THESEUS Time Domain Astronomy

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Theseus Science Working Groups teleconference, 3-4 June 2020

Theseus Science Working Group 3 – Time Domain Astronomy

Inputs gratefully received so far from:

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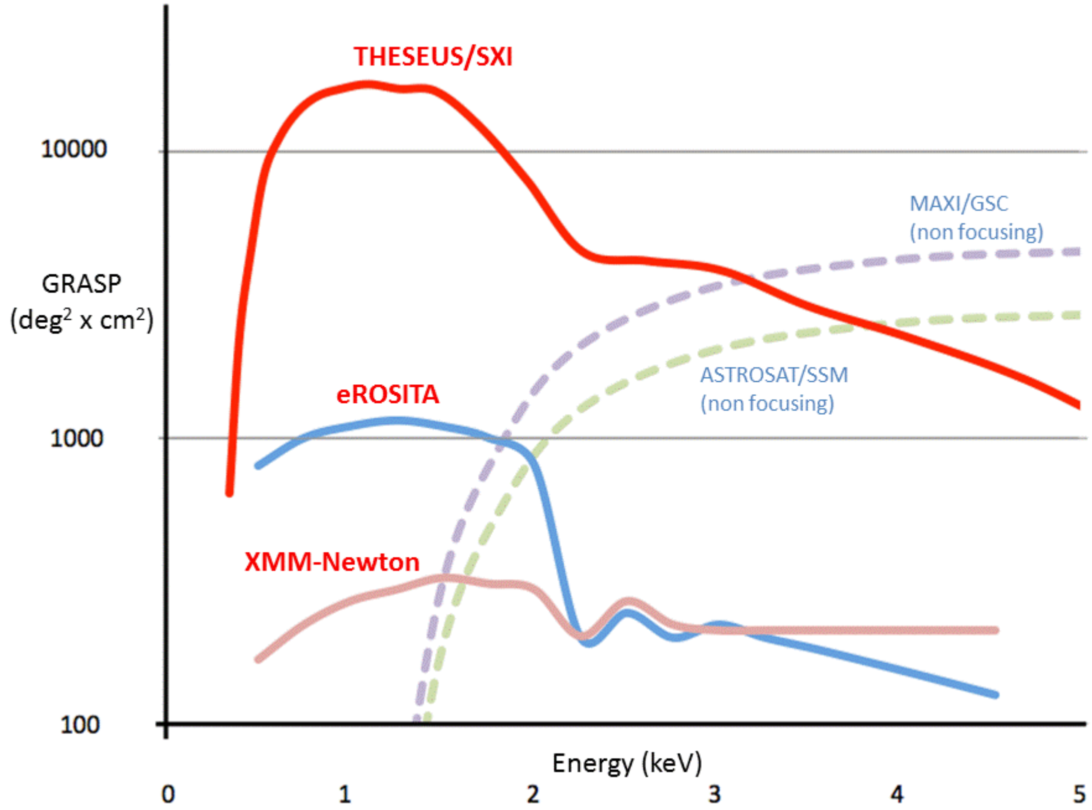
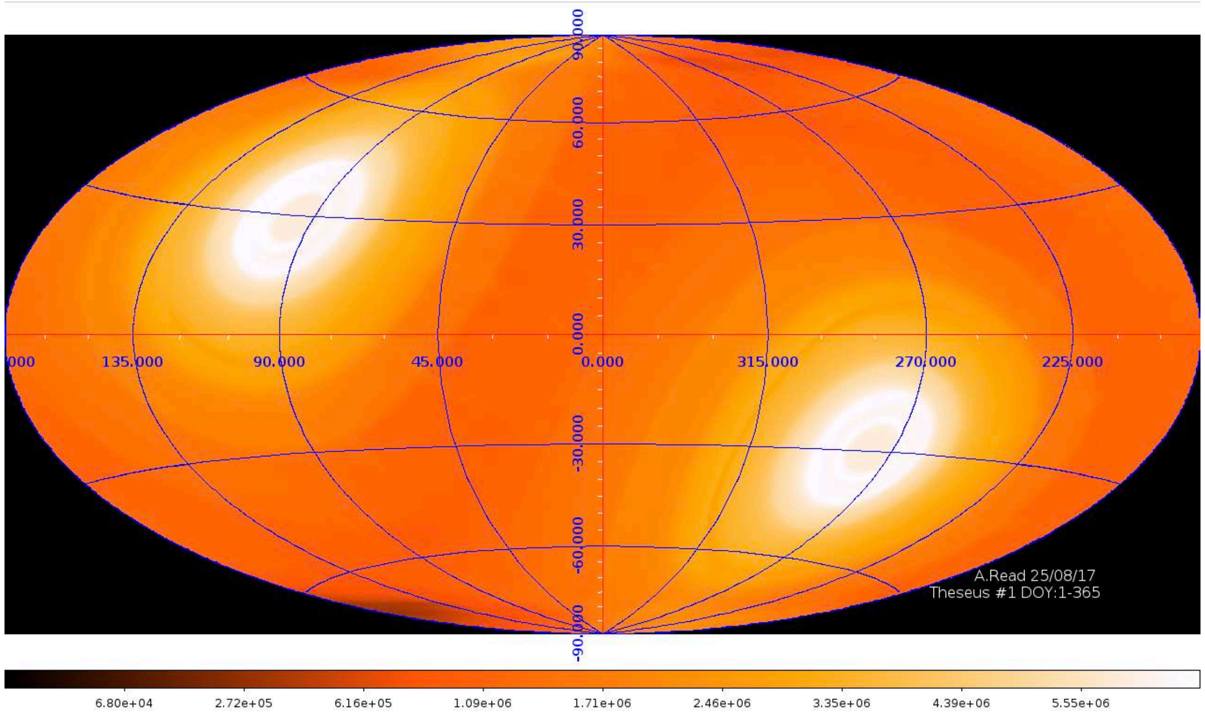
Victoria Grinberg	*Natalie Webb*
Jari Kajava	*Silva Zane*
Albert Kong	*+ core consortium members*

The Theseus advantage



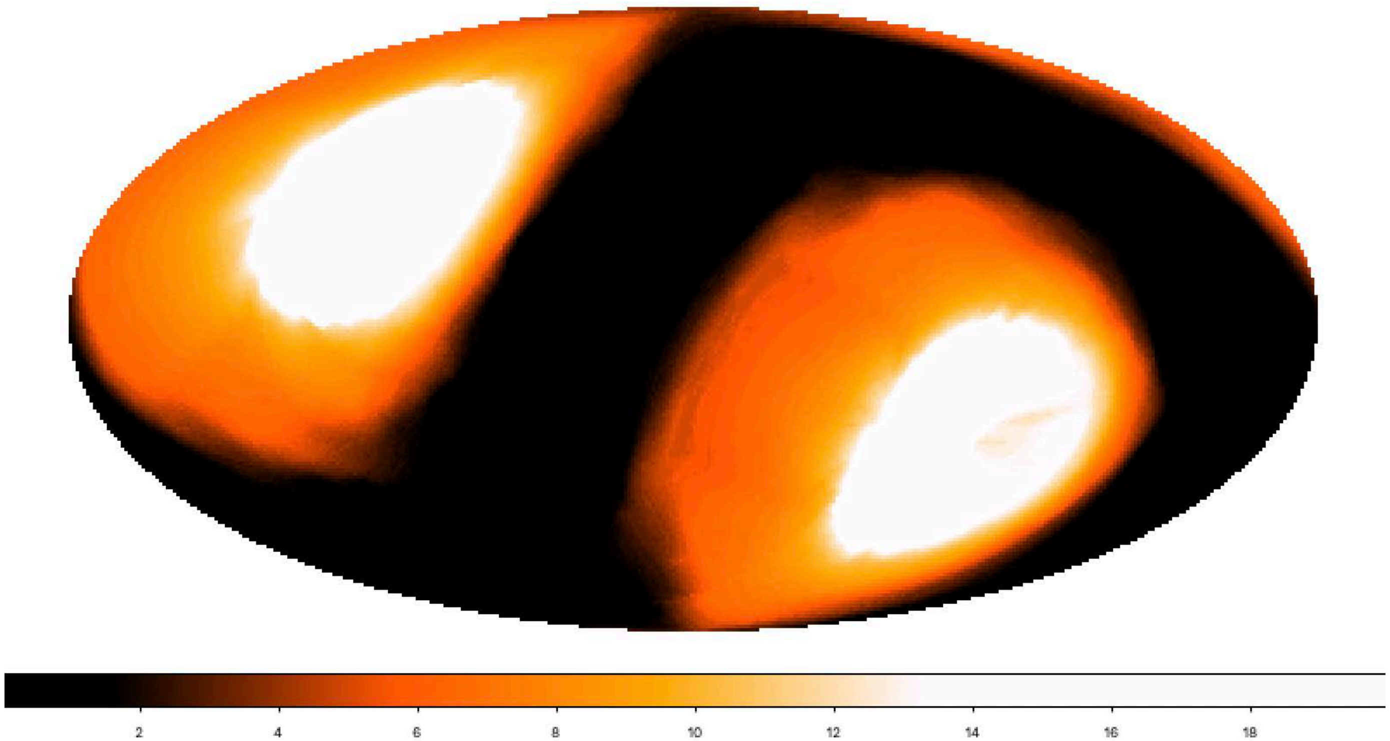
1-year SXI exposure map

– Unique observing duty cycle: peak ~20%



Galactic coordinates
Amati+ 18

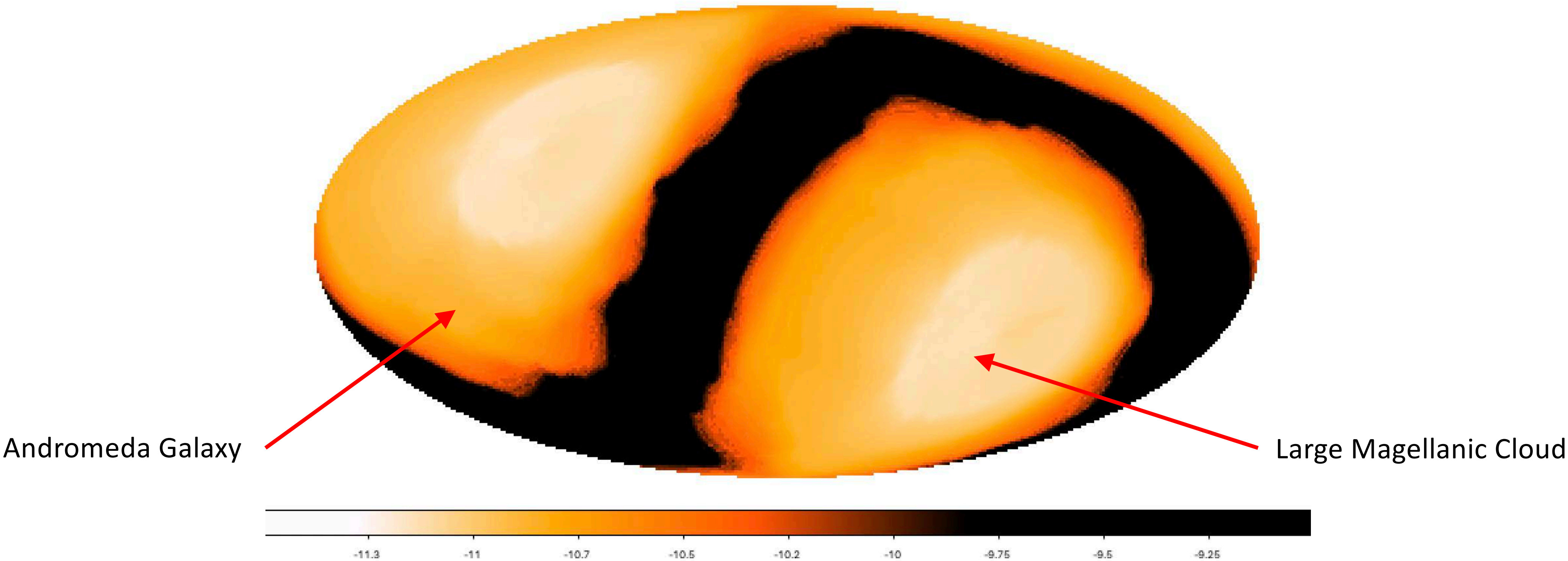
1-year SXI exposure map
– ‘dynamic tilt away from Earth, no pitch’



