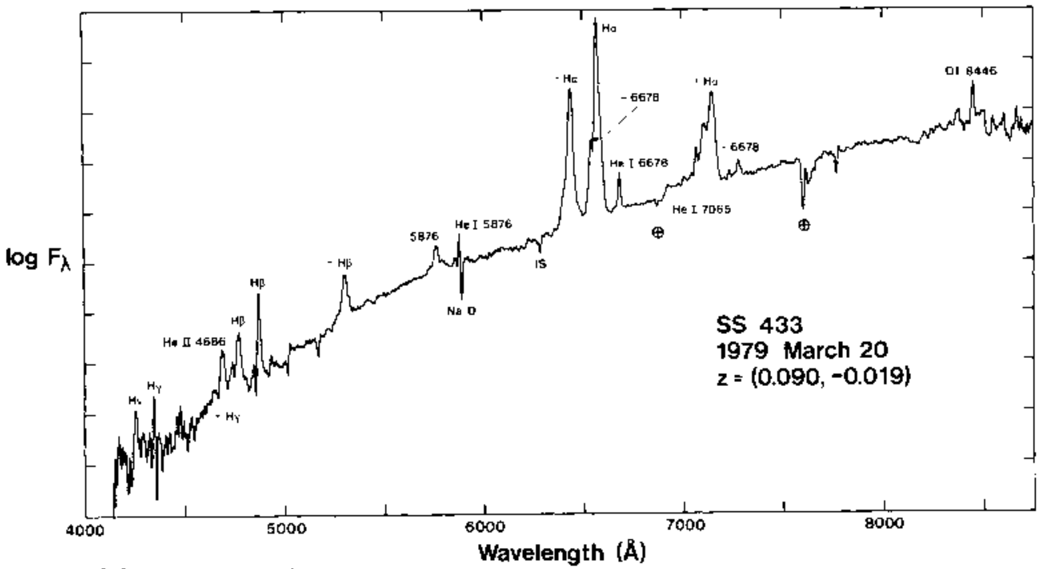
Russell et al., 2013

Jet power and composition

- One of the most important uncertainty: **jet composition** !
- In nearly all cases: jet radiation = synchrotron (only requires leptons)
  ⇒ not clear whether the jets are composed of e^+/e^- or p/e^-

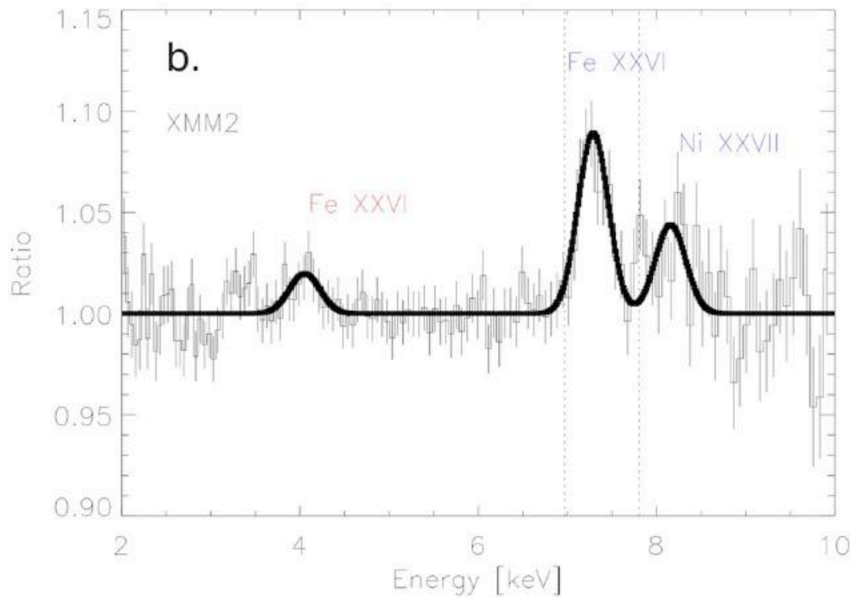
- <u>Two exceptions: SS 433 and 4U 1630-47</u>:

Doppler-shifted emission lines in SS 433 jets at ~0.25c



Margon et al., 1979

Doppler-shifted emission lines in gas moving at ~0.7c coincident with radio emission !



Diaz-Trigo et al., 2013

BUT detection of such "smoking gun" lines from jets having Lorentz factors well in excess of unity may be far more difficult than in SS 433, as the lines are anticipated to be very broad…

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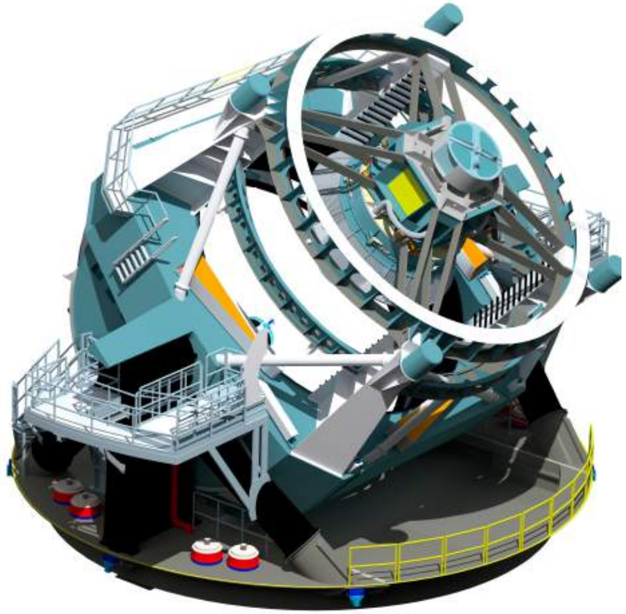
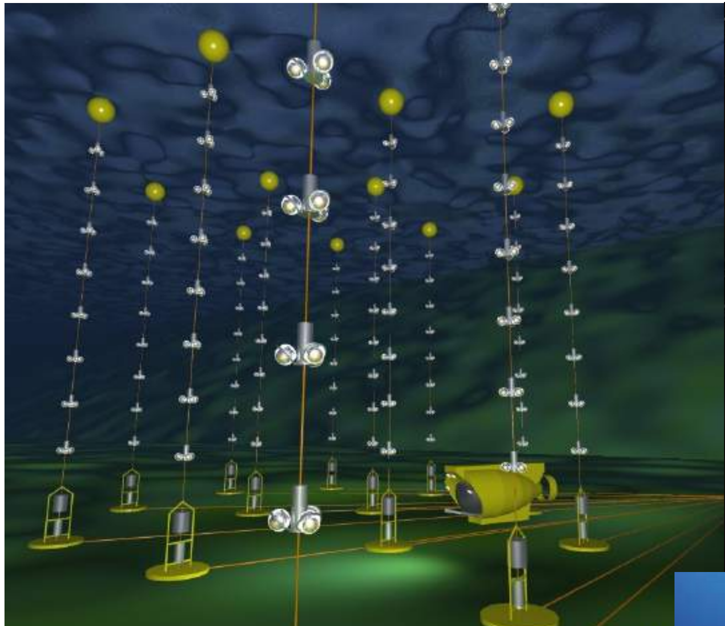
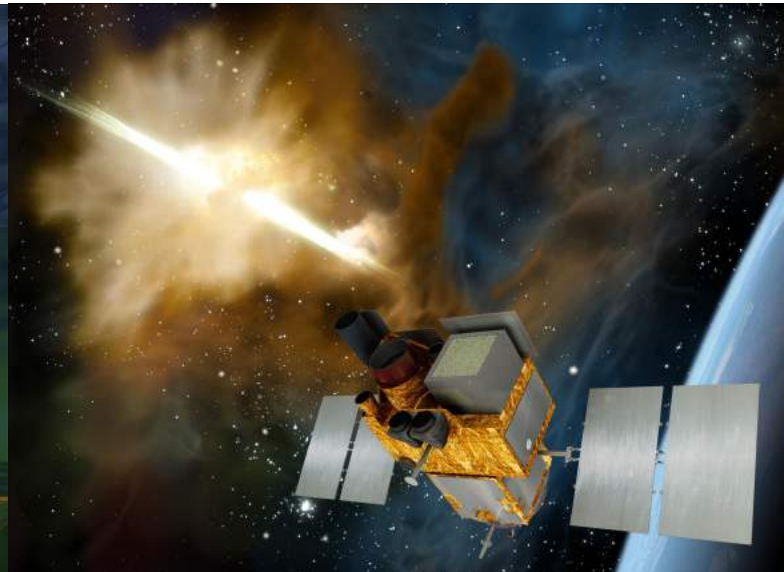
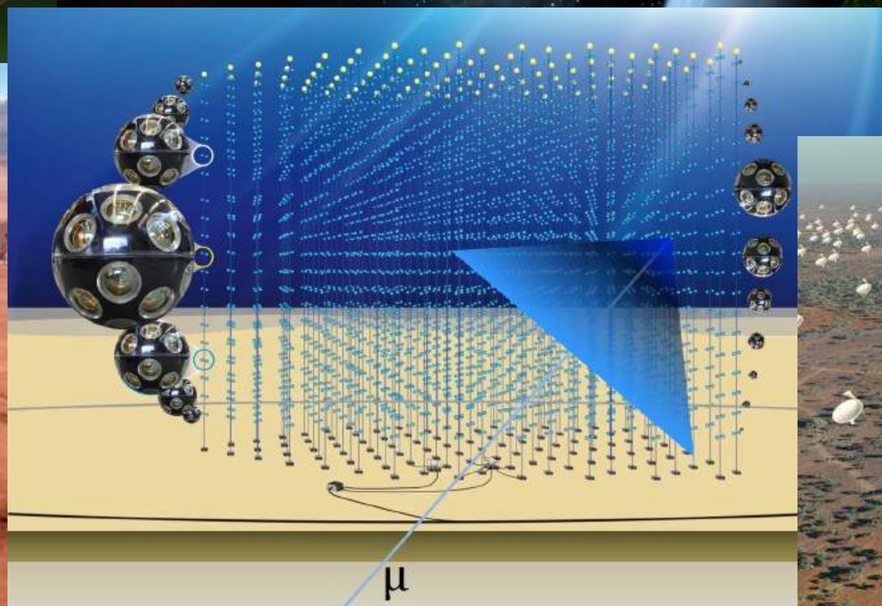
Multi-messenger approach

