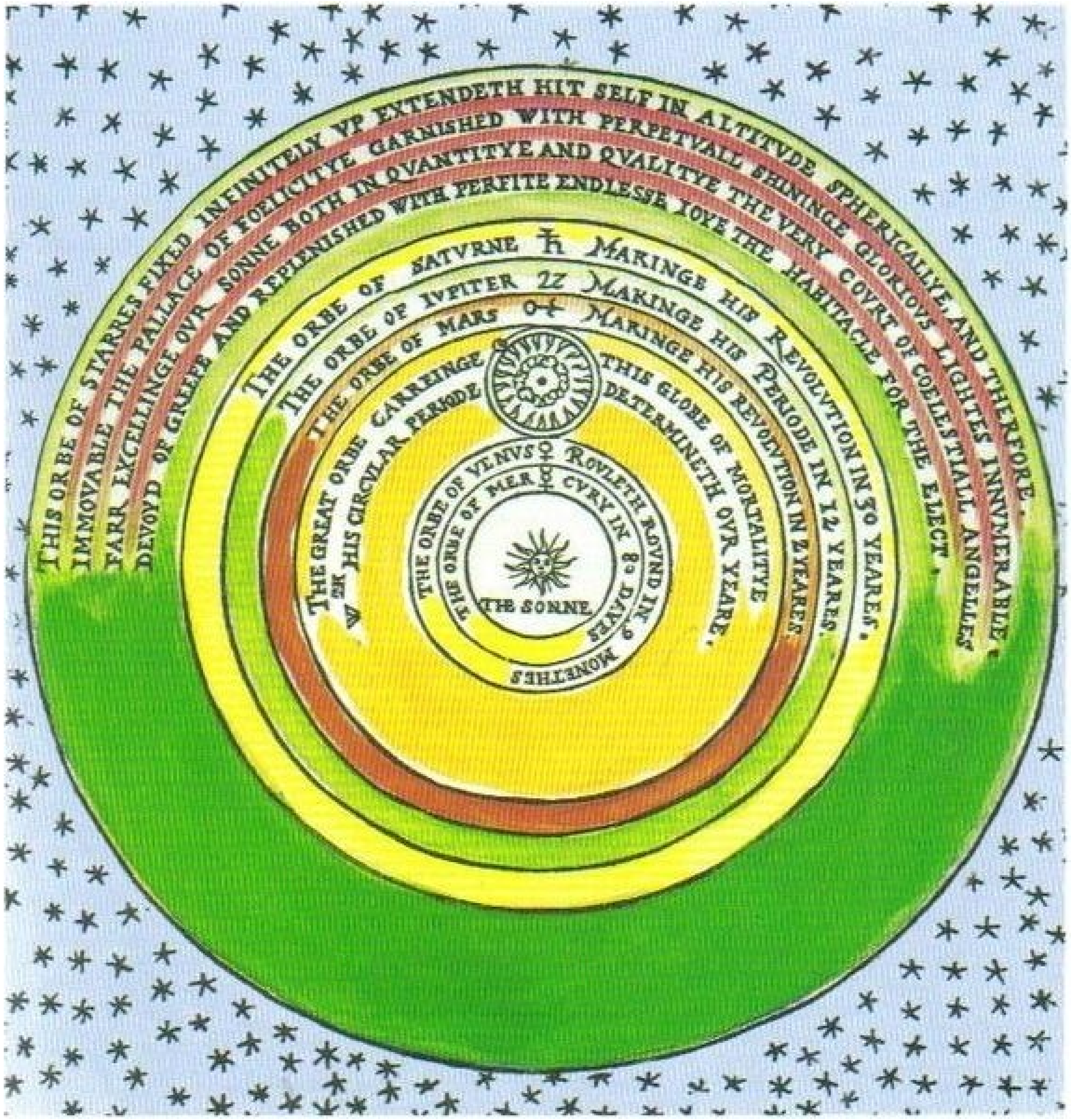
Transient Sky in the Era of Time-Domain Astronomy