Victor Doroshenko, Tübingen
From ESA MOS scenario 5c

Galactic coordinates
ksec per day

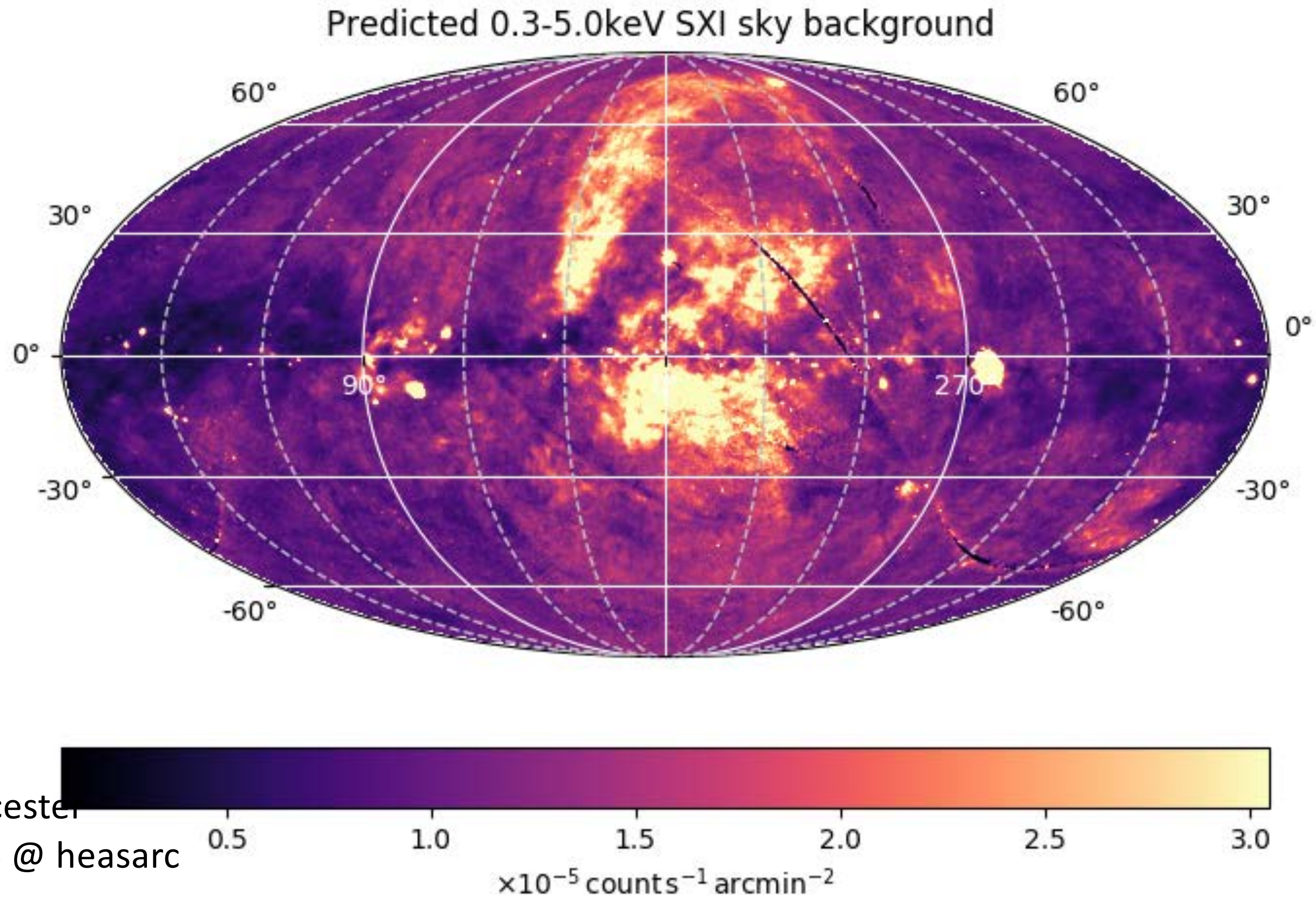
1-day SXI sensitivity map – median background



Victor Doroshenko, Tübingen
From ESA MOS scenario 5c, SXI Perf Doc

Galactic coordinates
Log flux

SXI sky background
– low background regions prioritised



Andy Beardmore, Leicester
From Snowden+ RASS @ heasarc

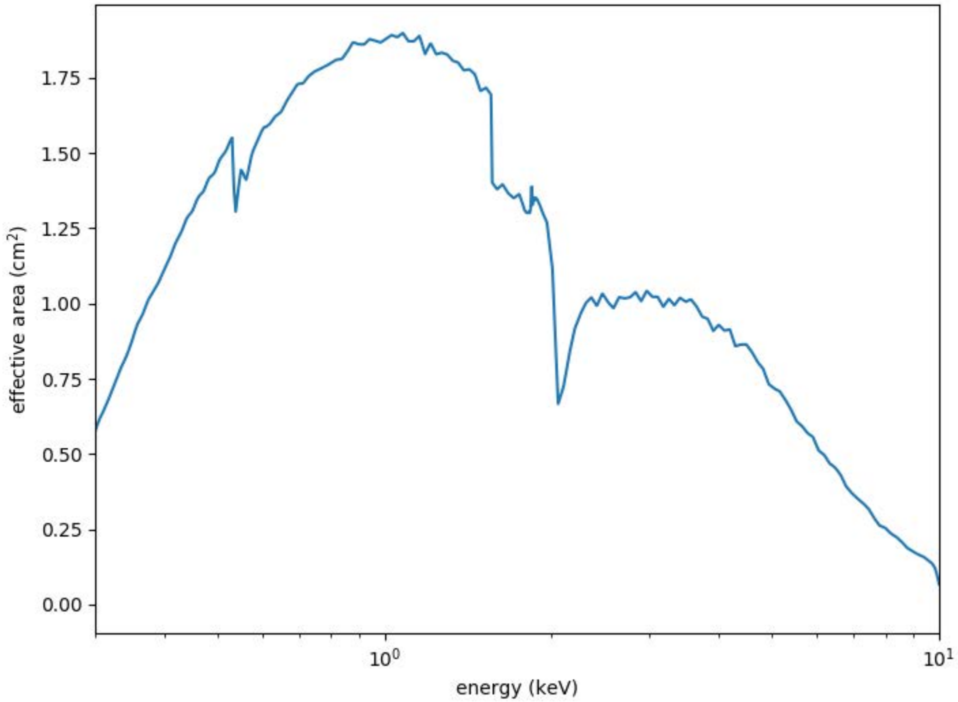
Galactic coordinates
Linear count rates

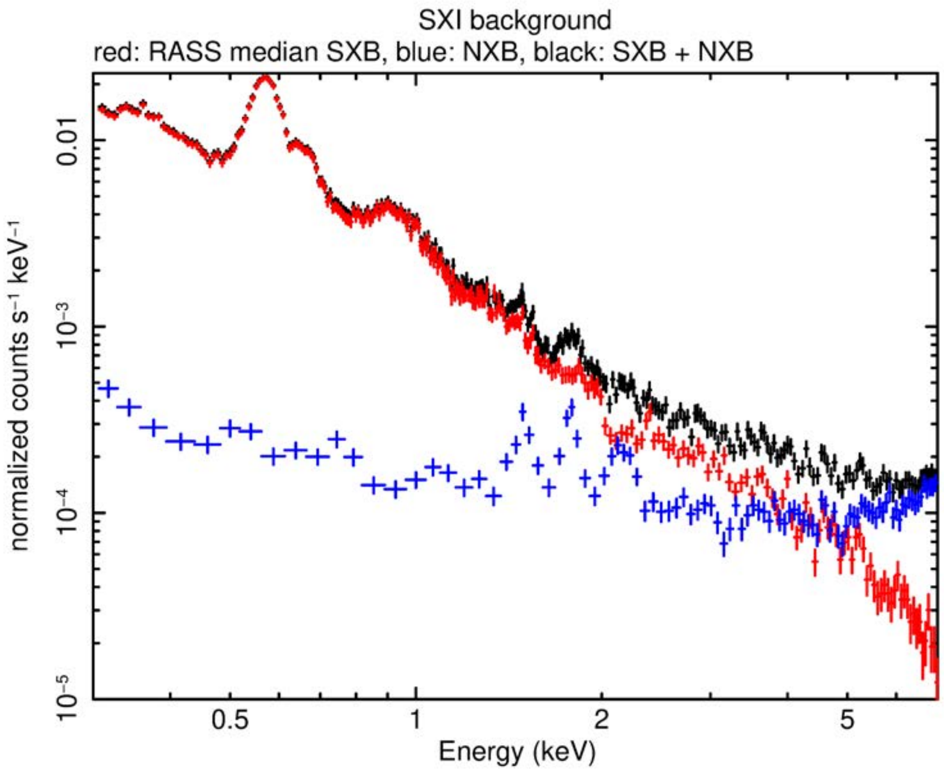
Comments:

- This is science ‘for free’
- Unique strengths:
    - High cadence and duty cycle of observations
    - Long unbroken continuous exposures possible
    - Nudging IRT to specific targets close to planned pointings
- But low exposure of Galactic centre

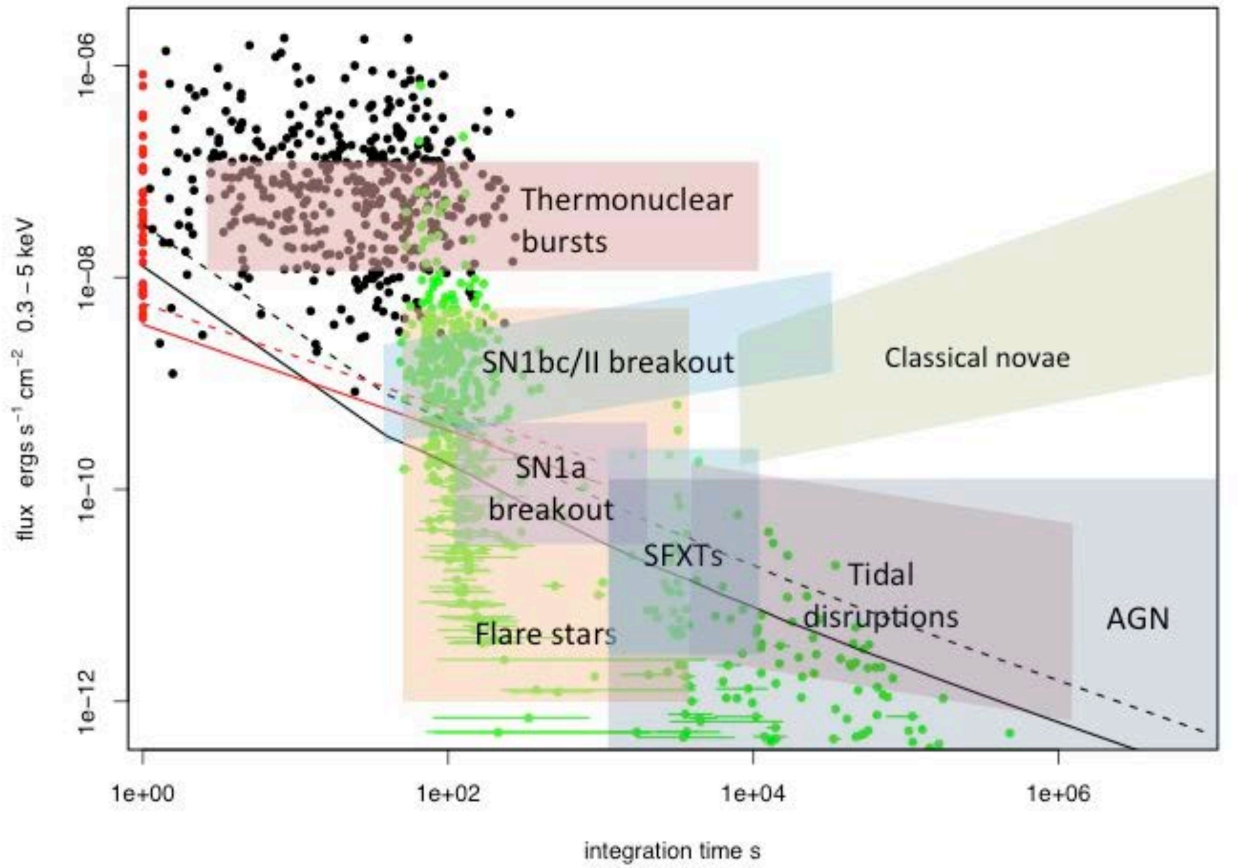
- Theseus can alert Athena to transient outbursts and changes of state for a wide variety of source types
- Swift has shown the widely perceived value of large facility follow-up observations of transients in outburst