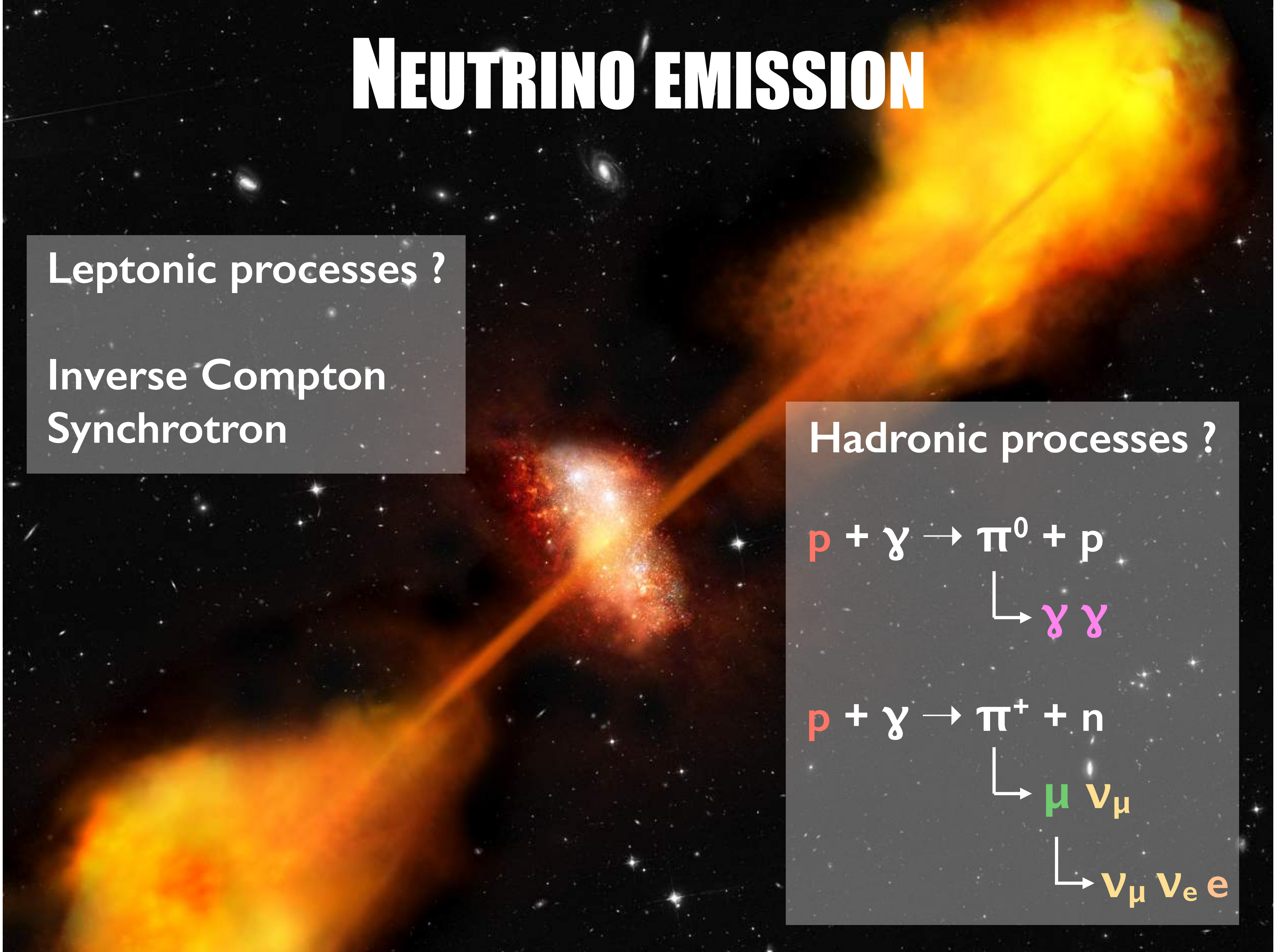








Neutrino emission



Leptonic processes ?

Inverse Compton
Synchrotron

Hadronic processes ?

$p + \gamma \rightarrow \pi^0 + p$

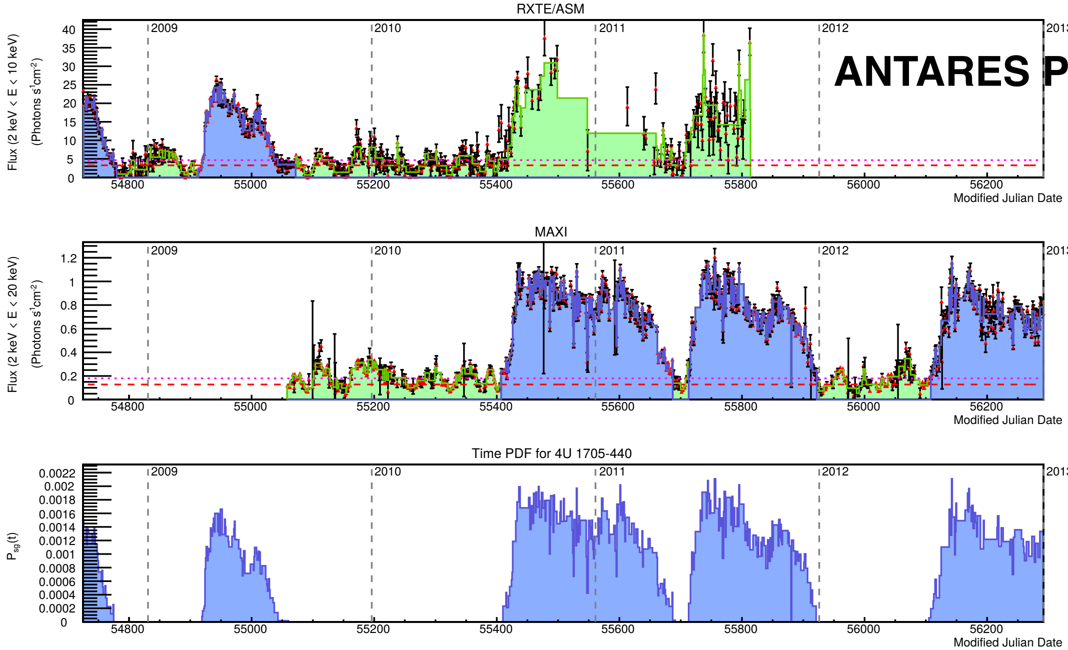
$\quad\quad\quad\quad \hookrightarrow \gamma\ \gamma$

$p + \gamma \rightarrow \pi^+ + n$

$\quad\quad\quad\quad \hookrightarrow \mu\ \nu_\mu$

$\quad\quad\quad\quad\quad\quad \hookrightarrow \nu_\mu\ \nu_e\ e$

X-ray binaries viewed by ANTARES

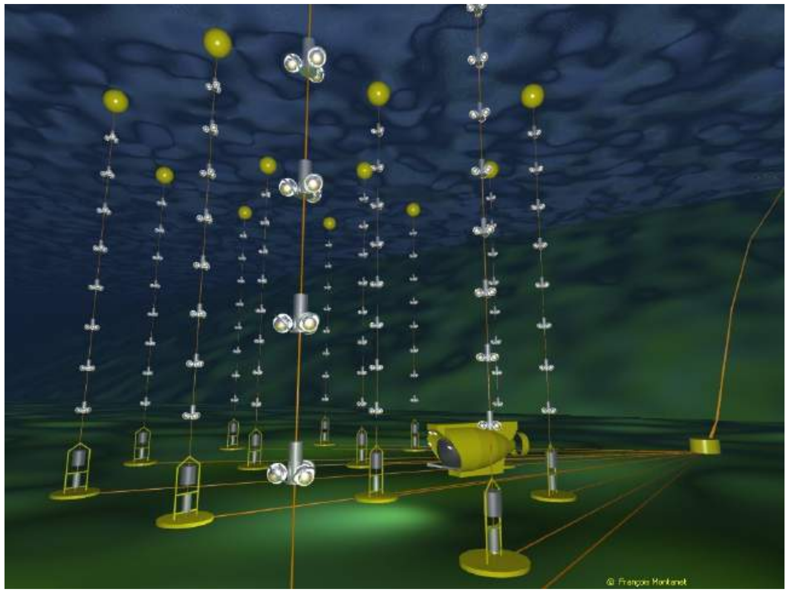


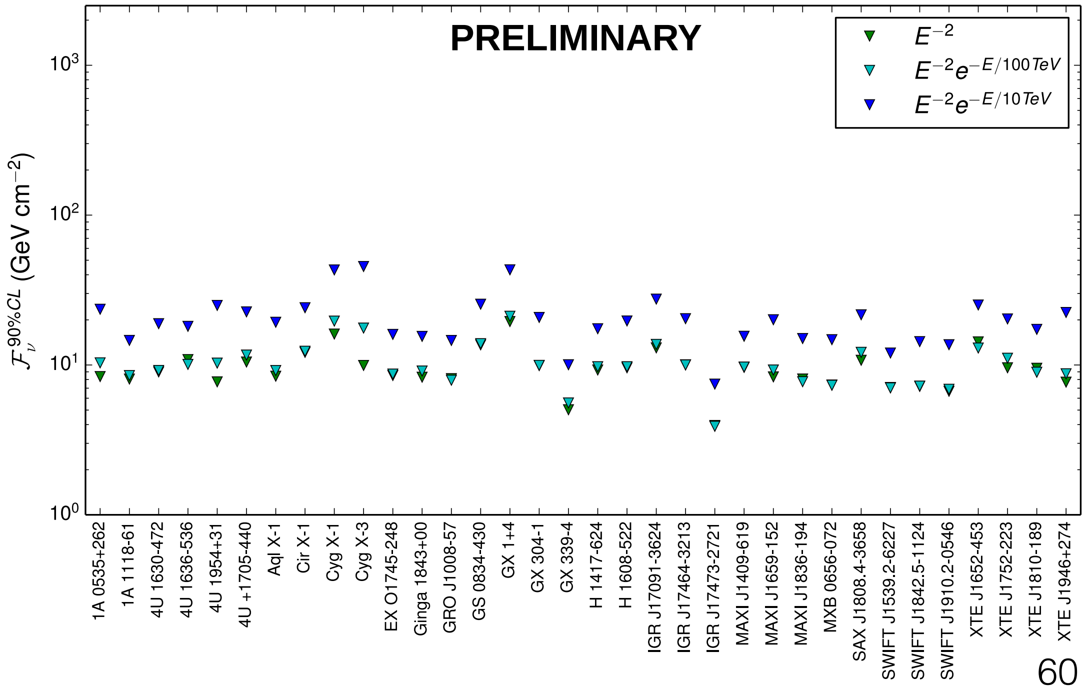
ANTARES Preliminary

$$\ln\mathcal{L} = \left(\sum_{i=1}^{N}\ln[\mathcal{N}_{\rm S}\mathcal{S}_i + \mathcal{N}_{\rm B}\mathcal{B}_i]\right) - [\mathcal{N}_{\rm S} + \mathcal{N}_{\rm B}]$$

$$\mathcal{S}_i = \mathcal{S}^{\rm space}(\Psi_i(\alpha_s,\delta_s))\cdot\mathcal{S}^{\rm energy}(dE/dX_i)\cdot\mathcal{S}^{\rm time}(t_i + lag)$$

$$\mathcal{B}_i = \mathcal{B}^{\rm space}(\delta_i)\cdot\mathcal{B}^{\rm energy}(dE/dX_i)\cdot\mathcal{B}^{\rm time}(t_i)$$





