Search for transient neutrino emission from microquasars with the ANTARES telescope

Salvatore Galatà
(APC)

GDR neutrino
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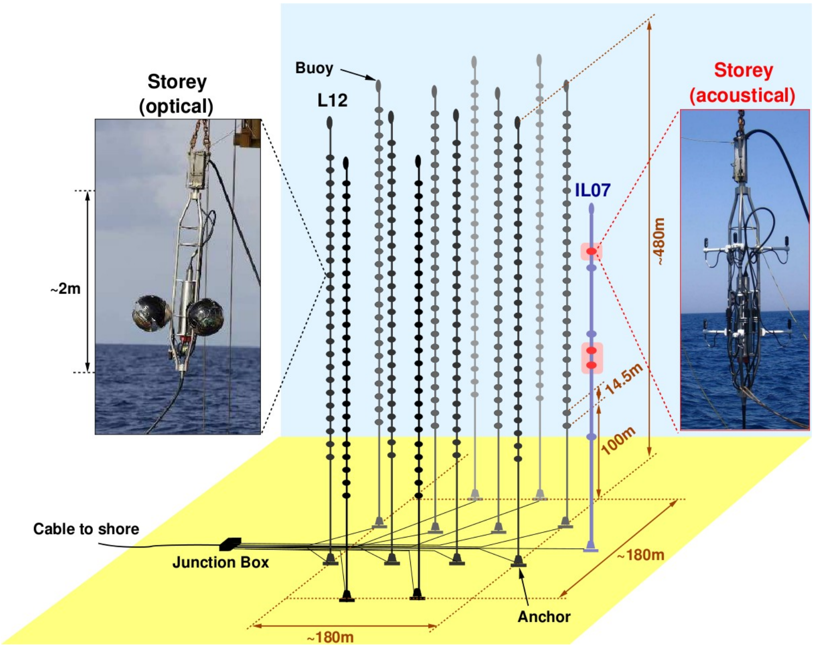
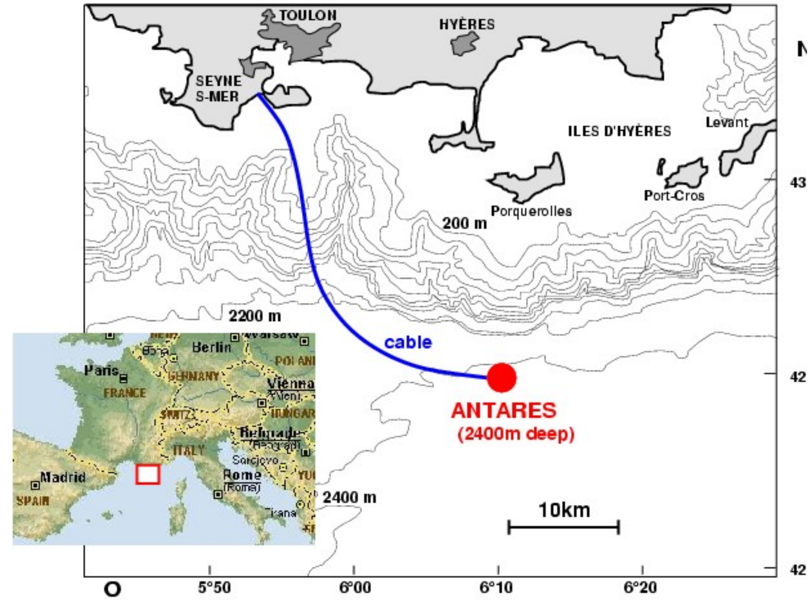
Paris

ANTARES

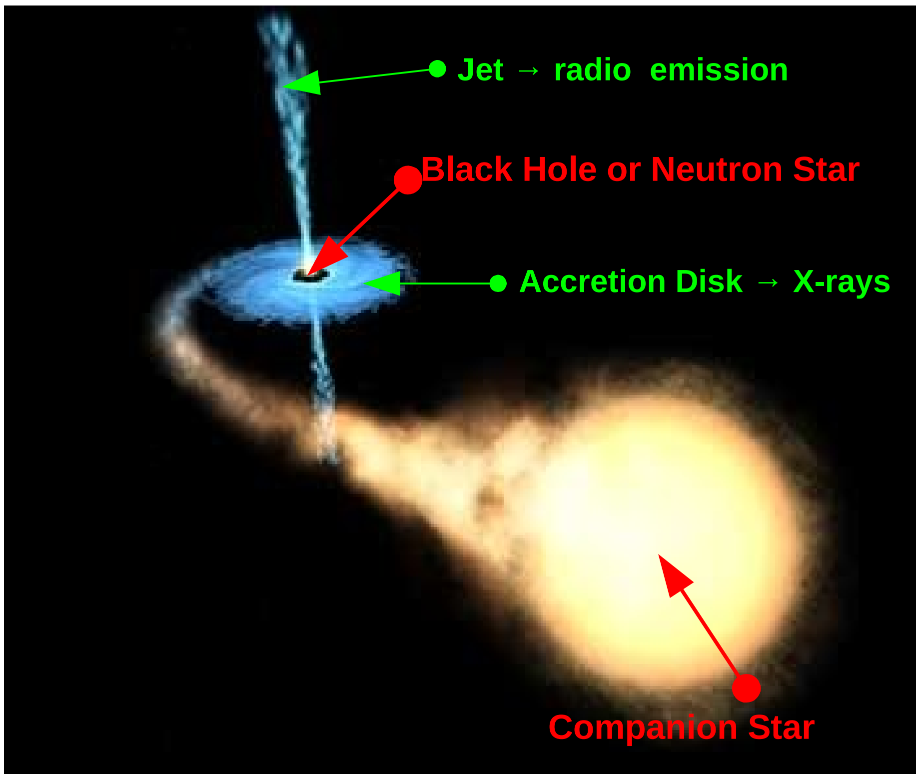




- Detector layout:
  - 2500m depth
  - 12 detection lines, 480m height
  - 25 floors per line
  - 3 optical modules (OMs) per floor
- Construction phases:
  - Jan 2007: 5 Lines
  - Dec 2007: 10 Lines
  - May 2008: 12 Lines
- Data for this work:
  - 2007-2010

Microquasars

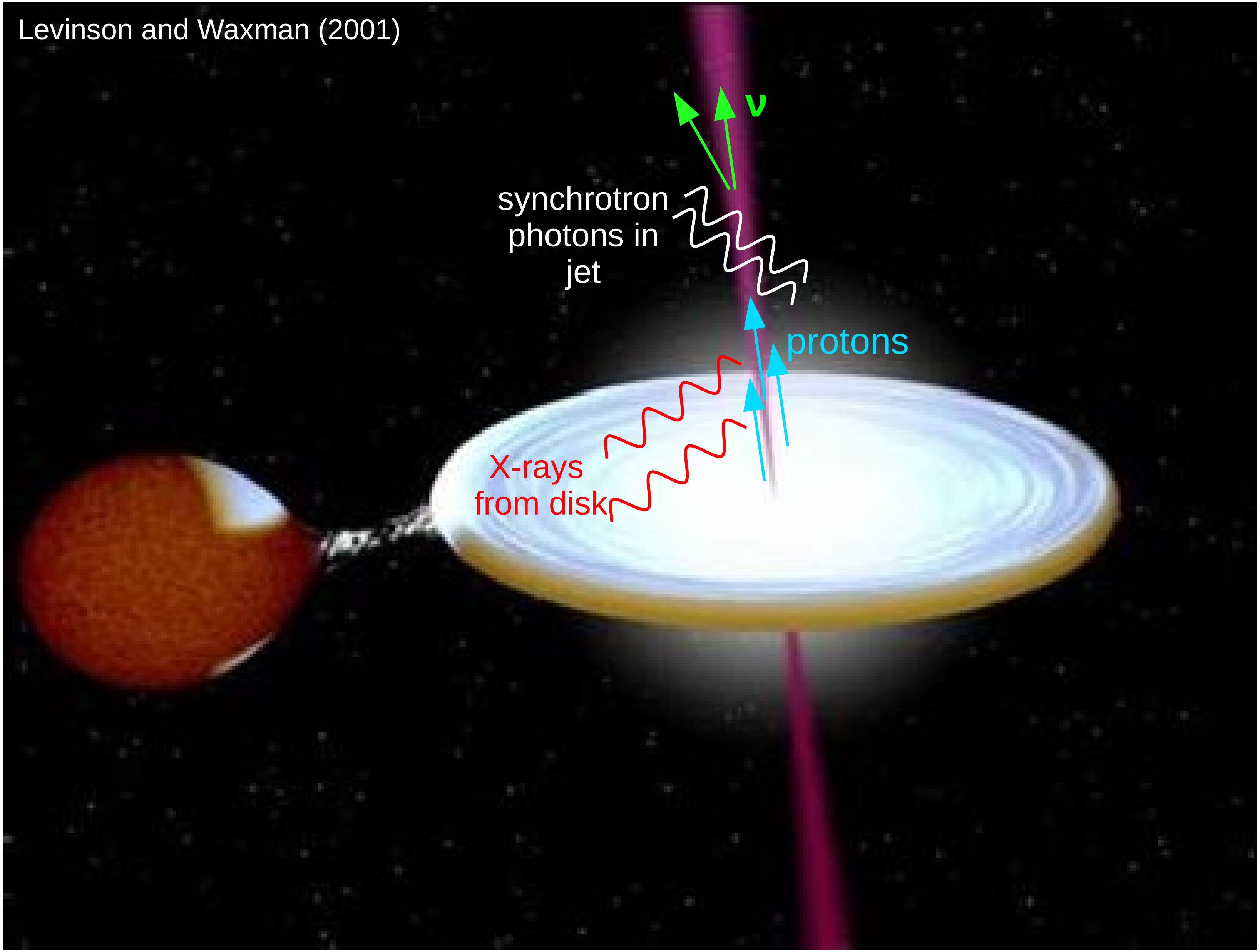
X-ray binary system
compact object & companion star
+ relativistic jets