SXI effective area & background
- 675 sq arcmin beam



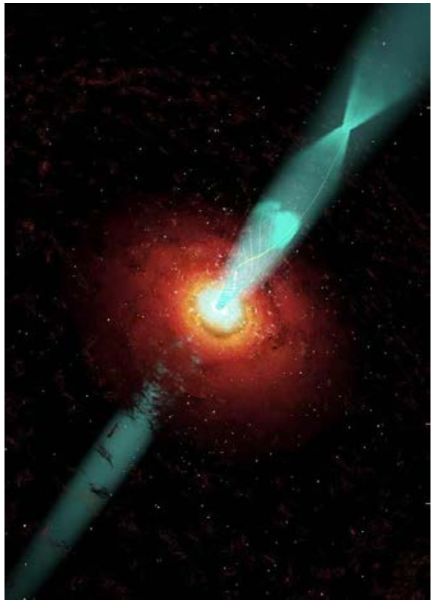


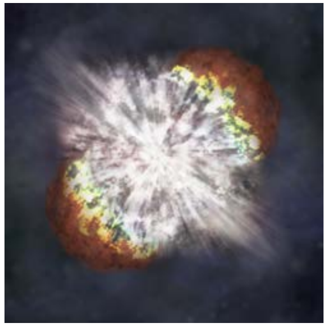
Situational awareness of the Universe

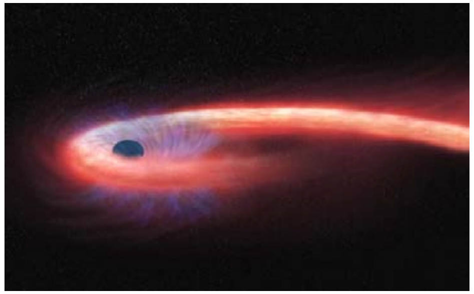


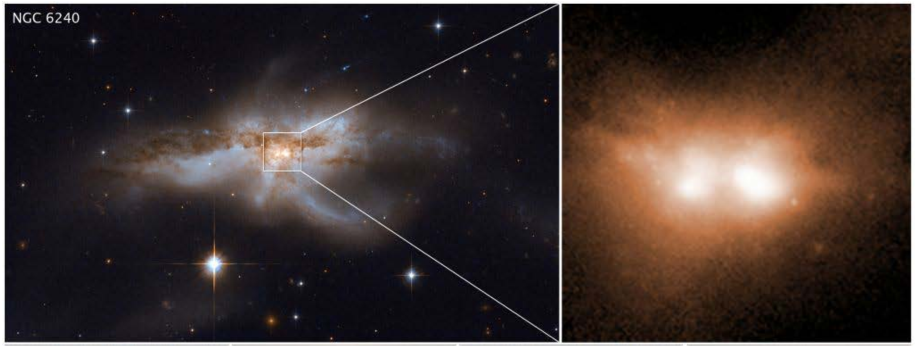
Potential extra-galactic transients/variables

- AGN
- Blazars
- Jetted & un-jetted TDEs
- SNe
    - Shock break-out
- FRB counterparts

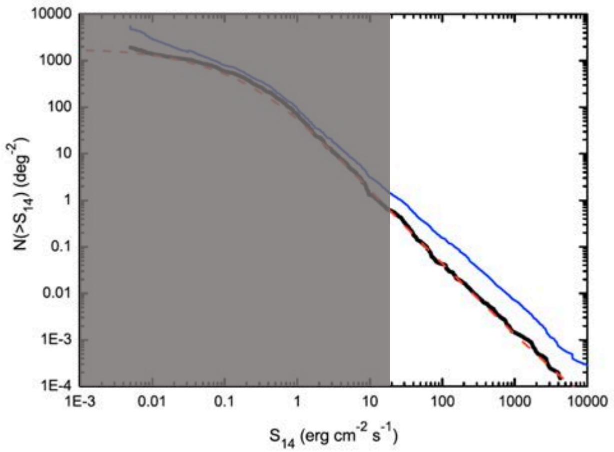


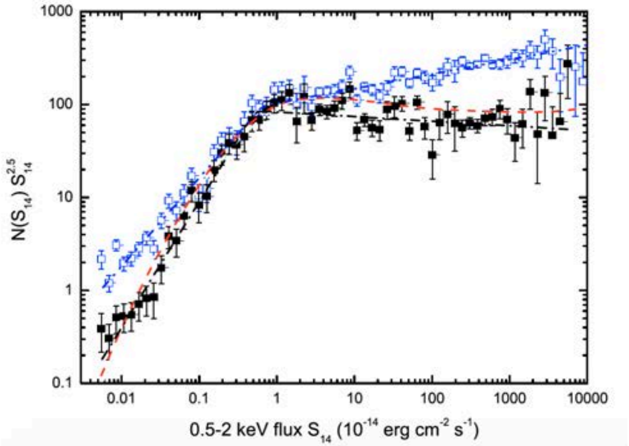




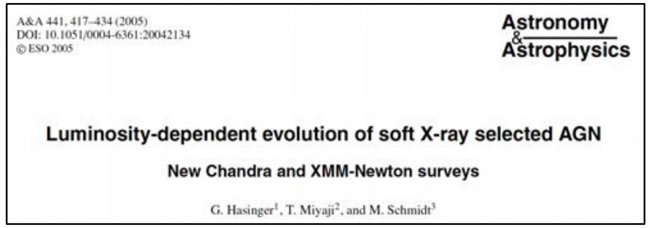


Source numbers





Hasinger, Miyaji & Schmidt 05
(bright end from Rosat)


A&A 441, 417–434 (2005)
DOI: 10.1051/0004-6361:20042134

Astronomy & Astrophysics

Luminosity-dependent evolution of soft X-ray selected AGN

New Chandra and XMM-Newton surveys

G. Hasinger[1], T. Miyaji[2], and M. Schmidt[3]

- Blue line is all sources
- Black line is type 1 AGN (optically identified)

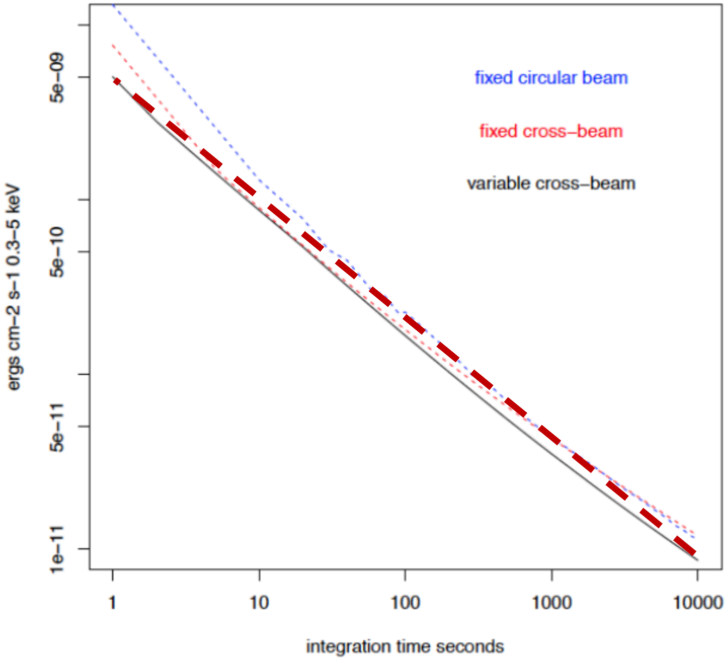
- Bright sources above Euclidian (blue) thought to be Galactic stars
  - Contribution will be mainly close to Galactic plane

Greyed out: too faint for SXI

All sources: Log N>S = - 16.82 - 1.33 Log S (erg/cm^2/s, 0.5-2 keV)

Flux conversion:
For a PL (Γ=2.0, N_H=0.75x10^{19}; HMS05): $f_{0.3\text{-}5}$ = 2.0 $f_{0.5\text{-}2}$

Source numbers



SXI sensitivity vs exposure time
(Performance Document THS-LU-SXI-RP-0001)

- Detection confidence = 10^{-10}, minimum 5 counts

Black curve parameterised as: log(Sens) = -8.30 – 0.675 log(T)

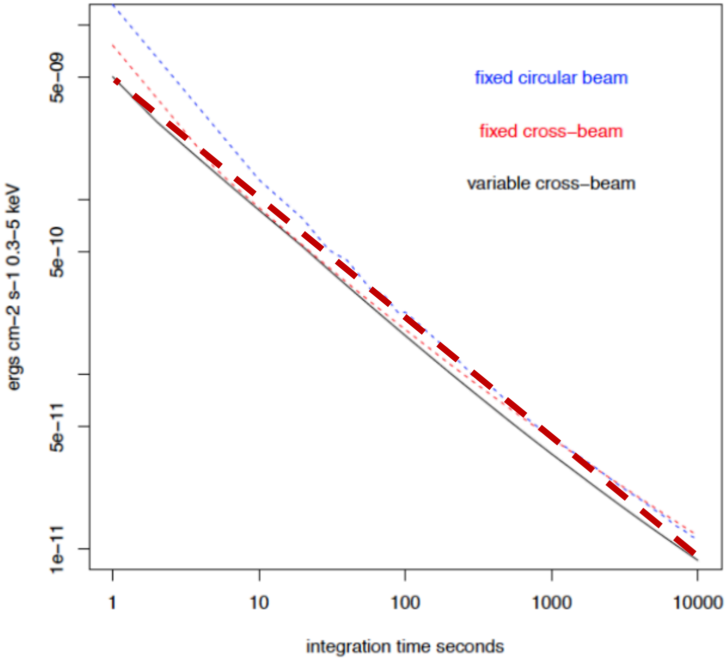
SXI FOV = 1 sr = 3283 sq degrees

Can now predict SXI source numbers:

In 1500 sec (typical exposure?) we will detect 10 sources/FOV

In 100 sec we detect 1 source/FOV
In 10 thousand sec we detect 53 sources/FOV
In 1 million sec we detect 3,300 sources/FOV

Source numbers



BUT source confusion has to be considered

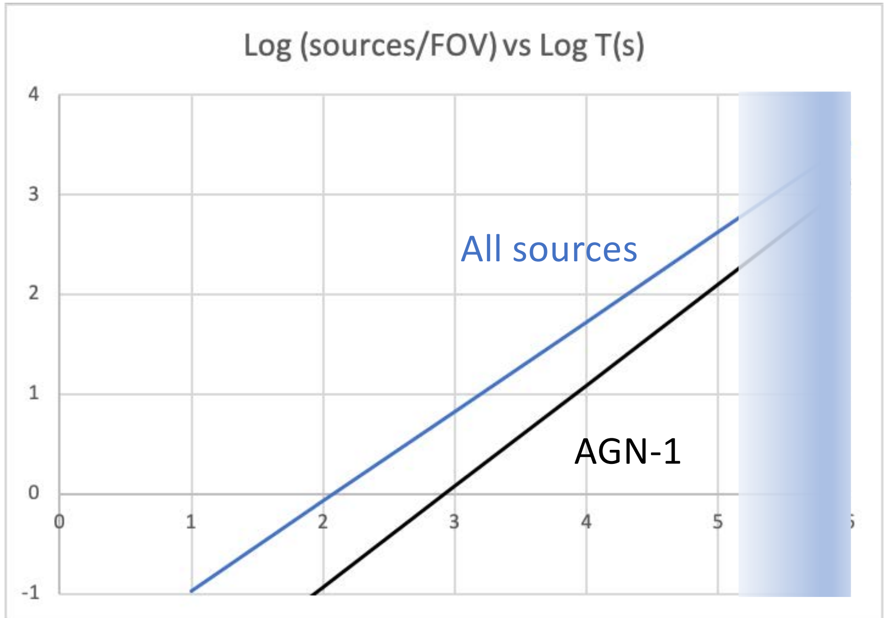
- Rule of thumb: 30 beams per source
  - Assumes Gaussian PSF, depends on logNlogS slope (Takeuchi & Ishii 2004 ApJ 604 40)

TABLE 3
THE RULE OF THUMB FOR THE CONFUSION LIMIT OF 5-σ SOURCES, WHEN THE BEAM IS GAUSSIAN.