X-ray binaries: neutrino emission models

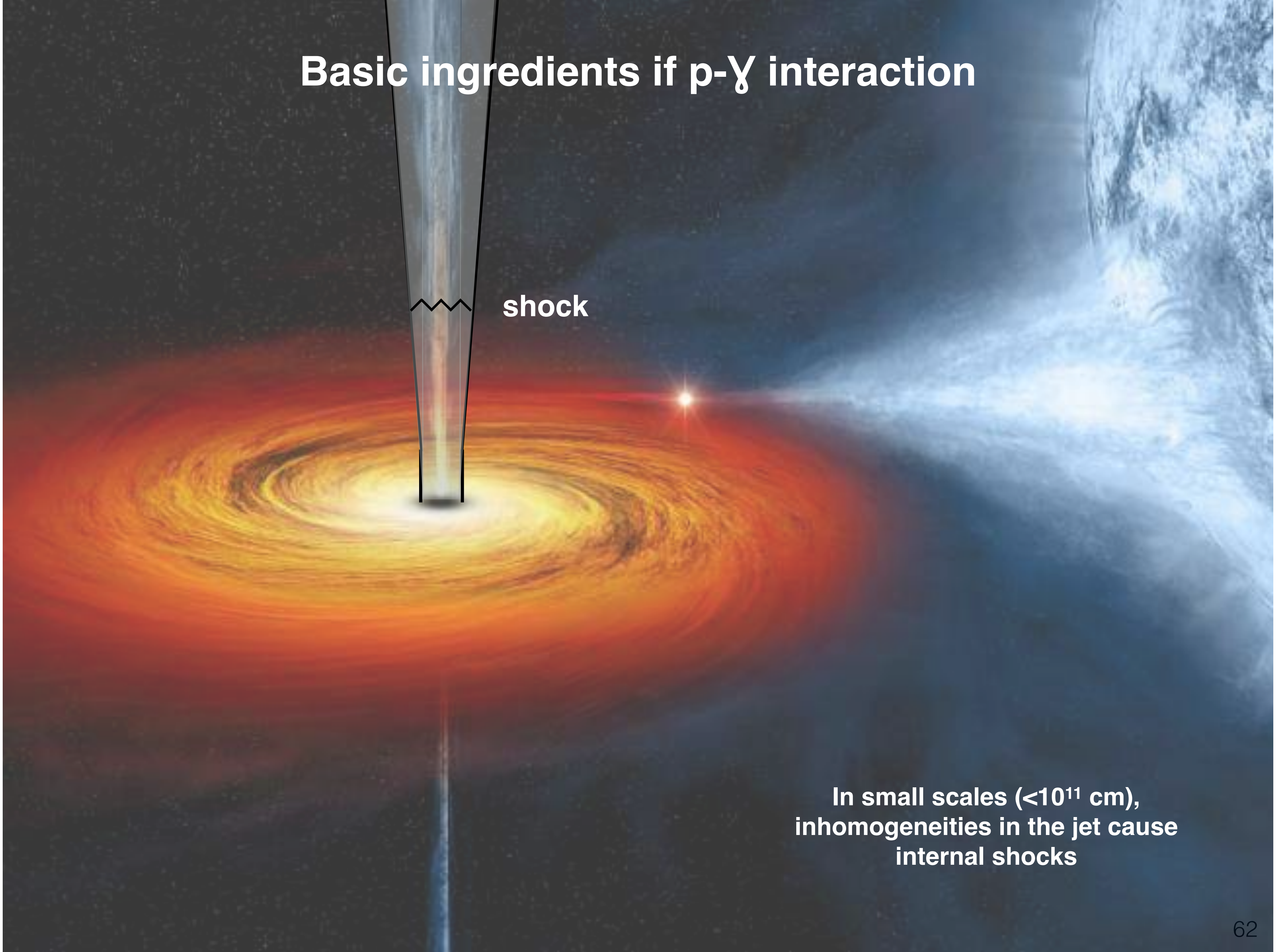
Several models describe neutrino emission from X-ray binaries:

p-p or p-γ interaction between jet and matter/radiation from the companion star or inside the jet directly:

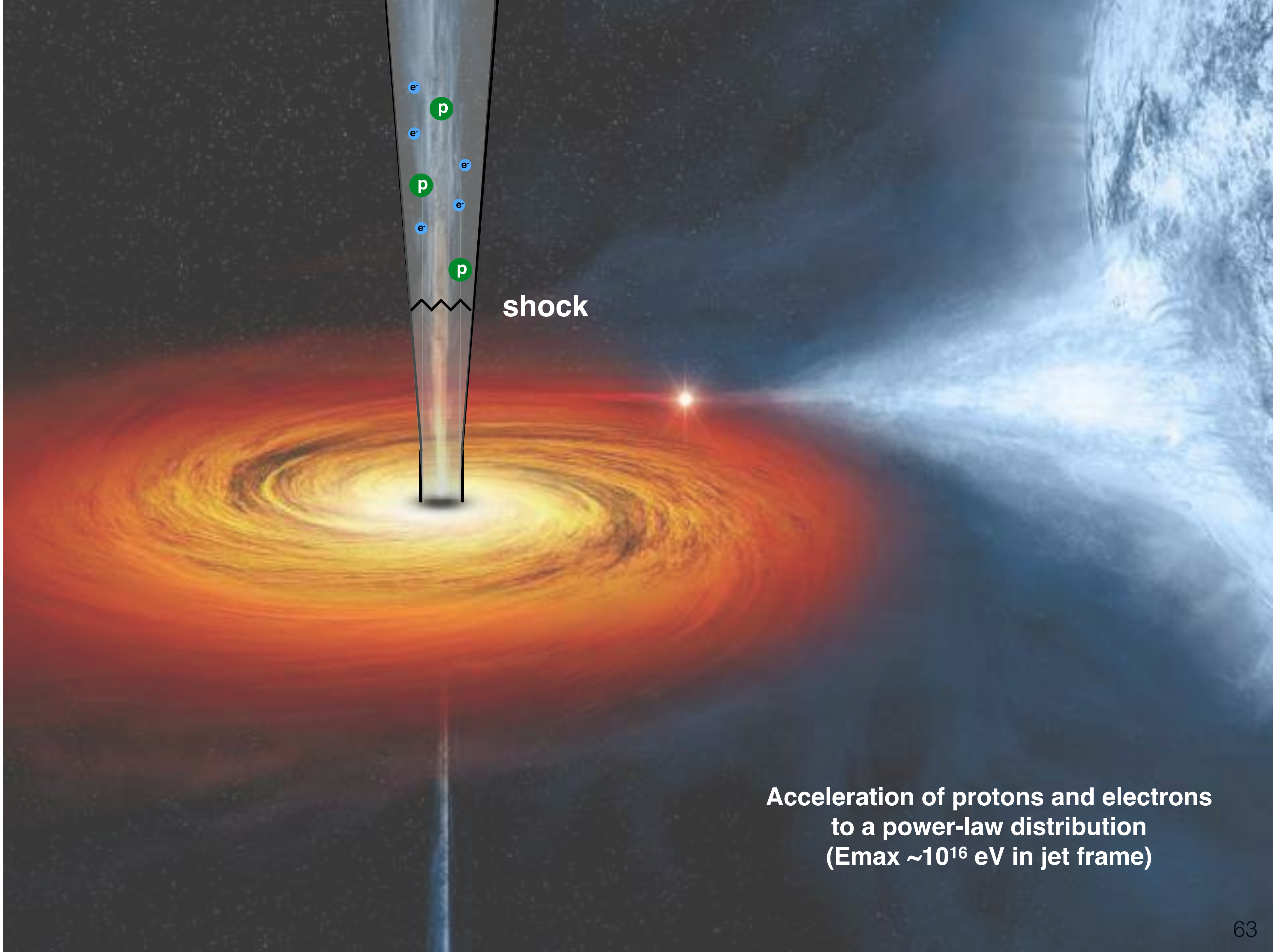
see e.g. :