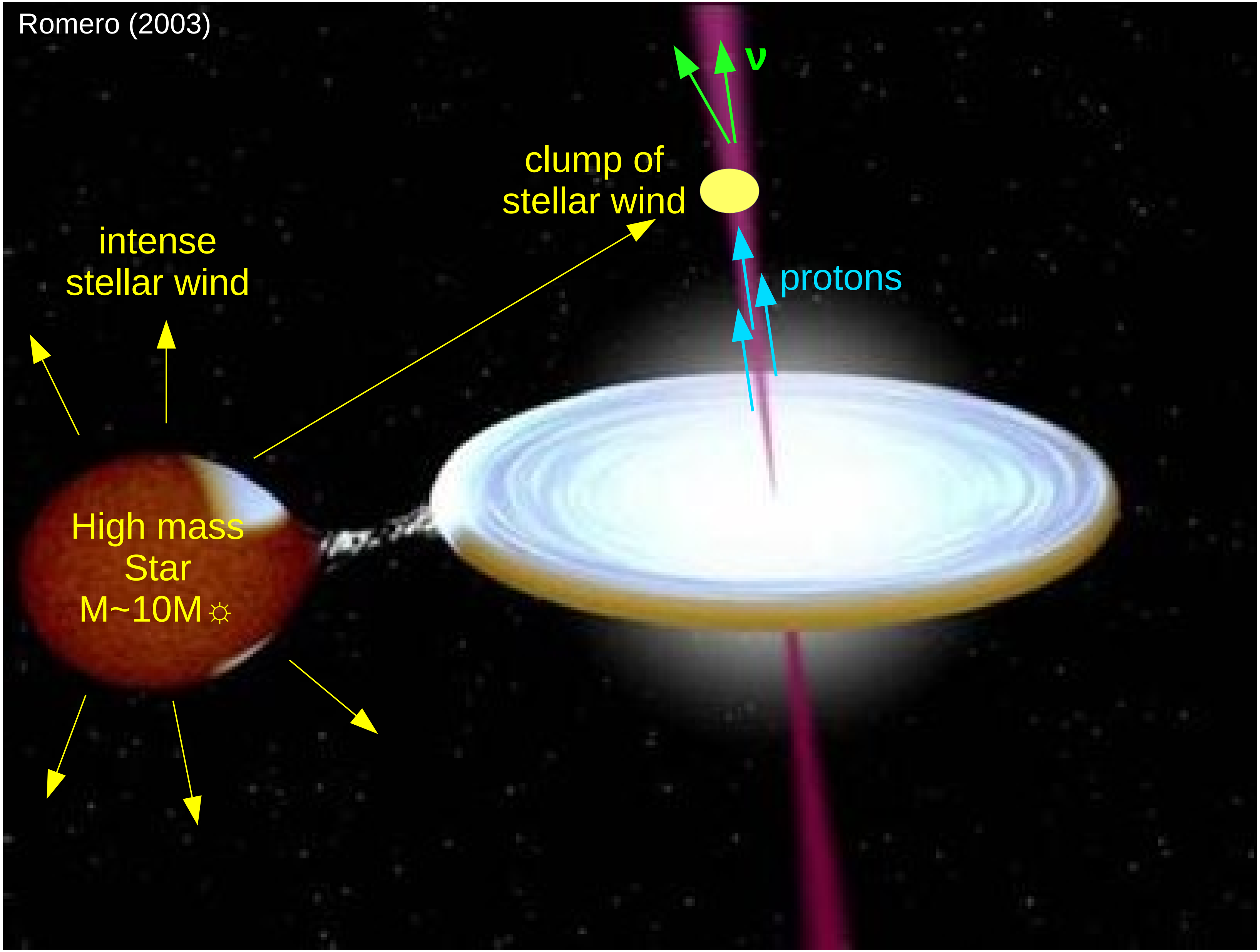
If hadrons are accelerated in the jets, neutrinos may be produced

- **Radio emission from jets:**
  - Non thermal synchrotron emission
- **X-ray emission:**
  - soft component from accretion disk (~1keV)
  - hard component(s), from comptonized corona or base of the jets
- **GeV/TeV emission:** for few of them
- **Time variability:** at different time scales, minutes to months
- **~25 microquasars in our galaxy**
- **Jet composition still unknown:** important for neutrino expectations (hadrons found only in the jets of SS433)

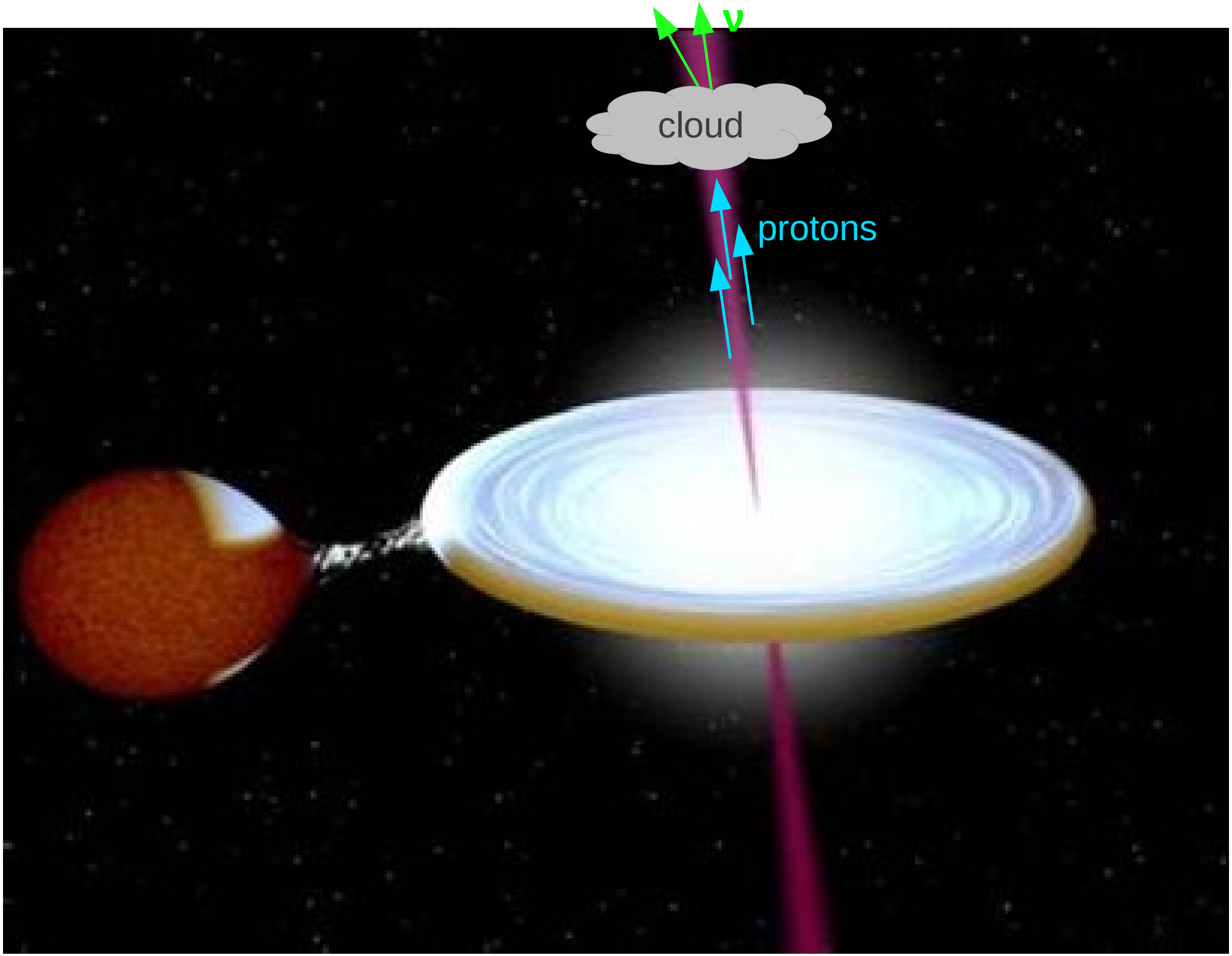
Neutrinos from microquasars



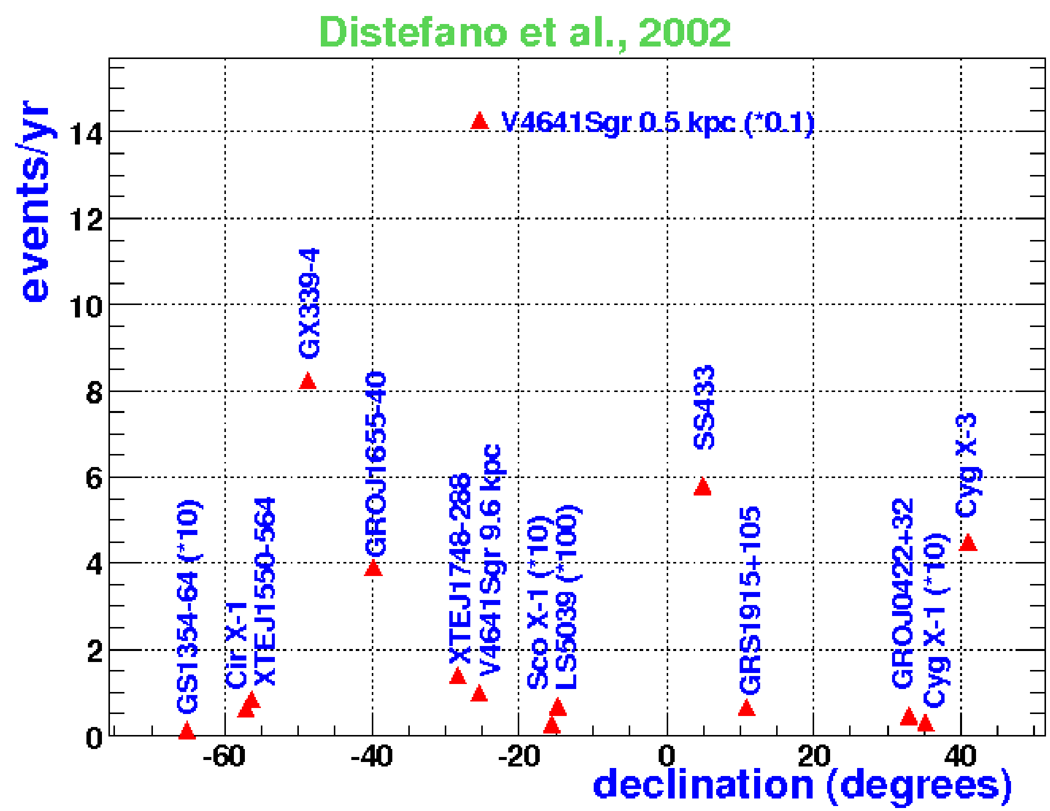
Neutrinos from microquasars



Neutrinos from microquasars



Expected ν's from µQSOs



- Neutrino events expected from the calculations of Distefano et al., (2002) per year of ANTARES data taking, using the model of Levinson and Waxman (2001).

