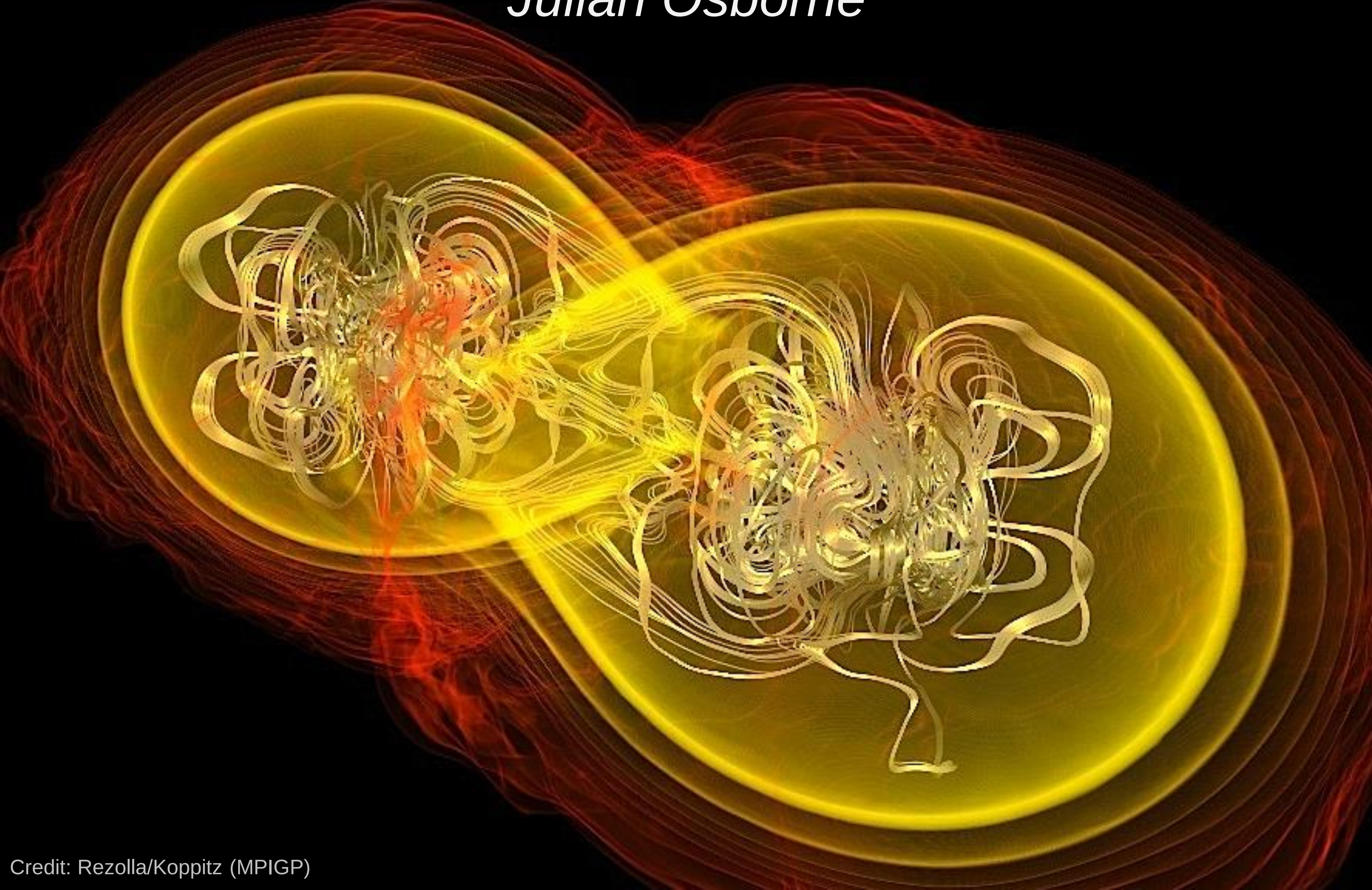
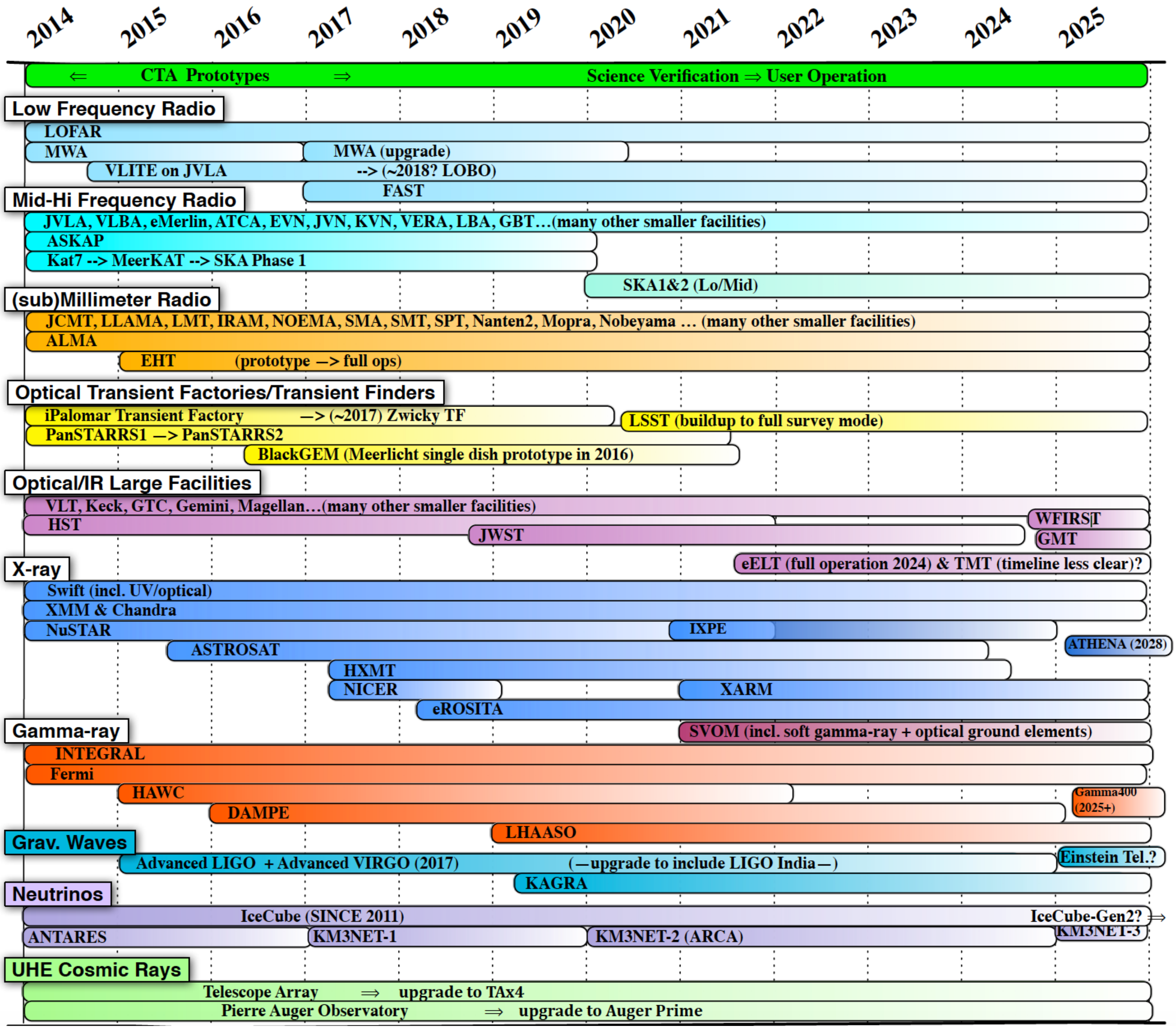
# Time Domain Astronomy

*Julian Osborne*



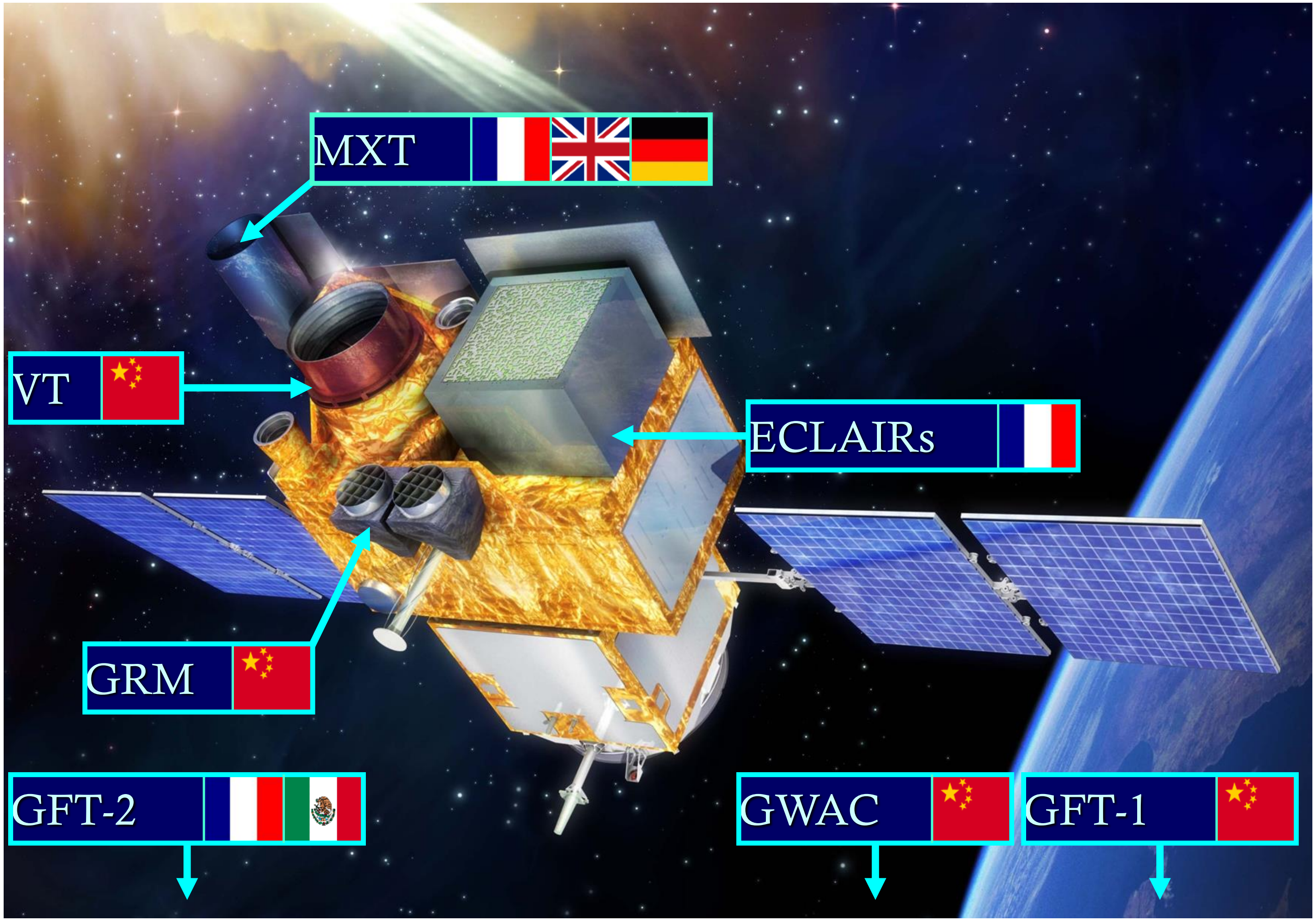
Credit: Rezolla/Koppitz (MPIGP)




'Science with CTA', arXiv:1709.07997

# SVOM

## (China-France + Leicester & MPE; Launch 2021)




Swift-like mission, but with GRM, 1 deg FOV X-ray telescope and a red-sensitive optical telescope (plus dedicated ground-based telescopes)

# Einstein-Probe 爱因斯坦探针

PI: Weimin Yuan (NOAC), IHEP, Tsinghua Uni, MicroSat (+Leicester)
Chinese medium-class mission

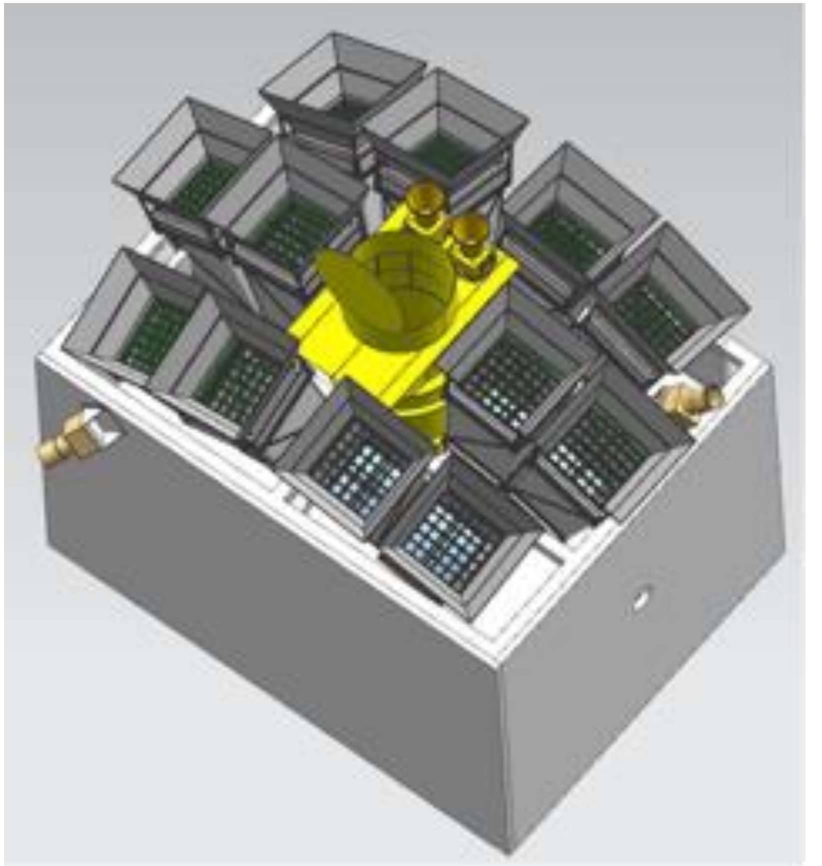
Science case:
- Find the EM counterparts to Gravitational Wave sources
- Systematic census of the X-ray transient sky (whole sky every 3 orbits)

Payload
- WXT: 3600 sq deg FOV (CMOS detectors)
- FXT: 1 degree FOV

Rapid slew and fast alert downlink

Launch: 2022

Lobster focussing optics, so much more sensitive than a coded mask or GBM-like device (x10 – x100 previous all-sky monitors)