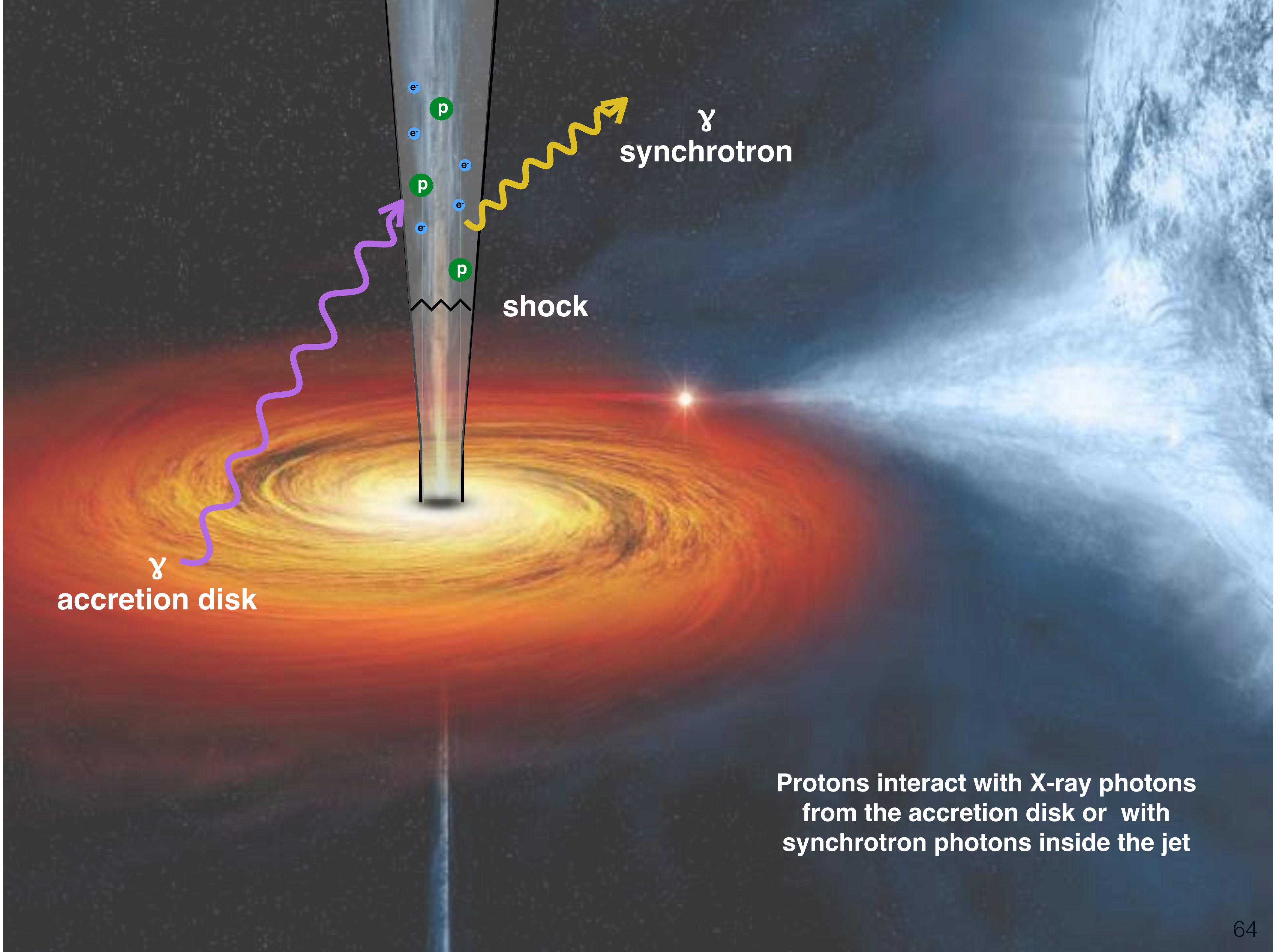
- Romero et al.: **« heavy jets » with dominant p+p collision**
- Levinson & Waxman; Aharonian et al.; Mannheim et al.: **relativistic jet interacting with dense photon field**

Basic ingredients if p-ɣ interaction

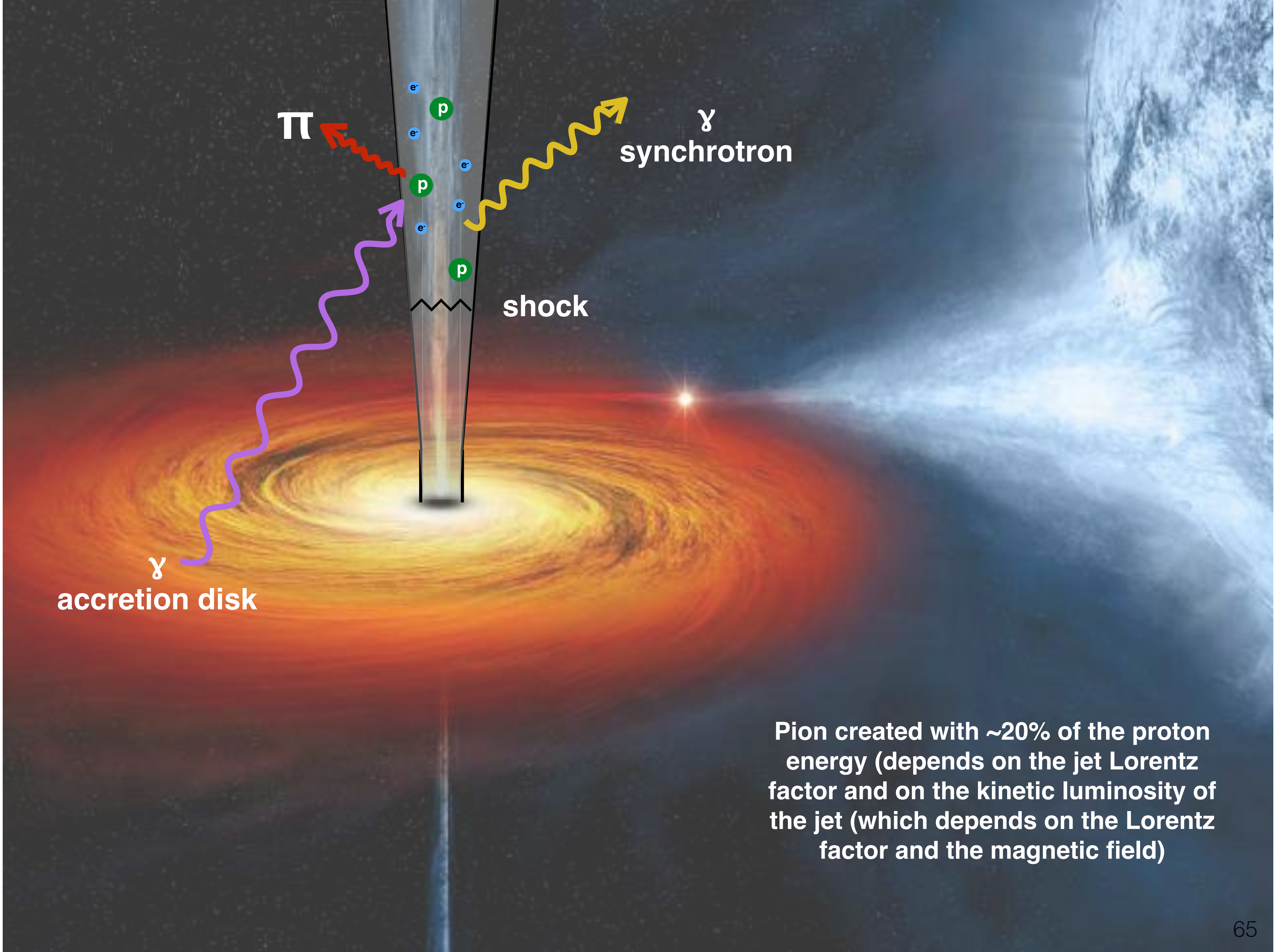


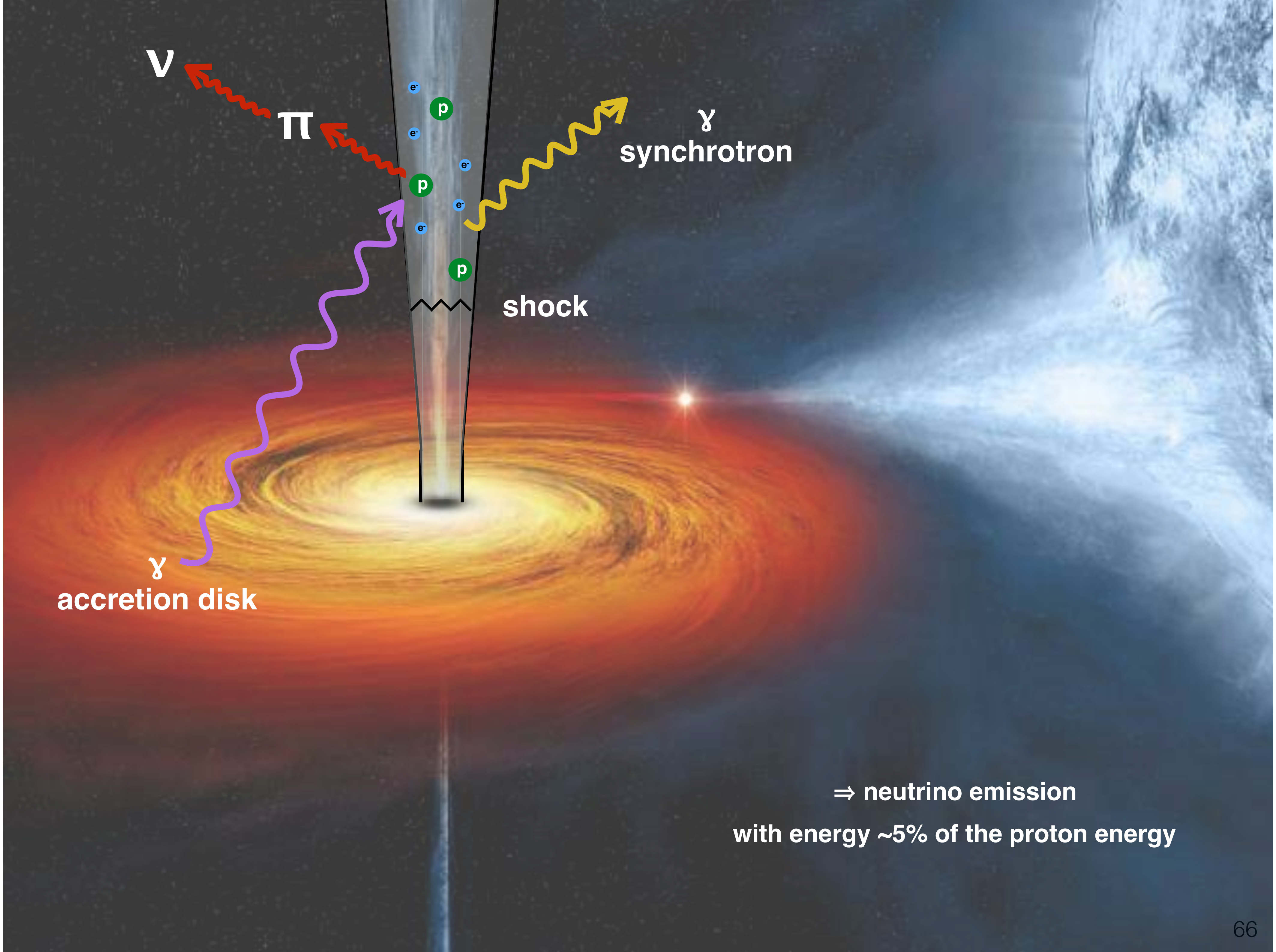
In small scales (<10^{11} cm), inhomogeneities in the jet cause internal shocks


e-
p
e-
e-
p
e-
e-
p
shock
Acceleration of protons and electrons
to a power-law distribution
(Emax ~10^{16} eV in jet frame)