Index γ	Sources per beam $(s/b)_C$
0.5	0.20
1.0	0.16
1.5	0.12
2.0	0.08
2.5	0.04
2.9	0.008

- SXI PSF is far from Gaussian
  - *Simulations required to determine confusion limit*
- Using 675 sq arcmin beam: confusion limit is 580 sources per FOV
  - Corresponds to roughly 1.45 10^5 sec exposure
  - $F_{0.3\text{-}5} > 1.6\ 10^{-12}$ erg/cm^2/s
  - $L_X > 1\ 10^{36}$ erg/s at LMC
  - $L_X > 2\ 10^{38}$ erg/s at M31

AGN numbers



Parameterising the Hasinger, Miyaji & Schmidt 05 AGN-1 curve above f = 2 10^{-13}:

Type 1 AGN: Log N>S = -19.38 - 1.50 Log S (erg/cm^2/s, 0.5-2 keV)

Apply bandpass conversion as before

In 1500 sec (typical exposure?) we will detect 2 AGN/FOV

In 100 sec we detect 0.1 AGN/FOV
In 10 thousand sec we detect 12 AGN/FOV
In 1 million sec we detect 1,300 AGN/FOV

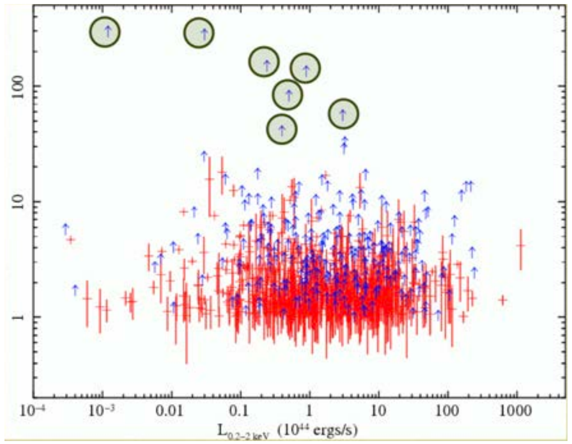
But still confused beyond around 1.45 10^5 sec exposure

- 180 AGN/FOV

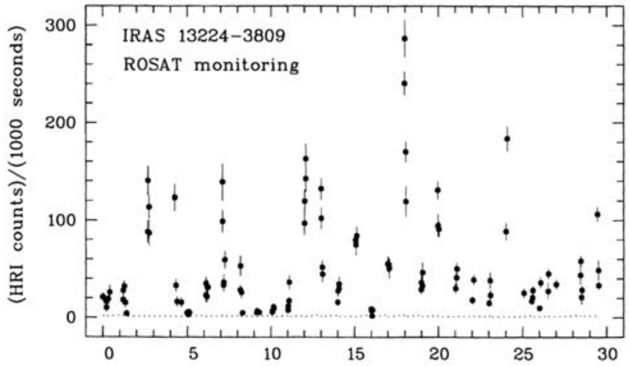
AGN science

- The most powerful continuous sources of energy in the Universe. Powered by supermassive BHs in galactic centres
- Activity varies over a large range in amplitude and timescale due to variations in the emission efficiency or accretion rate
- NL Sy I are soft and highly variable
- Sy 2 can show extraordinary soft variability
- ‘Changing look’ AGN very poorly understood, possible link to disk instability in ‘heartbeat states of X-ray binaries
- Unbiased sample of AGN variability

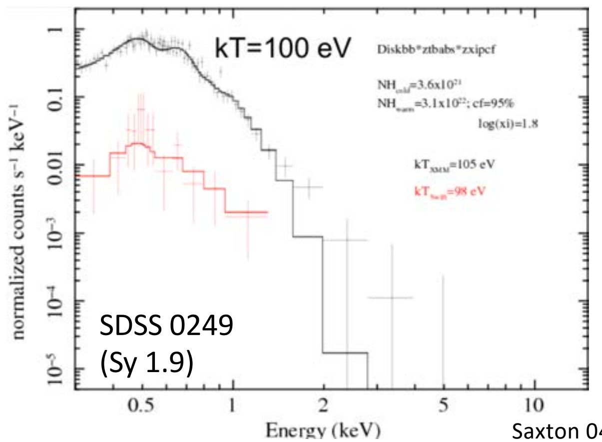
XMM-Rosat AGN flux ratio



Saxton 04

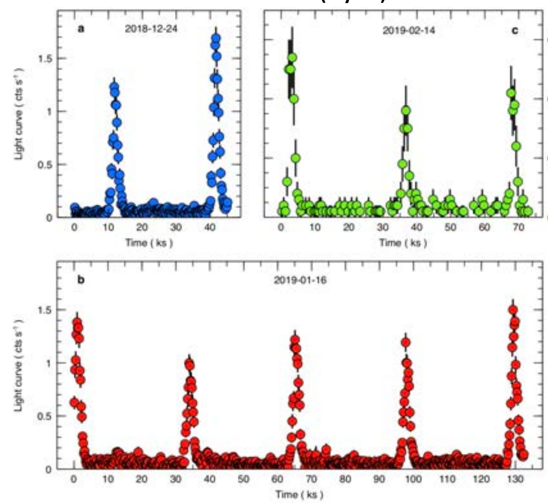


Boller+ 97



Saxton 04

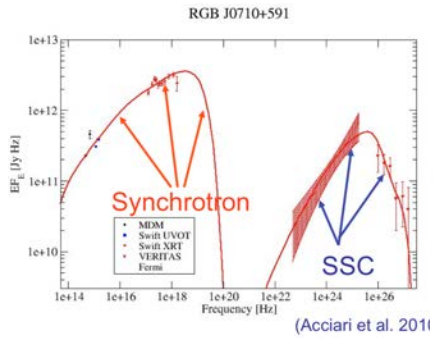
GSN 069 (Sy 2)



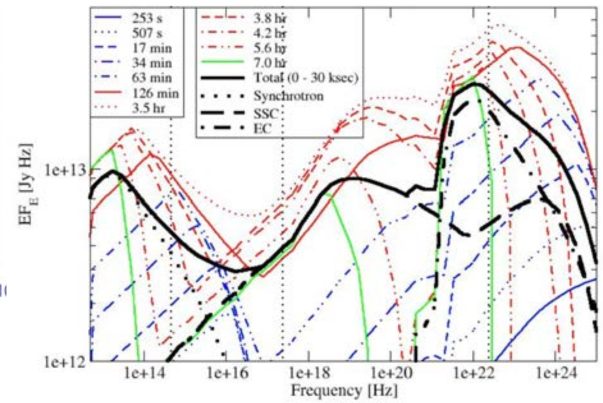
Minuitti+ 19

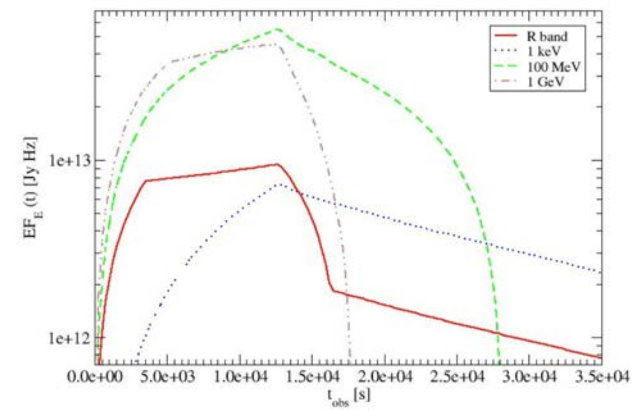
Blazars

- High luminous AGN with jets pointing towards us
- Some of the highest mass BH, some are TeV emitters
- Variability due to changes in the Γ~10 jet: open question is leptonic vs hadronic emission (e- synch, e- SSC, p+ synch, …)
- Radio to UV/X-ray emission is synchrotron from the jet, higher energies from jet Compton scattering (?)
- Measurement of the radio to hard X-ray spectrum constrains the jet particle acceleration and the heating/cooling balance; harder HE spectra from hadron energy. CTA will hugely increase the current TeV sensitivity, allowing study of hundreds of blazars
- Large outbursts allow high time resolution studies; monitoring with the XGIS will define the synchrotron shape. The SXI will measure the flux of tens of AGN daily and more on longer timescales
- Athena & CTA can address jet physics in variety of states guided by Theseus



Classical view



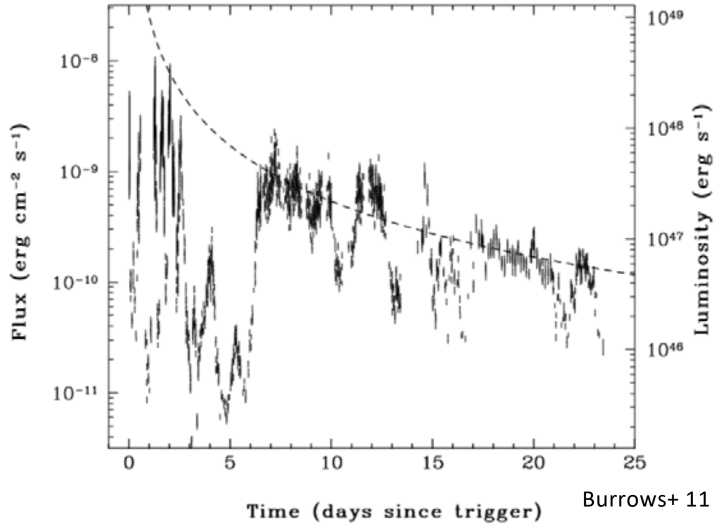


Bötcher talk 11

Tidal Disruption Events

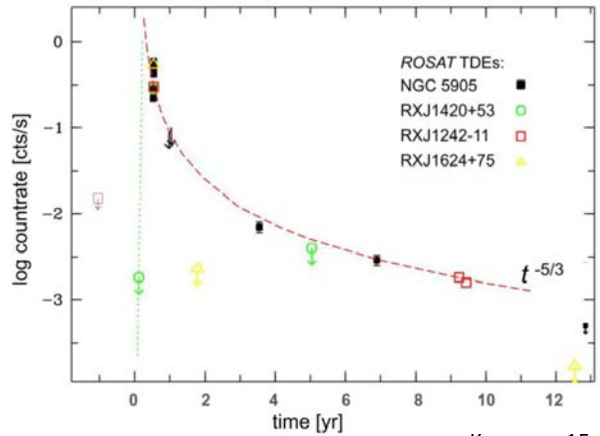
- TDEs provide a unique probe of otherwise quiet SMBH in galaxies. Stellar disruption when the BH tidal force exceeds the self-gravity of the star, half of the star falls in to form an accretion disc at $t^{-5/3}$
  - important in the study of the growth of BHs
- Many found in UV and soft X-rays. The discovery of two luminous hard X-ray TDE shows a relativistic jet can form
  - is this just an inclination effect?
  - a new discovery mode and a chance to study newly-born jets
- TDEs reveal dormant SMBH in galaxies to ~10^8 M_{sun}. Early identification allows is the BH mass and the nature of the star to be inferred: unique analogies of the AGN lifecycle over a few years
- TDEs can be used as tracers of BH mergers. The impact on nearby stars vastly increases the TDE rate ⇒ multiple events per galaxy
- THESEUS is ideal for TDE discovery. For classical TDEs the SXI horizon in a single orbit is ~200 Mpc (z~0.05). Both SXI and XGIS can see relativistic TDEs to z~1 ($L_{peak}=10^{48}$ ergs s^{-1})
- TDE rates ~ 10^{-4} – 10^{-5}/yr/galaxy

Swift J1644 jetted TDE soft X-ray flux



Burrows+ 11

Rosat soft X-ray TDEs

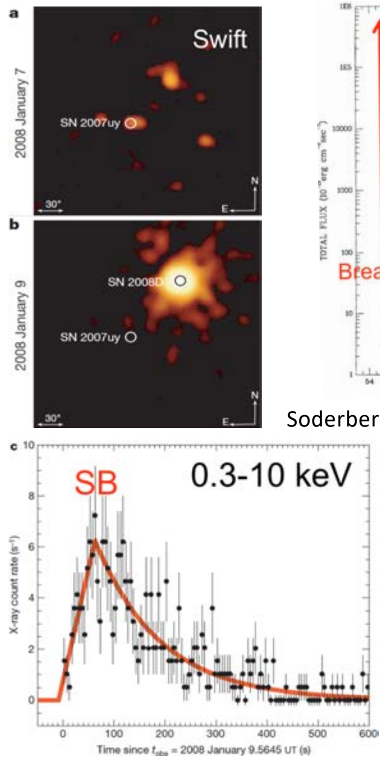


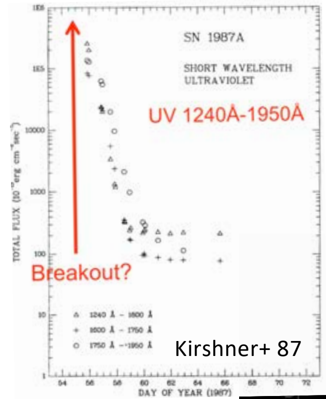
Komossa 15

Supernovae

- The death of massive stars in a core-collapse SNe distributes heavy elements through the Universe
- A new SN produces a burst of X-rays as the shock breaks out of the star, seen only once so far
- Shock breakouts of $L_X=10^{43}$–10^{46} erg s^{-1} for 10–1000 s are expected for Wolf-Rayet stars and red supergiants (the likely progenitors of Type Ibc and most Type II SNe)
- The SXI can detect these out to >50 Mpc.
- Relativistic shock breakout adds to the early X-rays in low-luminosity GRBs, Theseus can measure the breakout radius, constraining the progenitor and light curve physics
- THESEUS will search for the first SN Ia SBO, discriminating progenitor models and the explosion physics (with implications for SN Ia as standard candles). Galactic Ia SBO are seen by the XGIS as short pulses, those in a binary with a red giant wind make X-ray bursts of minutes to hours
- Soft X-ray SBO can constrain the progenitor radius better than optical. Adds value to subsequent studies by Athena.