# ISS-Transient Astrophysics Observer

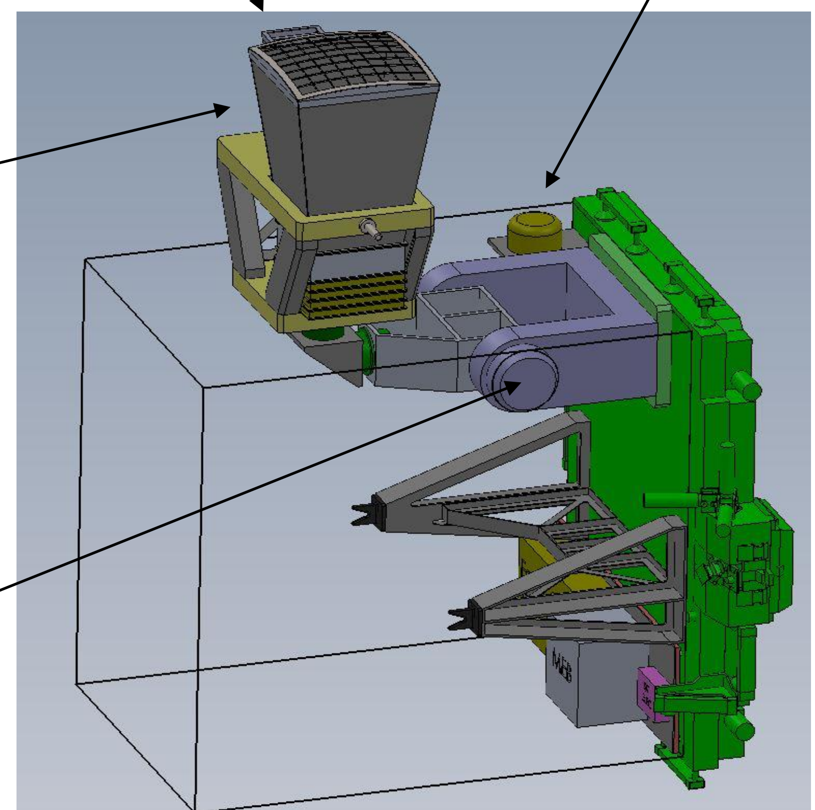
Under study as NASA MOO
Downselect due in 2019
Could fly in ~2022

Mounted on a pivot arm

**Star Tracker**

**Gamma-Ray Transient Monitor (GTM)**
**50 keV to 1 MeV**
**Technion, Israel**

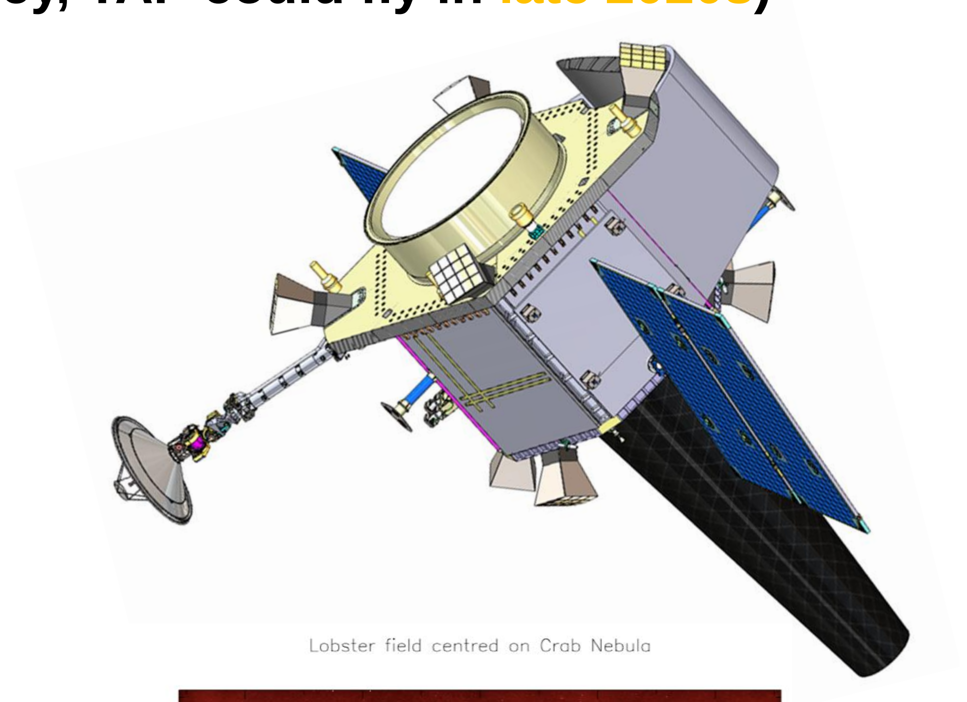
**Wide Field Imager (WFI)**
**FoV: 0.12 sr = 410 sq deg**
**Resolution = 1 arc min**
**Energy Range: 0.3 - 6 keV**
**Detectors: CCDs**
**Optics: Microchannel plates**
**$10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (2000 sec)**



**Pointing System**
**1 arc min**

# Transient Astrophysics Probe proposal

**(If supported by the US Decadal Survey, TAP could fly in late 2020s)**



Lobster modules (4-6)

- 500 $deg^2$ each
- $10^{-11}$ $erg/cm^2/sec$ in 2000 sec

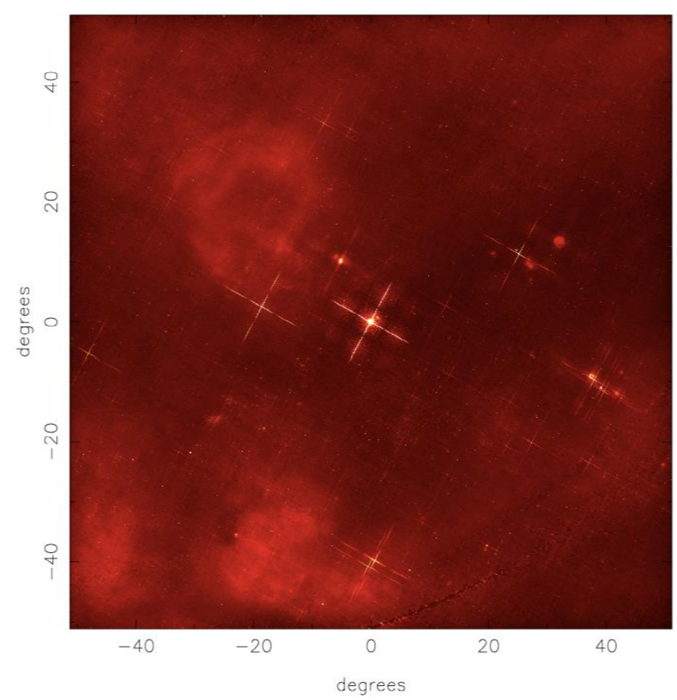
IR Telescope

- 1 $deg^2$
- 0.6 – 2.5 micron, 80 cm diameter
- 23-24 Mag across waveband in 500 sec

X-ray Telescope (single crystal silicon mirror)

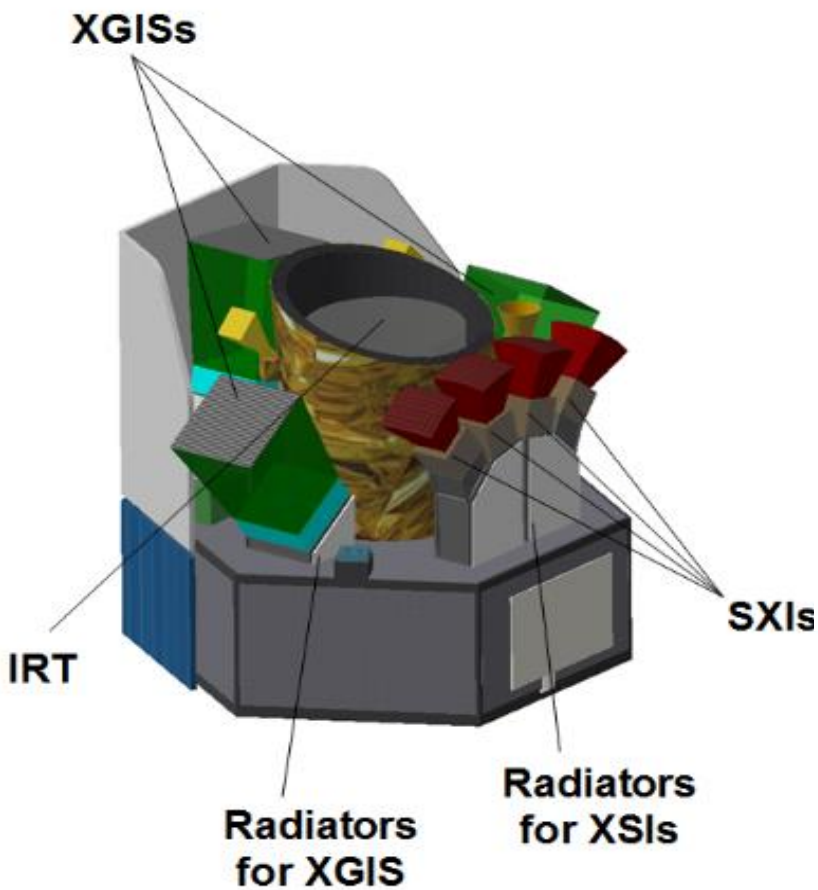
- 1 $deg^2$
- 3 x $10^{-15}$ $erg/cm^2/sec$ in 3000 sec

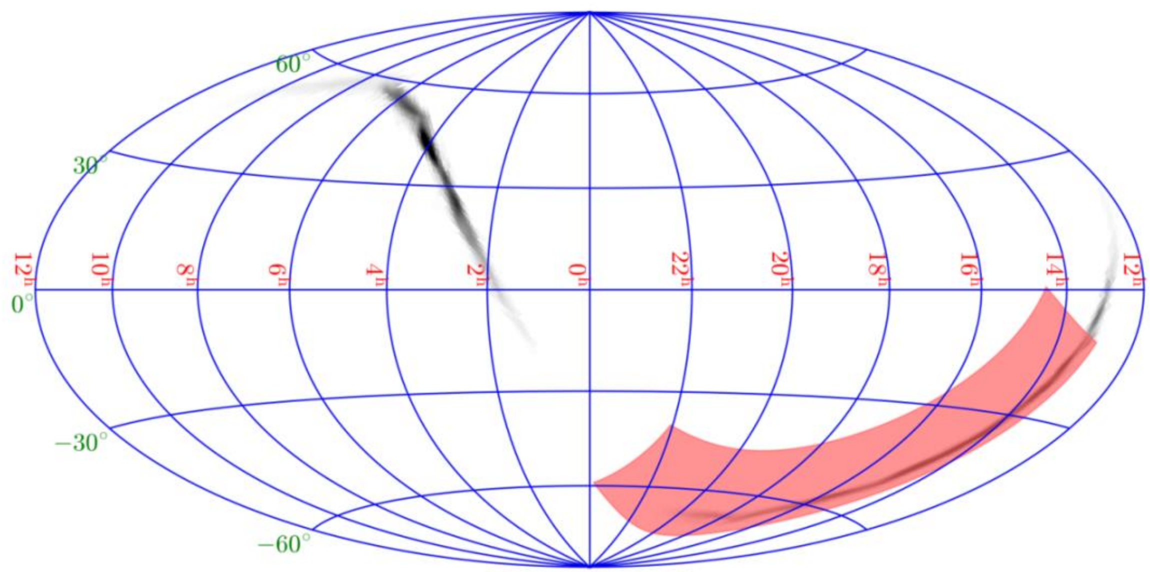
Lobster field centred on Crab Nebula



# ESA M5: THESEUS (launch 2029)

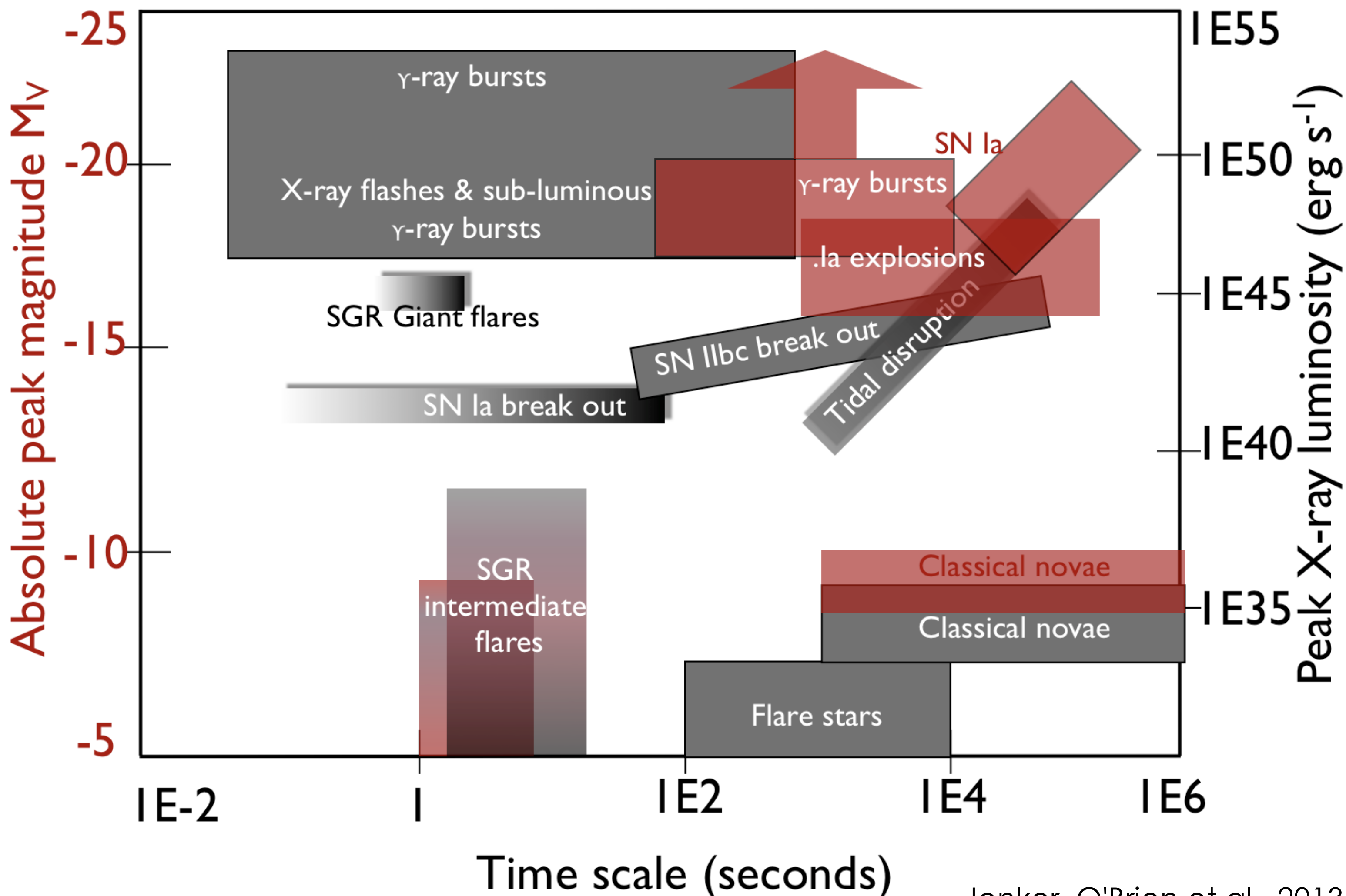
- **Soft X-ray Imager (SXI):** Lobster-Eye X-ray (0.3 - 6 keV) telescopes with CCD detectors. Total FOV of 3200 sq. deg. UK led consortium.
- **InfraRed Telescope (IRT):** 70 cm near-infrared telescope (IRT), 0.7-1.8 μm imaging and moderate spectral resolution. French led consortium.
- **X-Gamma Imaging Spectrometer (XGIS)**: Based on SDD+CsI. Total FOV 7800 sq. deg. Extends high-energy band up to 20 MeV. Italian led consortium.