Protons interact with X-ray photons from the accretion disk or with synchrotron photons inside the jet


π
e⁻
p
γ
synchrotron
shock
γ
accretion disk
Pion created with ~20% of the proton energy (depends on the jet Lorentz factor and on the kinetic luminosity of the jet (which depends on the Lorentz factor and the magnetic field)



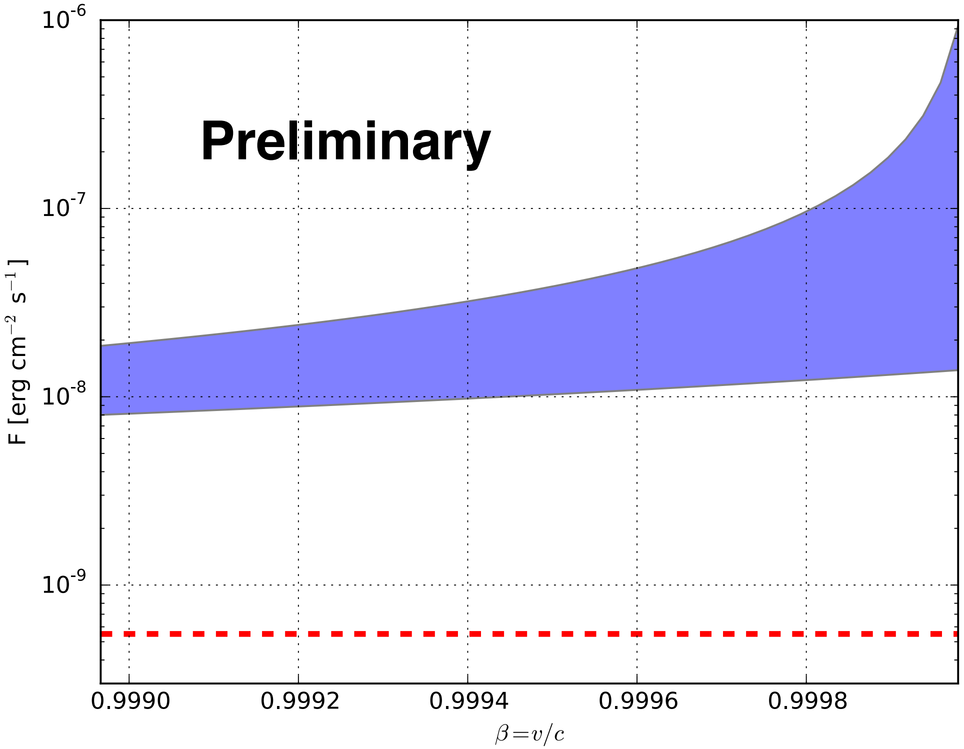
⇒ neutrino emission

with energy ~5% of the proton energy

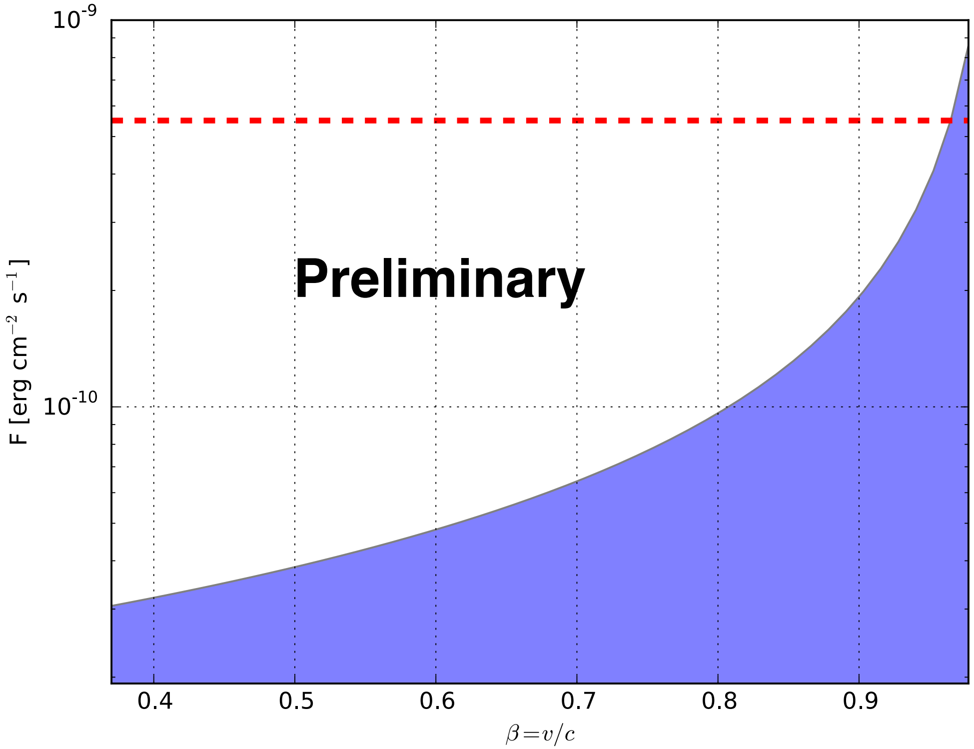
X-ray binaries viewed by ANTARES

Comparison with model of Distefano et al., 2002

Circinus X-1 (neutron star + normal star)



$\mathbf{\Gamma}$ > 22, $\boldsymbol{\theta}$ < 3°, D=9.4 kpc
(Heinz et al., 2015)

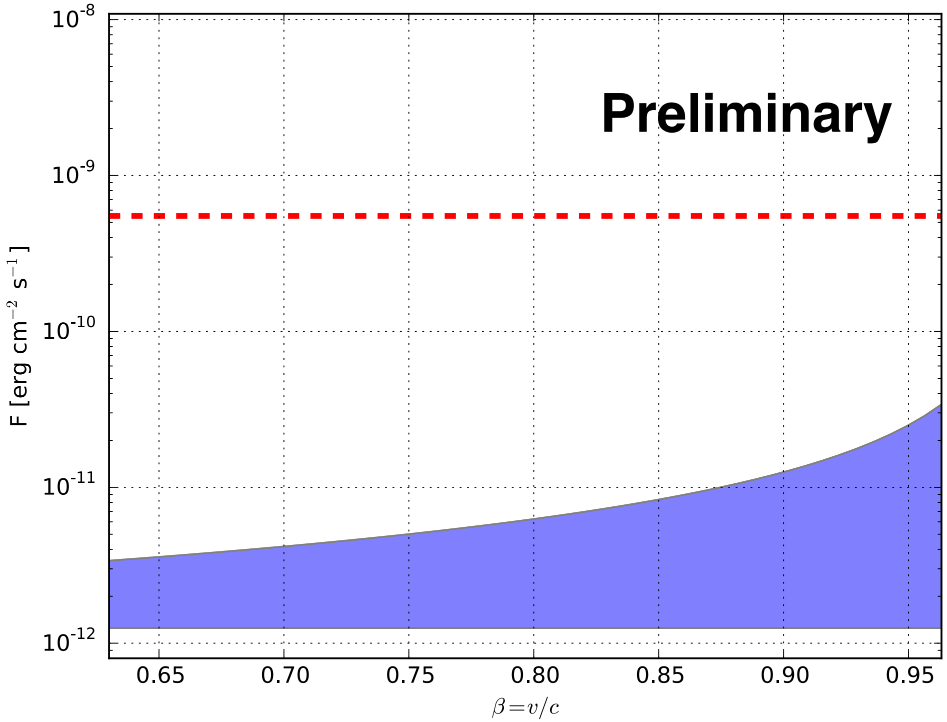


1.076<$\mathbf{\Gamma}$<5, $\boldsymbol{\theta}$ < 20°, D=7.8 kpc
(Miller-Jones et al., 2012)

X-ray binaries viewed by ANTARES

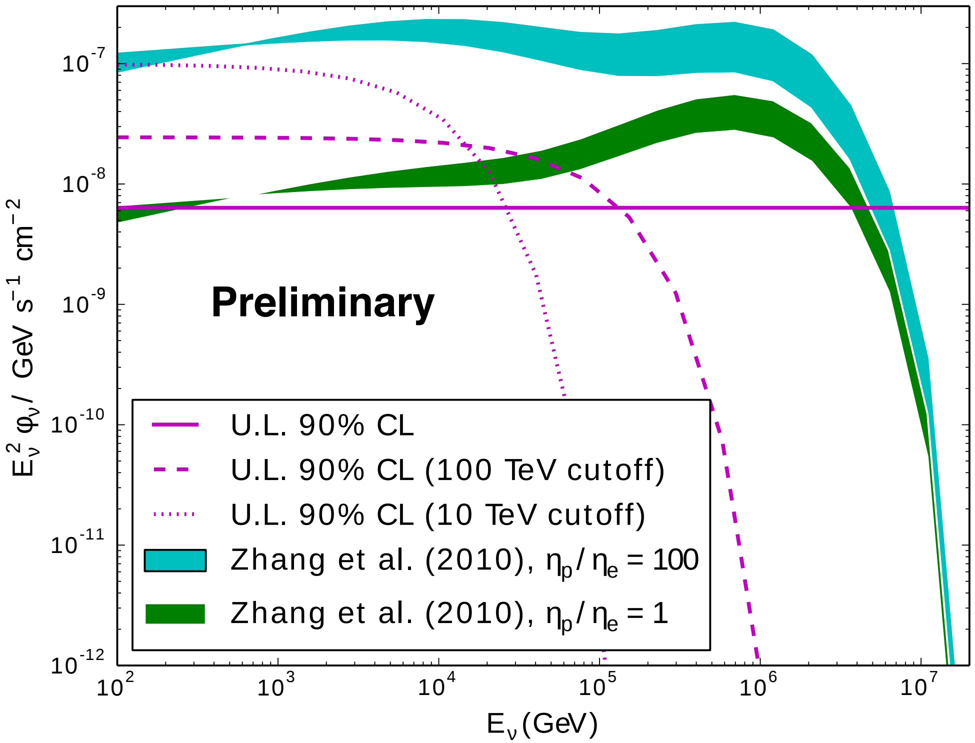
Comparison with models

Cyg X-1



0.6<**β**<0.97, **θ** = 40°, D=1.8 kpc
(Heinz et al., 2015)