Time dependent analysis

- Microquasars are variable in time:
  - long periods of quiescence (up to years)
  - periods of outburst (days to months) X-rays and radio
- Jets needed for neutrino production
- Restrain neutrino search to periods with radio jets:
  - reduce atmospheric neutrino background
  - increase probability of discovery

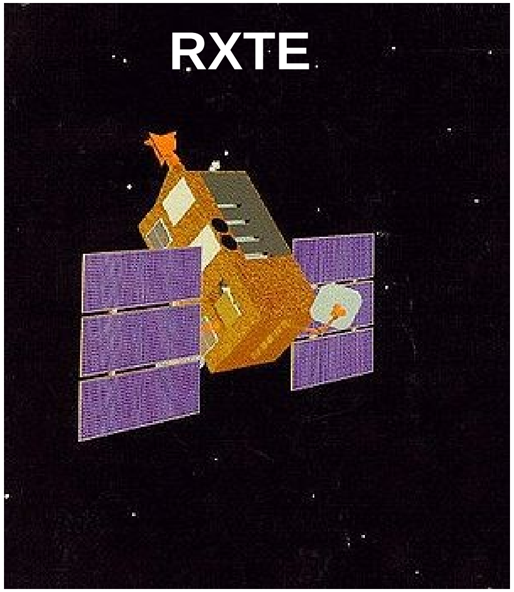
Analisys steps:

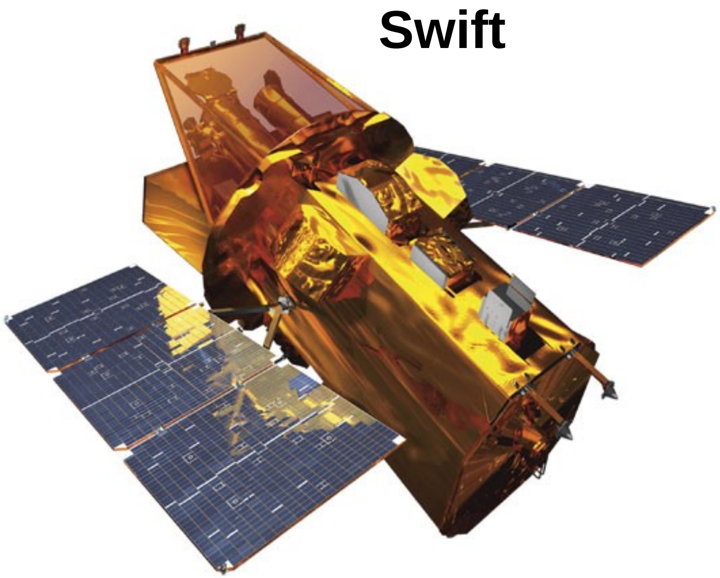
1) Select candidate microquasars and active times
2) Search in ANTARES data
   - Data driven background estimation
   - Unbinned likelihood method

Selection of candidate microquasars and active times

Inputs

- **RXTE/ASM**: soft X-rays (1.5-12 keV)
- **Swift/BAT**: hard X-rays (15-50 keV)
- **Fermi/LAT**: HE gamma rays (30 MeV-300 GeV)
- **Literature**





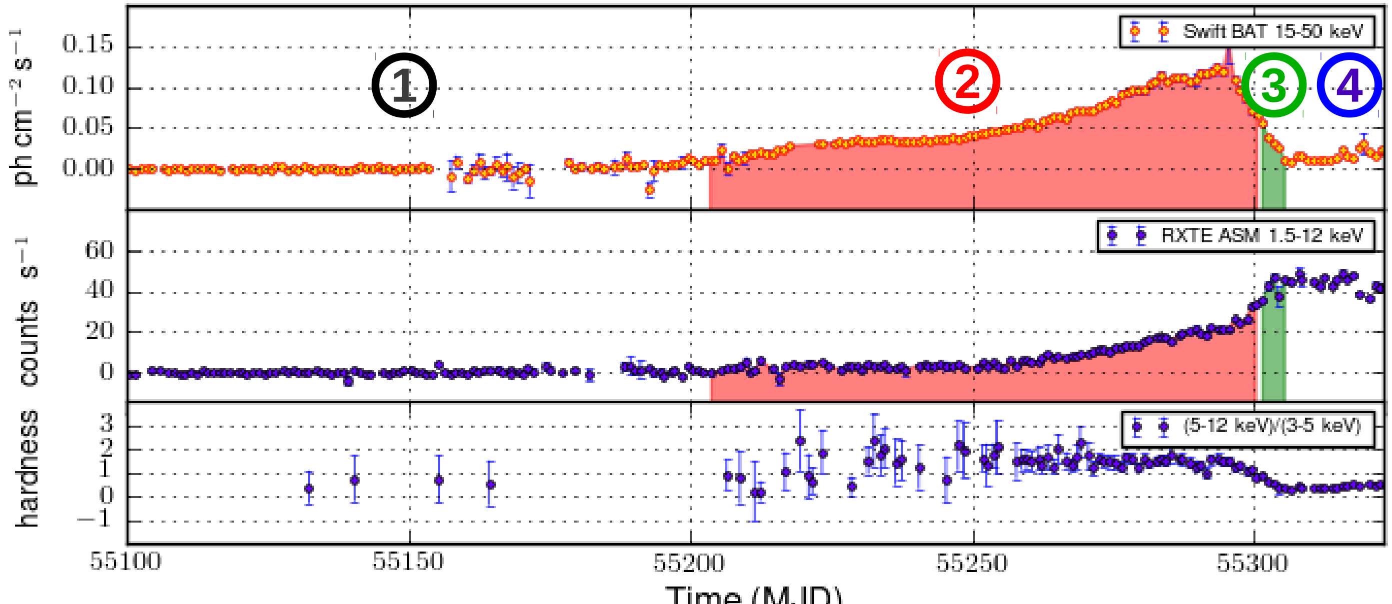
Time selection: black hole binaries

GX 339–4, H1743–322, IGR17091–2436, Cygnus X-1

- X-ray outburst evolution in black hole binaries (disk-jet coupling):
  - **1) Quiescent State** → no jet
  - **2) Hard State** → **steady jet with Γ~2**
  - **3) Transitional states** → **fast discrete ejection with Γ>2**
  - **4) Soft State** → no jet

Hard X-rays

Soft X-rays



GX 339–4
2010
outburst

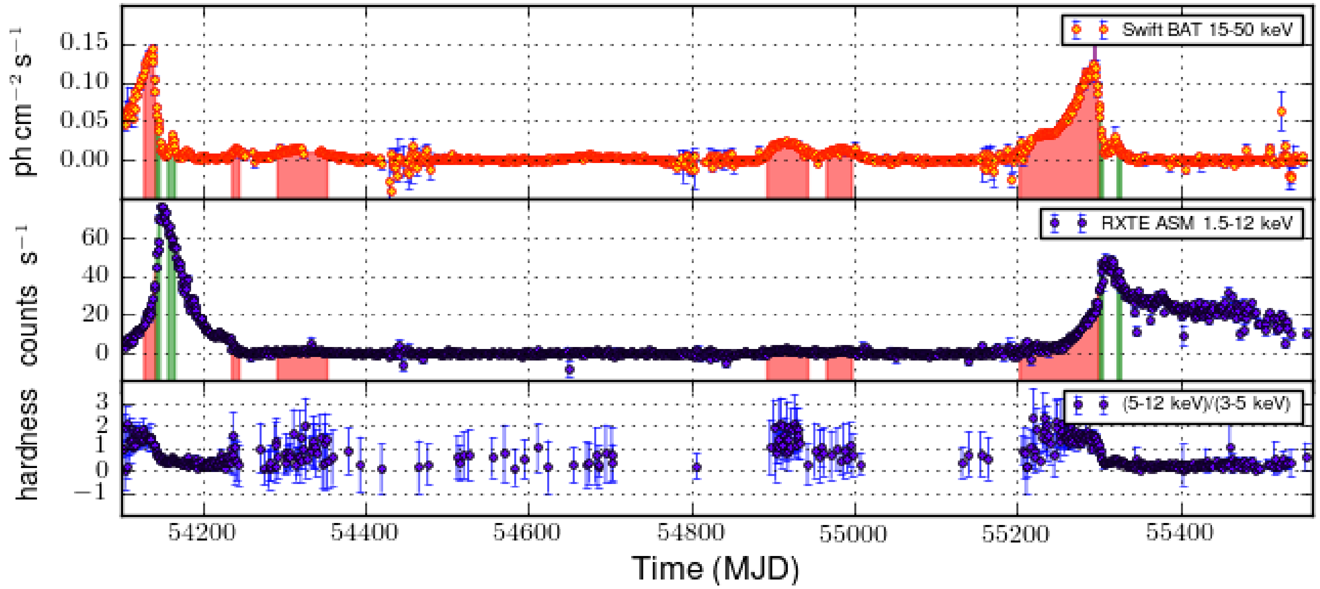
Time selection: black hole binaries

GX 339–4, H1743–322, IGR17091–2436, Cygnus X-1

- Radio jet correlated to:
  - hard X-ray states: slow steady jet
  - hard → soft transitions: fast discrete ejection

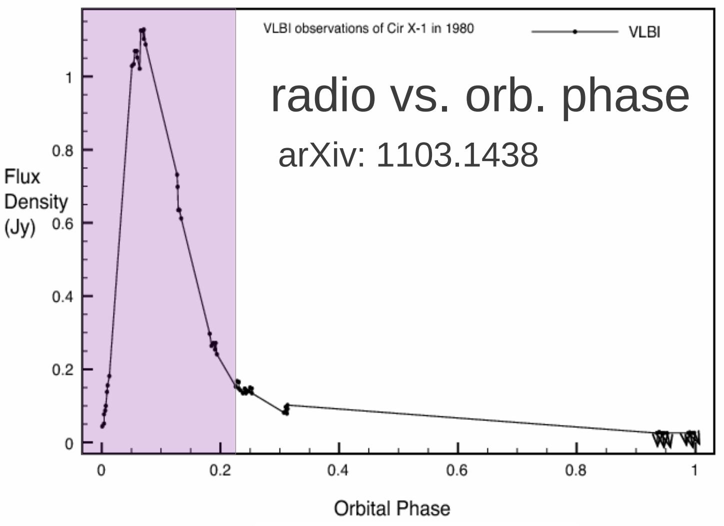
- Time selection:
  - hard X-ray states: outburst in BAT lightcurve (red areas)
  - transitional states: literature, publications or ATels (green areas)
- <u>Different physical scenarios → apply two separate neutrino searches</u>