Cristiano Guidorzi

Lecture 1



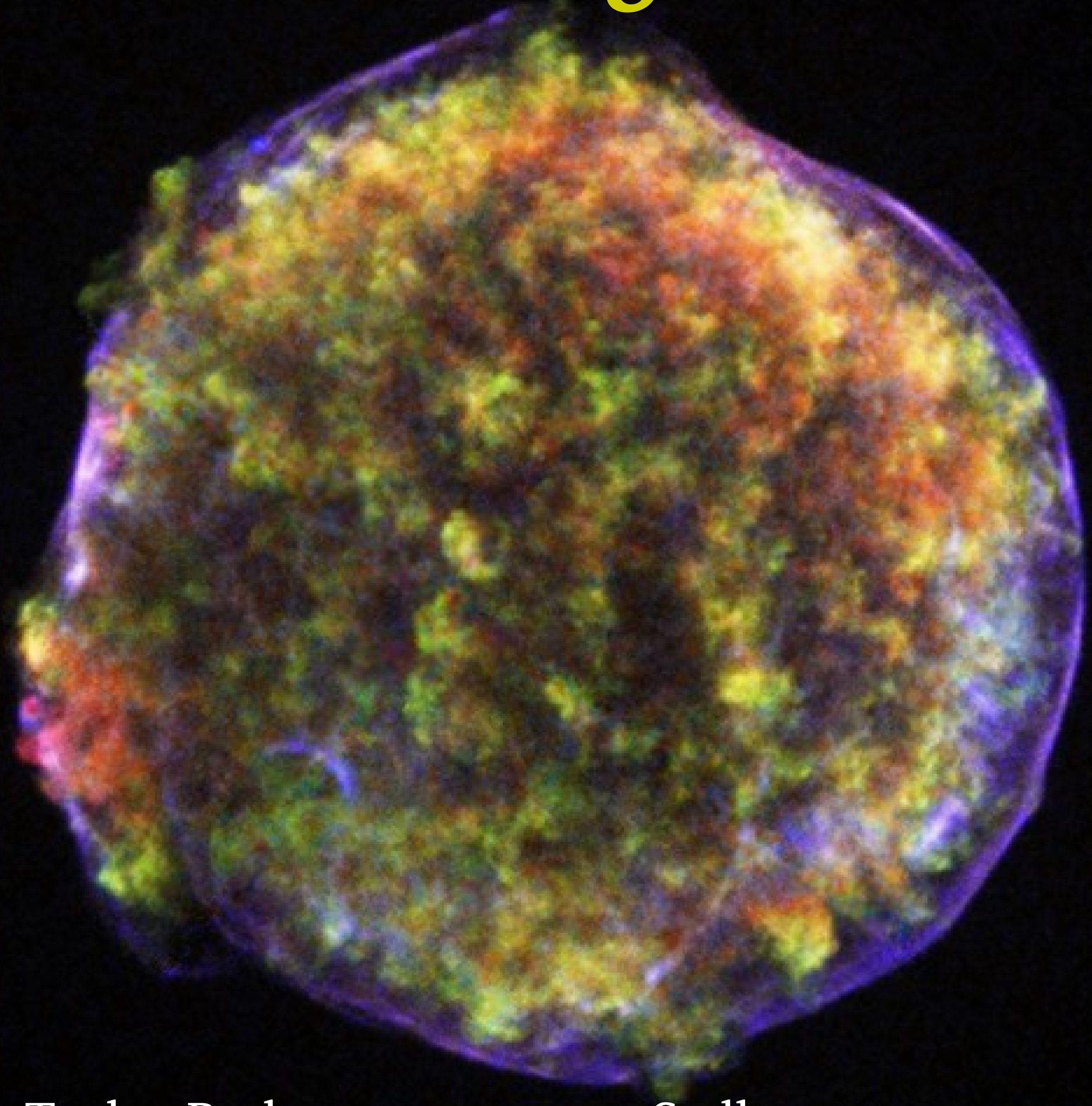
In ancient times

stars and Universe

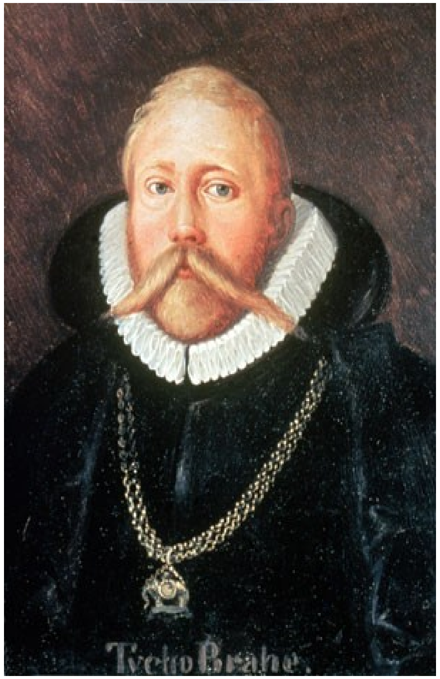
were believed to be

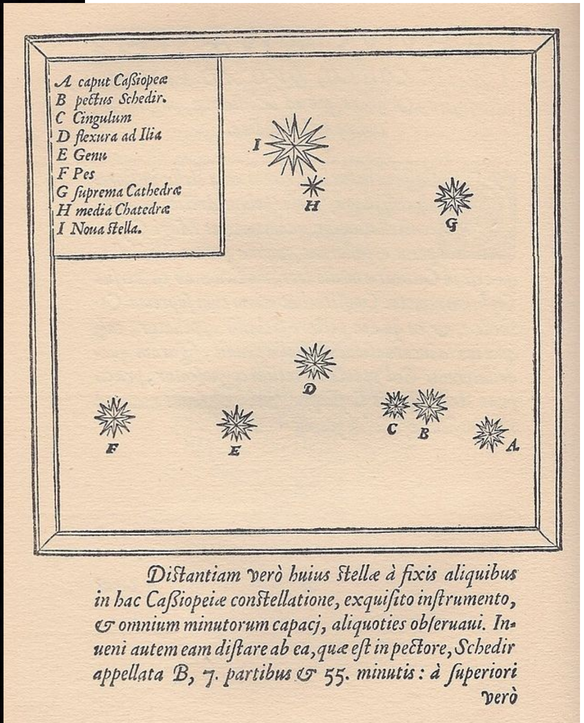
<u>immutable</u>

Breakthrough: 1572



Tycho Brahe reports on a Stella "nova"





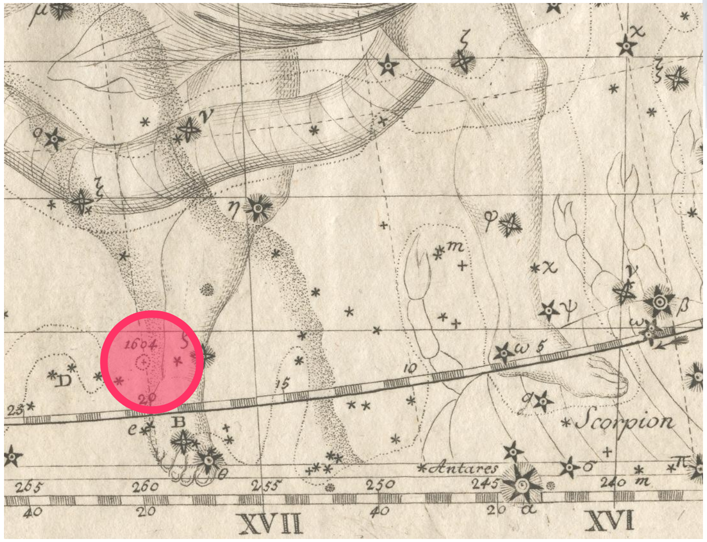
A caput Caſsiopeæ
B pectus Schedir.
C Cingulum
D flexura ad Ilia
E Genu
F Pes
G ſuprema Cathedræ
H media Chatedræ
I Noua ſtella.

Diſtantiam verò huius ſtellæ à fixis aliquibus in hac Caſsiopeiæ conſtellatione, exquiſito inſtrumento, & omnium minutorum capacj, aliquoties obſeruaui. Inueni autem eam diſtare ab ea, quæ eſt in pectore, Schedir appellata B, 7. partibus & 55. minutis: à ſuperiori

verò

Another one! 1604

Johannes Kepler observes another Stella "nova"