GX 339-4

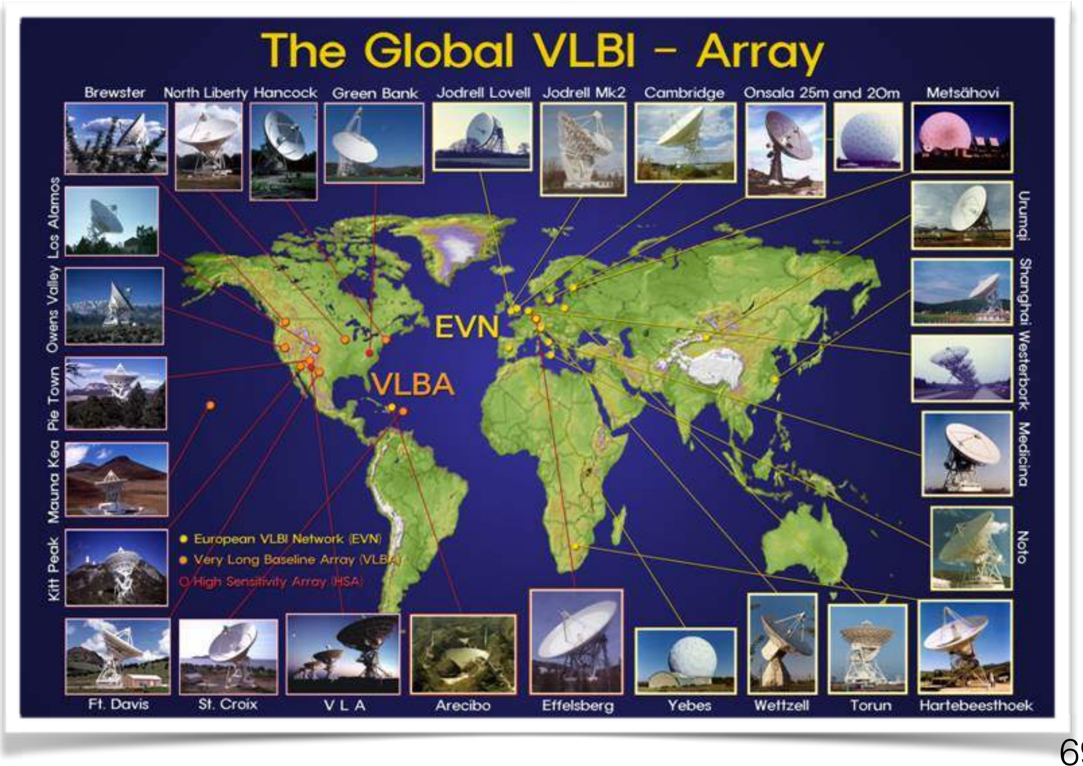


X-ray binaries viewed by ANTARES

need high angular resolution in radio domain

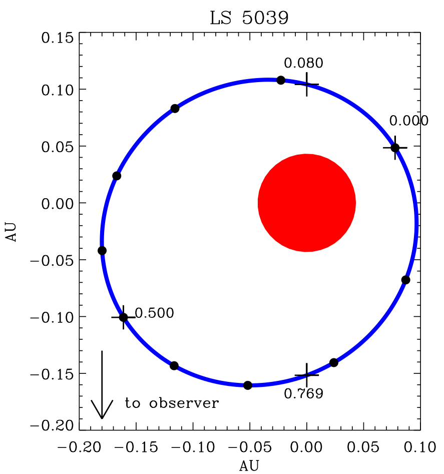
SKA in VLBI mode: sub-milli-arcsec resolution

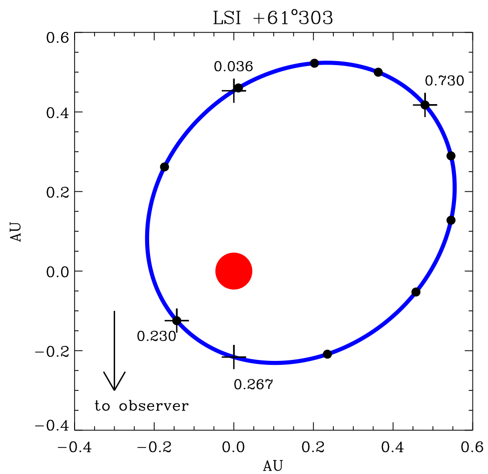
-estimation of β=v/c and θ (if distance is known)
+ spatial extension of the jet
+ polarization at different scales
+ proper motion ($\Rightarrow$ exact timing of ejection event)

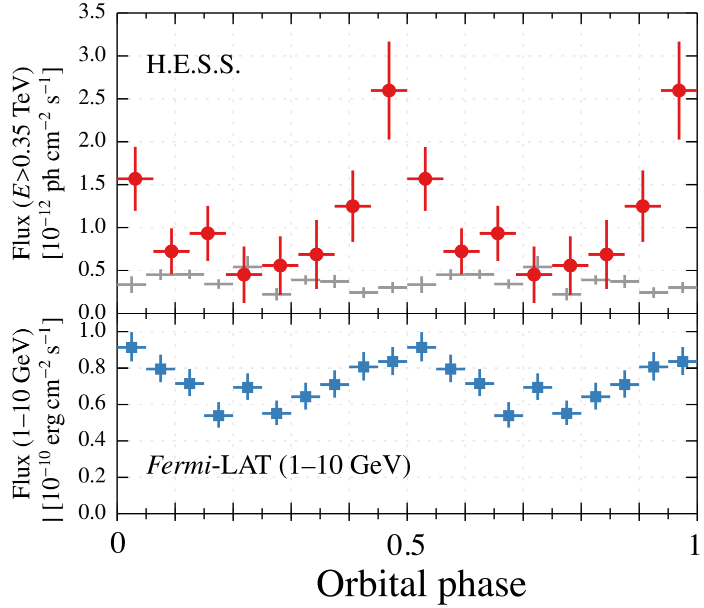


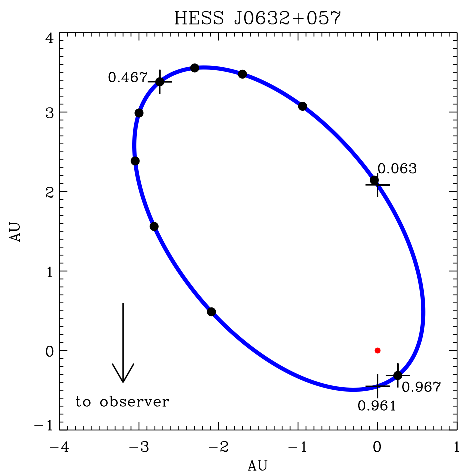
Gamma-ray binaries viewed by Antares

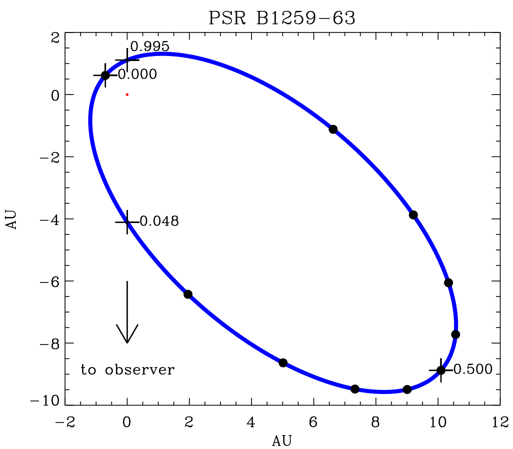
Looking for a potential neutrino transient emission in time coïncidence with TeV gamma-rays: work in progress…

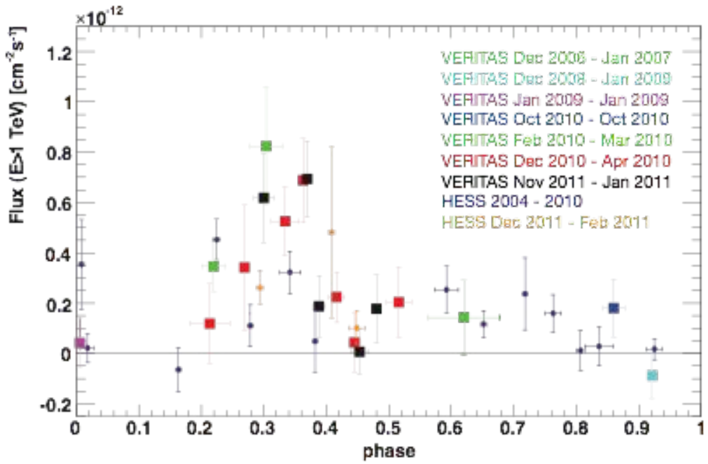












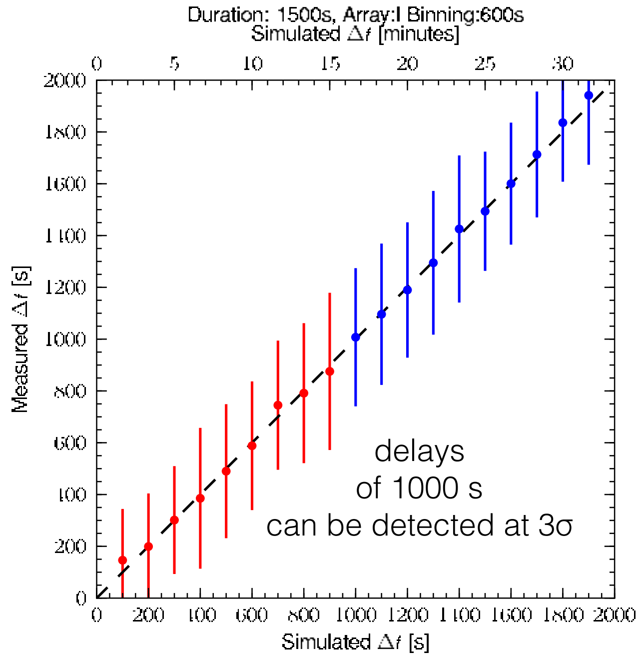
CTA: probing the VHE emission

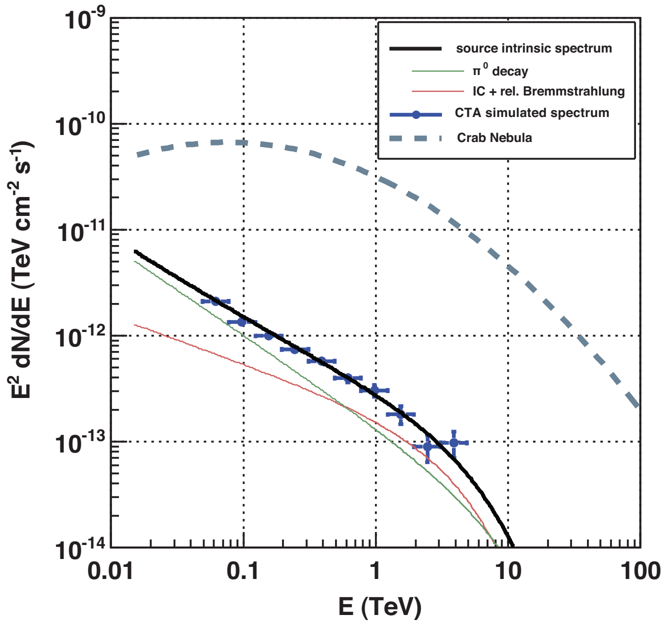
Some key questions:

- ***Relativistic outflows in binary systems with young non-accreting pulsars (gamma-ray binaries):*** need phase-resolved light curves and spectra (especially at low flux !) + extended spectral range to study connection to MeV-GeV emission and to constrain the HE cutoffs linked to particle acceleration.