GX 339–4

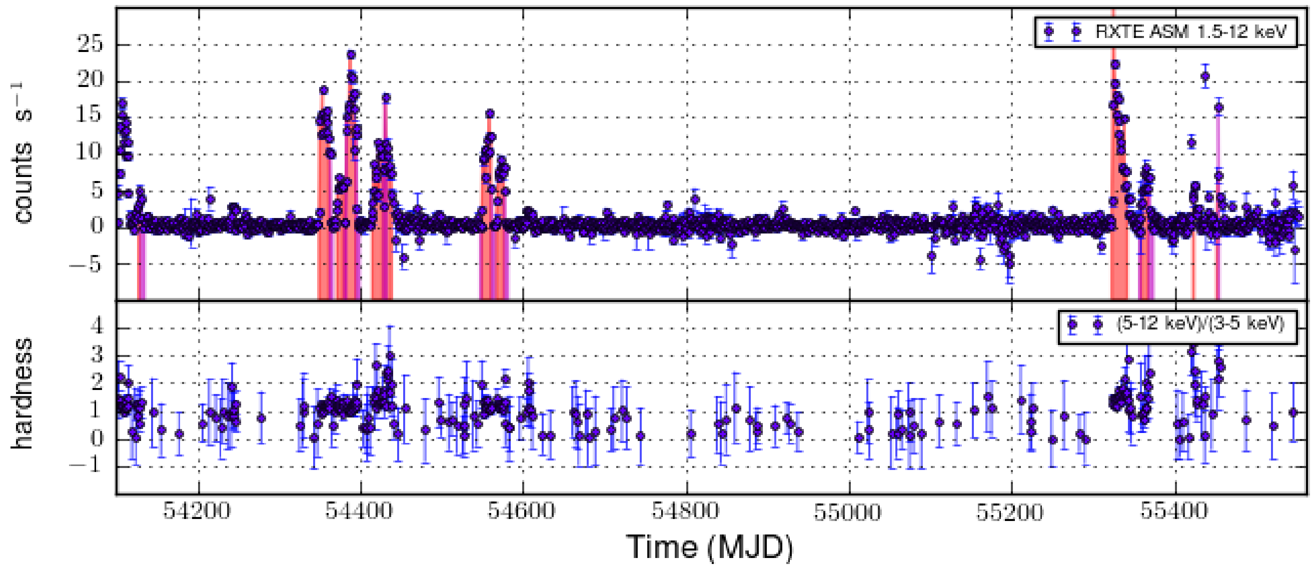


Time selection: Circinus X-1 (NS binary)

- Radio jet correlated to:
  - high X-ray flux
  - orbital phase of the system (plot on the right)
- Select high X-ray ASM flux periods (light red)
- Add adjacent periods with expected radio flare: orbital phases [0-0.2] (light purple)



16.6 days



threshold

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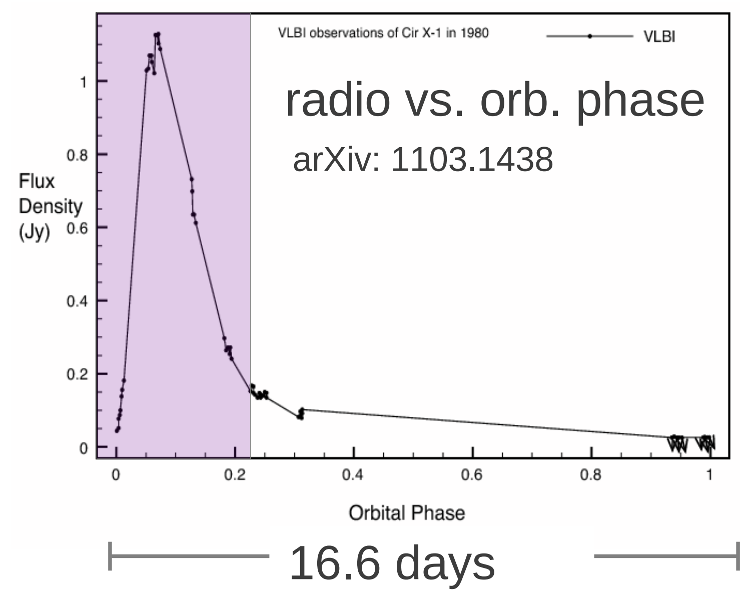

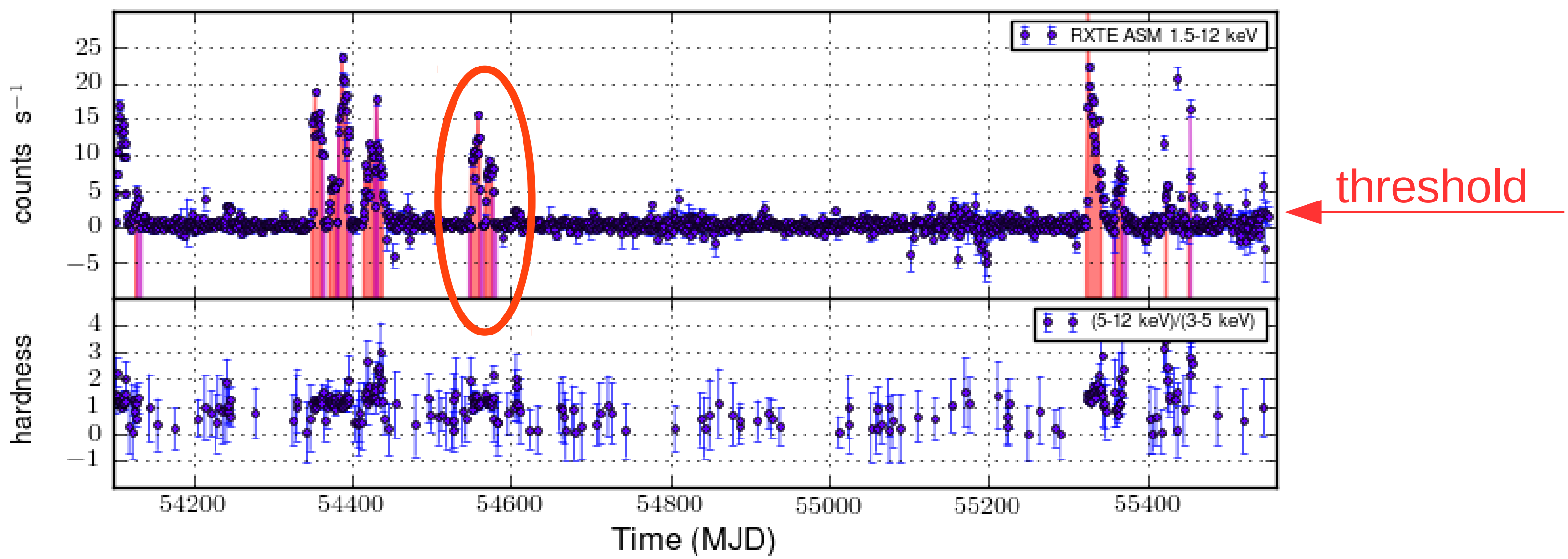

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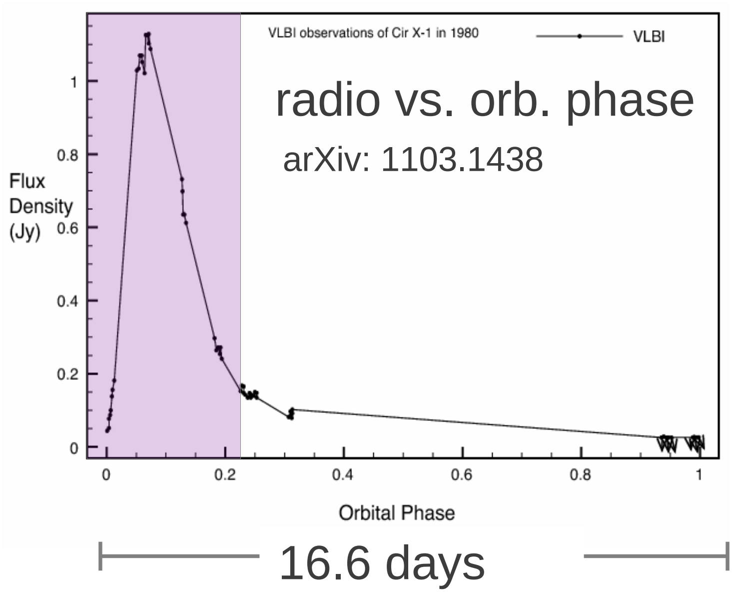
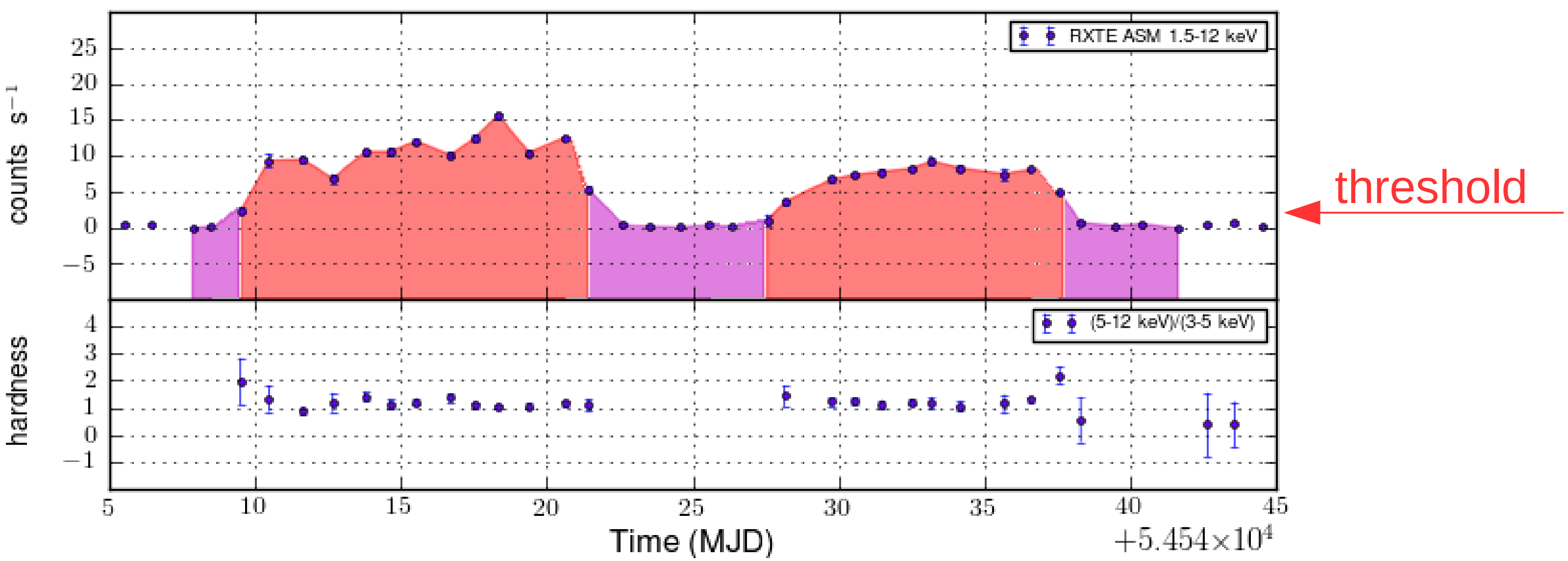
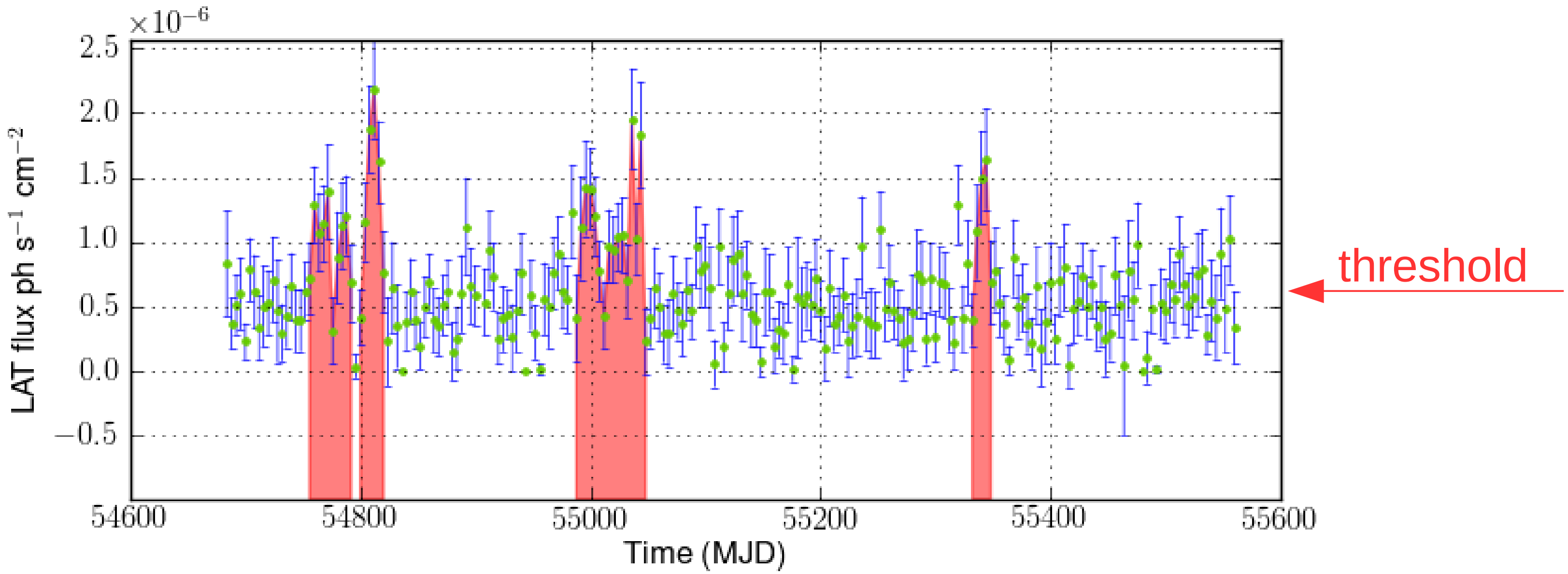