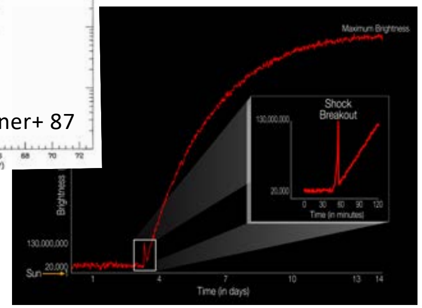
SN 2008D at 27 Mpc



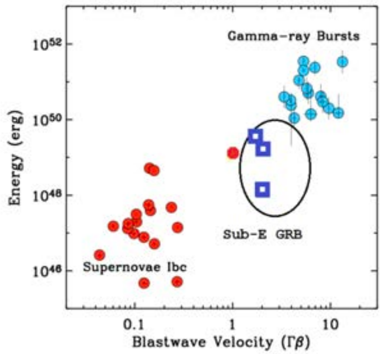


Soderberg+ 08

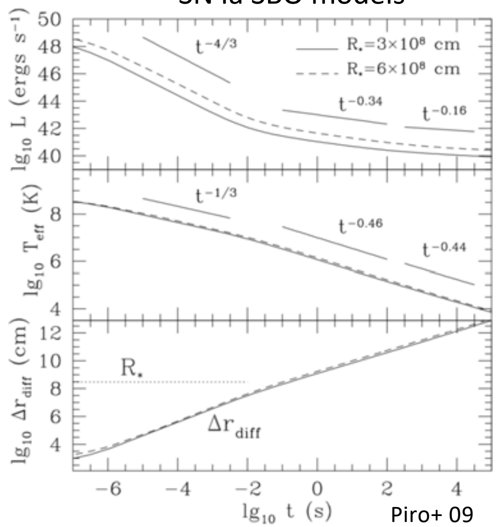
Kepler saw 20 min SNII SBO



SN Ia SBO models



Soderberg+ 10

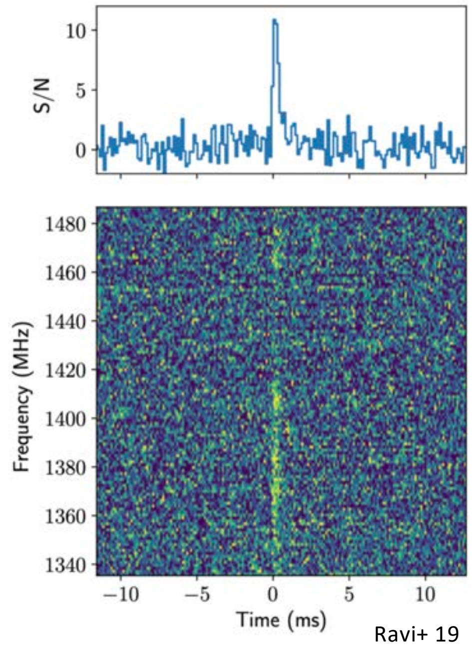


Piro+ 09

Fast Radio Burst Counterparts

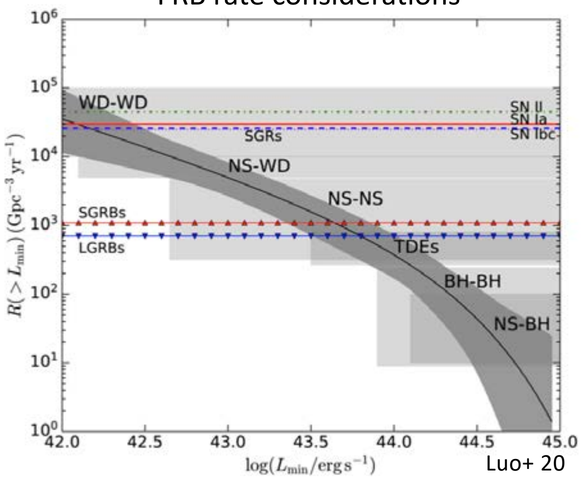
- >100 FRBs known, origin unclear
- Very short timescales (millisec) and large distances imply large energy (10^{38-40} erg) in a small space
- A few repeat – one is periodic
- Many model ideas:
    - Magnetars?
    - sGRBs?
    - High energy SNe?
    - Pulsar magnetosphere transformation by external magnetic field?
    - Axions/strings/BH magnetosphere collapse?
- Old and young hosts: multiple types?
- CHIME now finding large numbers of FRBs

FRB 190523 in low SFR galaxy
PSO 207+72 at z=0.66



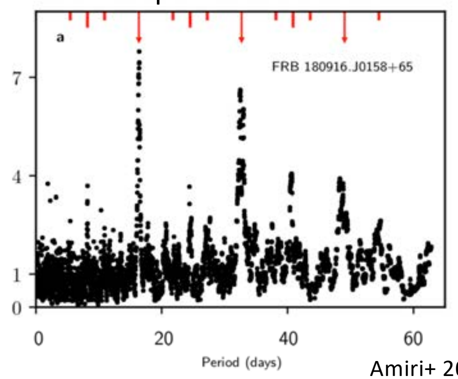
Ravi+ 19

FRB rate considerations



Luo+ 20

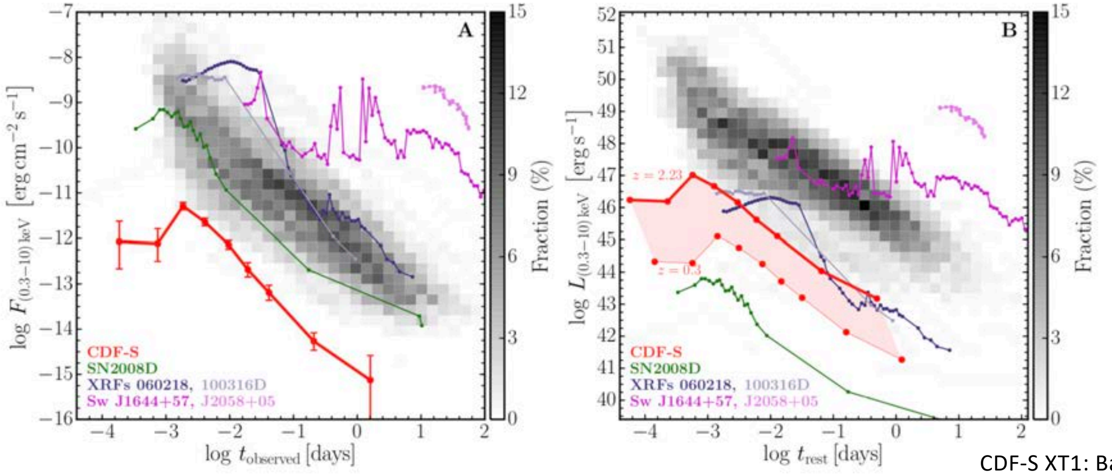
16.35 d period in FRB 180916



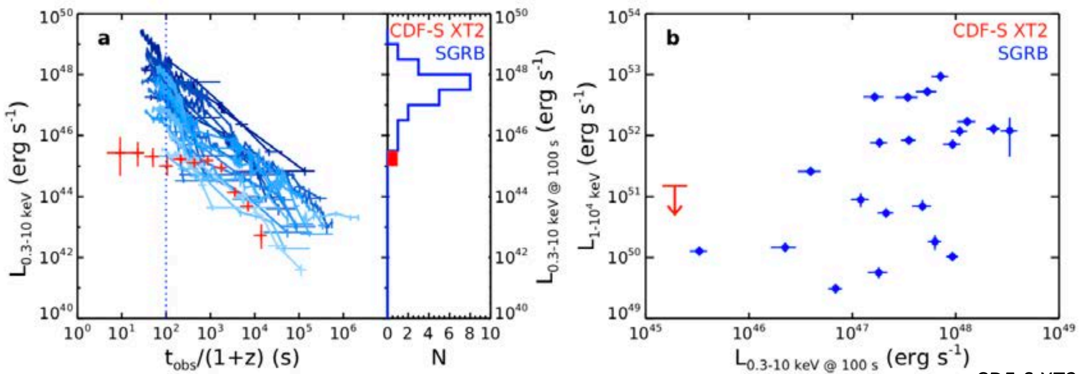
Amiri+ 20

Fast X-ray Transients

- 100 s rise, 3 hr duration X-ray outburst found in Chandra deep field south (Bauer+17)
- Not seen before or after at any wavelength: m_R > 25.7 80 mins after
- z ~ 2.2 (CANDELS SED); dwarf galaxy
- L_peak = 7x10^{46} erg/s
- Of known classes, only orphan GRB afterglow, LLGRB or jetted TDE viable
- Rate < 4/deg^2/yr
- This one faint for SXI, but brighter OK
- High discovery rate possible
- 2nd similar object (Xue+ 19) with 45 s rise at z = 0.7 identified with rapid spin-down of newly formed ms magnetar
- Dedicated Chandra archive search (Yang+ 19) gives 13 objects total: 60/deg^2/yr
    - all new 11 are stellar flares
    - extragalactic rate for EP ~ 150/yr (SXI similar)



CDF-S XT1: Bauer+ 17

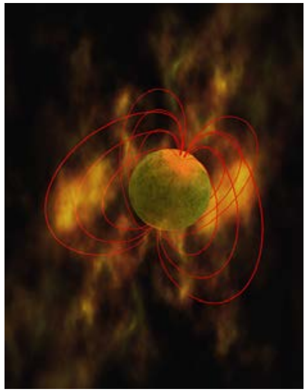


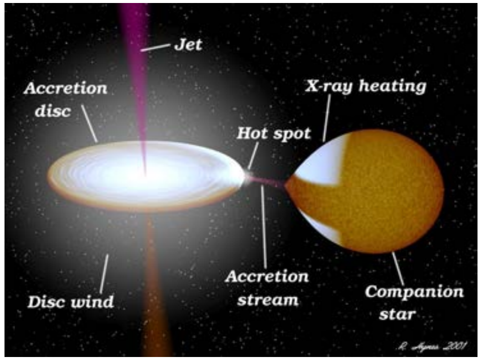
CDF-S XT2: Xue+ 19

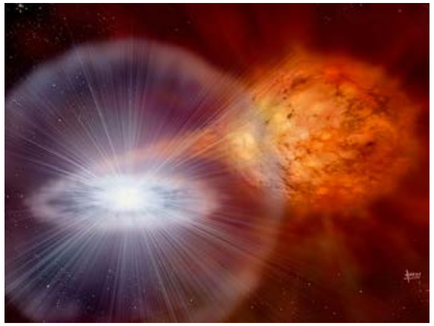
Potential Galactic transients/variables

- Accreting NS/BH binaries
    - LMXRBs
    - HMXRBs
        - SFXRTs
    - Bursters
        - Super-bursts
- Accreting WDs
    - Novae
    - Magnetic CVs
    - Non-magnetic CVs
- Magnetars/AXPs, …
- Stellar coronae
    - Super-flares