- ***The accretion/ejection link in microquasars:*** Determining the time variability of the TeV to X-ray spectrum will help constrain the jet composition + link between VHE and radio flares (requires monitoring + ToO + long term monitoring possible with sub-array obs.)

- ***Collision of the outflow with the interstellar medium:*** Need good sensitivity (~few 10^{-13} TeV s^{-1} cm^{-2} (~one order of mag. better than current instruments) + 1' angular resolution (+ possibility of probing the < 50 GeV energy range)



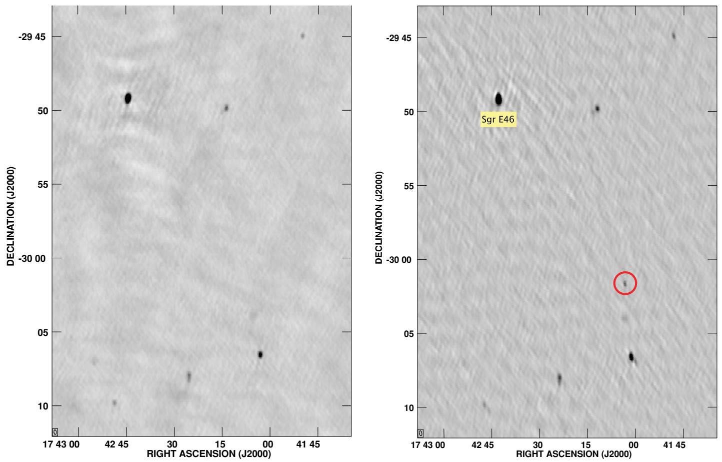


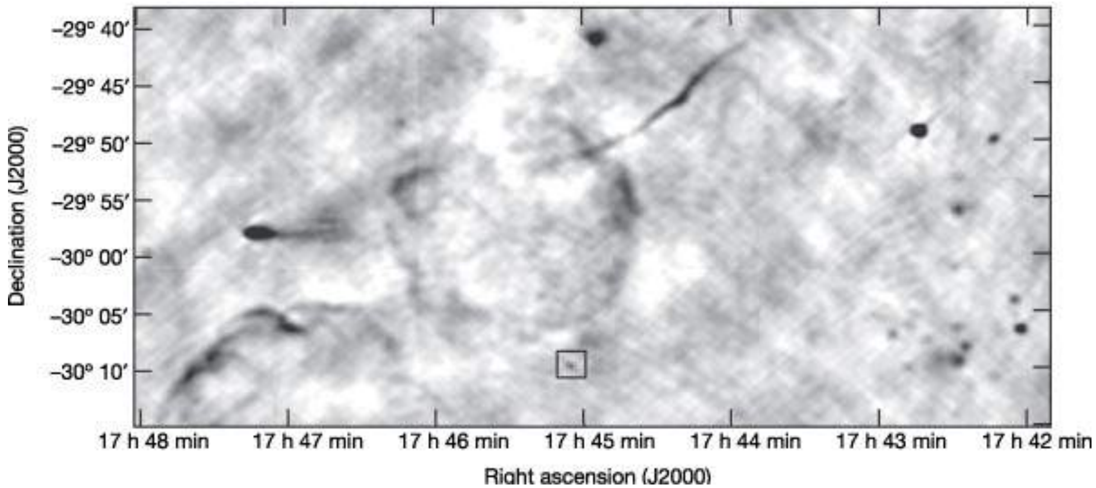
Paredes et al., 2012

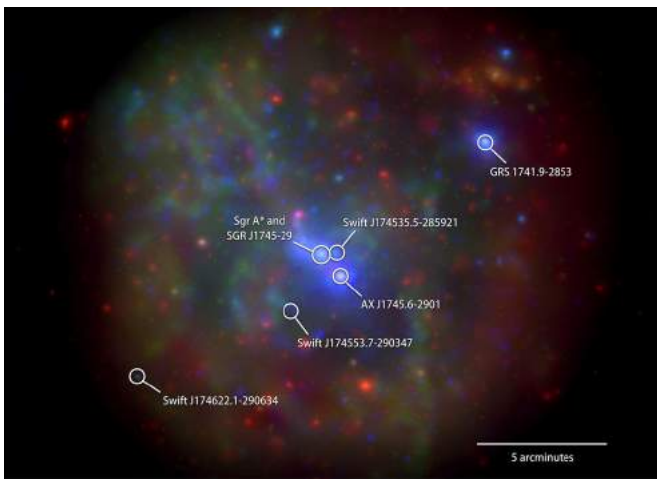
Multi-messenger strategy

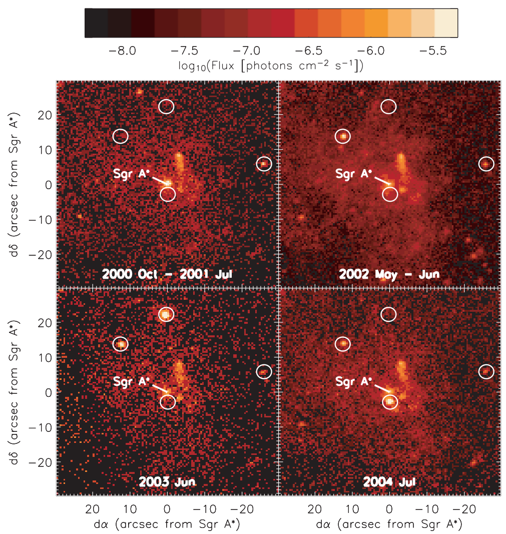
> transient sources in the galactic center ?

Unknown **transient radio sources** in the GC: GCRT J1745–3009 and GCRT J1742-3001
→ Hyman et al., 2005 and 2009







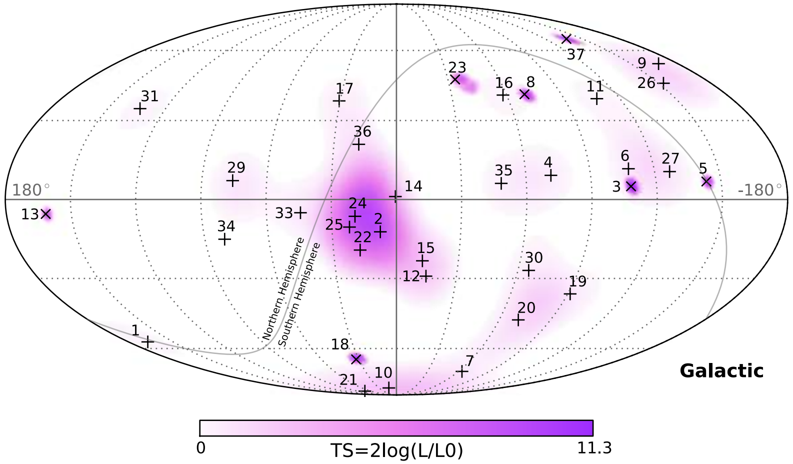


Many **X-ray transient sources** in the GC:

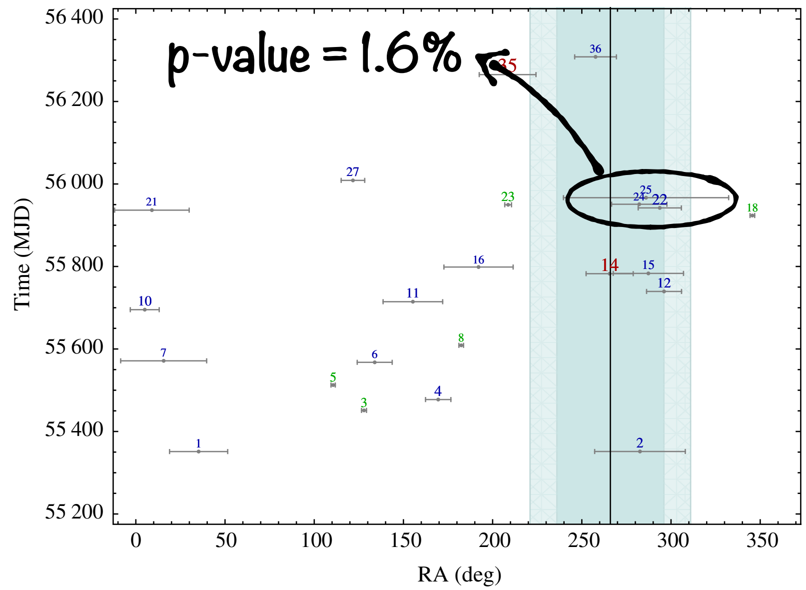
at least 4 X-ray Binaries within 1 pc from SgrA* (Muno et al., 2005)
→ transients are overabundant by a factor of >20 per unit stellar mass within 1 pc of Sgr A*