Time selection :Cygnus X-3

- Extract Fermi/LAT light curve:
  - perform basic event selection
  - remove pulses from close-by pulsar PSR 2032+4127
  - get livetime cubes and exposure maps (Pass 6 v11 response)
  - likelihood analysis to get the light curve
- Radio jet correlates to gamma ray outbursts from Fermi/LAT
  - select gamma ray outburst periods
  - add ± 5 days time window to account for radio/γ-ray time lag



Search in ANTARES data

The Data set

- ANTARES data taken between 2007 and 2010
  - selected quality runs: 7411
  - livetime: 813 days

- ANTARES data + time cuts → 9 data subsets:

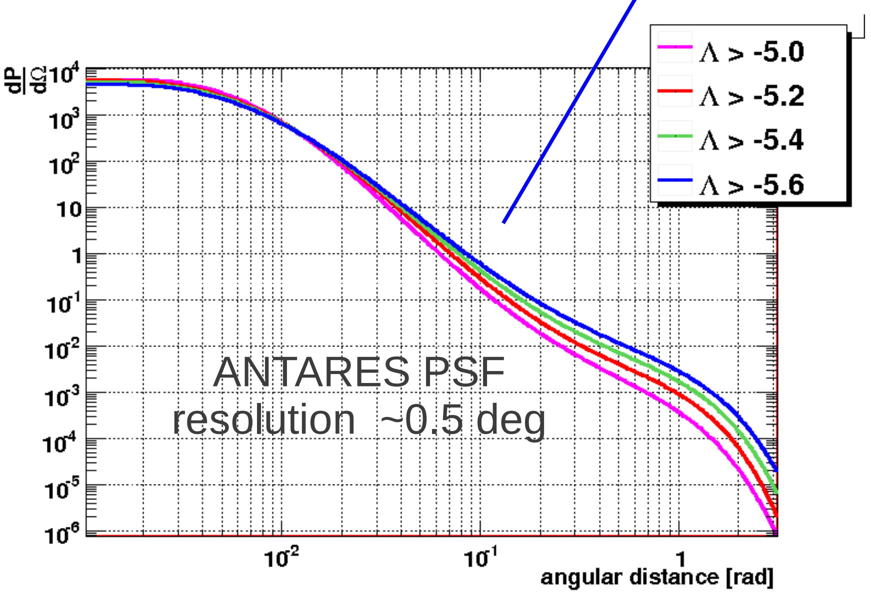
source	livetime
Cir X-1	100.5
GX 339−4 (HS)	147.0
GX 339−4 (TS)	4.9
H1743−322 (HS)	84.6
H1743−322(TS)	3.3
IGR J17091−3624	8.5
Cyg X-1 (HS)	182.8
Cyg X-1 (TS)	18.5
Cyg X-3	16.6

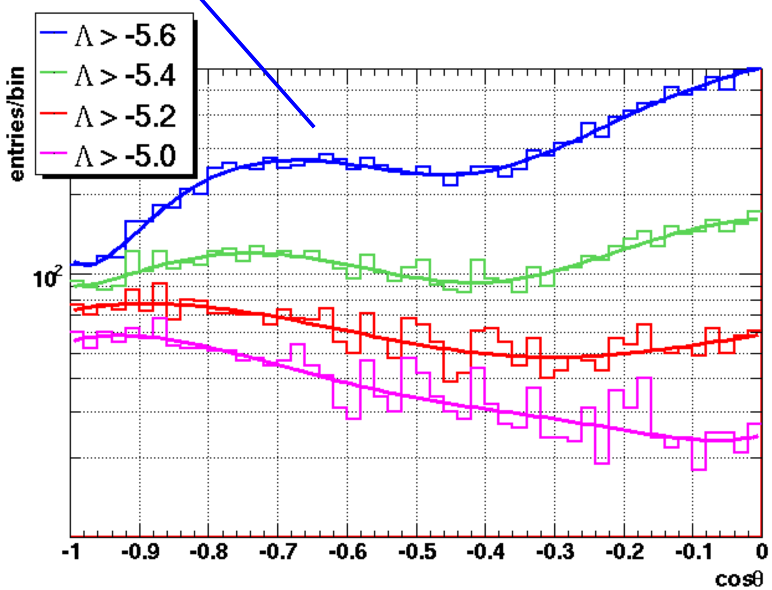
HS=Hard State
TS=Transitional State

Likelihood ratio search method

- **<u>Log likelihood</u>** depending on the background distribution and PSF:

$$\log(L)=\sum_{i=1}^{n_{tot}}\log\left[n_{sig}PSF(\beta_i)+n_{tot}Bkg(\cos\theta_i)\right]-n_{tot}-n_{sig}$$