The SXI could observe a large GW error region very quickly. Example: GW151226

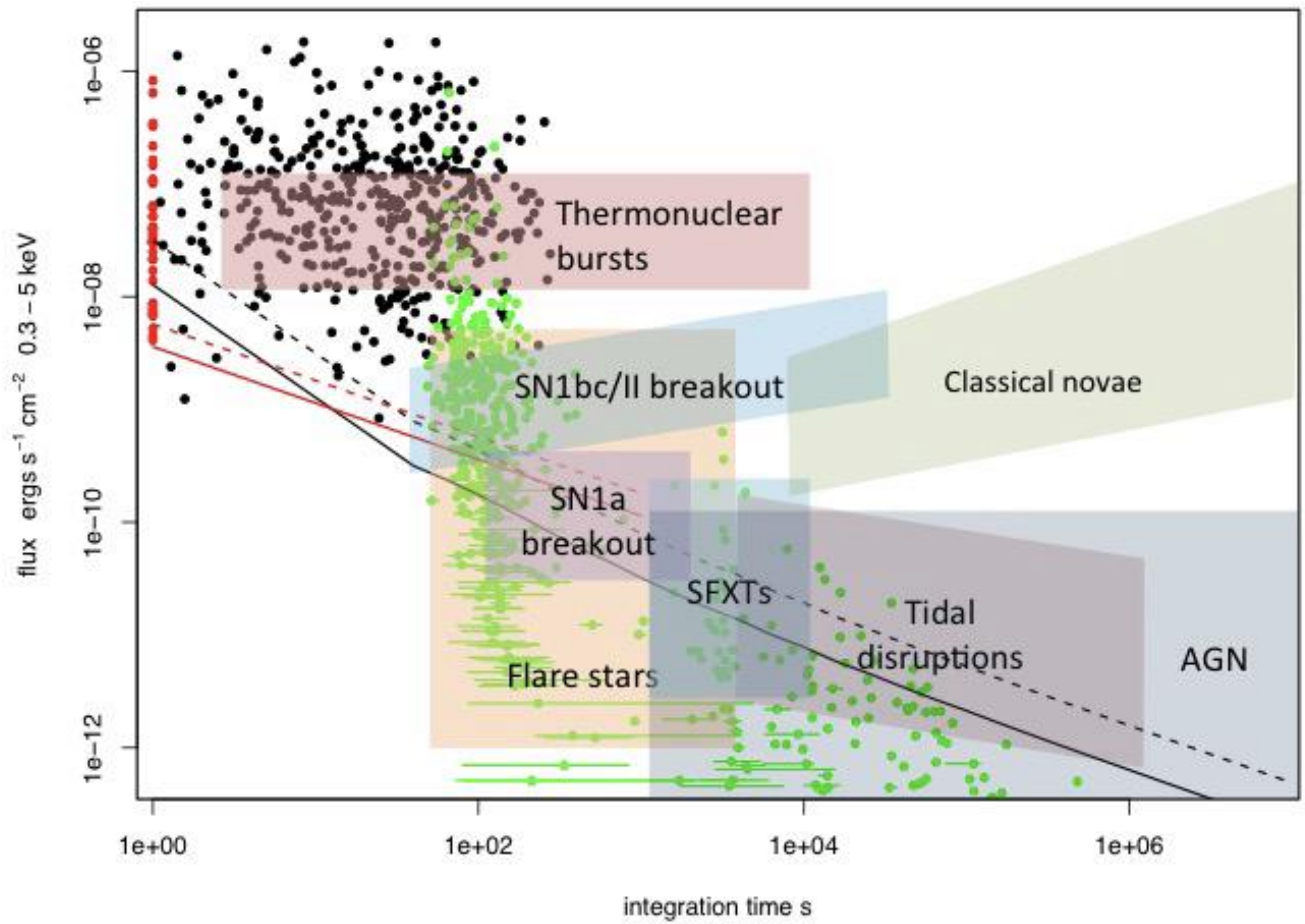
# Explosive transients



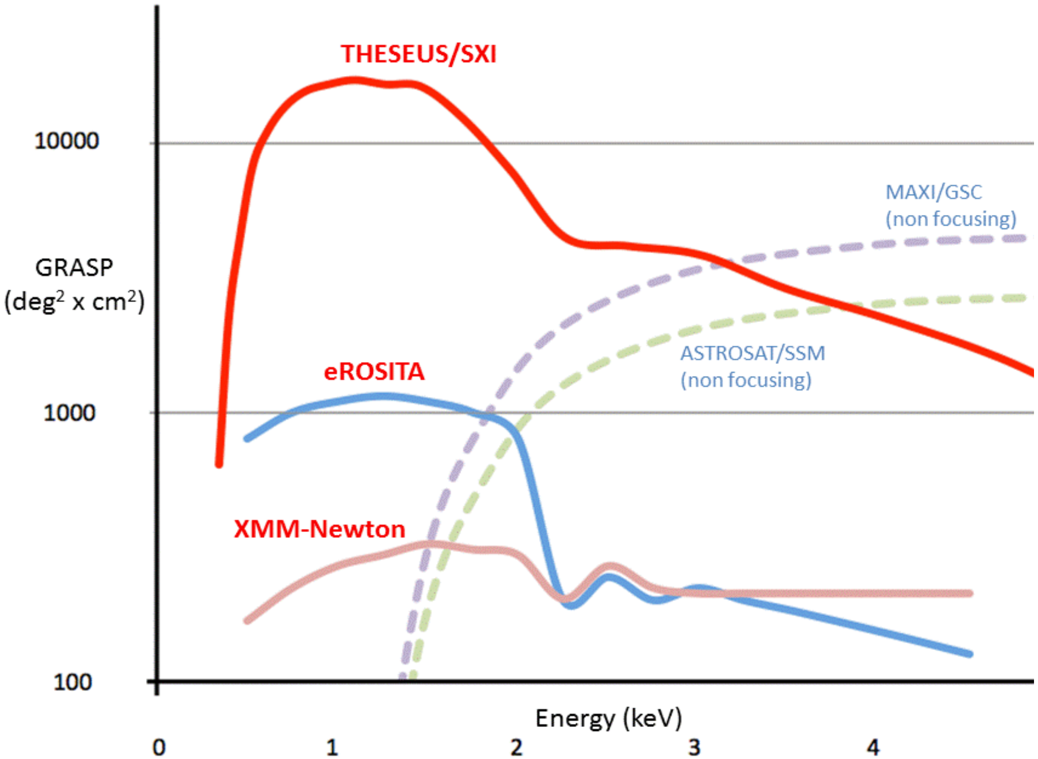

Jonker, O'Brien et al., 2013 arXiv1306.2336
*Luminous extragalactic transients*

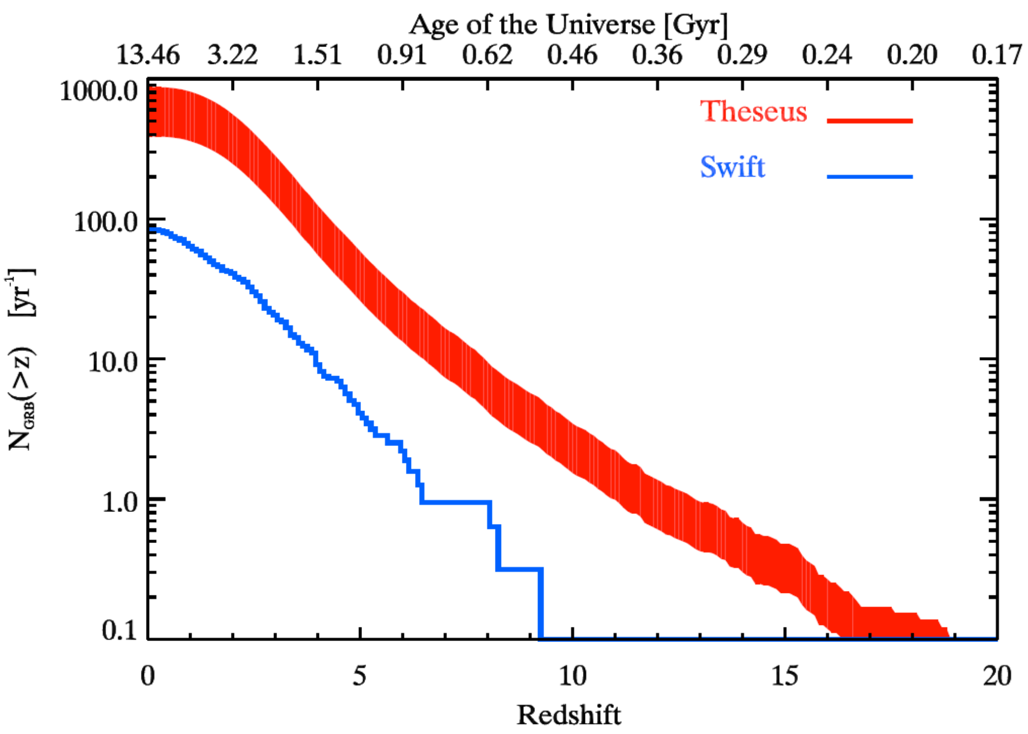
At all redshifts GRBs and TDEs are the most luminous (rare) HE transients
(also bright in flux, particularly in short exposures – less confusion than in optical/IR)

# SXI sensitivity



# Survey machines



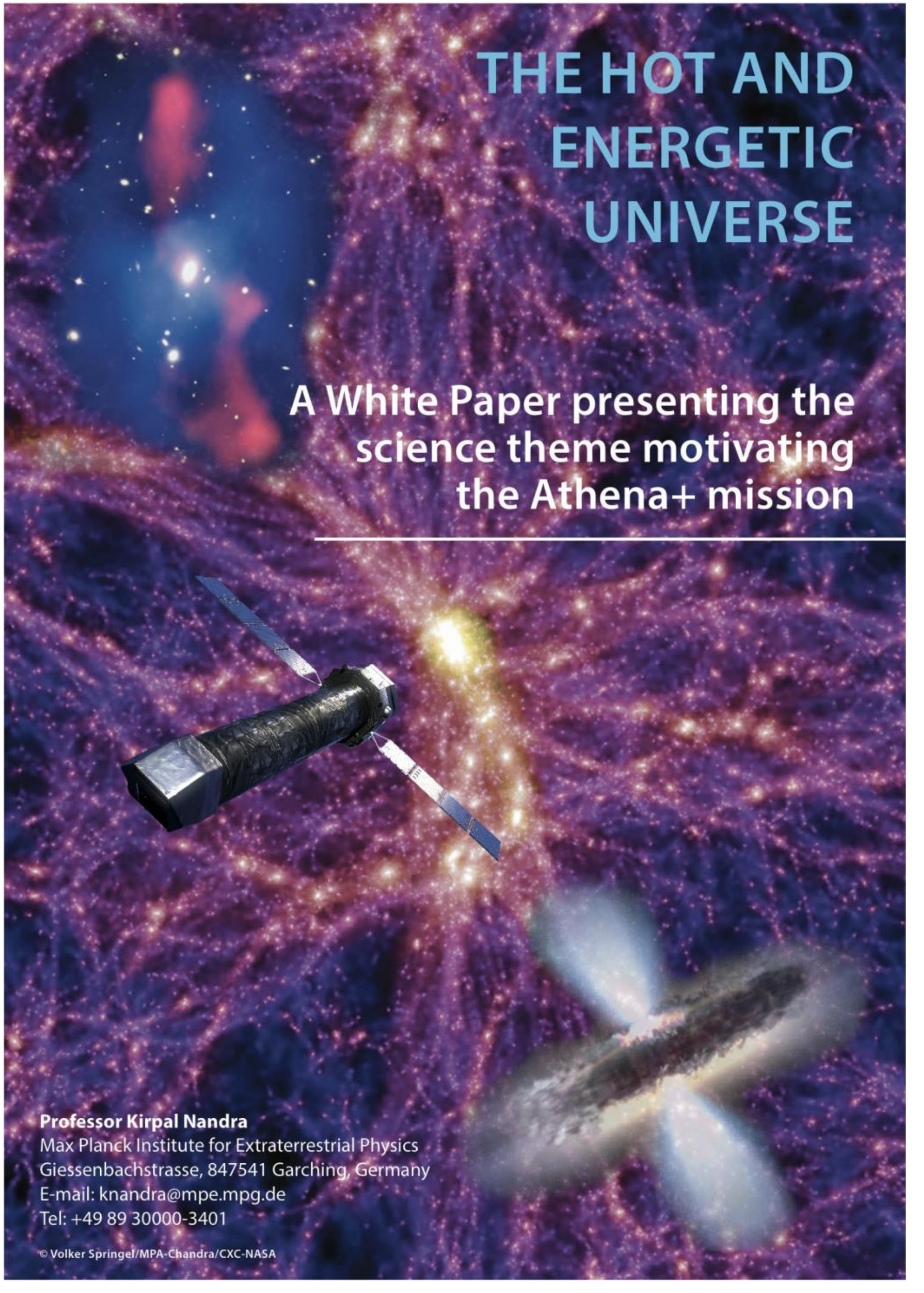

Facilities like THESEUS, Einstein Probe, TAO and TAP have huge GRASP in soft X-rays and hence they would detect very large numbers of transients, including X-ray transients current facilities may not be sensitive to.