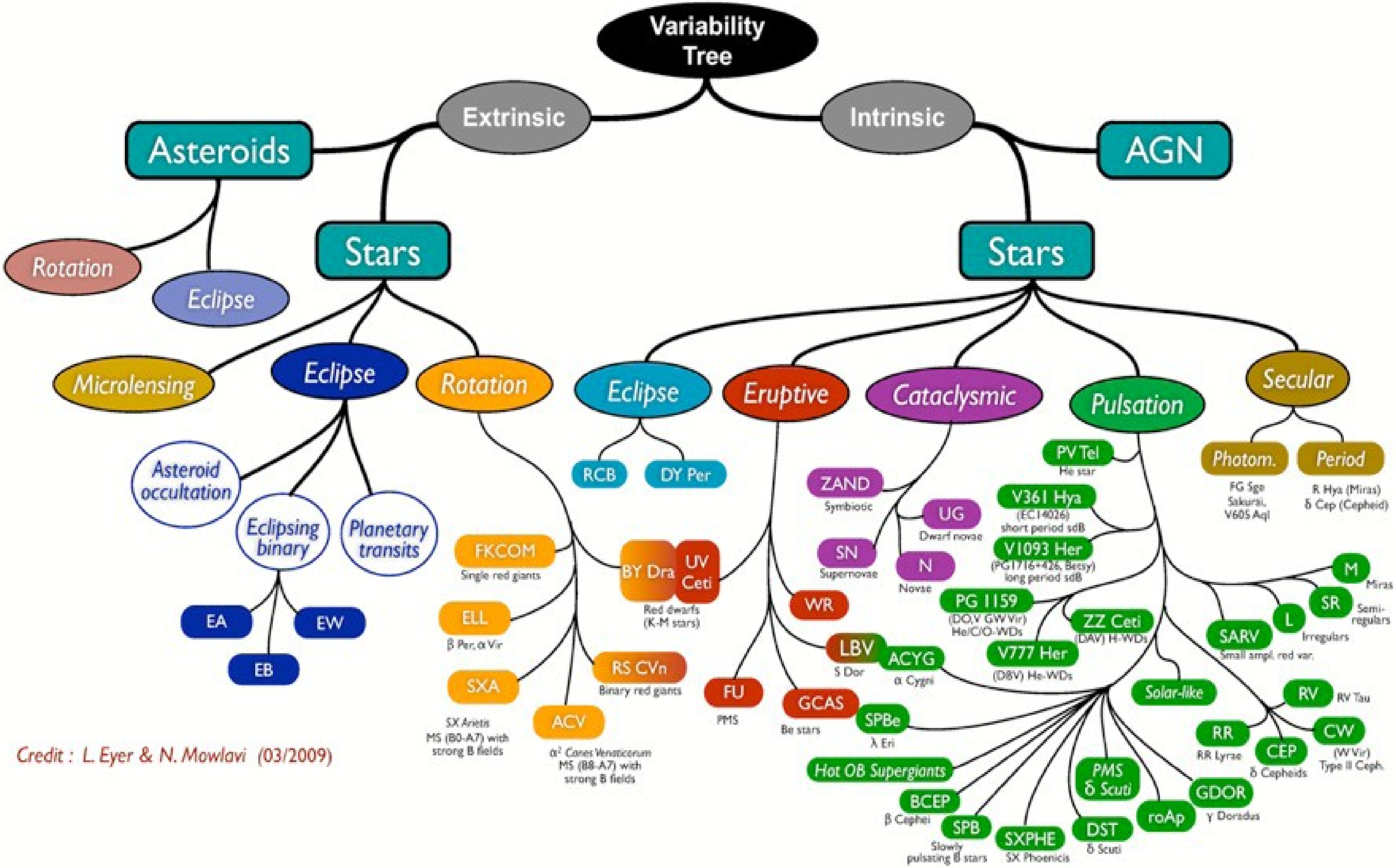


TIME DOMAIN ASTRONOMY

- (periodic) variable stars:
  - RR Lyrae
  - Cepheids

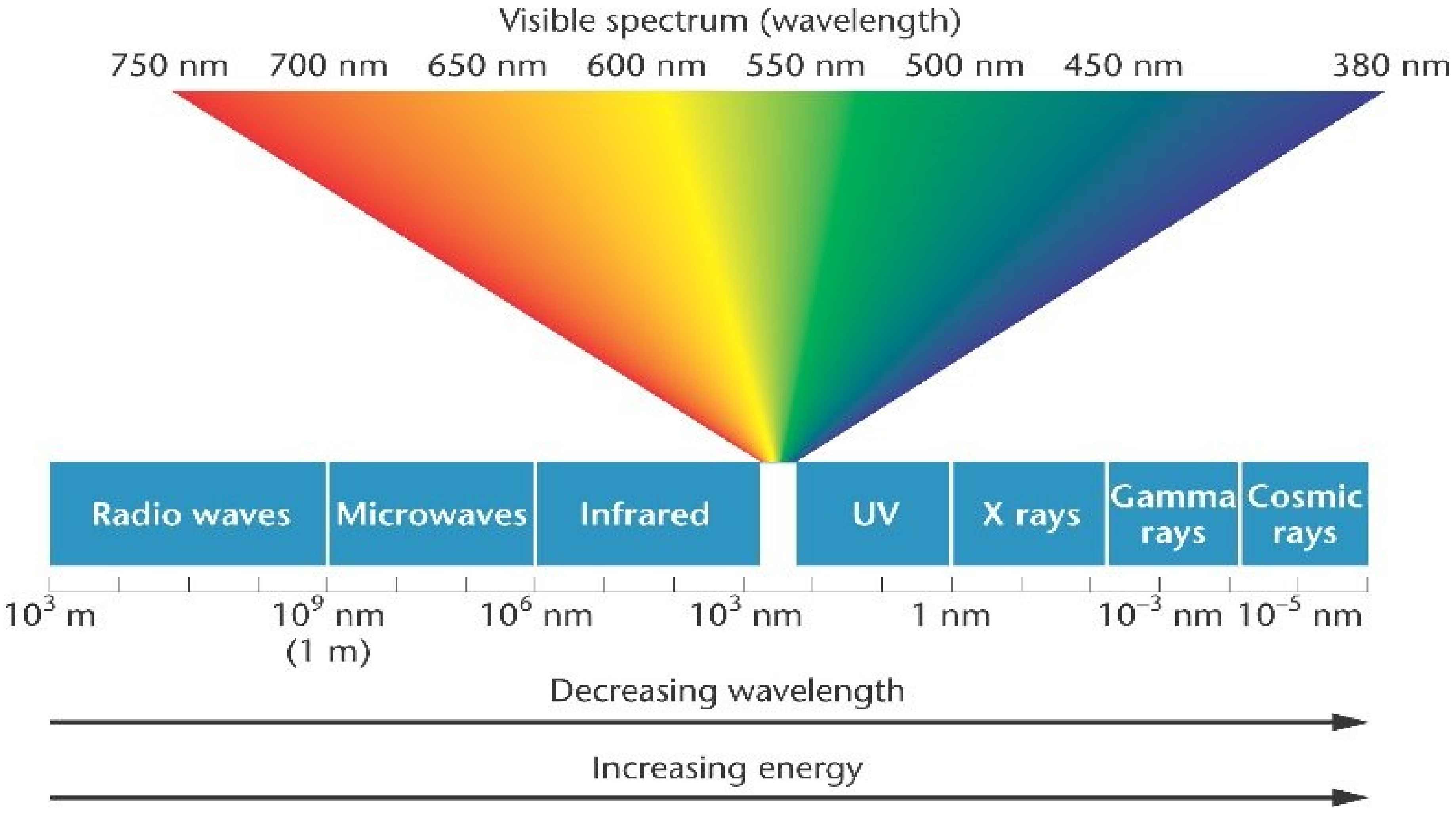
- Aperiodic (explosive) events:
  - Novae
  - cataclysmic variables (Cvs)
  - AGNs

- Disruptive events:
  - Supernovae (SNe) of different spectral classes

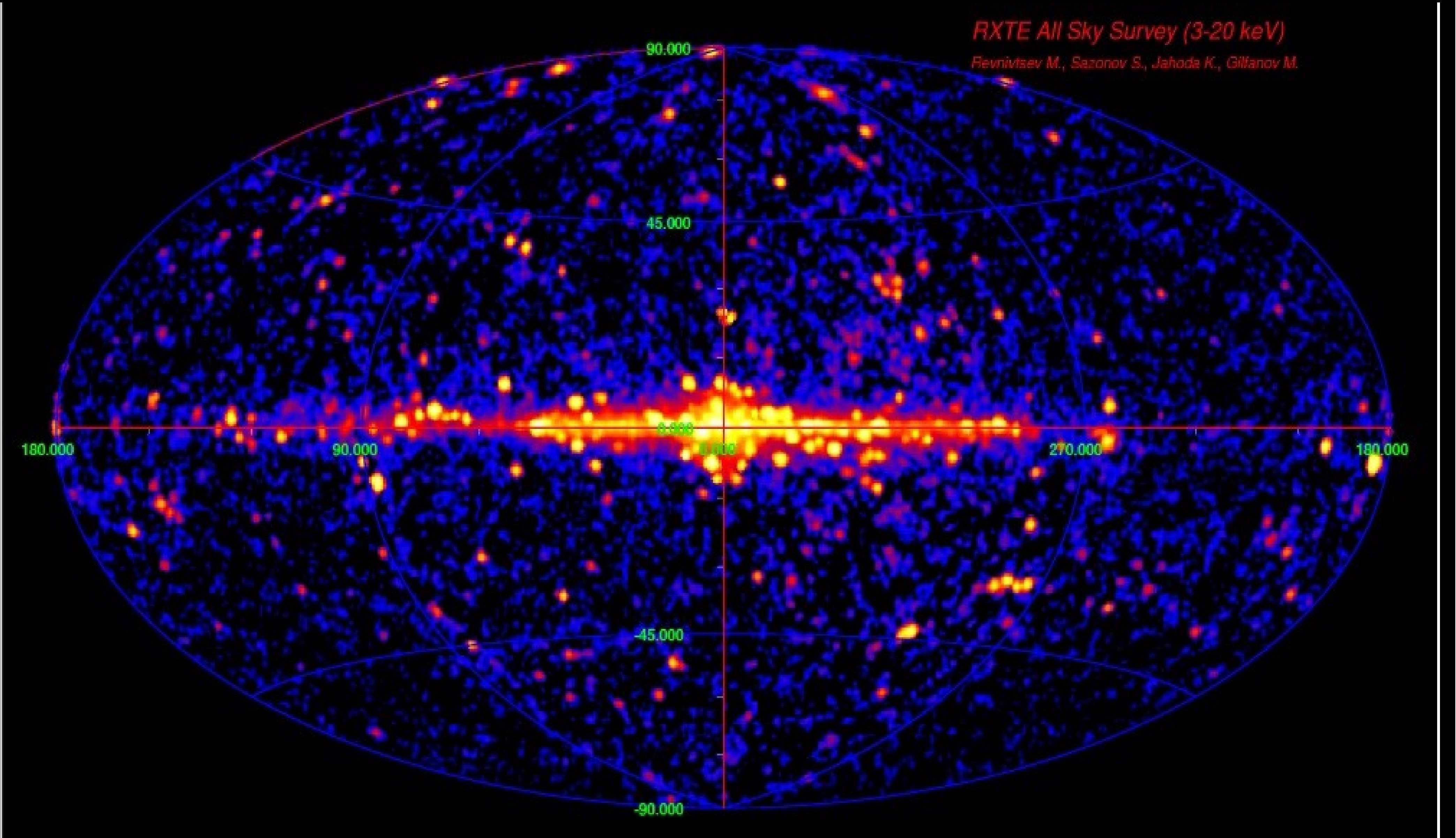


Credit : L. Eyer & N. Mowlavi (03/2009)