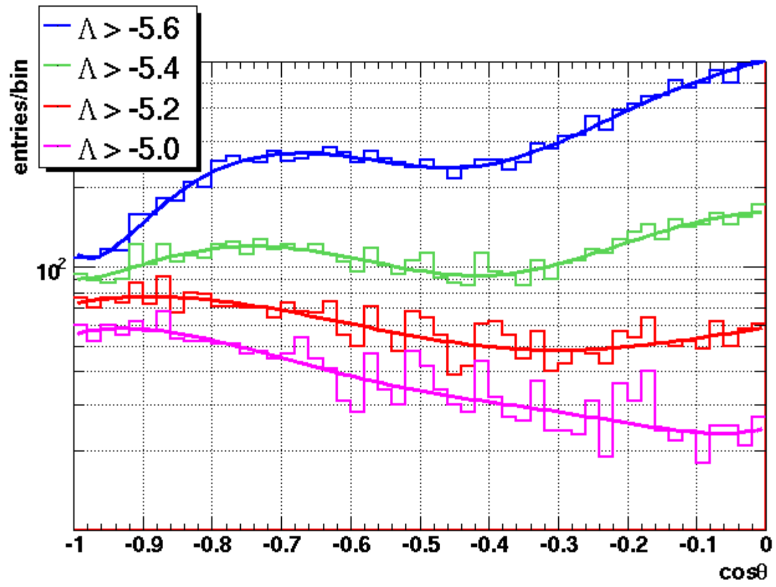


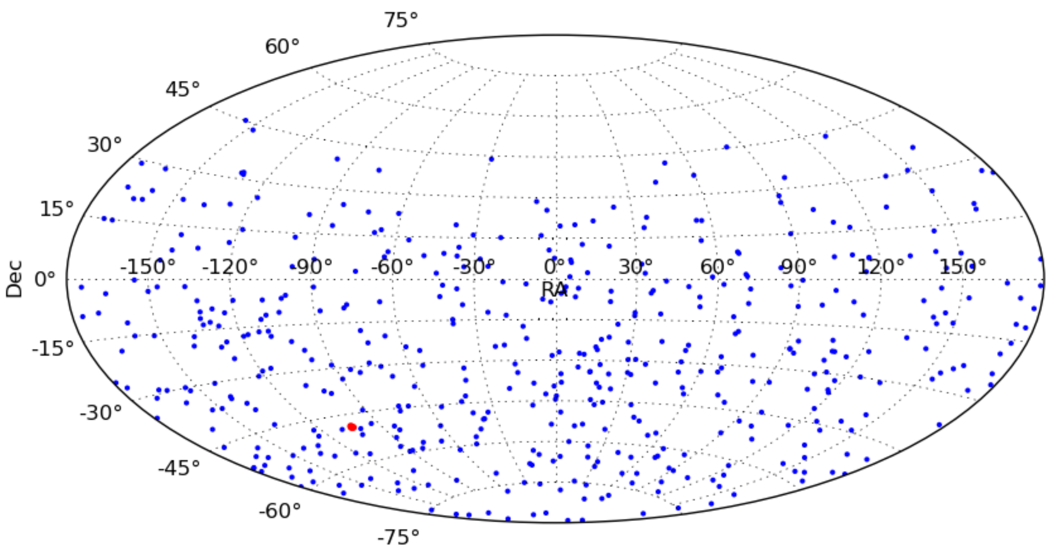


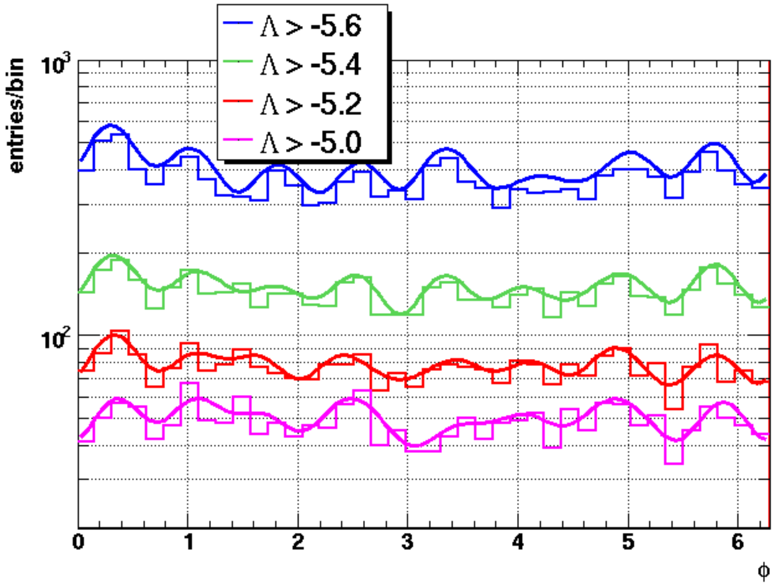
Test statistic definition: $Q=\max_{n_{sig}}\{\log(L)\}-\log(L)_{n_{sig}=0}$

Pseudo experiment generation

- **<u>Blind analysis:</u>** optimize quality cuts and define discovery conditions before looking at real data
- **<u>Data randomization</u>** w.r.t. local coordinates of the selected events in data (plots on the right)
- **<u>Signal injection</u>**: up to 30 signal events per pseudo-experiment around simulated source (PSF)

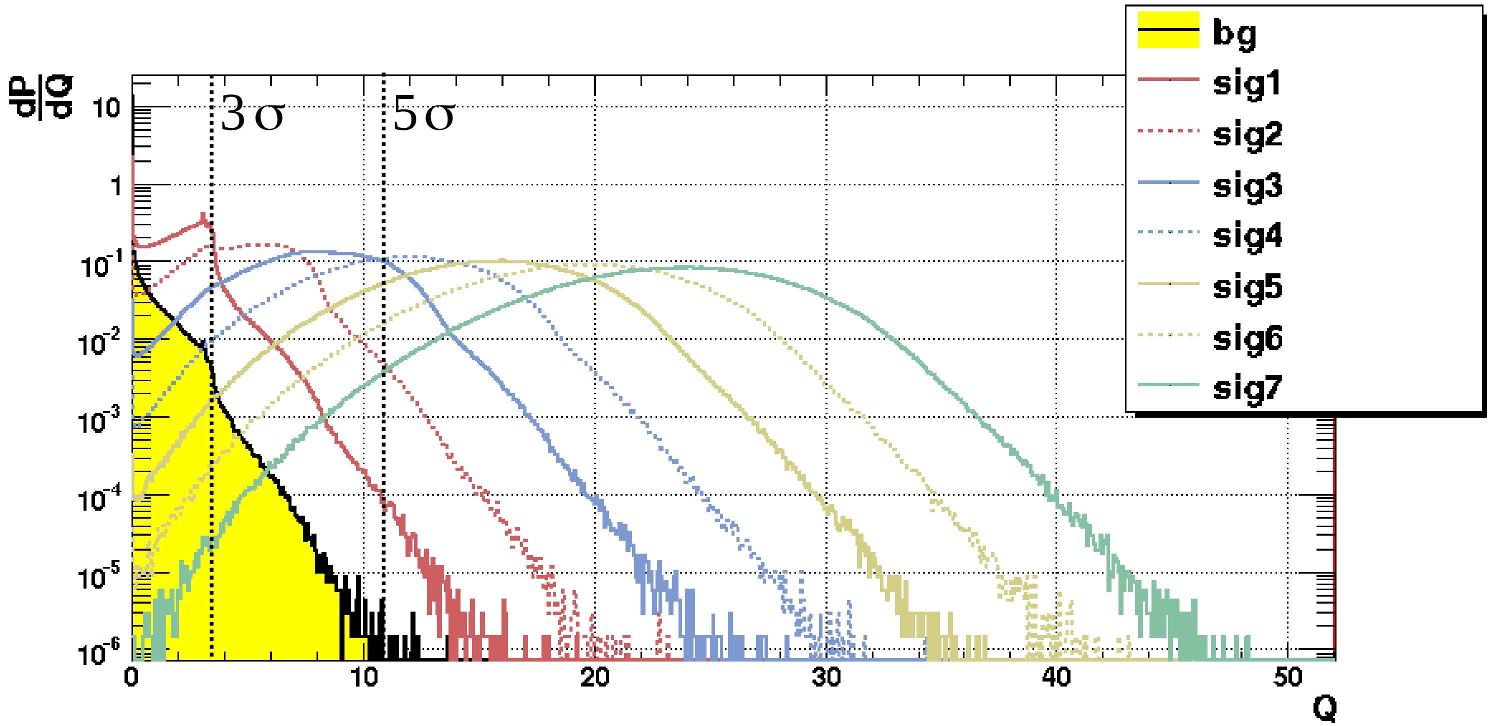






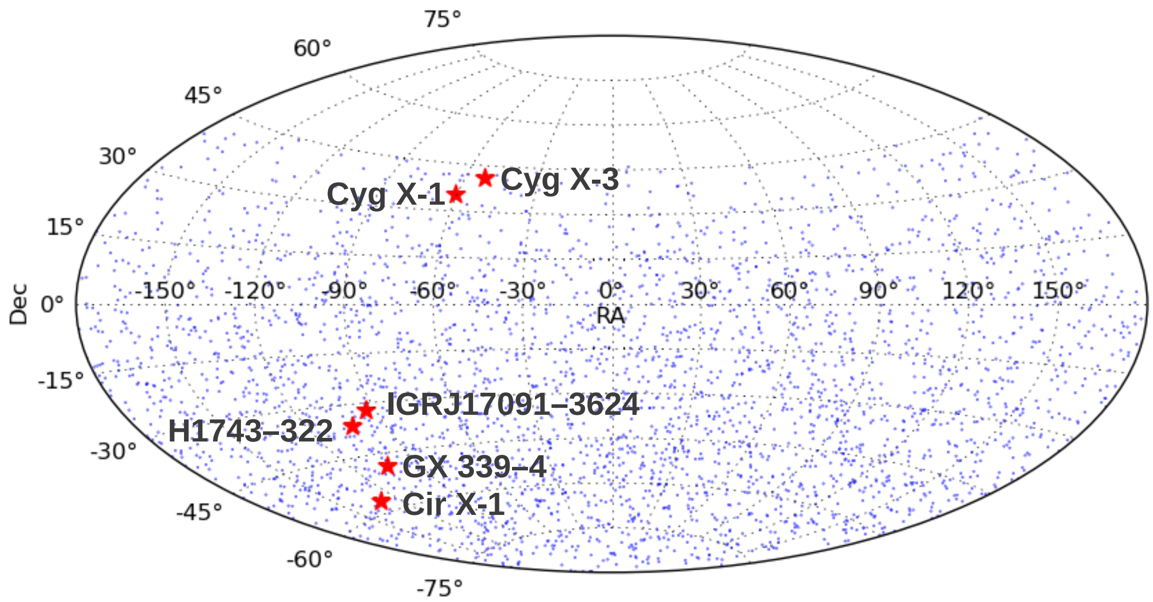
Pseudo experiment results

- Different test statistic distributions according to injected signals n_{sig}
- Background-only distribution (yellow) used to calculate critical 5σ and 3σ values
- Background-only and background + signal distributions used to calculate the corresponding neutrino flux:
  - Q → $\langle n_{sig} \rangle$, through Poissonian convolution of Q distributions
  - $\langle n_{sig} \rangle$ → Φ_{υ} , through simulations



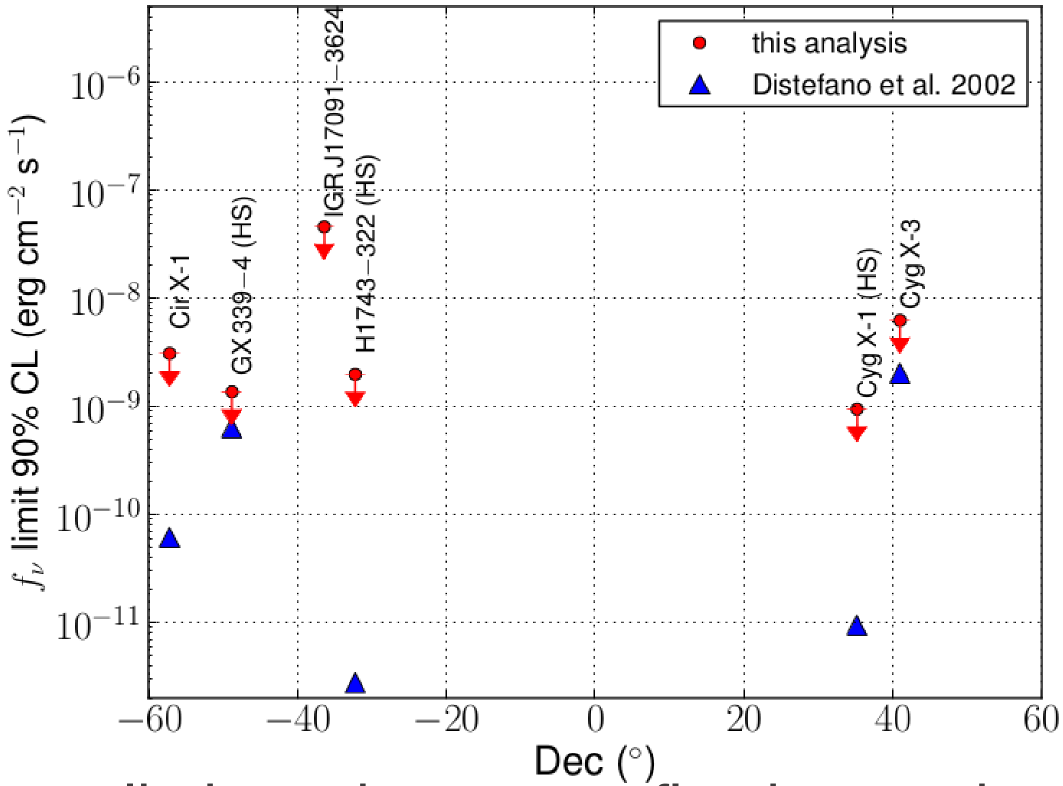
case of GX 339–4 (HS)