NB L_{Edd} @ GC: f_{Edd} ~ 3×10^{-8} cgs

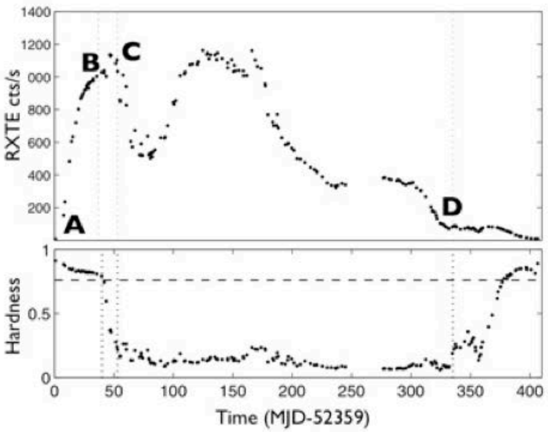




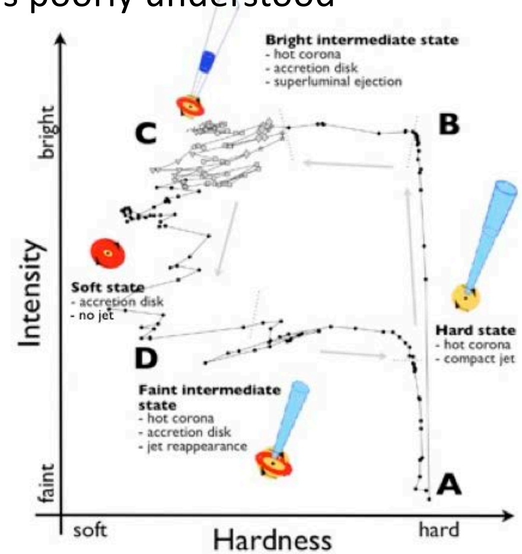


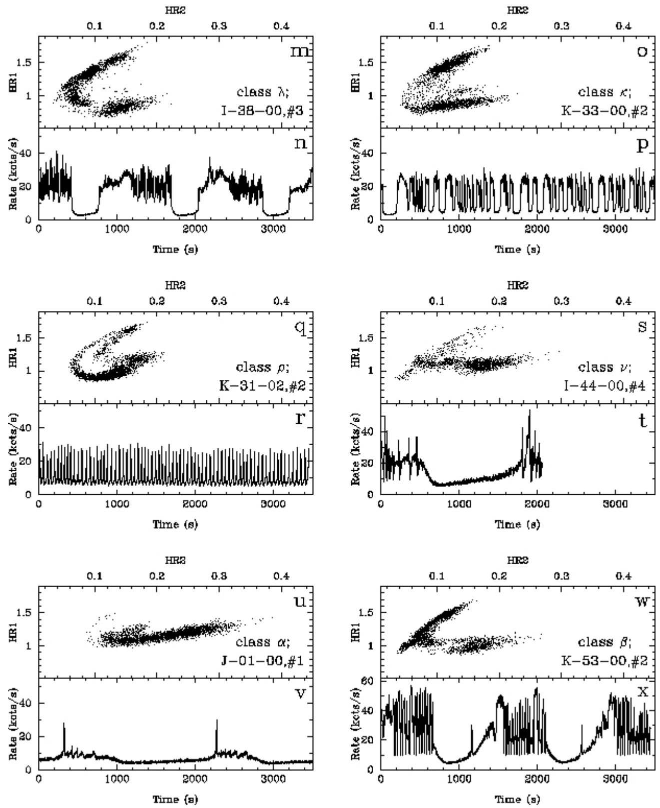
Low Mass X-ray Binaries

- NS/BH in few-hour orbit with, and accreting from, a near-MS companion
- BH systems are X-ray novae (75% of XRN are BH):
  - ~ decades between outbursts
  - outbursts due to viscosity increase in accretion disk
  - study jet mechanism, irradiation mapping, inner disk thermal & non-thermal emission, IRT SED evolution, SXI-XGIS spectra
  - micro-quasars are a link to AGN
    - Large range of variability types poorly understood



CHAOS; Belloni+05

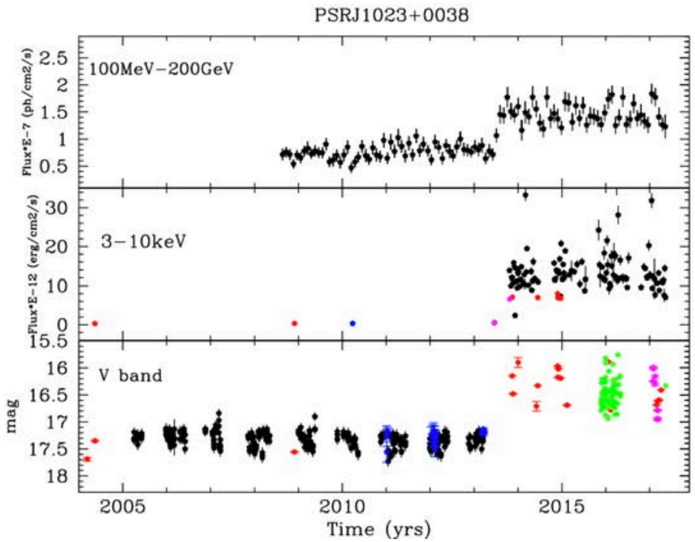


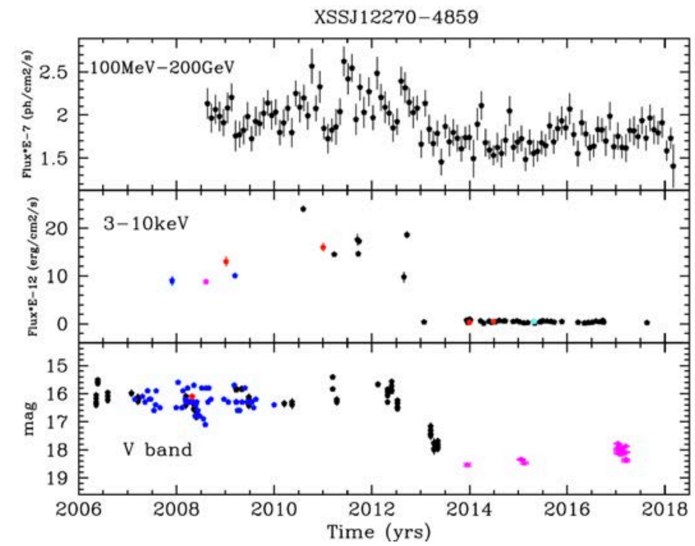


Microquasar GRS1915+105 – Arne Rau

Millisecond X-ray pulsars

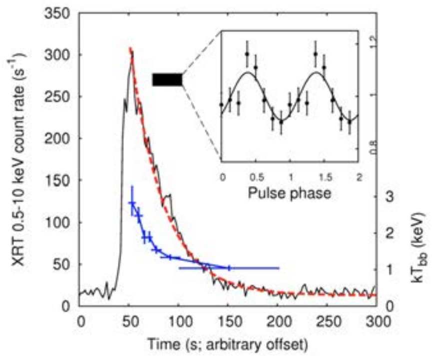
- Neutron star millisecond pulsar binaries and transitional millisecond pulsar binaries are strong X-ray sources at high accretion rate but can be radio pulsars if accretion drops
- Important to observe their long-term X-ray behaviour
- Aim to see them going from radio (rotation-power) to disk-state over days-months, followed by months-years in one of the states
- Outbursts going to 10^{36} erg/s have so far been observed in one transitional MSP (M28) (Papitto+ 13)
- THESEUS will catch many in globular clusters (which likely are those having also outbursts)
- Can lead to tests of the physics of NS spin-up by disk accretion





De Martino, priv comm

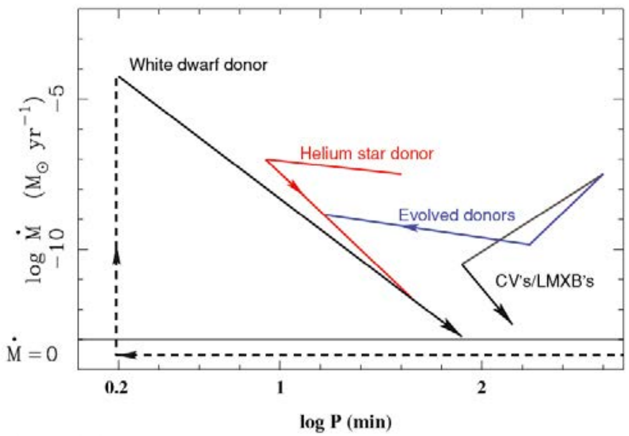
254 Hz spin modulation seen in X-ray burst from IGR J18245-2452
Papitto+13

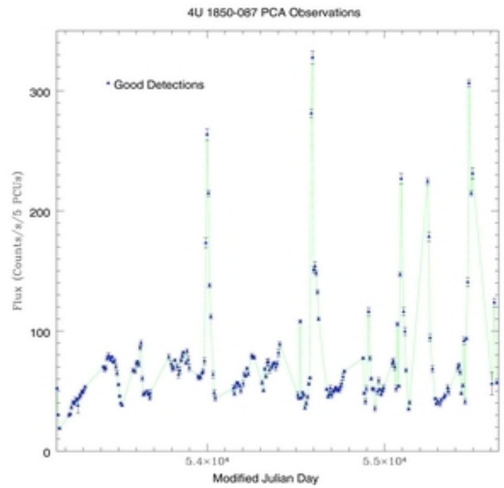


Ultra-compact X-ray binaries

- Orbital period < 1 hour
- H-poor accretion onto neutron star
- Lx ~ 1% Eddington
- Rare: large fraction in globular clusters
- High fraction of msec pulsars
- Interesting:
  - LISA GW sources
  - unique chemically peculiar accretion physics
  - probes of binary evolution (CE phase)
  - He/CO/ONe WD donor?
  - low-luminosity SN I progenitors?
- AM CVn systems are accreting WD counterparts

UCB evolutionary scenarios. Nelemans+ 10

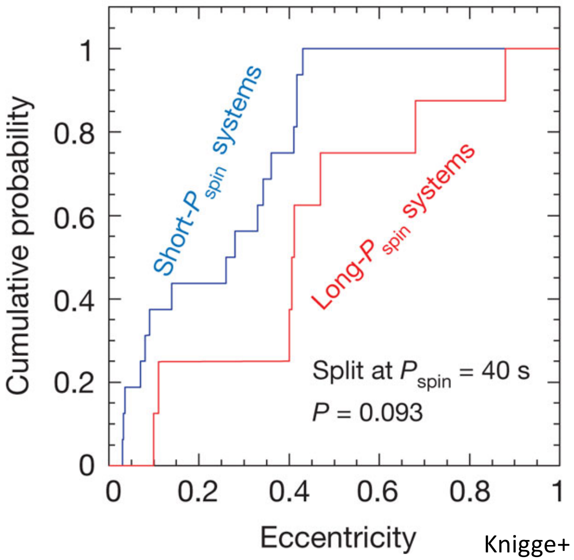




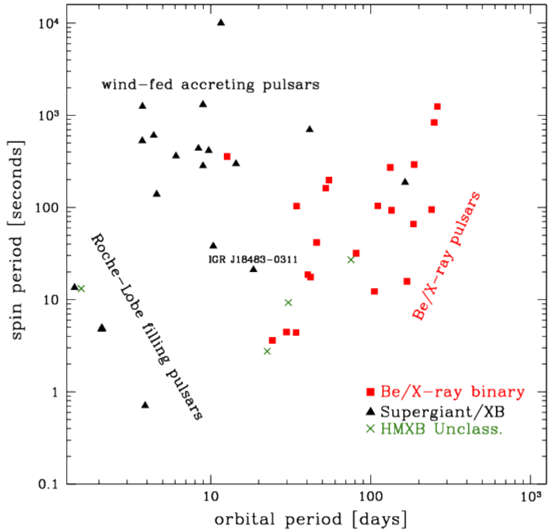
X-ray flares in UCB 1840-087. Cartwright+13

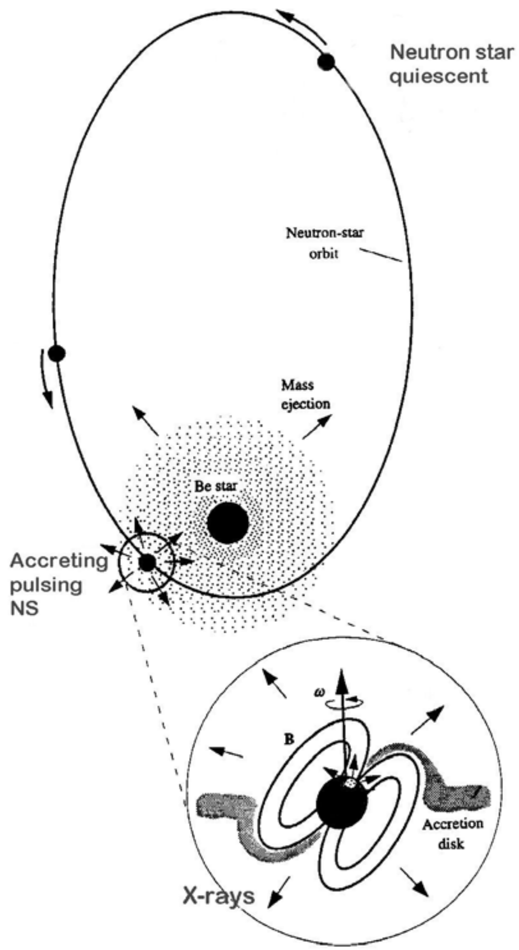
High Mass X-ray Binaries

- Companion mass > 10 Msun
- Transient X-ray sources: $L_X \sim 10^{37}$ cgs
- Wide & eccentric orbits
- Accretion from Be star equatorial disk: test of accretion physics over large rate range
- Spin, orbit and disk precession periods seen
- Corbet diagram: multiple formation channels