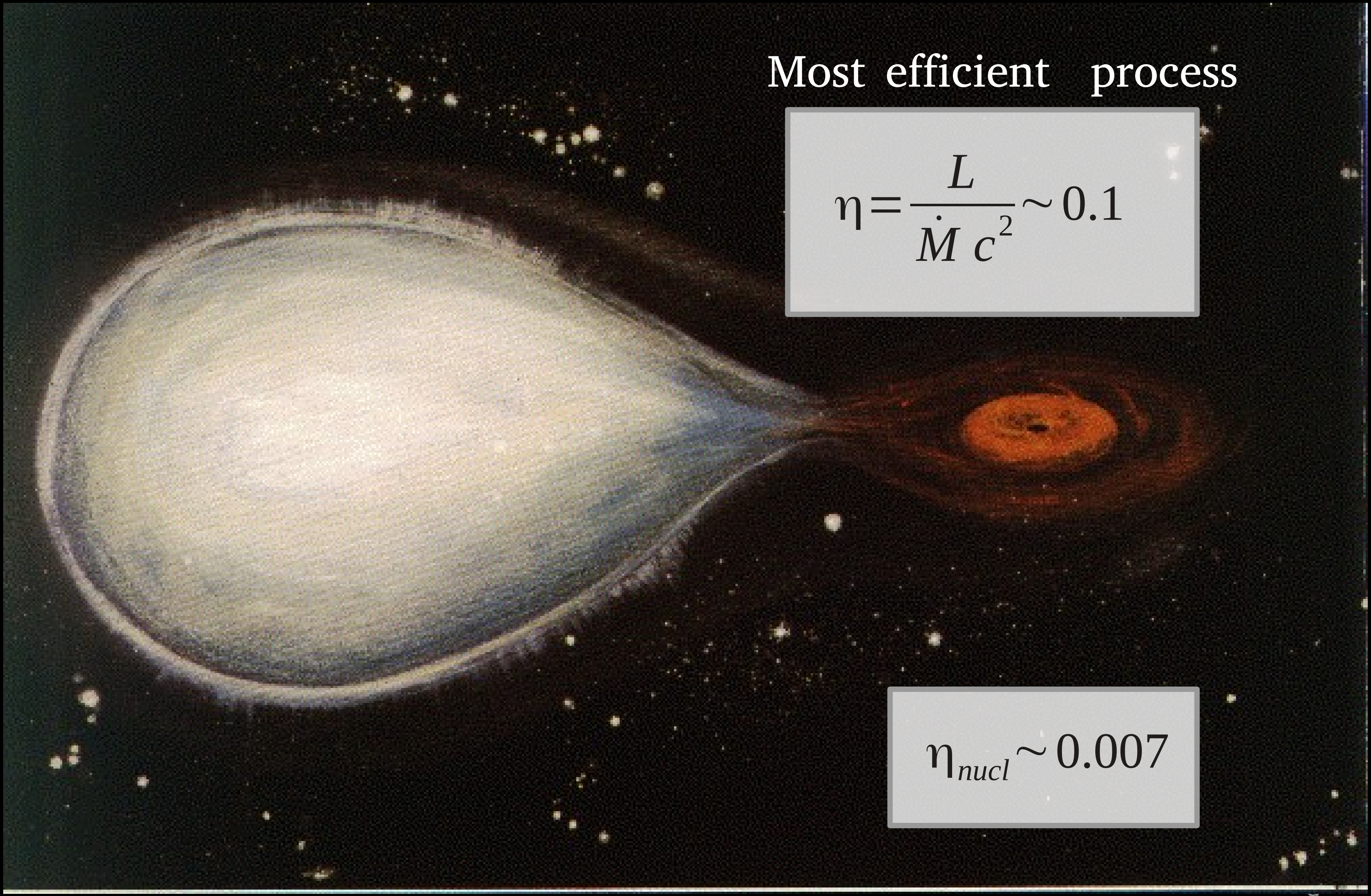
Multi-wavelength Astronomy



The X-ray sky


RXTE All Sky Survey (3-20 keV)
Revnivtsev M., Sazonov S., Jahoda K., Gilfanov M.
90.000
45.000
0.000
-45.000
-90.000
180.000
90.000
0.000
270.000
180.000