Athena is a tremendous machine for high energy astrophysics

It has utterly unique capabilities

There are no alternatives that give us the wide and detailed view of Athena

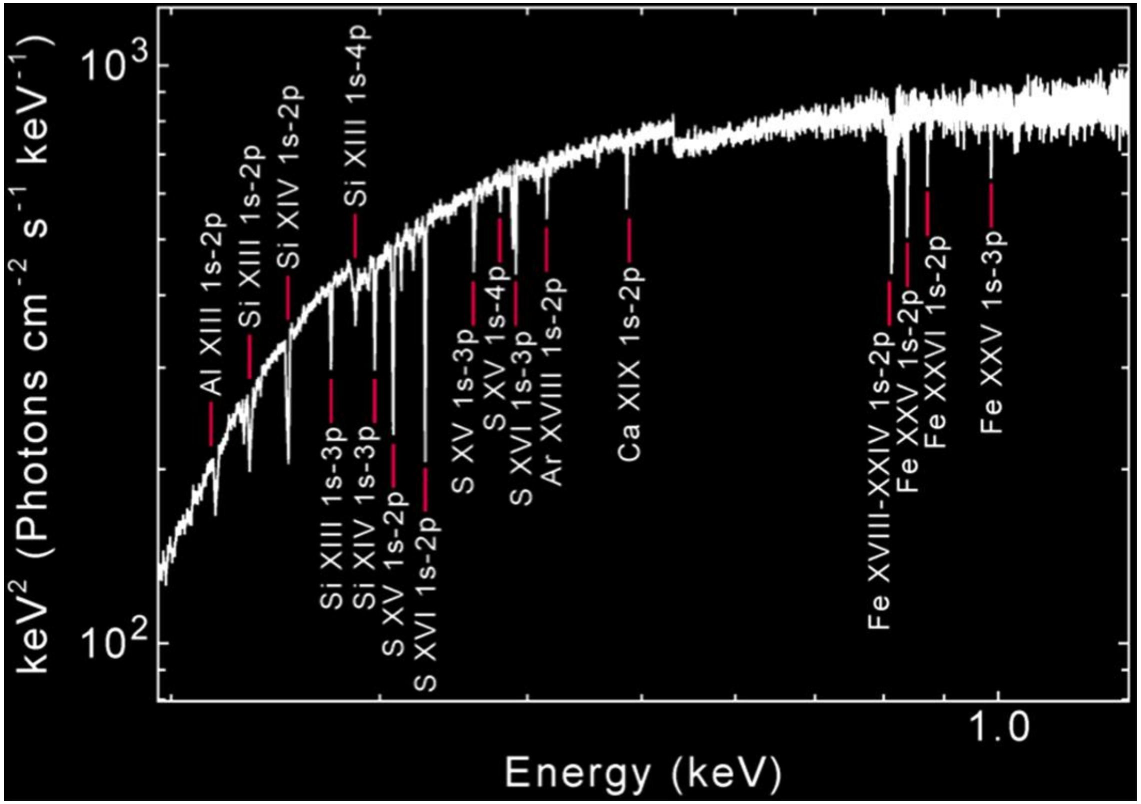
It is essential that Athena gets all the support that the scientific community can give it




https://arxiv.org/abs/1306.2307 ++

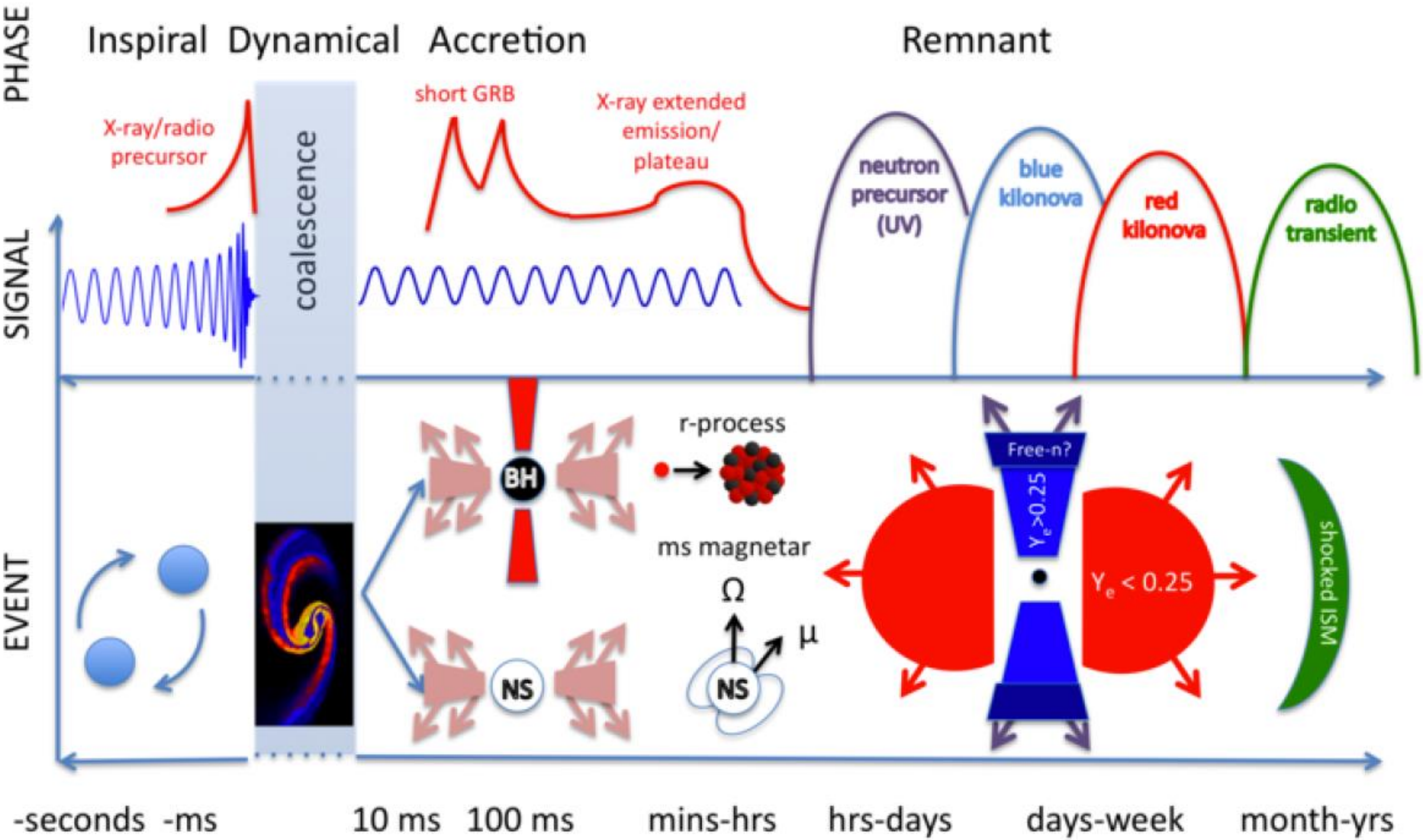
When did the first generation of stars explode to form the first seed black holes and disseminate the first metals in the Universe?