Multi-messenger strategy

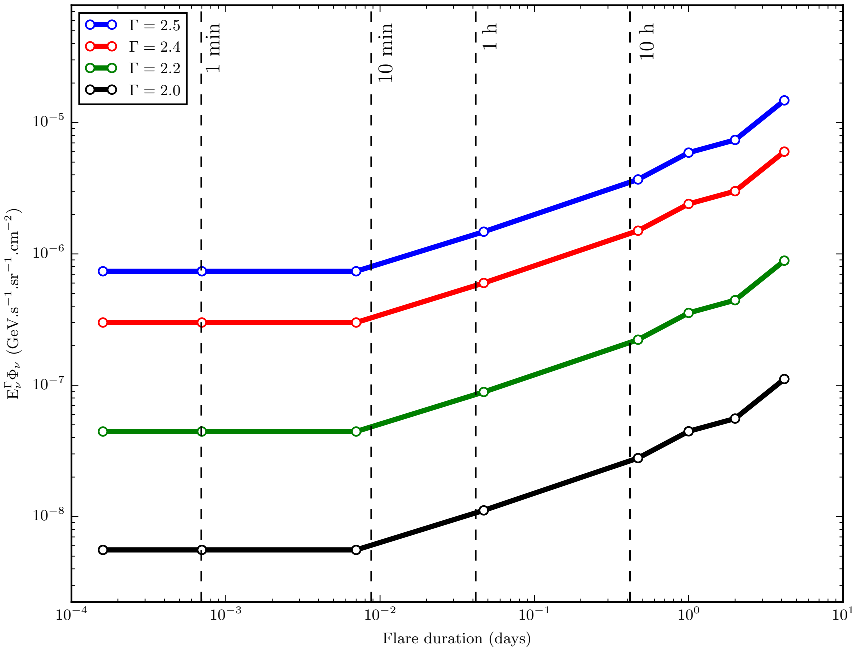
> transient sources in the galactic center ?



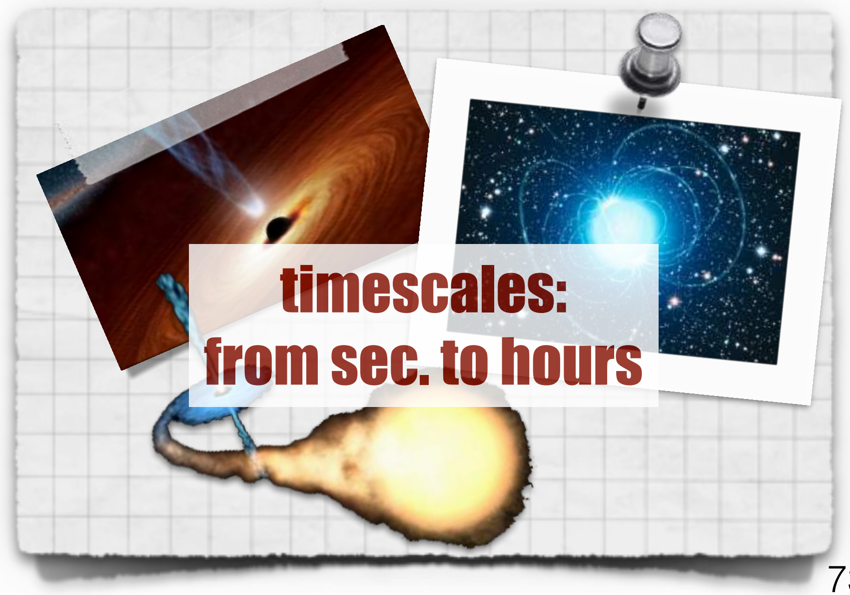
IceCube Collab., PRL 113, 2014



Bai et al., 2014

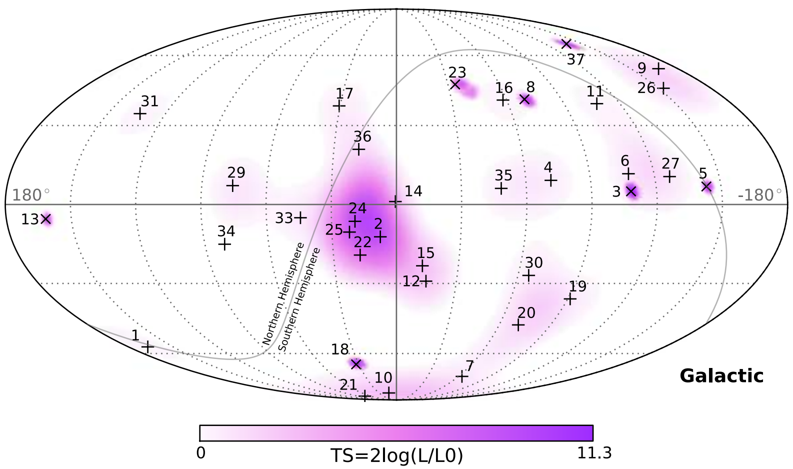


ANTARES coll. (Coleiro), ICRC 2015



Multi-messenger strategy

> transient sources in the galactic center ?



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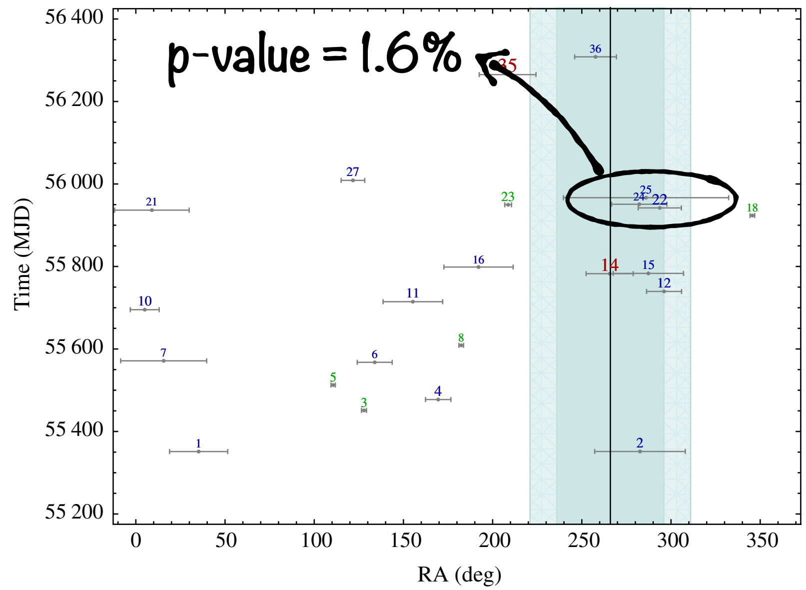
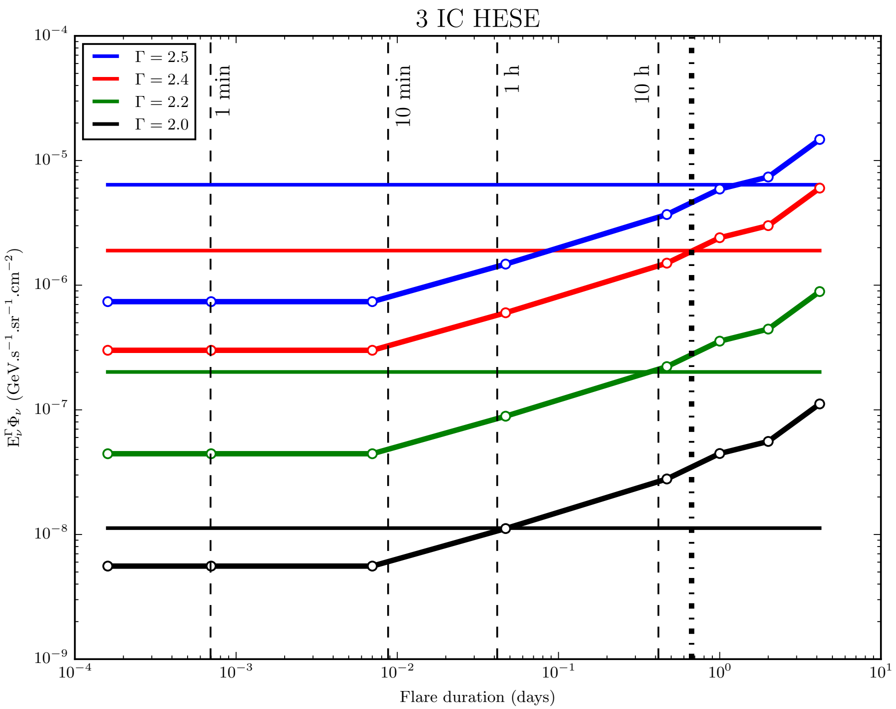


Bai et al., 2014



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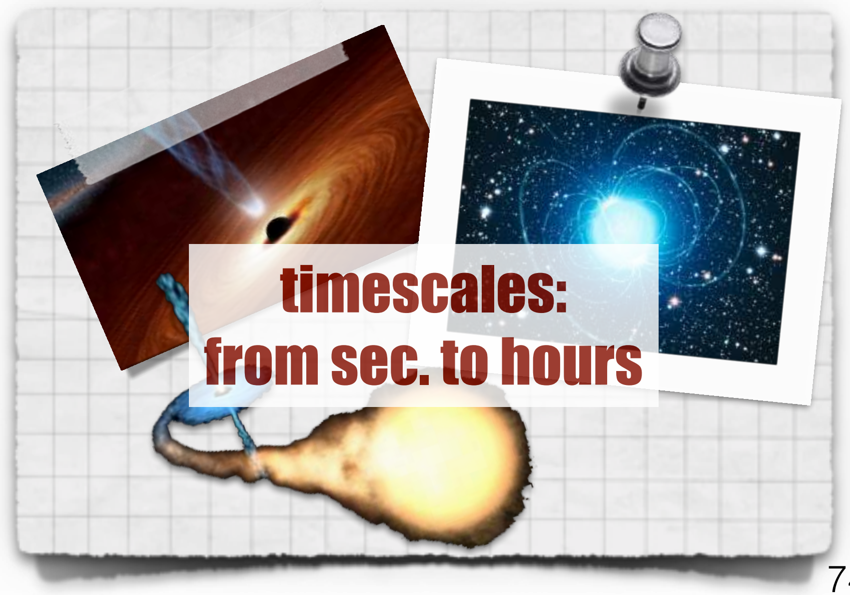

Conclusions

- Time domain astronomy will revolutionize the study of transient sources (SVOM will have a crucial role !!)

- X-ray binaries are extensively studied all over the electromagnetic spectrum

- Multi-messenger strategy are becoming a reality and present a important potential to further understand these sources and the acceleration of particles in the Universe…stay tuned !

Thank you for your attention !