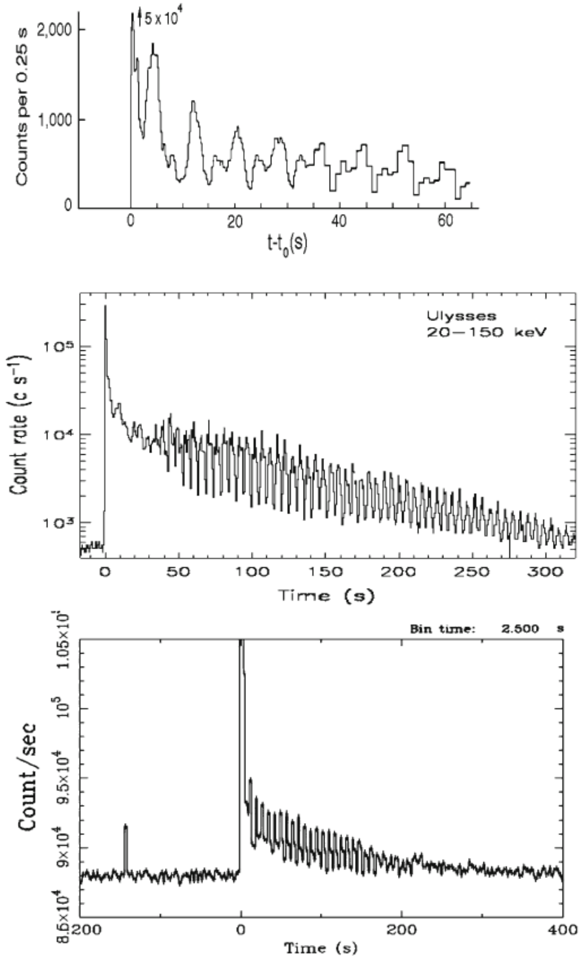
Knigge+ 11





Magnetars

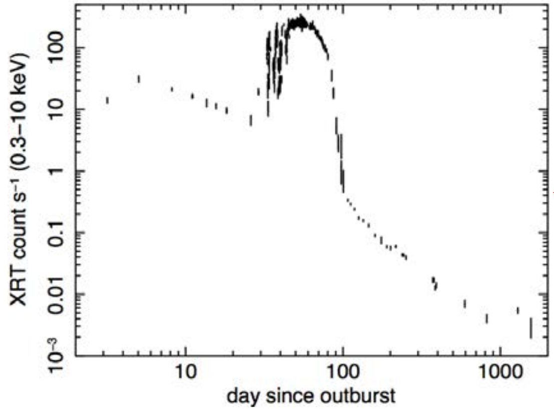
- Young INS with B ~ $10^{13\text{-}15}$ G, 100-1000x typical pulsars
- Highly super-Eddington bursts (SGRs) and rare giant flares (up to 10^{47} erg/s) with QPOs
  - AXPs are persistent counterparts, with a soft X-ray spectrum, Lx~10^{35}
- Impulsive dissipation of magnetic energy with low duty cycle
  - 29 known (McGill on-line cat)
  - likely large population still to be discovered (Mereghetti AAR 2008)
- Intermediate flare evolution to be studied with SXI – an ideal wide-field soft X-ray science case
- Magnetars hypothesized in GRBs/SNe
  - properties key to a range of areas



SGR giant flares: 0526-66, 1900+14, 1806-20.
Mereghetti 08

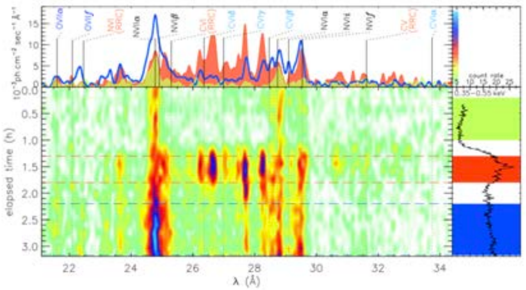
Classical & Recurrent Novae

- Thermonuclear runaway of accreted matter on a WD
- Some are candidate SN Ia progenitors: do WDs grow?
- All repeat: classical novae ~ 10^4 y, recurrent novae <100 y
- Bright hard and soft X-ray emission from ejecta shocks & hot WD
  - Super-soft source on-time: ejecta properties
  - SSS off time: residual burning mass
  - SSS temperature: WD mass
- Shock emission also seen in radio & by Fermi LAT
  - points to structured ejecta
- TNR shock breakout not seen so far:
  - M31 nova search @ 6 hr with Swift XRT
  - SXI well suited

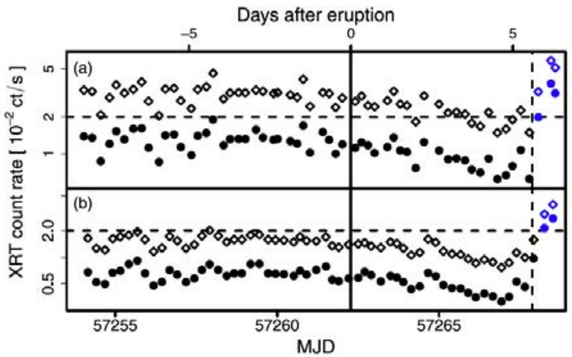


SXI 2000 s sensitivity

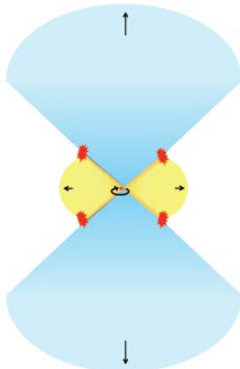
RS Oph. Osborne+ 11



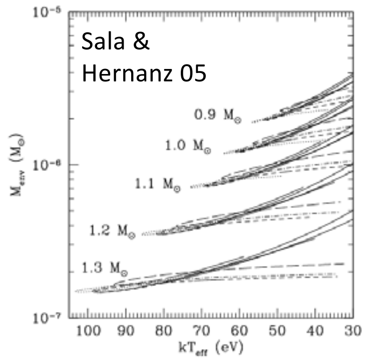
Great XIFU synergy: Ness+ 18



Kato+ 16



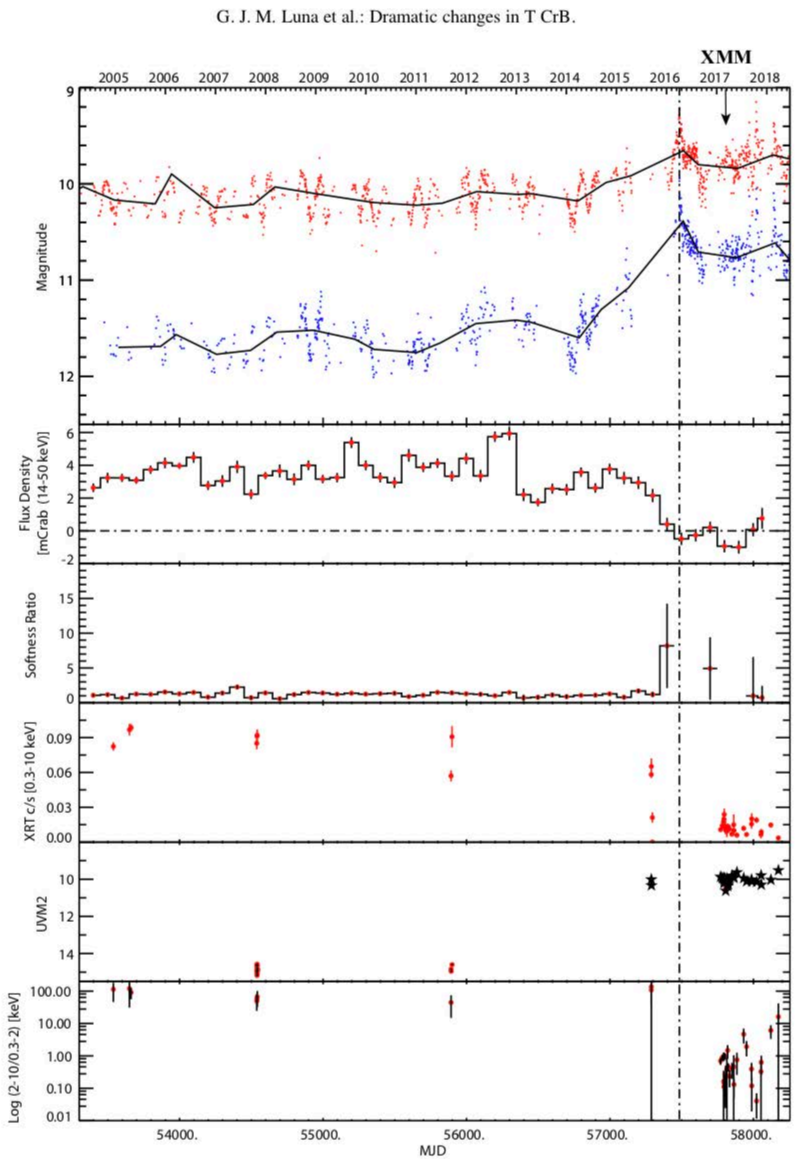
Chomiuk+ 14



Cataclysmic Variables

- White dwarf accreting from a binary companion
- Rich phenomenology, variability on sec - yrs
- Optically bright
- Excellent laboratories for accretion disk physics
- Symbiotic systems especially poorly understood:
  - wide binaries with NS/WD/MS? accretor
  - strong test of disk models due to large size
  - disk instability powered novae?

- CVs with SXI flux >4 10^{-12} erg/cm^2/s as measured by the Swift 2XSPS catalogue, cross-correlated with Ritter & Kolb CV catalogue
- These span 90 – 3000 pc
- $L_X > 10^{31}$ erg/s
- ~40 fall in 5c exposure regions
- 10 ksec per detection
- Brightest also accessible by XGIS
- All visible to IRT



Luna+ 18
A&A 619 A61

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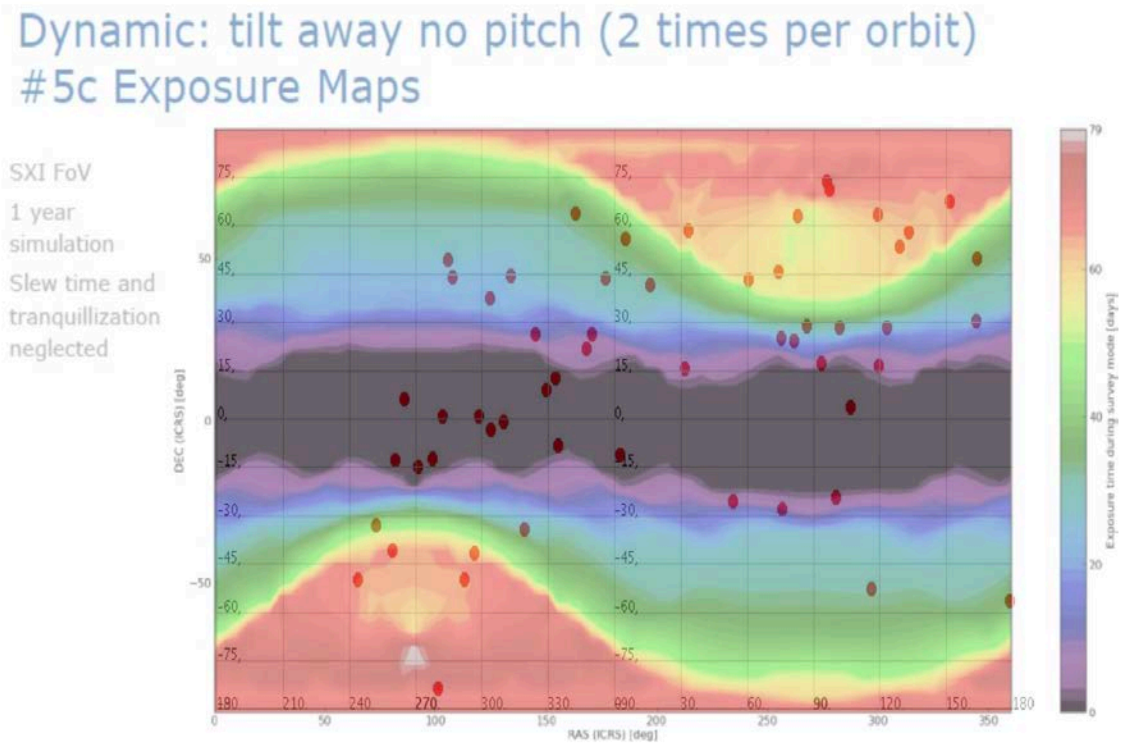