Search results



	$\Lambda >$	TS	n_{sig}	livetime	$N_{\nu,bg}$	closest ν	fluence u.l.$^{90\%\mathrm{C.L.}}$
Cir X-1	−5.2	0	0	100.5	256	5.7°	16.9
GX 339−4 (HS)	−5.2	0	0	147.0	484	2.8°	10.9
GX 339−4 (TS)	−5.4	0	0	4.9	14	11 °	19.7
H1743−322 (HS)	−5.2	0	0	84.6	447	4.6°	9.1
H1743−322(TS)	−5.4	0	0	3.3	22	15.9°	30.3
IGR J17091−3624	−5.4	0	0	8.5	40	12 °	21.3
Cyg X-1 (HS)	−5.2	0	0	182.8	675	1.4°	14.1
Cyg X-1 (TS)	−5.4	0	0	18.5	104	6.4°	6.0
Cyg X-3	−5.4	0	0	16.6	149	6.9°	5.7

Comparison with model



- 90% CL upper limit on the energy flux in neutrinos during the selected periods for a flux:

$$\propto E_\nu^{-2} \cdot e^{\frac{-E_\nu}{100\,\mathrm{TeV}}}$$

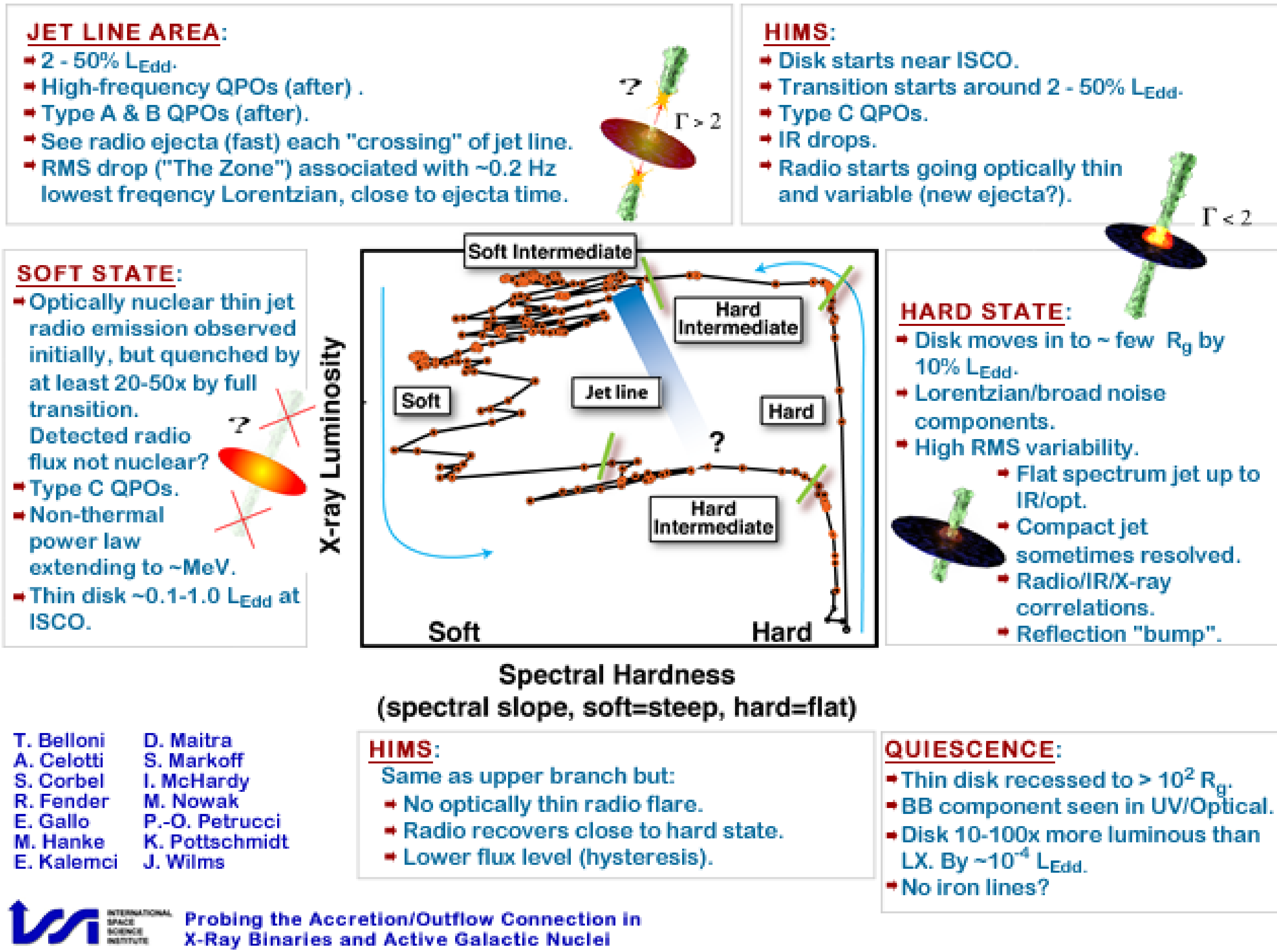
compared to the model expectations of Distefano et al., (2002). Cutoff introduced to compare with the model.

Conclusions

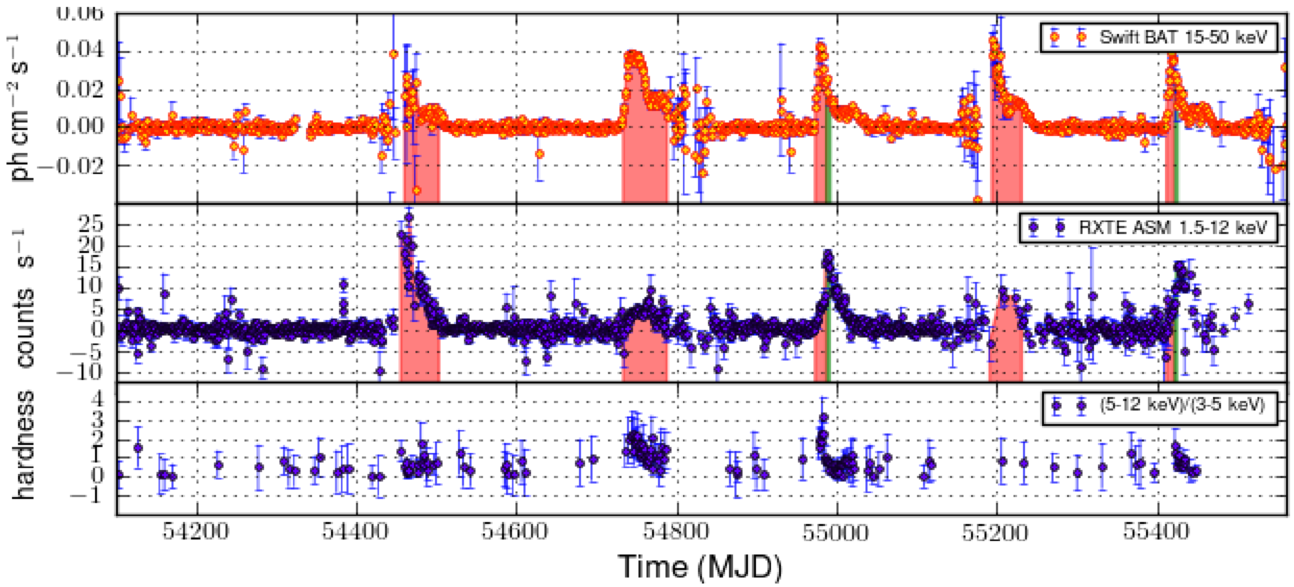
- Performed a search for neutrino emission from microquasars with ANTARES 2007-2010 data
- Time cuts were applied to select outbursting periods with radio jets, using information from two X-ray and one gamma ray telescope
- The unbinned likelihood analysis has been optimized for discovery
- Upper limits were obtained on neutrino fluences
- KM3NeT should allow the constraint of model parameters for GX 339–4 and Cyg X-3, within the first years of data taking