Gamma Ray Burst at z=7 by ATHENA-XIFU



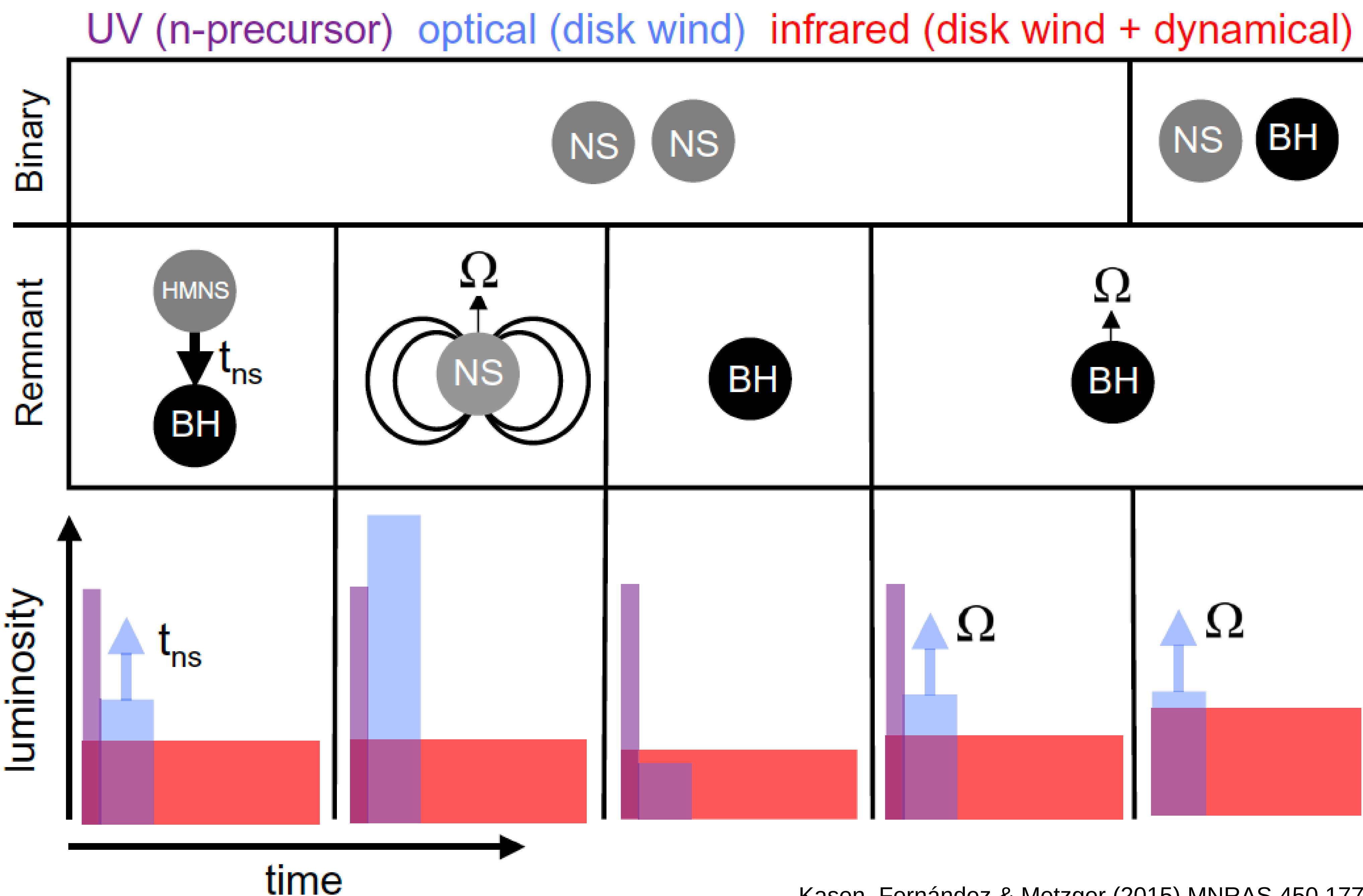

Jonker, O'Brien et al., 2013 arXiv1306.2336

# Binary merger phases



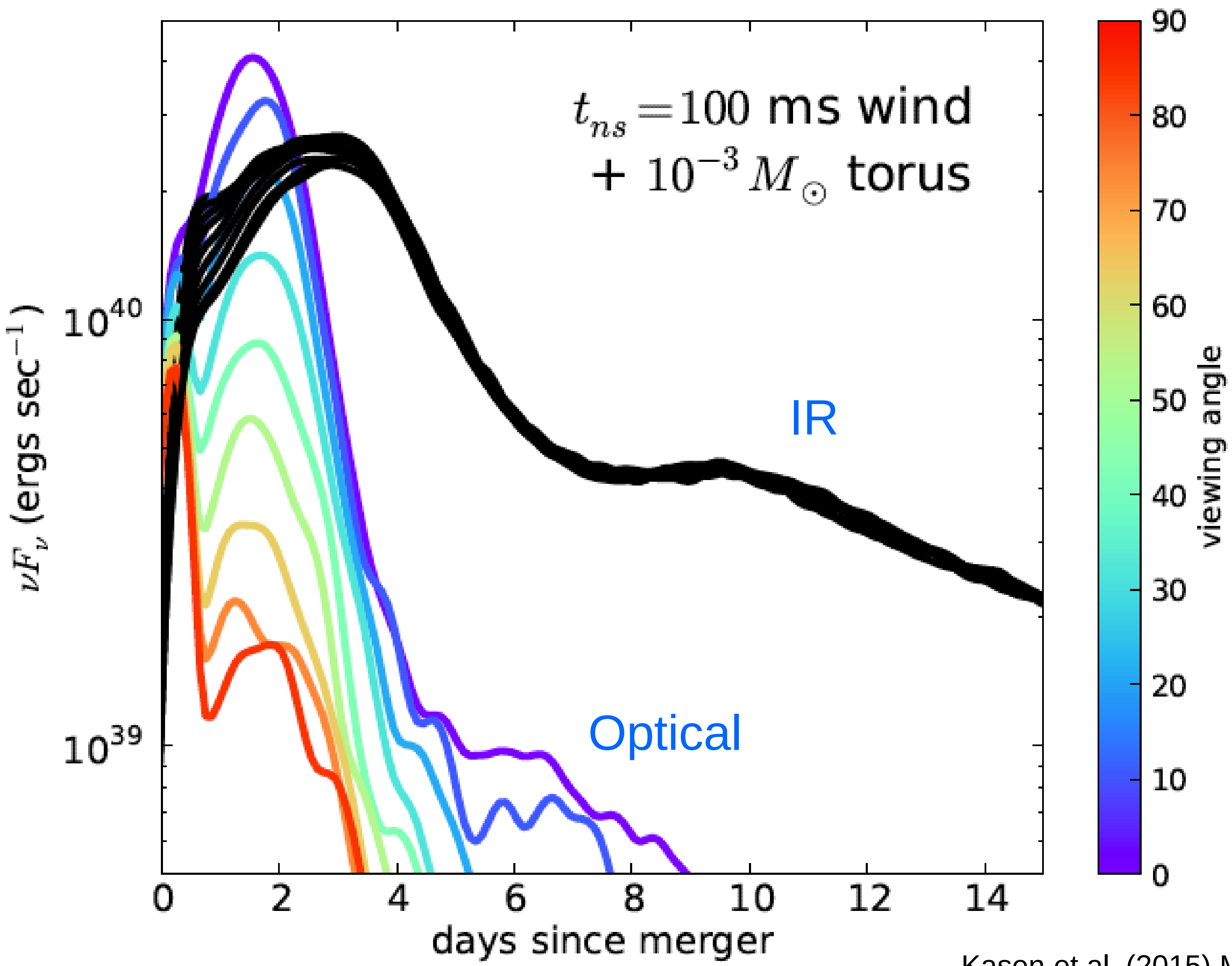

Fernández & Metzger (2016) ARNPS 66 1

# Binary merger outcomes



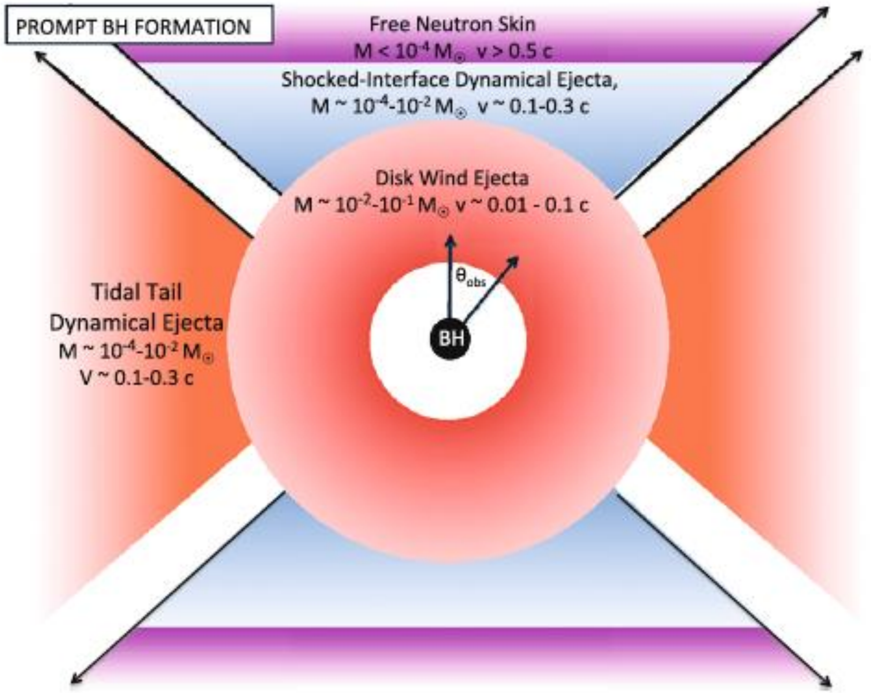

Kasen, Fernández & Metzger (2015) MNRAS 450 1777

# Opt & IR kilonova emission

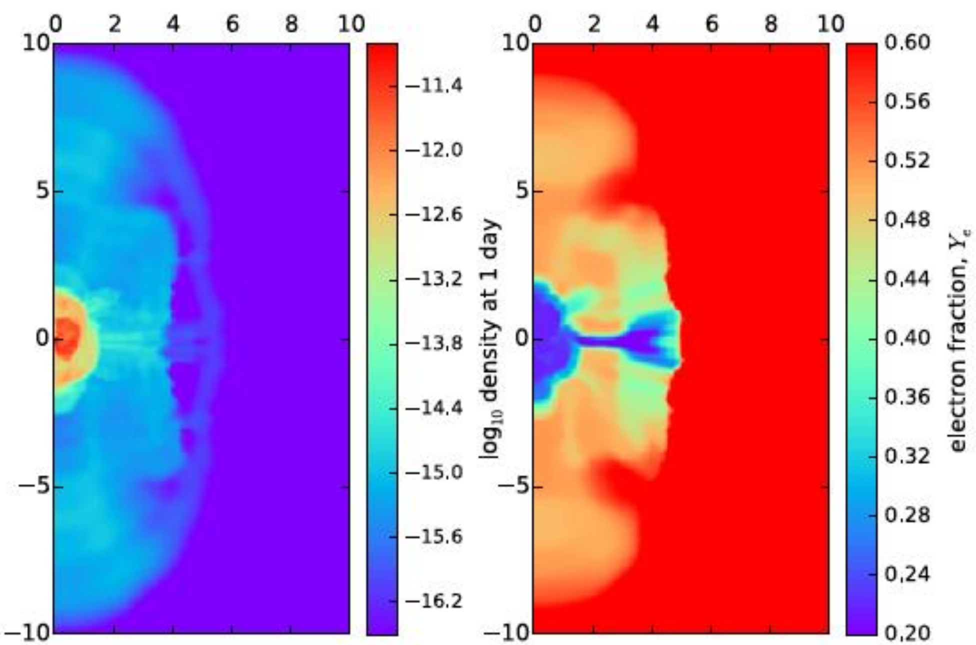



Kasen et al. (2015) MNRAS 450 1777

# Binary merger scenarios




Metzger (2017) Liv Rev Rel 20 3

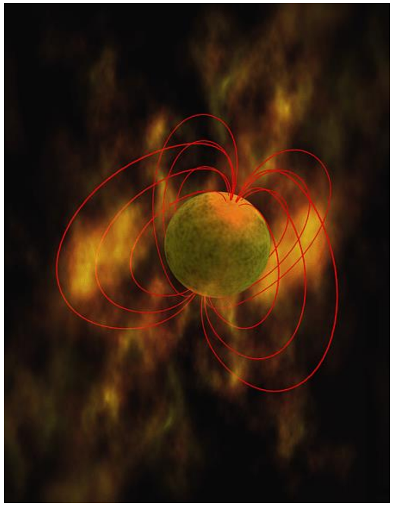


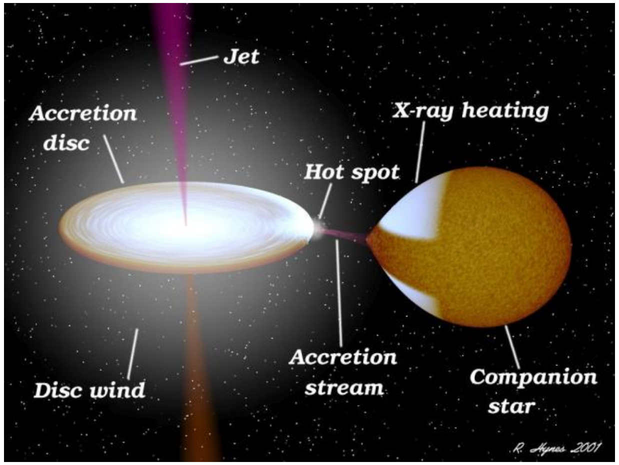

Kasen, Fernández & Metzger (2015) MNRAS 450 1777

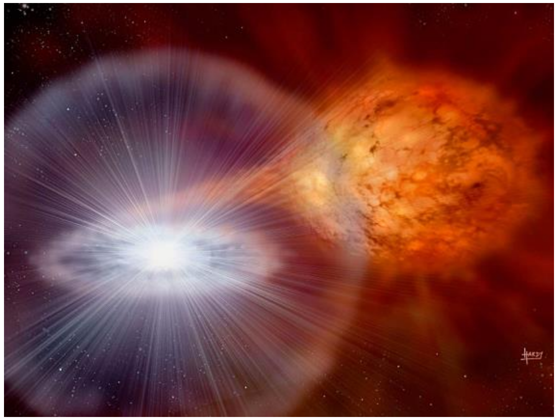
# Potential Galactic transients/variables

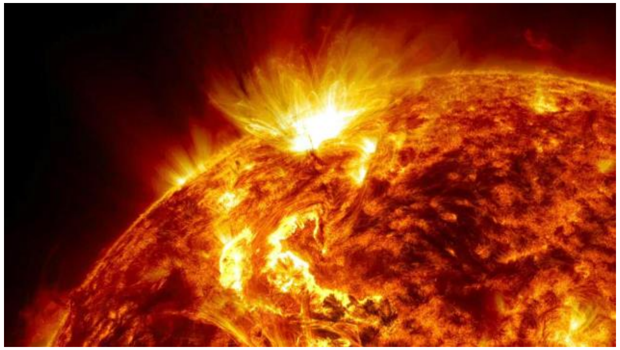
- Galactic center SBMH
- Accreting NS/BH binaries
  - LMXRBs
  - HMXRBs
    - SFXRTs
  - Bursters
    - Super-bursts
- Accreting WDs
  - Novae
  - Magnetic CVs
  - Non-magnetic CVs
- Magnetars/AXPs, …
- Stellar coronae
  - Super-flares

NB $L_{Edd}$ @ GC: $f_{Edd} \sim 3\times10^{-8}$ cgs



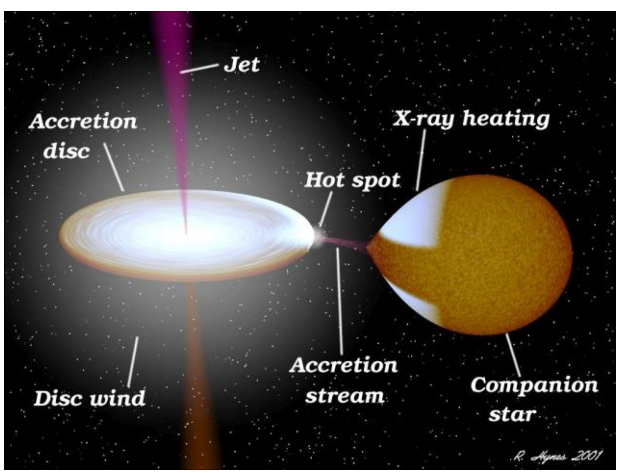


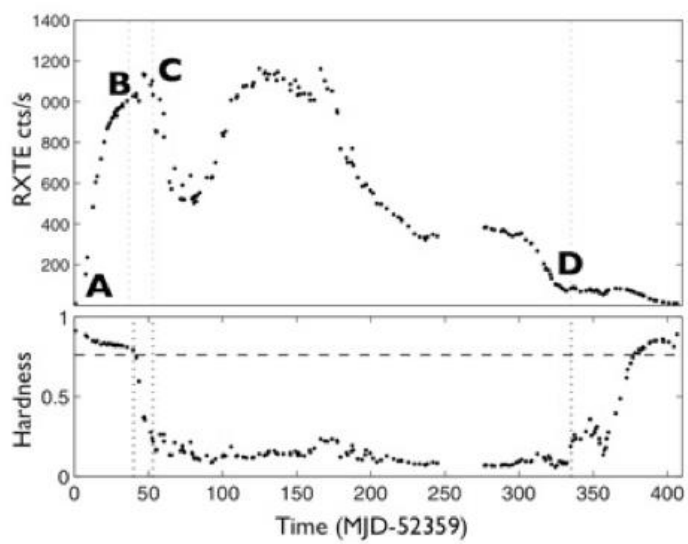



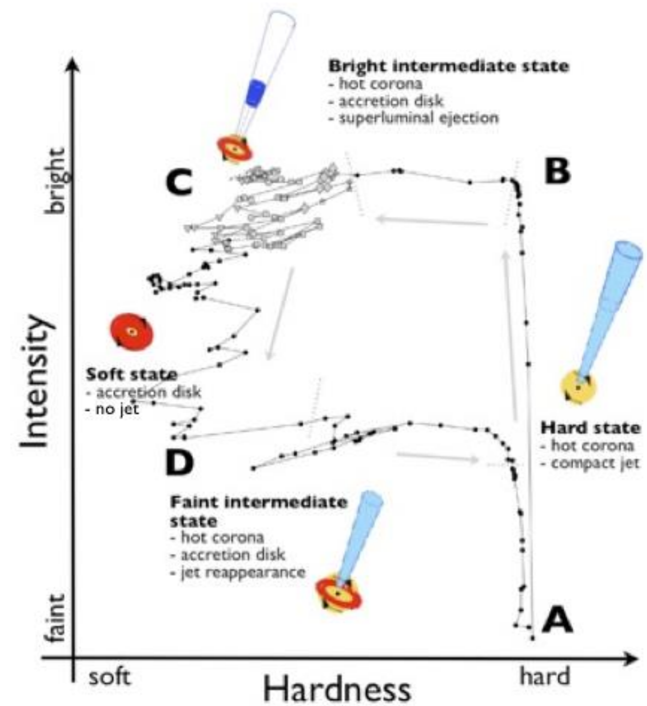


# Low mass X-ray Binaries:

- 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
    - optically faint in quiescence (8m class ground-based tels reqd)
    - outbursts due to viscosity increase in accretion disk
    - study jet mechanism, irradiation mapping
    - micro-quasars are a link to AGN



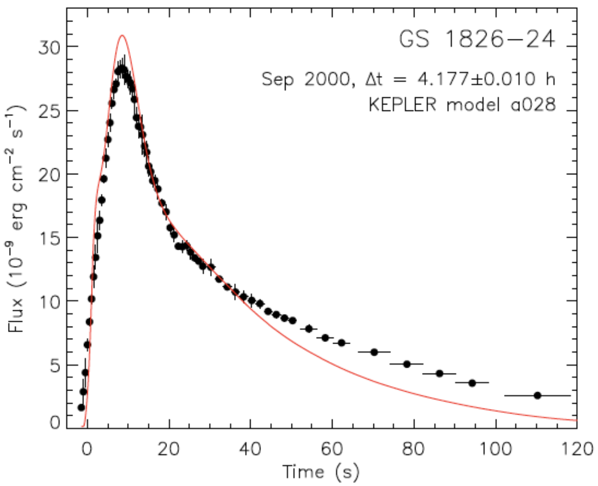



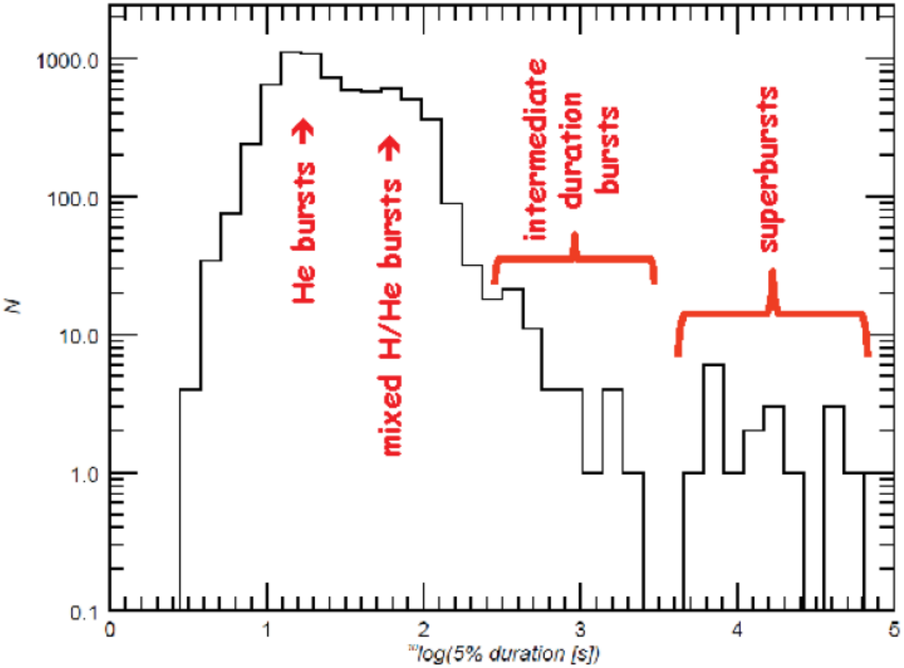

CHAOS; Belloni+05

# Low mass X-ray Binaries:

- Thermo-nuclear bursts or regular pulsations reveal NS
- ~45% of LMXBs show bursts – accumulated He(/H) burning runaway
  - burst models constrain NS mass, radius, EOS, distance, abundance of accreted material, ignition depth
- Rare Super-bursts last hours – deep C-burning shell flash
  - only 26 known, SXI will collect a large sample
  - Probe NS crust, help to understand SNIa ignition