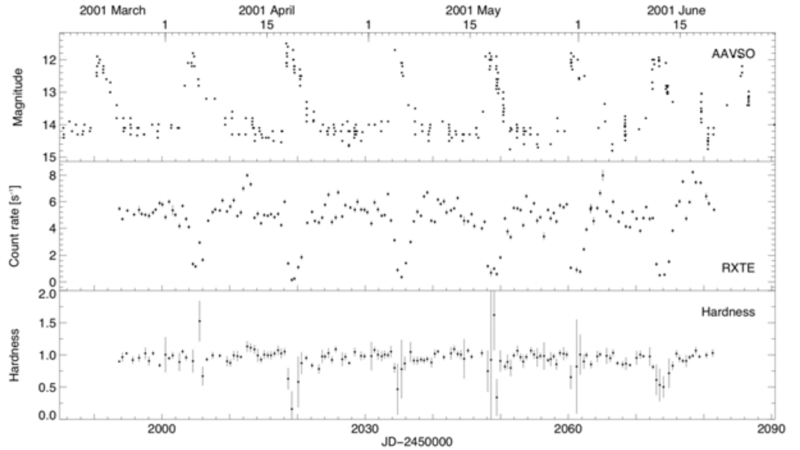
de Martino, priv comm

Non-magnetic Cataclysmic Variables

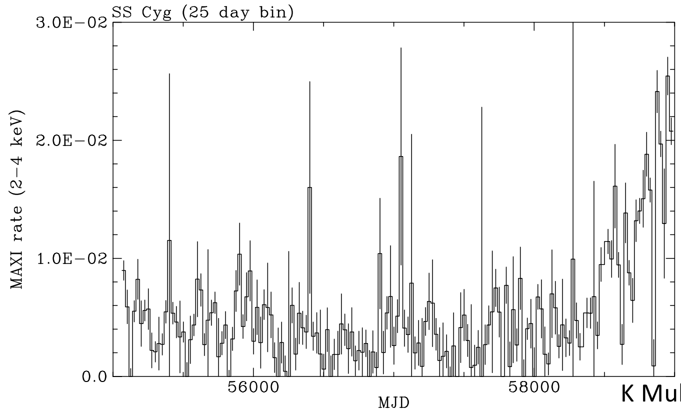
Littlefair+/Science 06

- Disk reaches close to WD surface
- Outbursts due to disk ionization/viscosity instability
  - ultra-soft optically thick boundary layer in outburst rarely seen
  - origin of harder X-ray emission in outburst unclear
  - X-ray/optical ratio from outburst to quiescence not uniform
  - Circumstances of radio jet launching unclear
  - extreme systems with secondary evolving to a brown dwarf (WZ Sge type) have very rare huge outbursts ($\Delta m \sim 8$)
    - poorly understood, possible missing inner disk
- SXI can see brightest Dwarf Novae in each pointing
  - long-term X-ray monitoring is largely unexplored
    - e.g. MAXI slow rise of SS Cyg over ~2 years (Negoro+ 20)
      - why doesn't boundary layer go into high state?
    - search for super-orbital periods as seen in X-ray binaries
  - behavior of quiescent emission through outburst cycle important for disk instability model
    - predicted X-ray rise in quiescence not seen
    - high quiescent flux hints missing inner disk
- IRT photometry constrains the outer accretion disk state

Dwarf Nova SU Uma



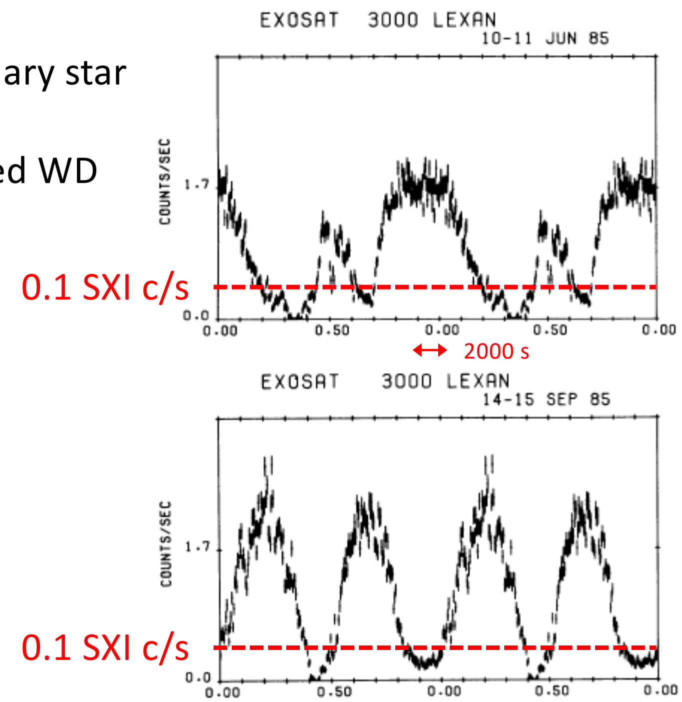
Collins & Wheatley 09



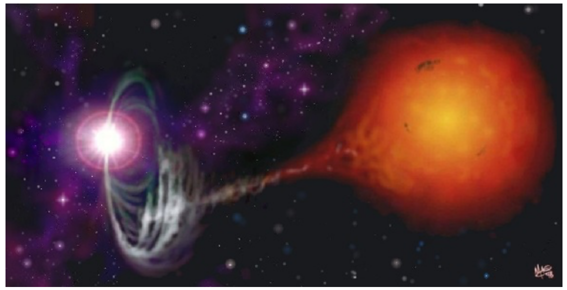
K Mukai, priv comm

Magnetic Cataclysmic Variables

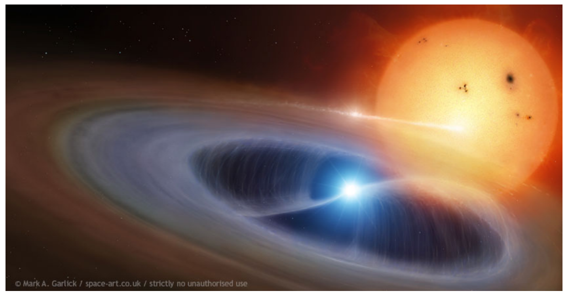
- Accreting WDs in which WD magnetic field dominates flow
- Variable rather than transient
- Polars have no accretion disk
    - state changes due to secondary star
        - frequency unknown
    - bright soft X-rays from heated WD
    - WD spin locked to orbit
- Intermediate polars have some sort of accretion disk
    - reduced disk outbursts due to missing inner region
    - allows study of disk instability model
    - spin-modulated absorption probes accretion curtains



Polar (QQ Vul) state change in soft X-ray folded light curve. Osborne+ 87



Polar. © Garlick 98

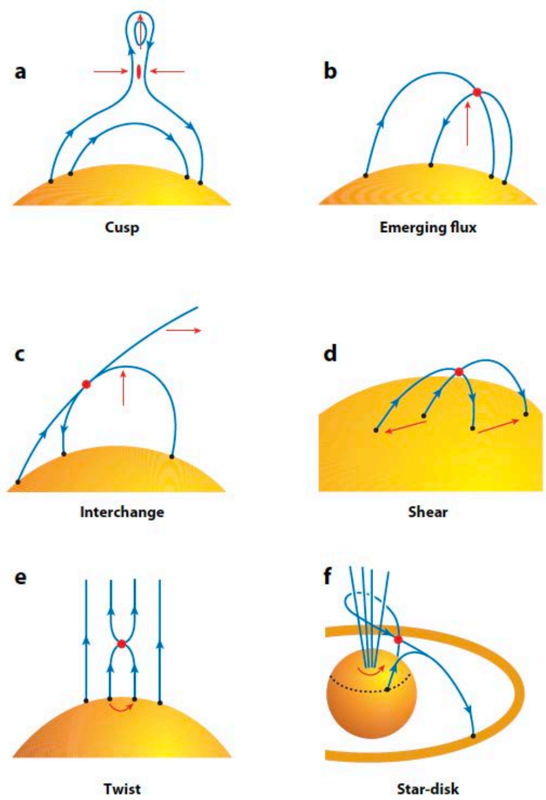


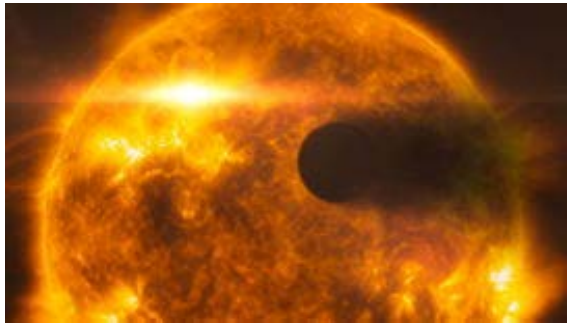
Intermediate polar. © Garlick 98

Stellar Coronae

- Güdel ARA&A 2004, Benz & Güdel ARA&A 2010:
    - How are coronae heated & structured?
        - SXI: systematic study across the HR diagram
    - What is the physics behind flares?
        - SXI: huge numbers of flares observed
    - How does magnetic activity evolve?
        - SXI: accretion in YSOs
    - How do magnetic fields and flare X-rays affect the environment?
        - SXI: activity vs planet formation
- Now we can add:
    - What are the impacts of activity for life on exoplanets?
        - Theseus: Simultaneous SXI & IRT study

- Stellar coronae expected to be the dominant SXI source population

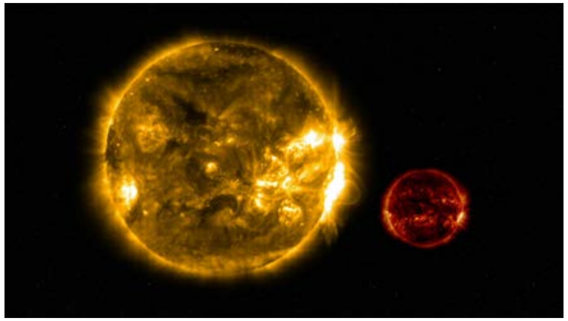



Exoplanet atmosphere eroded by stellar flaring.
Lecavelier+ 12

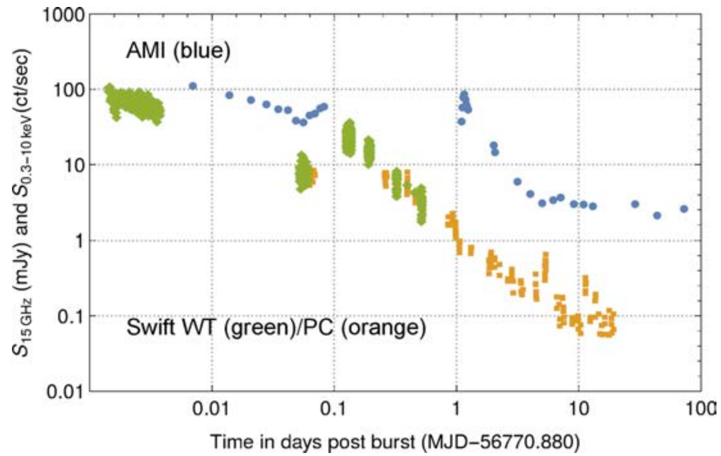
Stellar Coronae – super-flares

- Exceed the star's luminosity. 10,000x solar flare energy: up to 10^{38} ergs
- Detected up to tens of keV
- Can occur on Sun-like stars
- Thought to be very rare:
    - Algol, AB Dor, EV Lac, UX Ari, II Peg, DG CVn, CC Eri
    - but some have frequent SFs: up to 10% of days (Shibayama+ 13)
- Associated with large star spots?
- Used to study magnetic field strength and configuration, abundance anomalies, particle energy dissipation
- Prompt radio follow-up probes particle acceleration

- SXI is ideal discovery and follow instrument
- XGIS will constrain total energy
- IRT can trace optical flare decay



DG CVn is a dim red dwarf. NASA



Prompt radio/X-ray super-flare on DG CVn. Fender+ 15