Mass Accretion

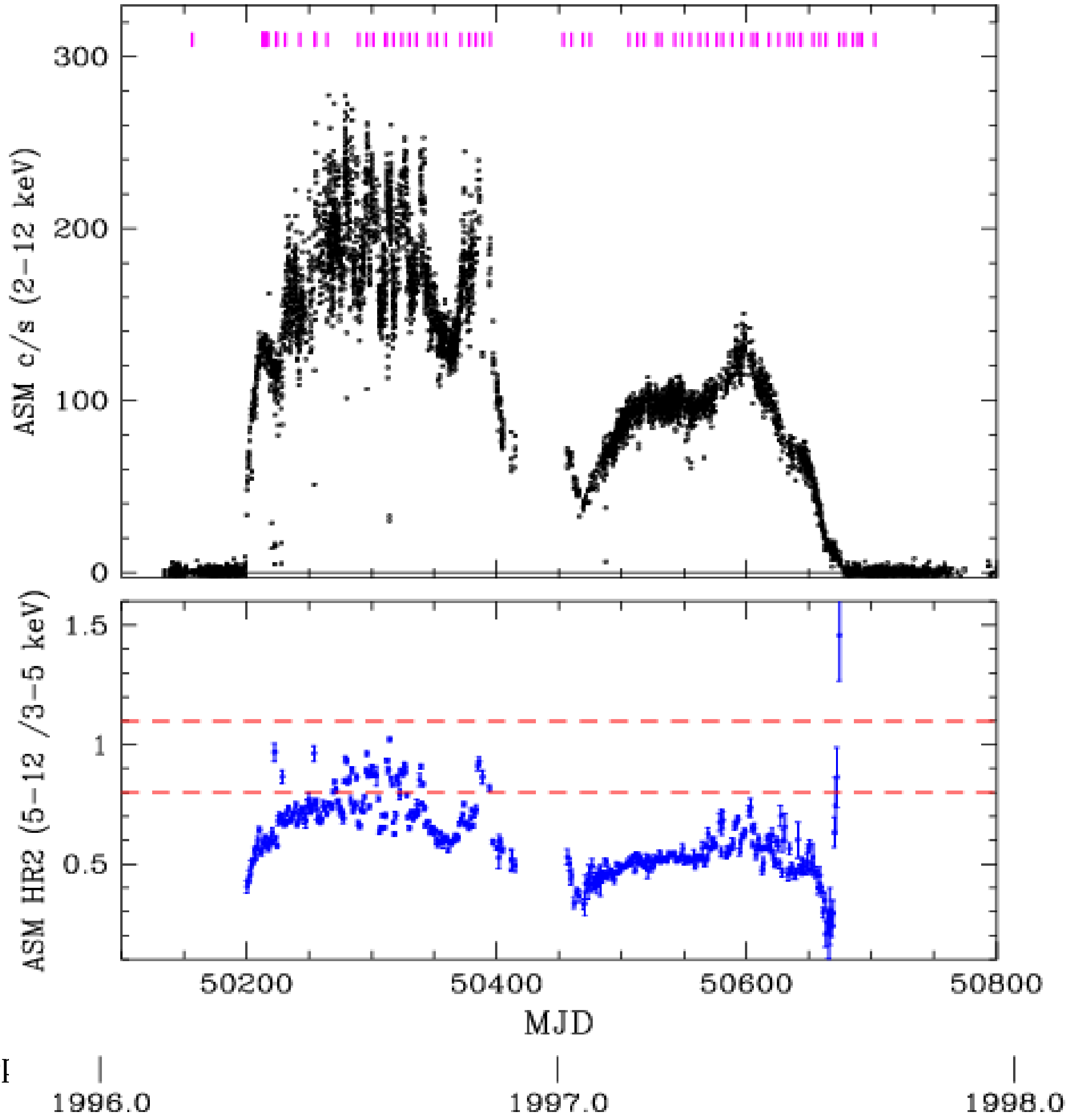


Most efficient process

$$\eta = \frac{L}{\dot{M} c^2} \sim 0.1$$

$$\eta_{nucl} \sim 0.007$$

Black Hole X-ray Transients



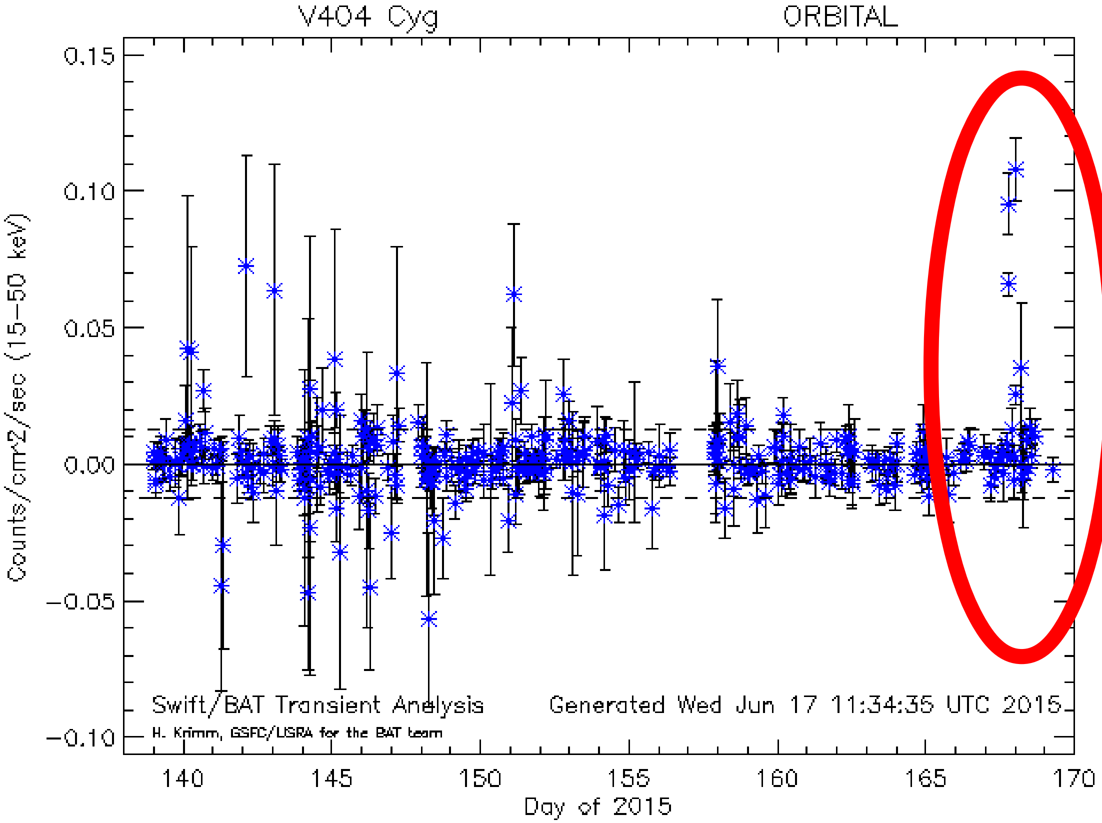
GRO J1655-40

Different X-ray states

V404 Cygni: comeback after 26 years!

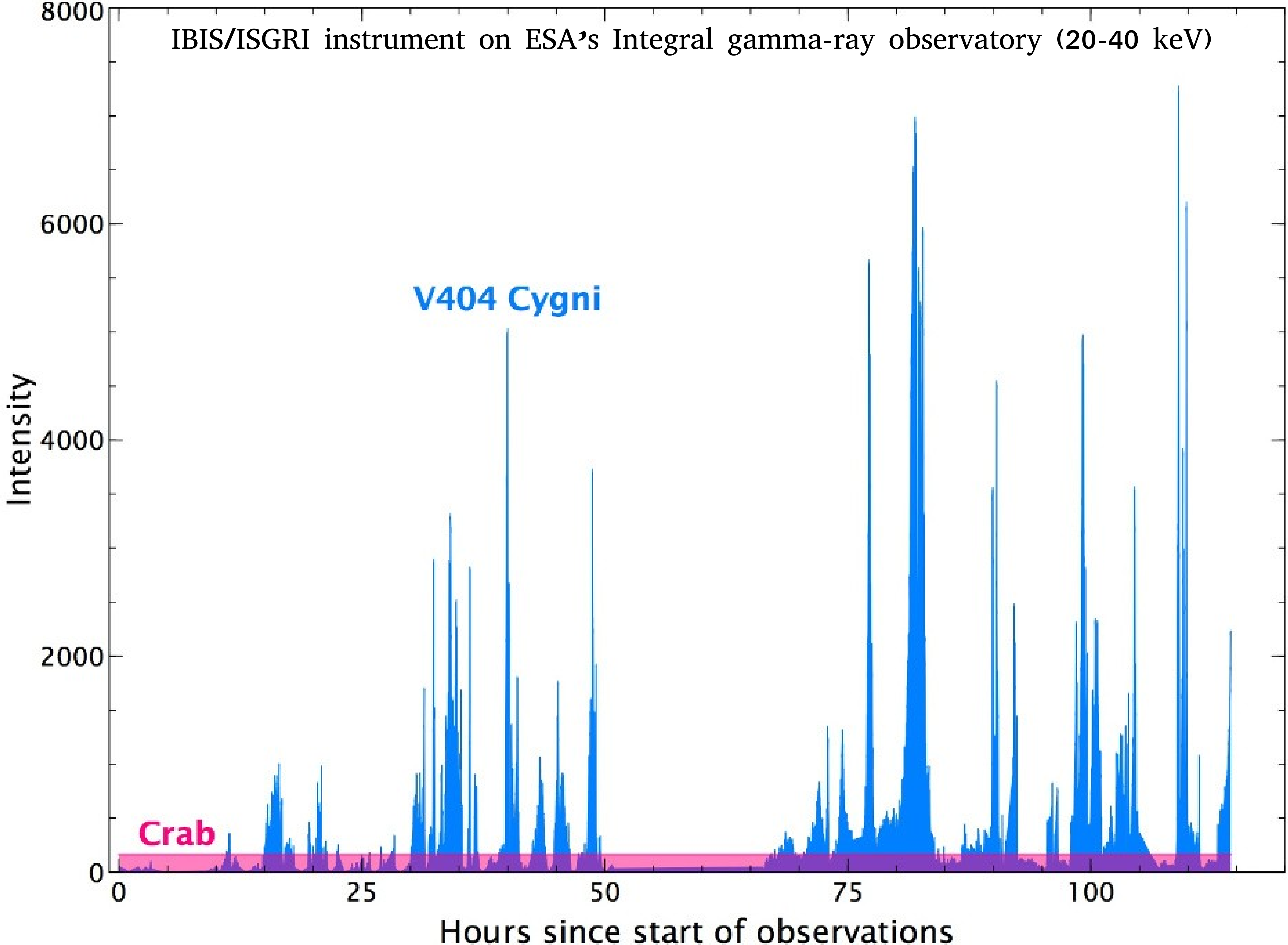
June 15, 2015, 18:32 UT

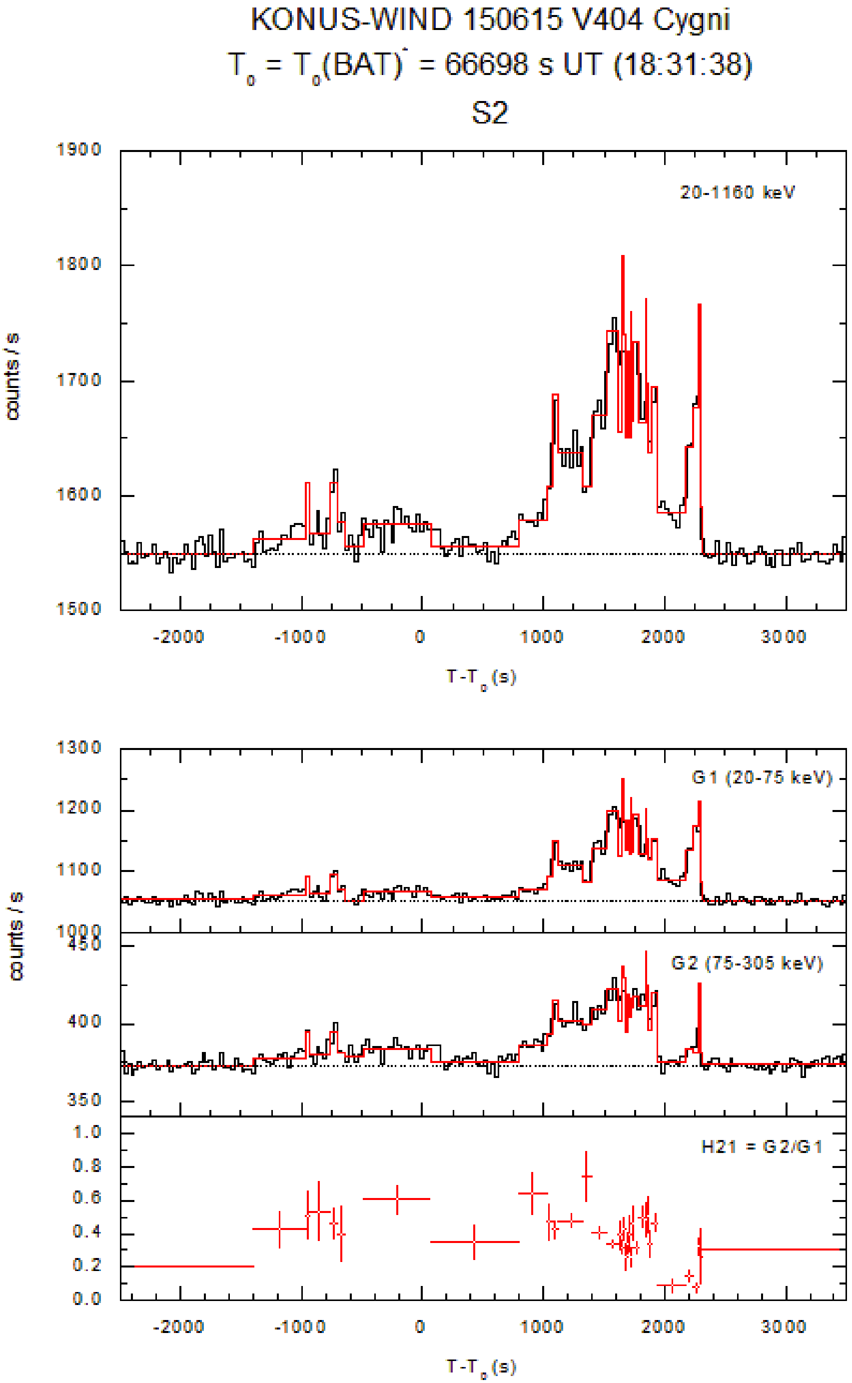
Swift, Konus-WIND, MAXI ... triggered on it.