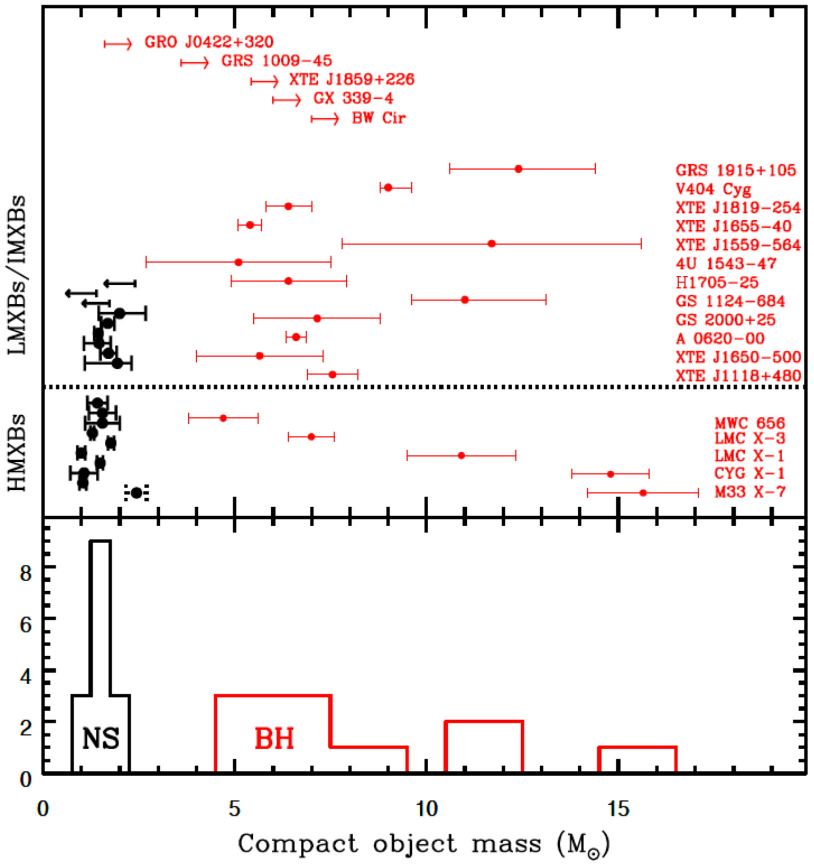

Type1 burst. Galloway+17




in ‘t Zand 17

# Discovery of new XRBs leads to NS/BH mass determinations

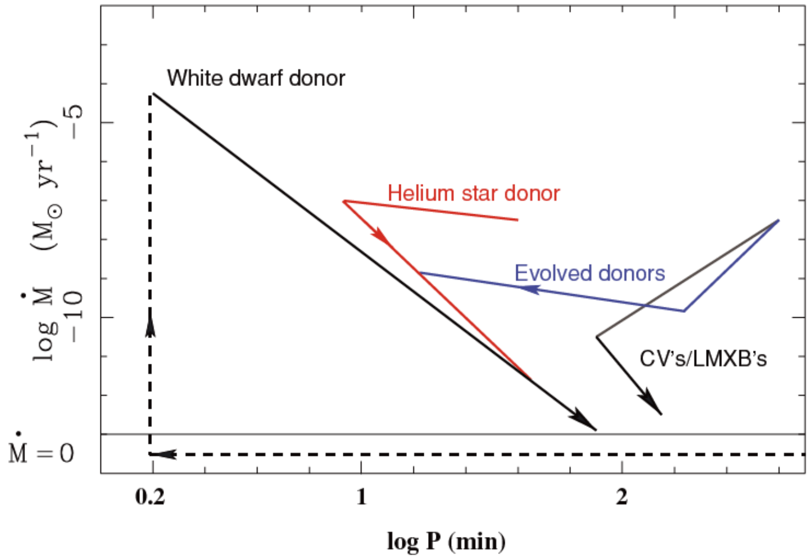
- Important for understanding SN1b/c & SN II
- Only 22 BH masses known (before aLIGO)
- 2-5 Msun gap has implications for models of:
  - convection instabilities and core-bounce
  - neutrino-driven explosions
  - 17-25 Msun progenitors as failed SNe
- Highest mass BHs seen in HMXRBs
  - indicates low-metalicity?
- Mean LMXRB BH mass > mean HMXRB BH
  - older BHs have accreted more mass?



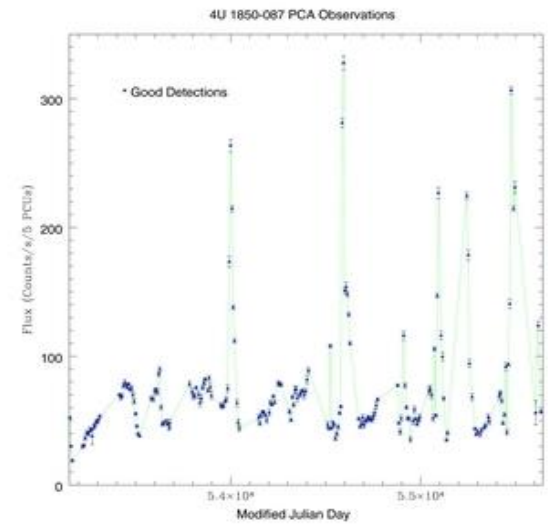

Casares+ 17

# Ultra-compact X-ray binaries:

- Orbital period < 1 hour
- H-poor accretion onto NS
- Lx ~ 1% Eddington
- Rare: large fraction in globular clusters
- High fraction of ms 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



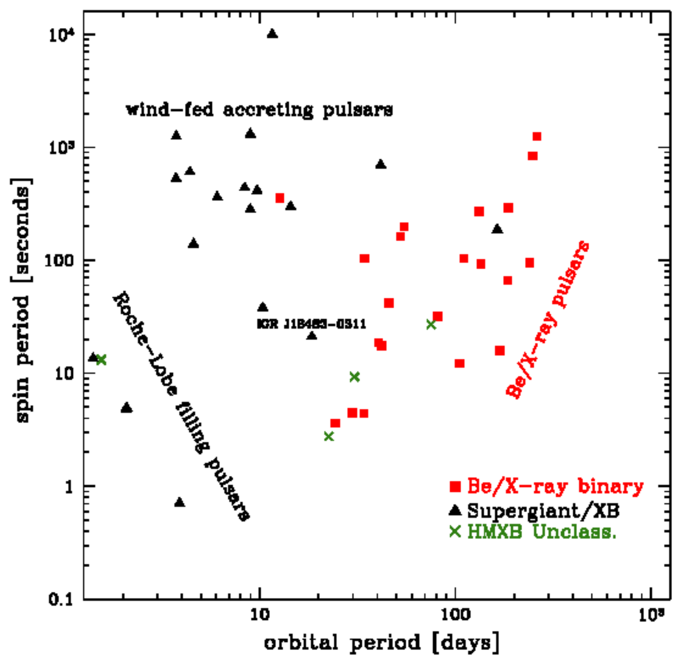
UCB evolutionary scenarios. Nelemans+ 10

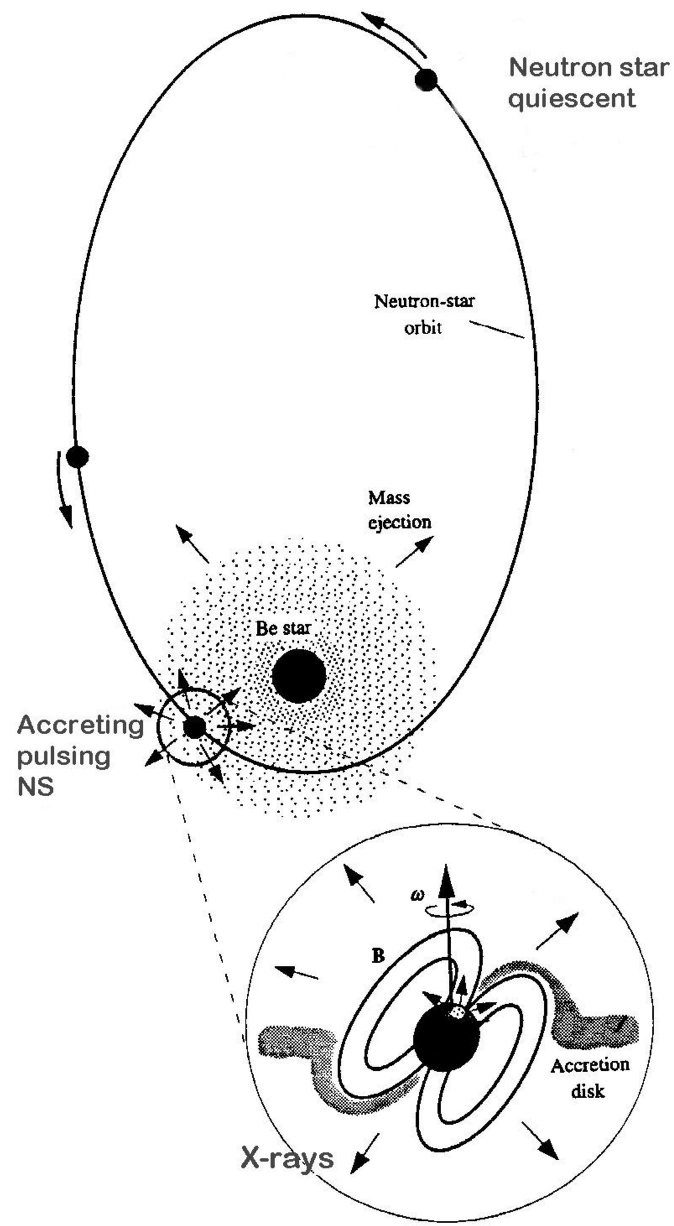


Flares in UCB 1840-087. Cartwright+13

# High Mass X-ray Binaries:

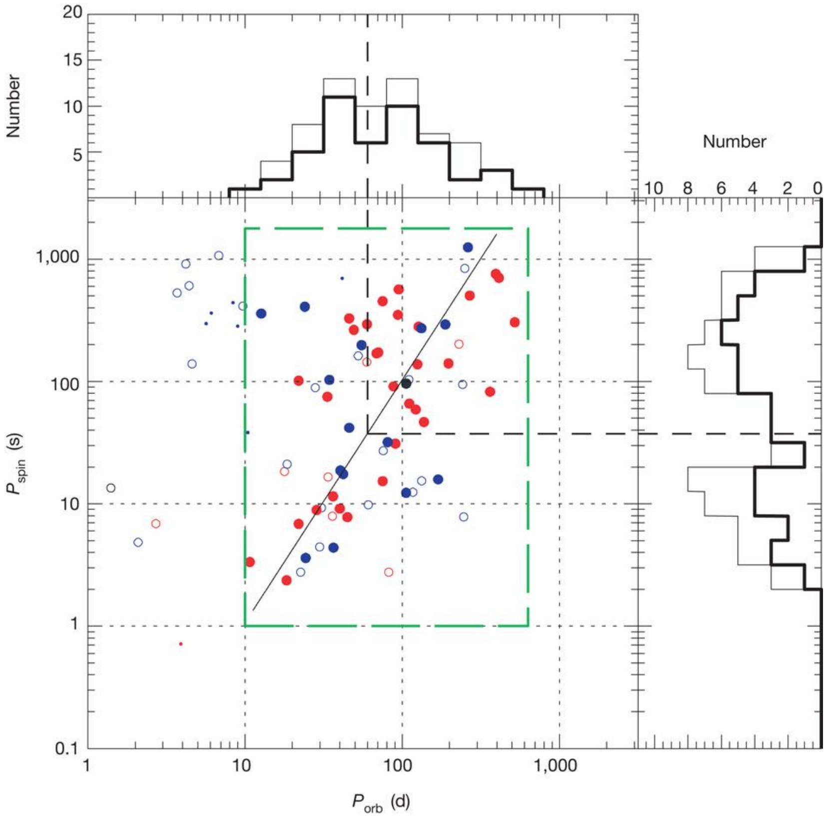
- Companion mass > 10 Msun
- Transient X-ray sources: LX ~ $10^{37}$ cgs
- Wide & eccentric orbits
- Accretion from Be star equatorial disk
- Spin, orbit and disk precession periods seen
- Corbet diagram

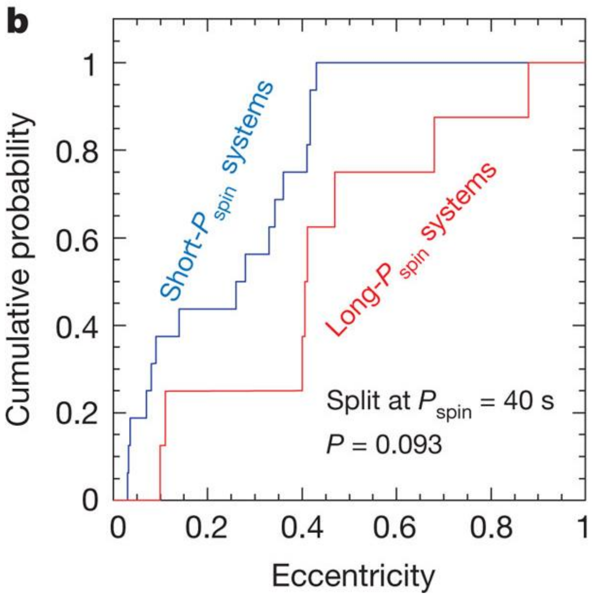


# High Mass X-ray Binaries:

- Two classes in Corbet diagram hints at two formation channels
  - Fe core collapse
  - electron capture
- Fe core collapse SNe expected to produce higher kick velocities, and so eccentricities
- Clear need to find more




Knigge+ 11

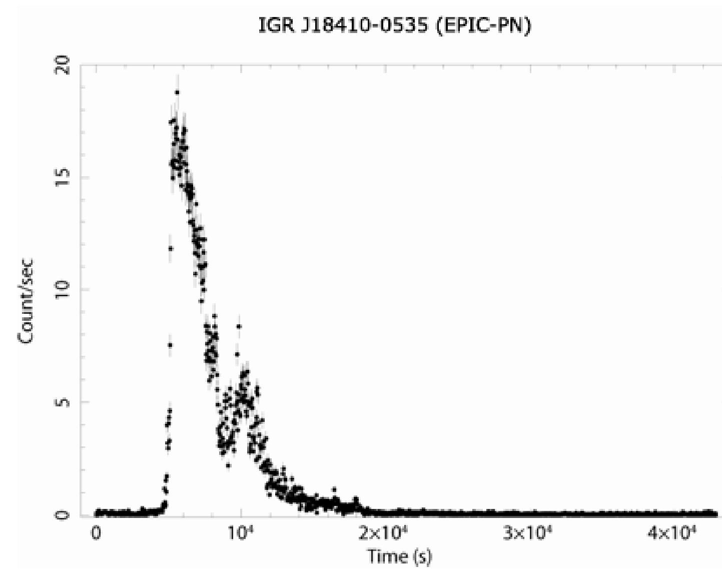
# Supergiant High Mass X-ray Binaries:

- Bright and persistent. Lx ~ $10^{36-38}$ cgs
- Hard spectra of accreting pulsars
- Frequent flaring related to structured wind
- Related to common envelope phase of binary evolution?
- Can be absorbed

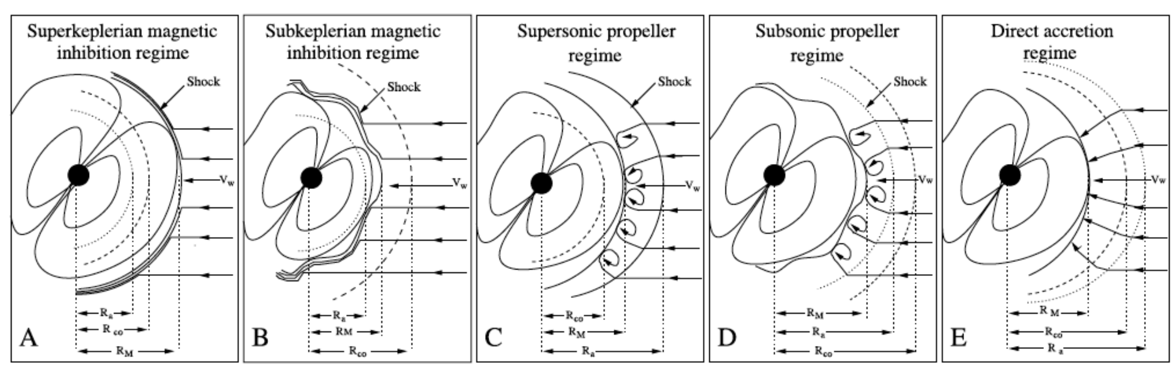
ISSI Bern

Supergiant Fast X-ray Transients:

- Show short flares (~ few hours) with dynamic range up to $10^5$
- Timescales much shorter than typical HMXRB outbursts
- Evidence of accretion gating?
- If so, NS may be a magnetar



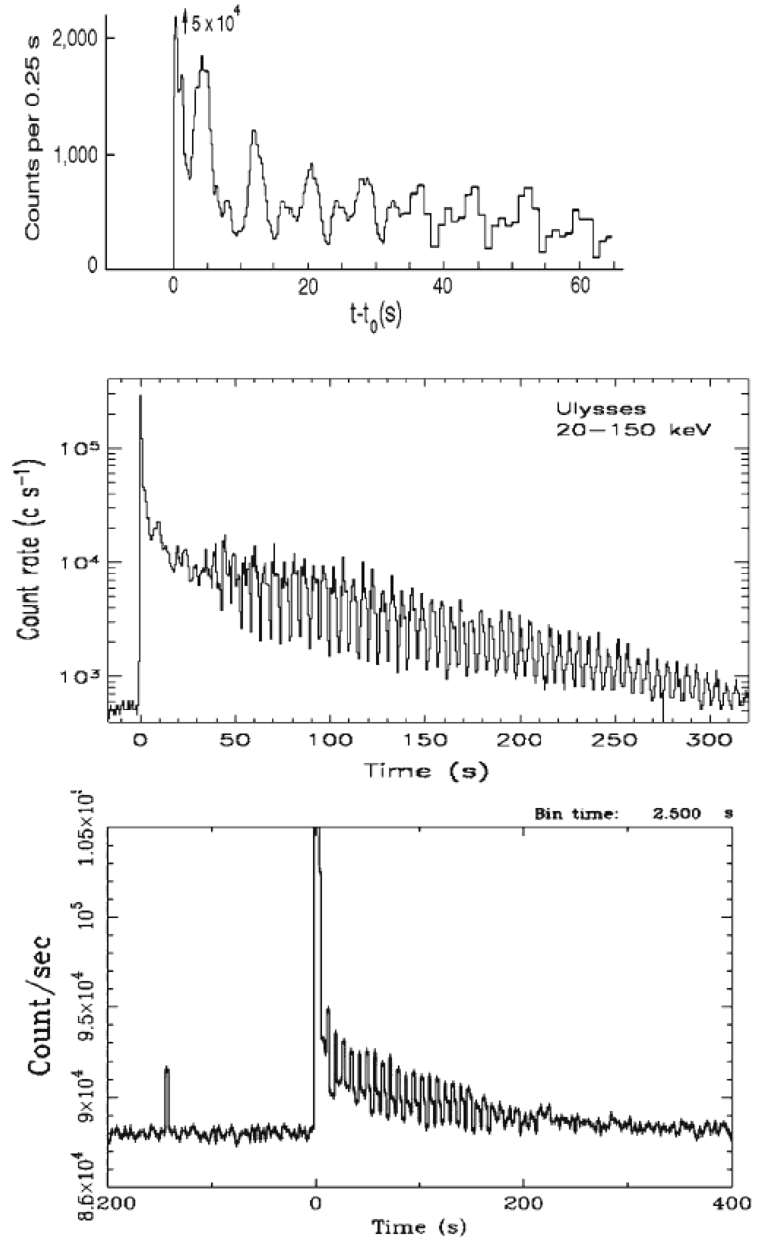

Bozzo+ 11




Magnetic and propeller accretion suppression. Bozzo+ 08

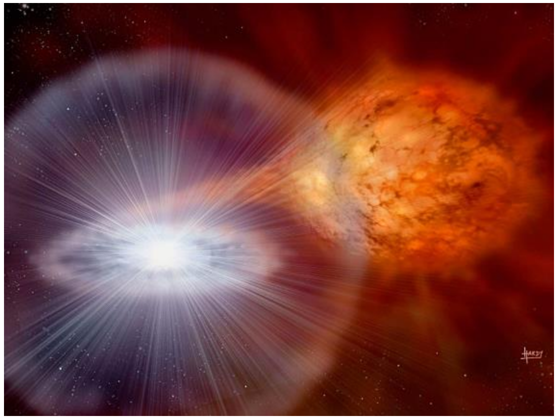
# Magnetars:

- 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

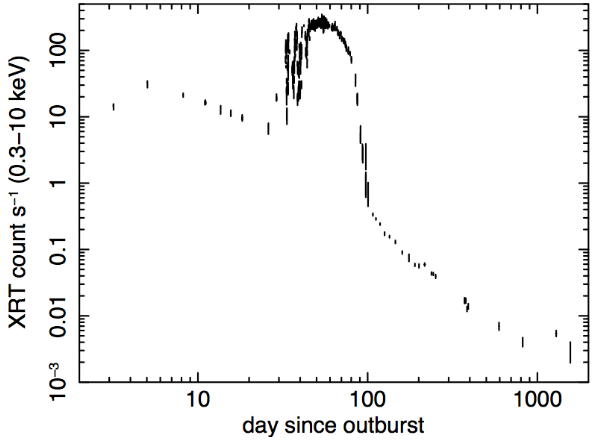



SGR giant flares: 0526-66, 1900+14, 1806-20. Mereghetti 08

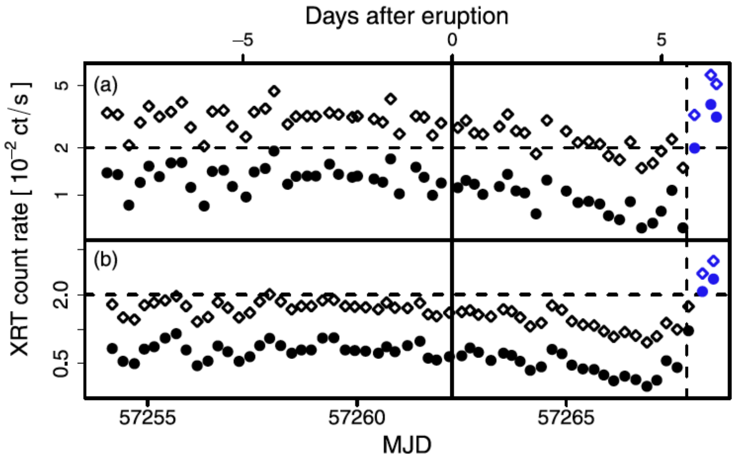
# Novae:



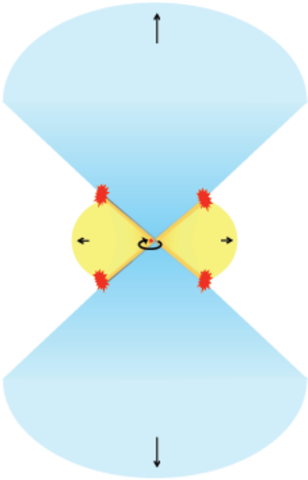
- Thermonuclear runaway of accreted matter on a WD
- Some are candidate SN Ia progenitors
- All repeat: classical novae ~ $10^4$ y, recurrent novae <100 y
- Bright hard and soft X-ray emission from ejecta shocks & hot WD
    - Super-soft source on-time: ejecta properties
    - SSS off time: residual 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

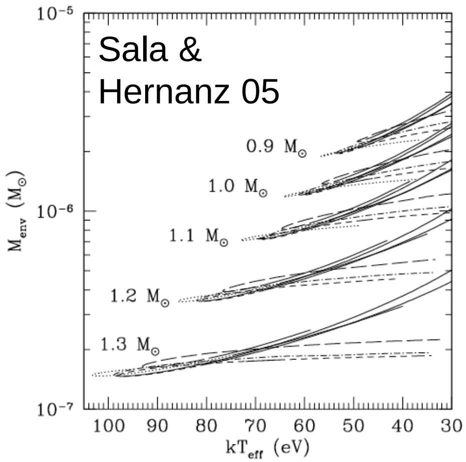


RS Oph. Osborne+ 11



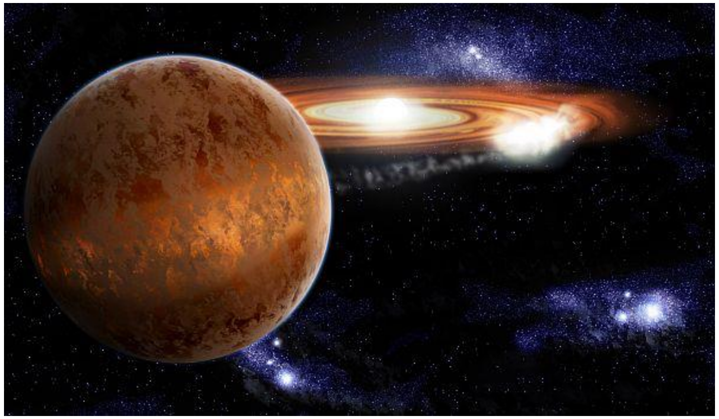
Kato+ 16


Chomiuk+ 14



# Non-Magnetic Cataclysmic Variables:

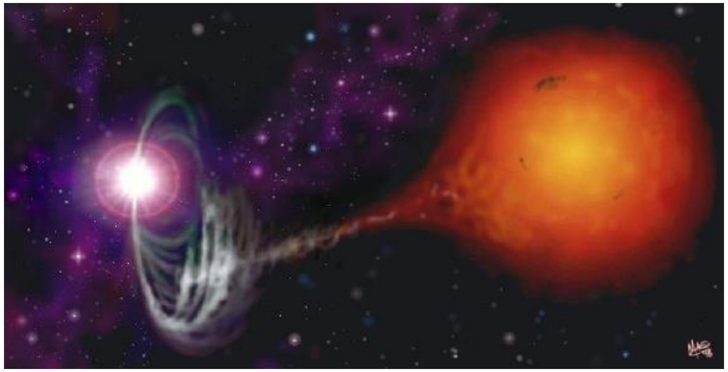
- Disk accreting WDs in close binaries
- Outbursts due to disk ionization/viscosity instability
  - ultra-soft optically thick boundary layer in outburst rarely seen
  - origin of harder X-ray emission in outburst unclear
  - extreme systems with secondary evolving to a brown dwarf (WZ Sge type) have very rare huge outbursts ($\Delta m \sim 8$)
    - poorly understood, possible missing inner disk
- SXI can see brightest DNe in each pointing
  - long-term X-ray monitoring is largely unexplored
  - behavior of quiescent emission through outburst cycle important for disk instability model
    - DIM successful for outbursts
    - predicted rise in quiescence not seen
    - high quiescent flux hints missing inner disk



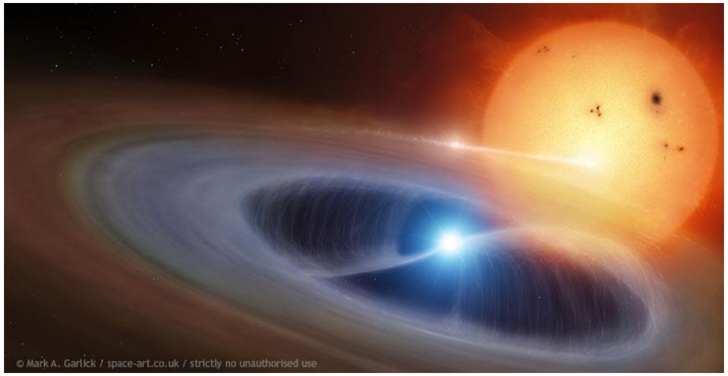
Littlefair+/Science 06

# Magnetic Cataclysmic Variables:

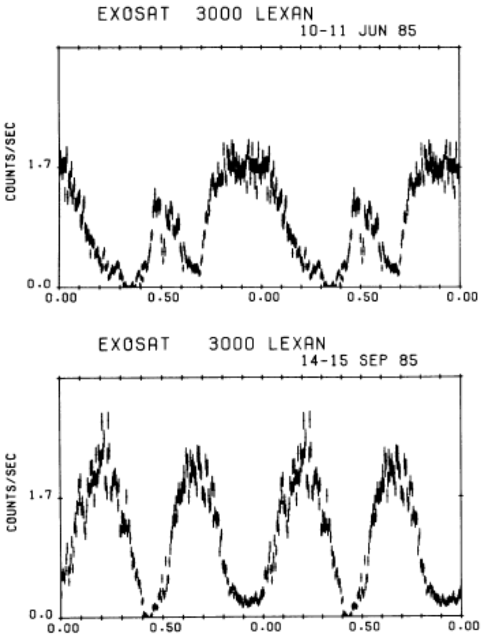
- Accreting WDs in which WD magnetic field dominates flow
- Variable rather than transient
- Polars have no accretion disk
  - state changes due to secondary star
    - frequency unknown
  - bright soft X-rays from heated WD
  - WD spin locked to orbit
- Intermediate polars have some sort of accretion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



Polar. © Garlick 98



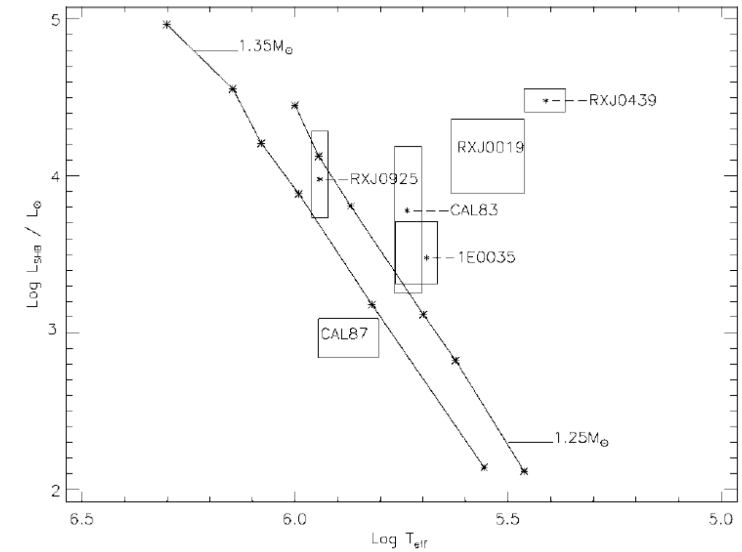
Intermediate polar. © Garlick 98



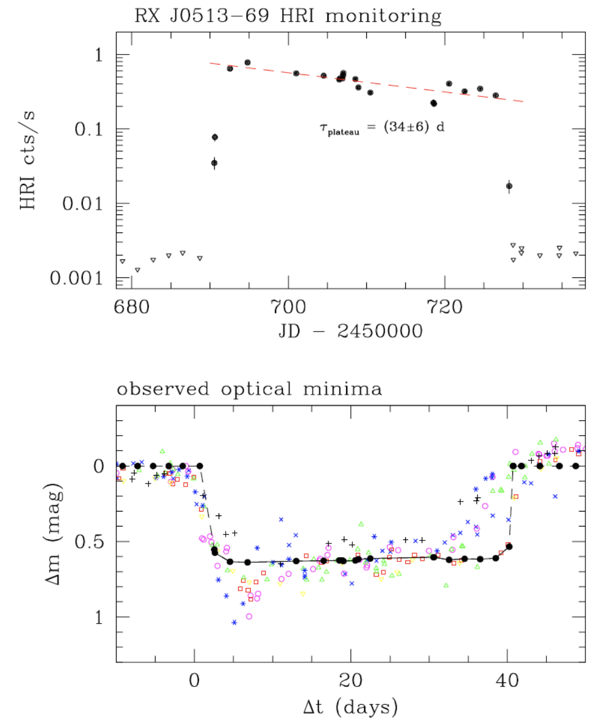

Polar (QQ Vul) state change in soft X-ray folded light curve. Osborne+ 87

# Super-soft sources:

- kT ~ tens of eV, Lx ~ $10^{36\text{-}38}$ erg/s
- Disk accreting WDs in close binaries undergoing continuous nuclear burning
- Potential SN Ia progenitors
  - high WD mass required
  - continuous accretion
  - all accreted H & He burned
- X-ray/optical state changes
  - viscosity change driven by irradiation?
- THESEUS: X-ray – NIR long-term monitoring