BACKUP

X-ray states in black hole binaries



H1743-322

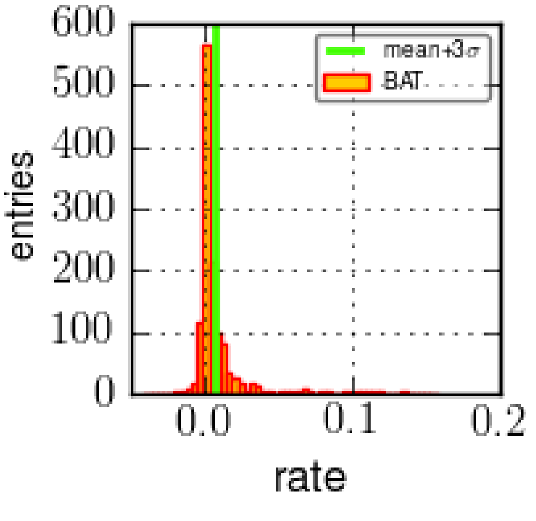


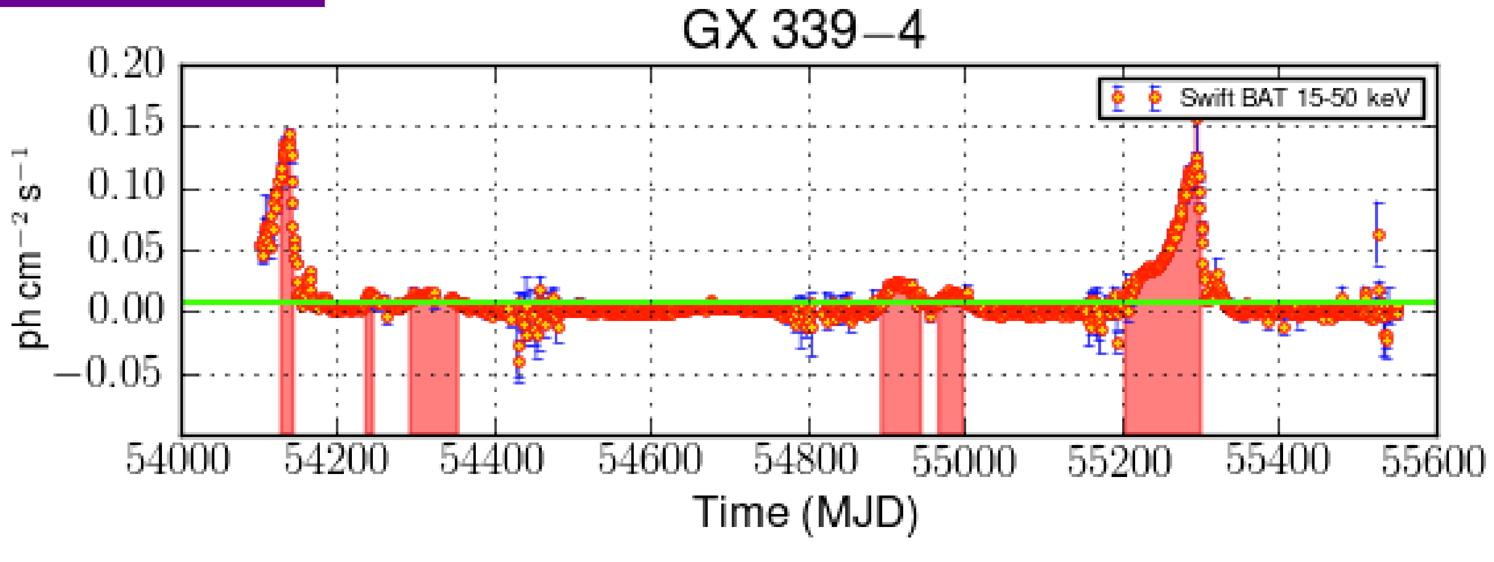
Swift BAT 15-50 keV
RXTE ASM 1.5-12 keV
(5-12 keV)/(3-5 keV)
ph cm^{-2} s^{-1}
counts s^{-1}
hardness
Time (MJD)

Selection of X-ray outbursts

- Gaussian fit of X-ray rates (histogram on the left)
- Get the ***mean + 3σ***$_{hist}$ (green line)
- Select fluxes "sufficiently above" this level:
  - 1st seed ***3σ***$_{flux}$ above green line
  - Plus adjacent ones **1*σ***$_{flux}$ above

Not the only criterion for time selection

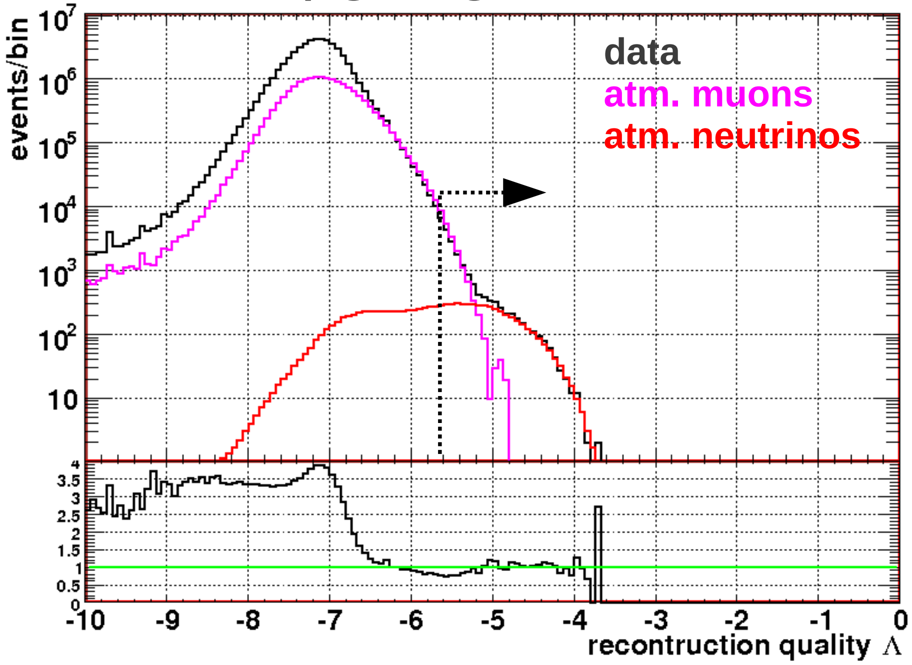




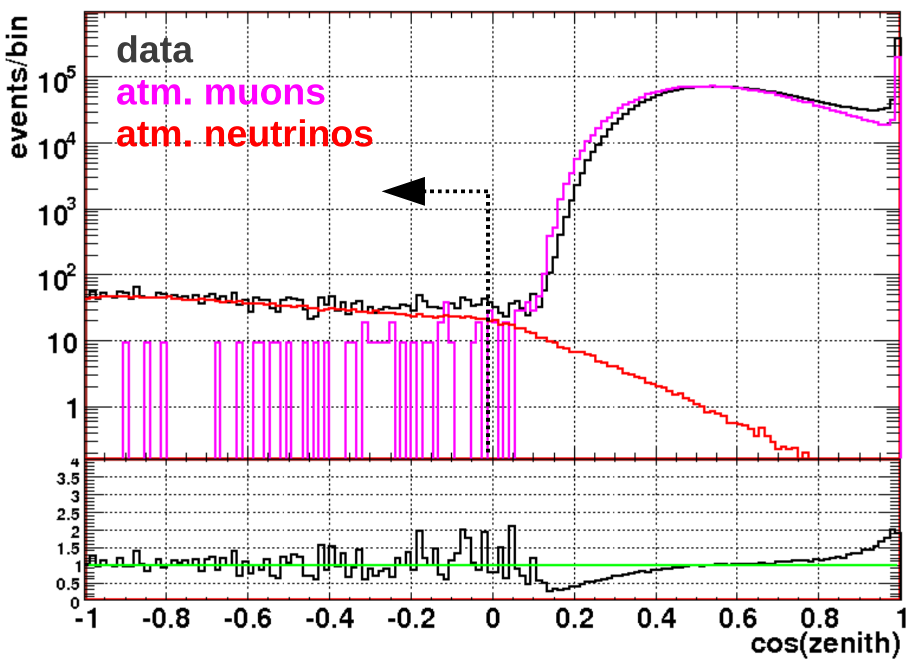
Data - Monte Carlo

Full data set: 813 days

upgoing events



events with Λ>–5.2

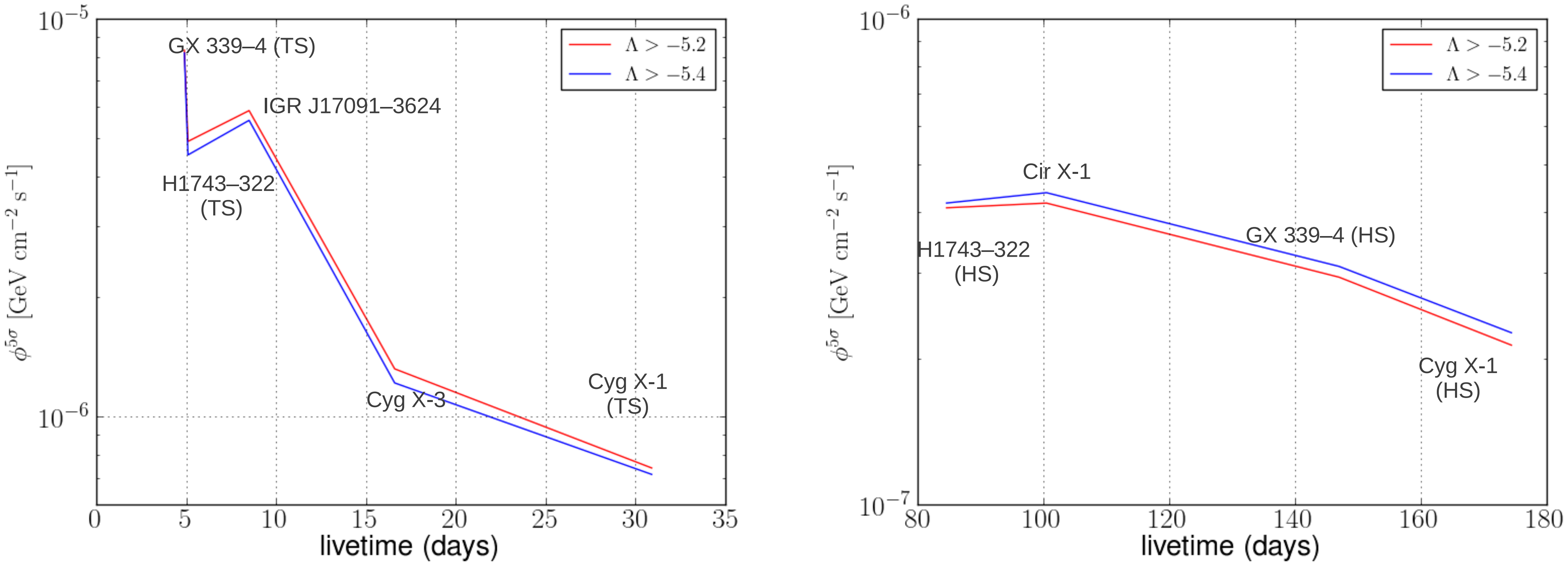


Event selection

- Cuts applied for the event selection
  - Λ> -5.0, -5.2, -5.4, -5.6 → **will optimize discovery potential**
  - error estimate <1 degree
- The number of selected events in each data subset will be used to estimate the background of the corresponding search:

Source		Selected Events			
		$\Lambda > -5.0$	$\Lambda > -5.2$	$\Lambda > -5.4$	$\Lambda > -5.6$
Cir X-1		139	256	583	1607
GX 339−4	(HS)	316	484	956	2609
	(TS)	3	5	14	45
H1743−322	(HS)	283	447	746	1817
	(TS)	10	20	27	90
IGR J17091−3624		10	16	40	120
Cyg X-1	(HS)	417	638	1254	3210
	(TS)	58	109	182	507
Cyg X-3		64	93	149	333

Optimal quality cuts



- Apply cut that minimizes flux needed for a 5σ discovery:
  - looser cut Λ>– 5.4 when livetime<30 days (left plot)
  - stricter cut Λ>– 5.2 when livetime>80 days (right plot)