- LXMB with a BH with **M_{BH}=6.08 ± 0.06 $M_\odot$**
- accreting matter from a K0 subgiant companion star
- P = 6.5 days
- Distance: 2.4 kpc (~8000 lyght-years)
- In 1989 it gave an outburst peaking at 17 Crab with L=7x10^{38} erg/s

Miller-Jones+09


IBIS/ISGRI instrument on ESA's Integral gamma-ray observatory (20-40 keV)
V404 Cygni
Crab
Intensity
8000
6000
4000
2000
0
25
50
75
100
Hours since start of observations



Assuming the distance 2.4 kpc

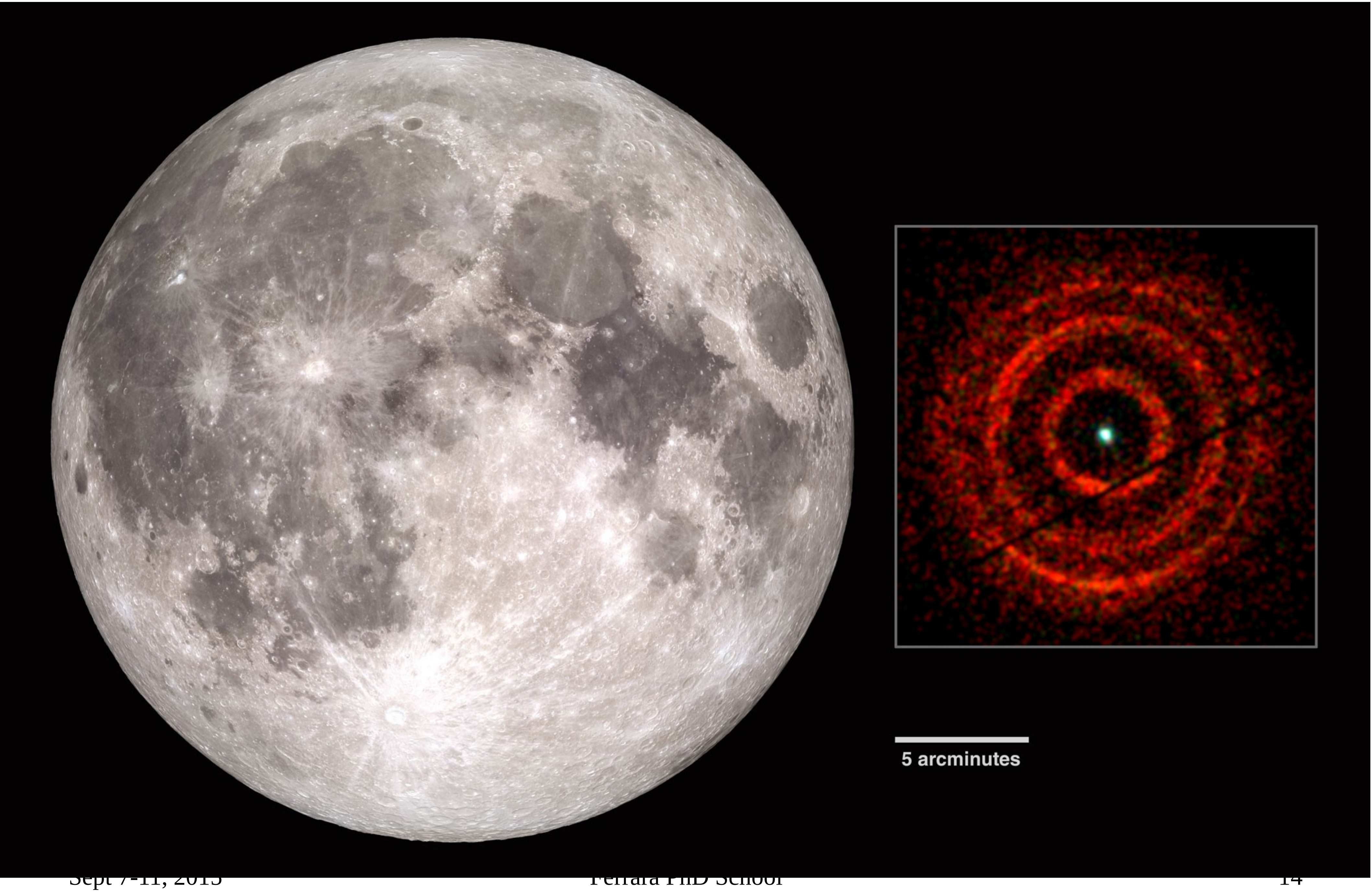
Energy ~ 8.9 x 10^40 erg,

peak luminosity L is ~1.1x10^38 erg/s.

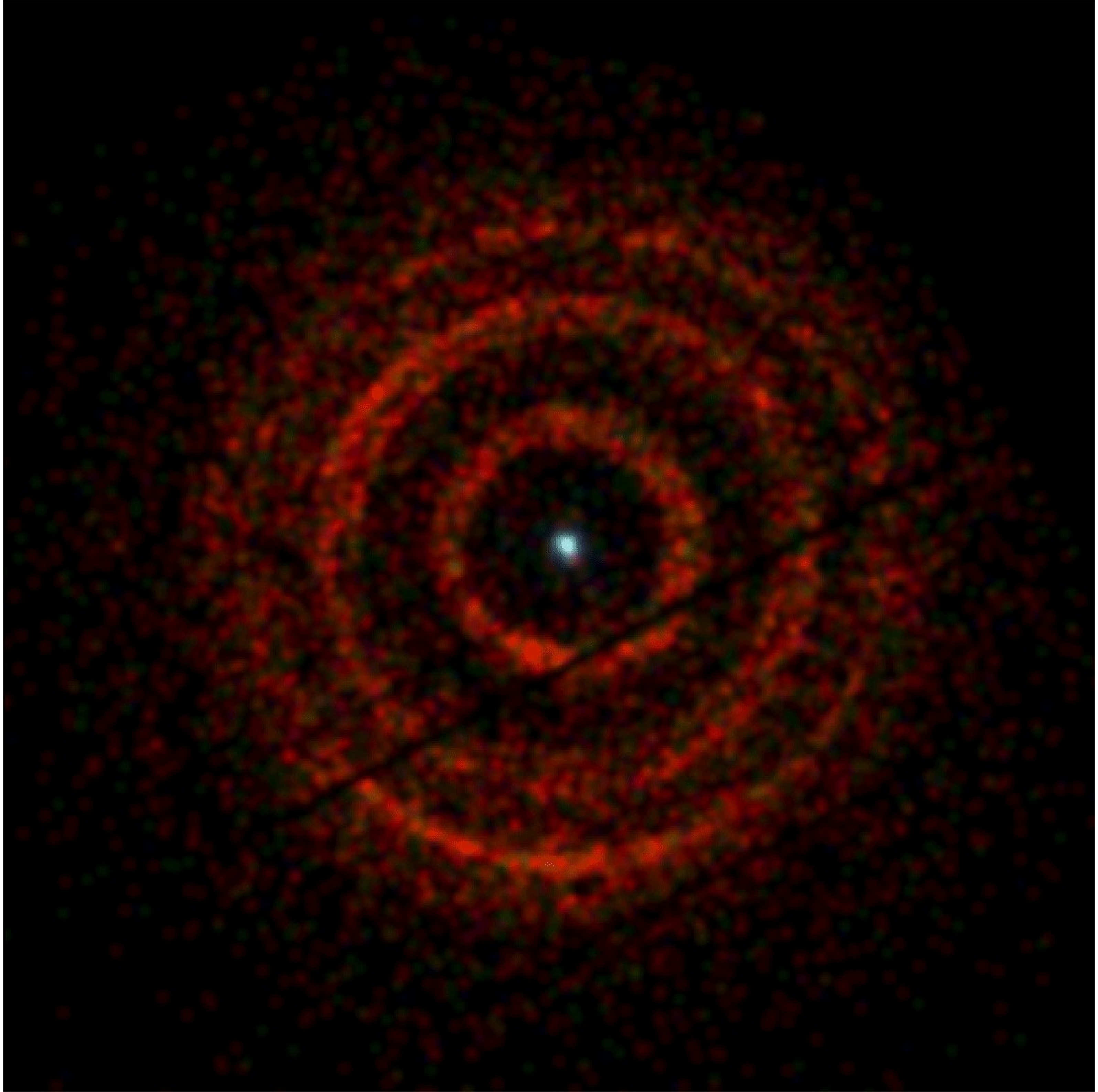
Further activity:
there are at least two episodes
detected on June 16, 2015.