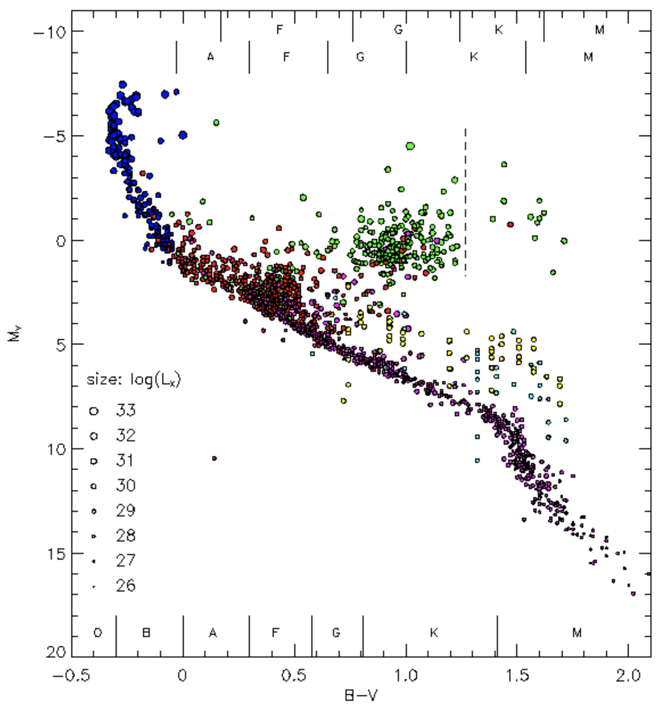

Surface nuclear burning models compared to observations. Starrfield+ 04



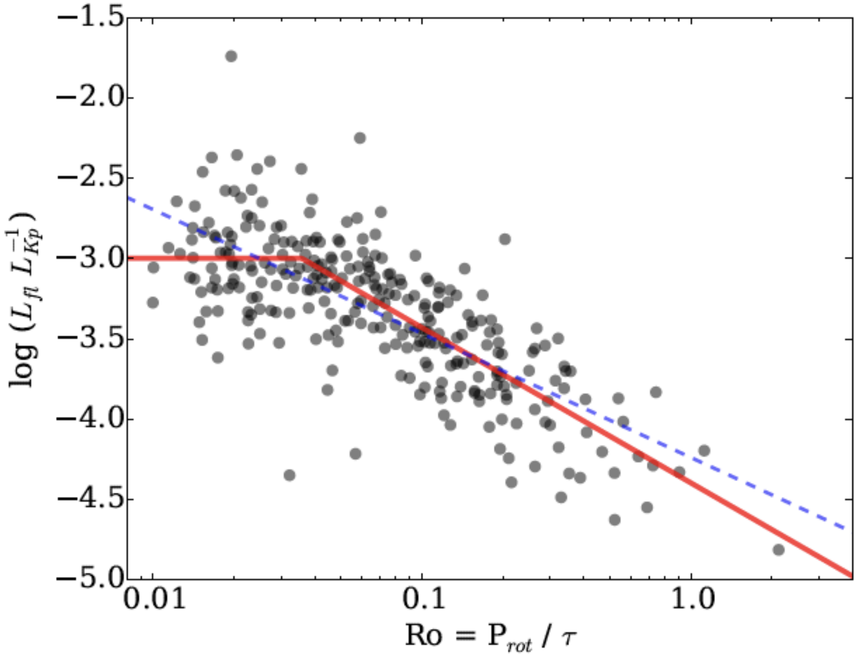

Correlated X-ray/optical flux changes due to changing size of WD photosphere. Reinsch+ 00

# Stellar Coronae:

- Young, low mass stars can be significantly more active than the Sun
- Rotation-convection stellar dynamo powers explosive reconnection events
- Kepler detected flares in ~2% of stars observed, $E_{mean} \sim 10^{35}$ erg
- Saturation of activity at highest rotation rates may relate to active region filling factor, although different levels seen in white light and in X-rays raise doubts



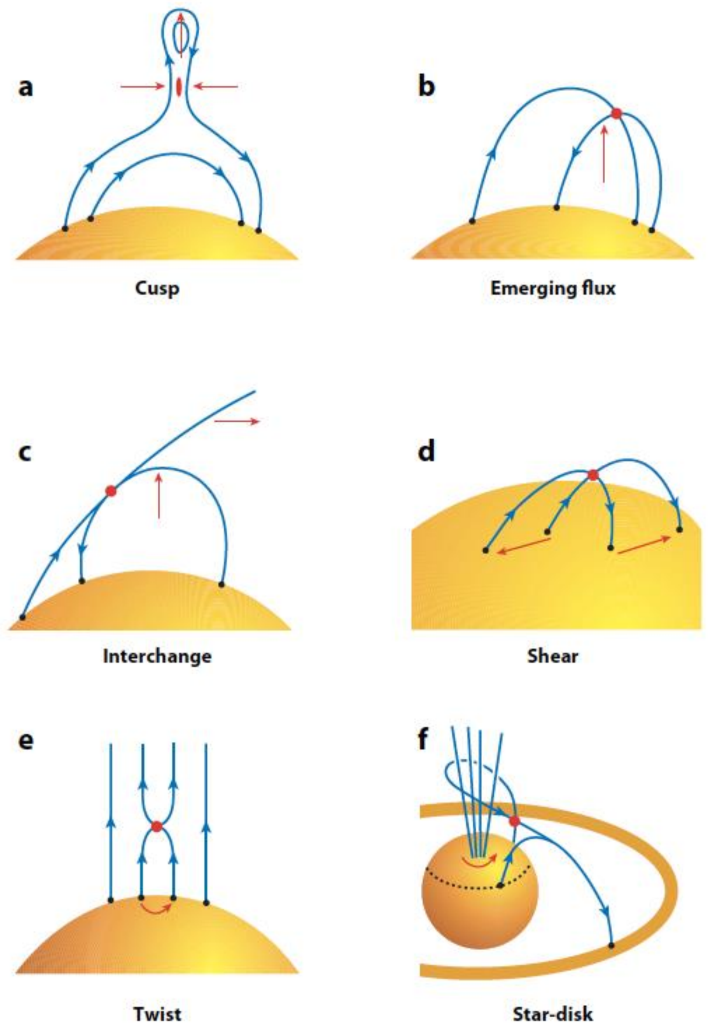

Stellar luminosities in the HR diagram. Guedel 2004




Saturation of relative white-light flare luminosity. Davenport 16

# Stellar Coronae:

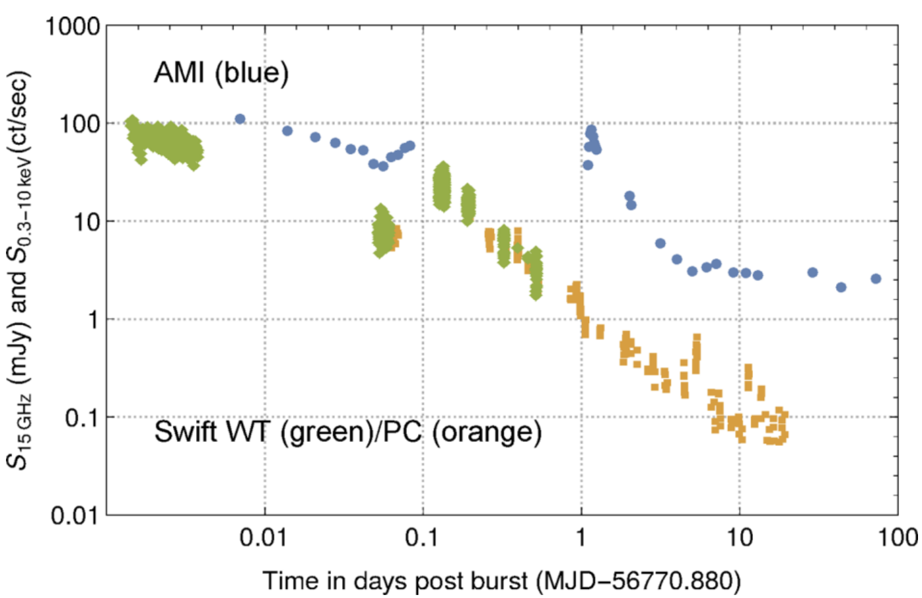
- Güdel ARA&A 2004, Benz & Güdel ARA&A 2010:
  - How are coronae heated & structured?
    - THESEUS: systematic study across the HR diagram
  - What is the physics behind flares?
    - THESEUS: huge numbers of flares observed
  - How does magnetic activity evolve?
    - THESEUS: accretion in YSOs
  -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

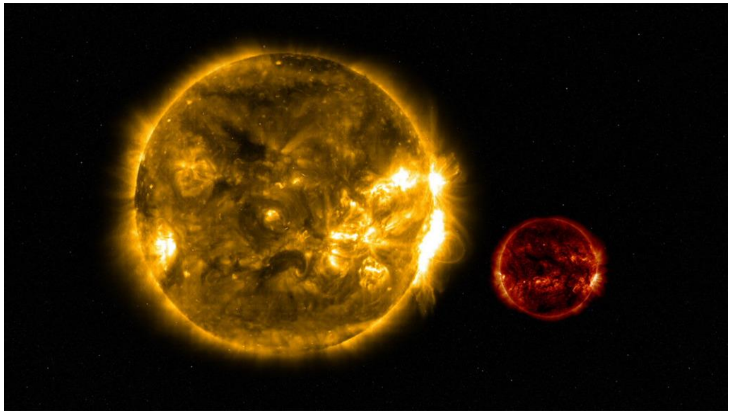



Exoplanet atmosphere eroded by stellar flaring.
Lecavelier+ 12

# 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

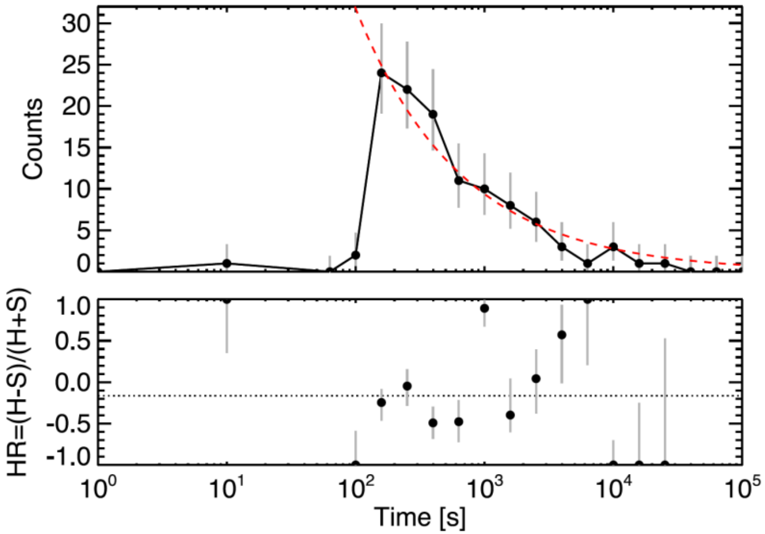


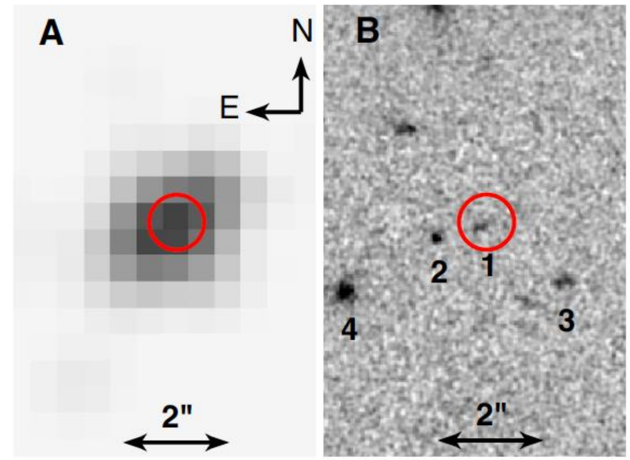



DG CVn is a dim red dwarf. NASA

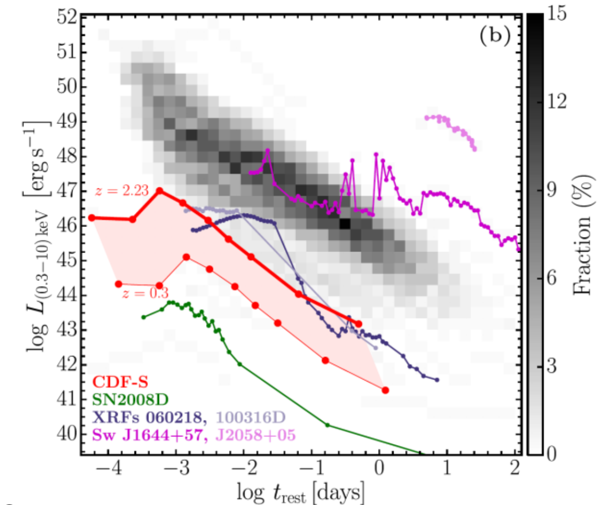
Prompt radio/X-ray super-flare on DG CVn.
Fender+ 15

# Surprises - New transient type?




Chandra 2014    HST ACS/F606W 2008




- Chandra deep field south
- $f_{x,peak}$ ~ 5x10$^{-12}$ erg/cm$^2$/s
- $f_{x,peak}/f_{x,quies}$ > 1000
- $m_R$ ~ 27.5
- Photo-z ~ 2.2
- LX ~ 7x10$^{46}$ erg/s
- Dwarf host galaxy, SFR ~1 Msun/yr
- Rate ~ 5 /deg$^2$/yr

- Factor 10 too faint for SXI
- Closer examples?

- Orphan afterglow?
- LL soft GRB?
- Beamed WD TDE from IMBH?
- Something new?

Bauer et al. (2017) MNRAS 467 4841