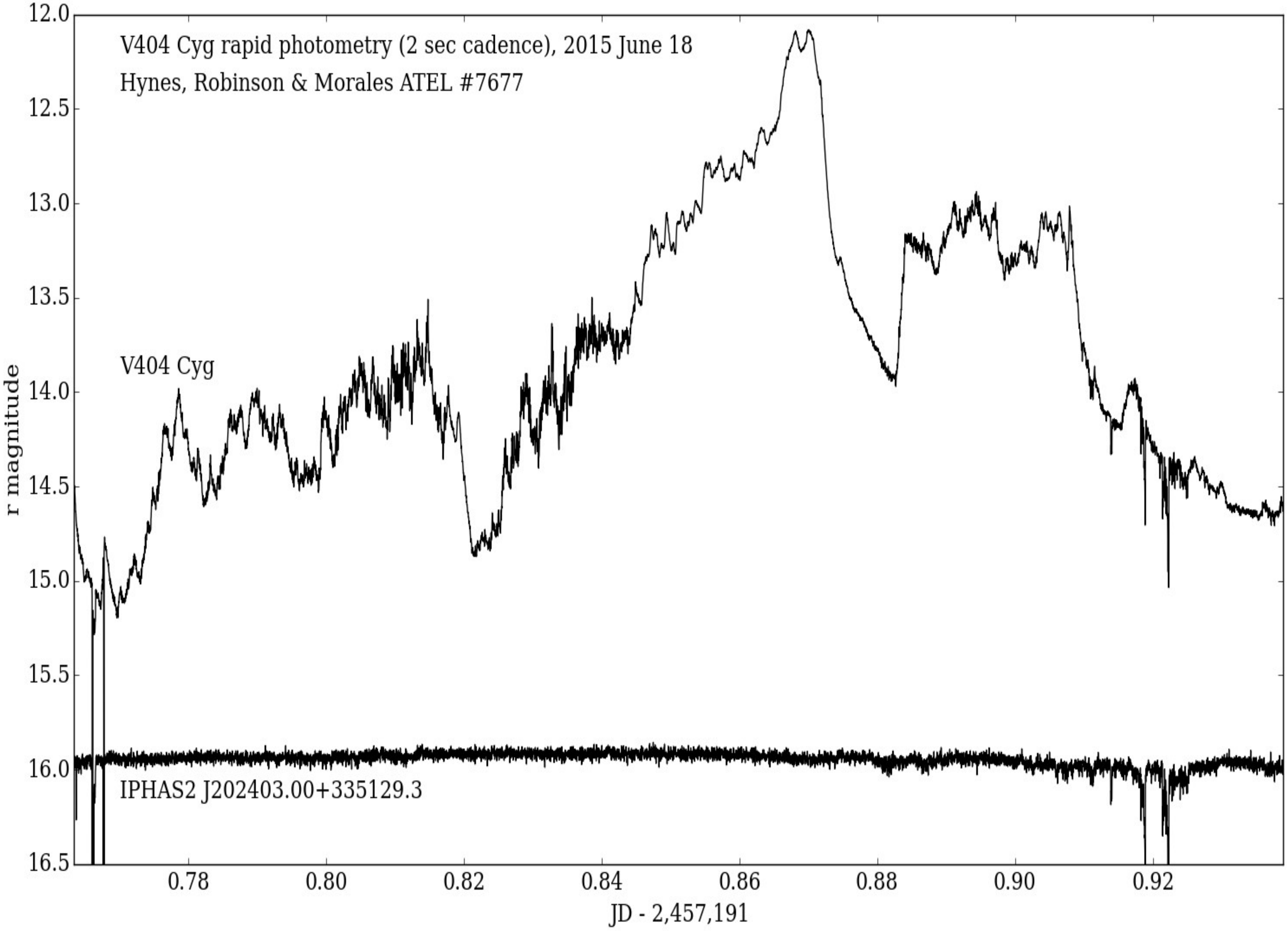
(Golenetskii et al. GCN 17938)

X-ray echo rings caused by foreground Galactic dust.

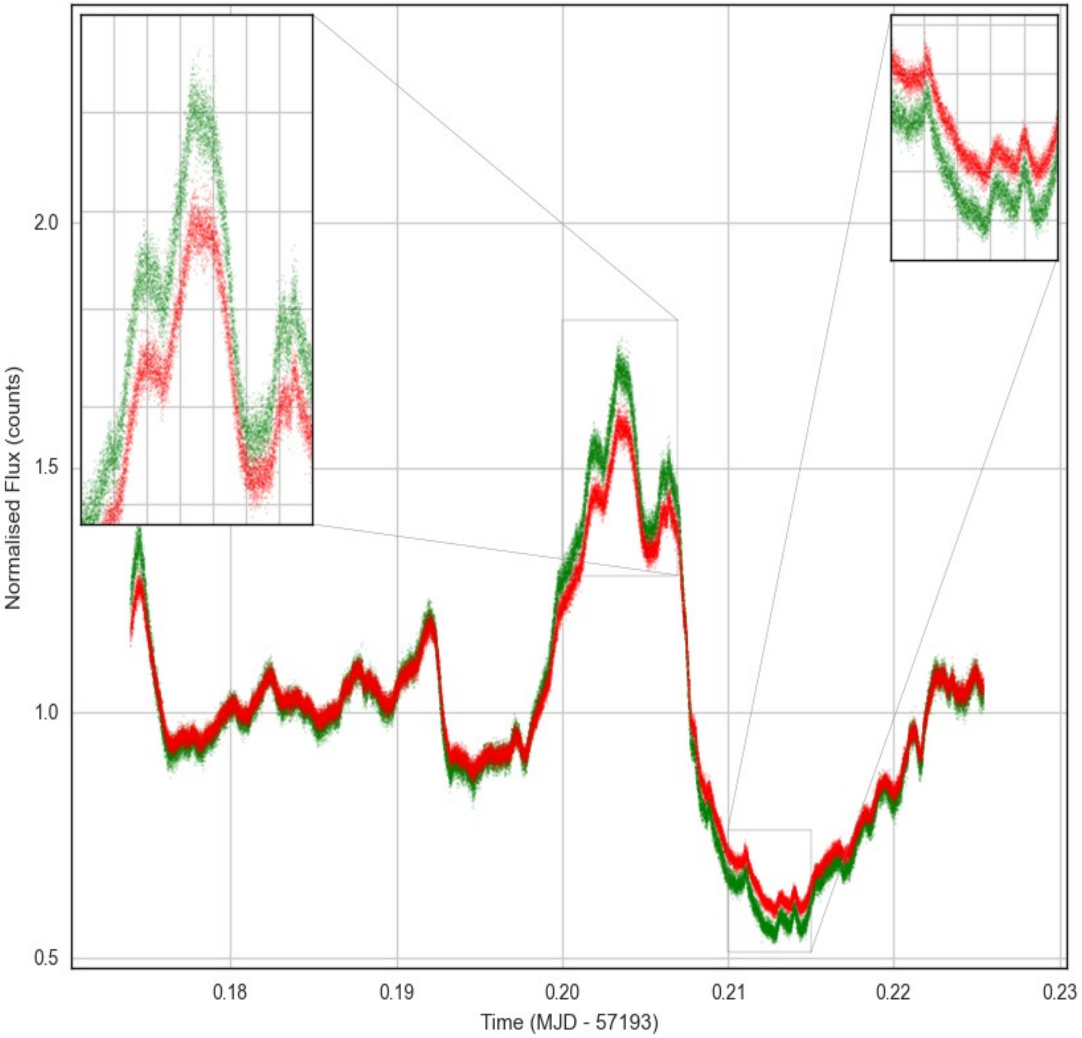


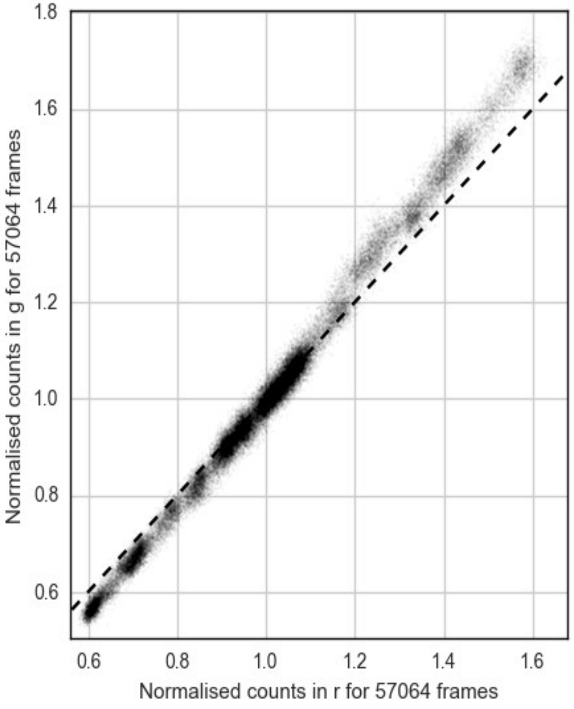
Swift



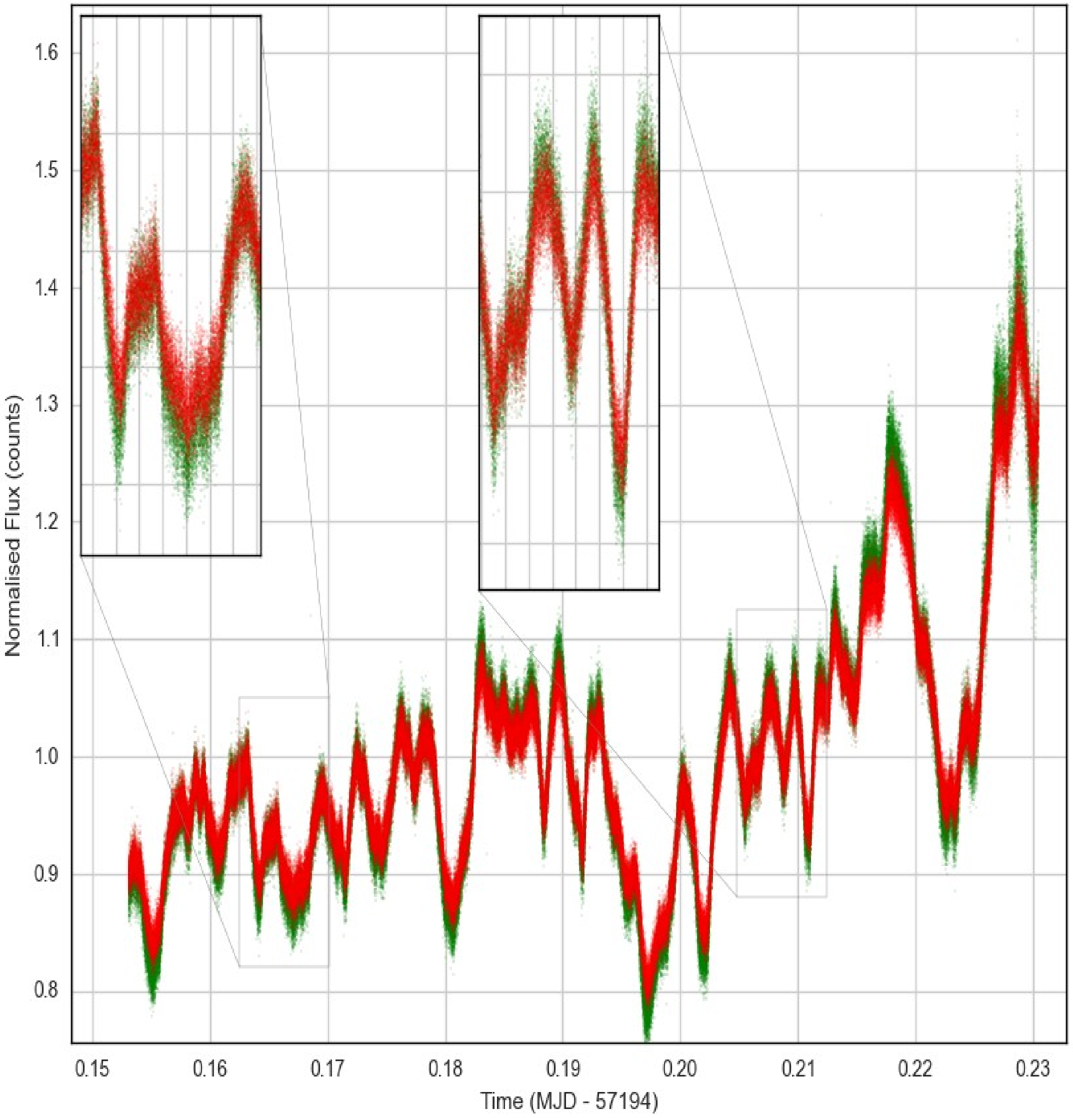

V404 Cyg rapid photometry (2 sec cadence), 2015 June 18
Hynes, Robinson & Morales ATEL #7677
V404 Cyg
IPHAS2 J202403.00+335129.3
r magnitude
12.0
12.5
13.0
13.5
14.0
14.5
15.0
15.5
16.0
16.5
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
JD - 2,457,191

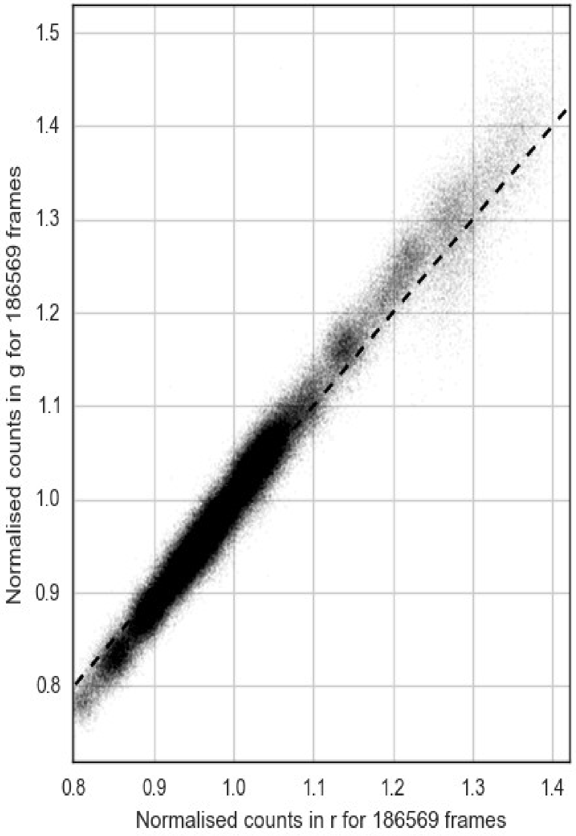
Gandhi+15, Atel 7686 (ULTRACAM fast camera at 4.2-m WHT)

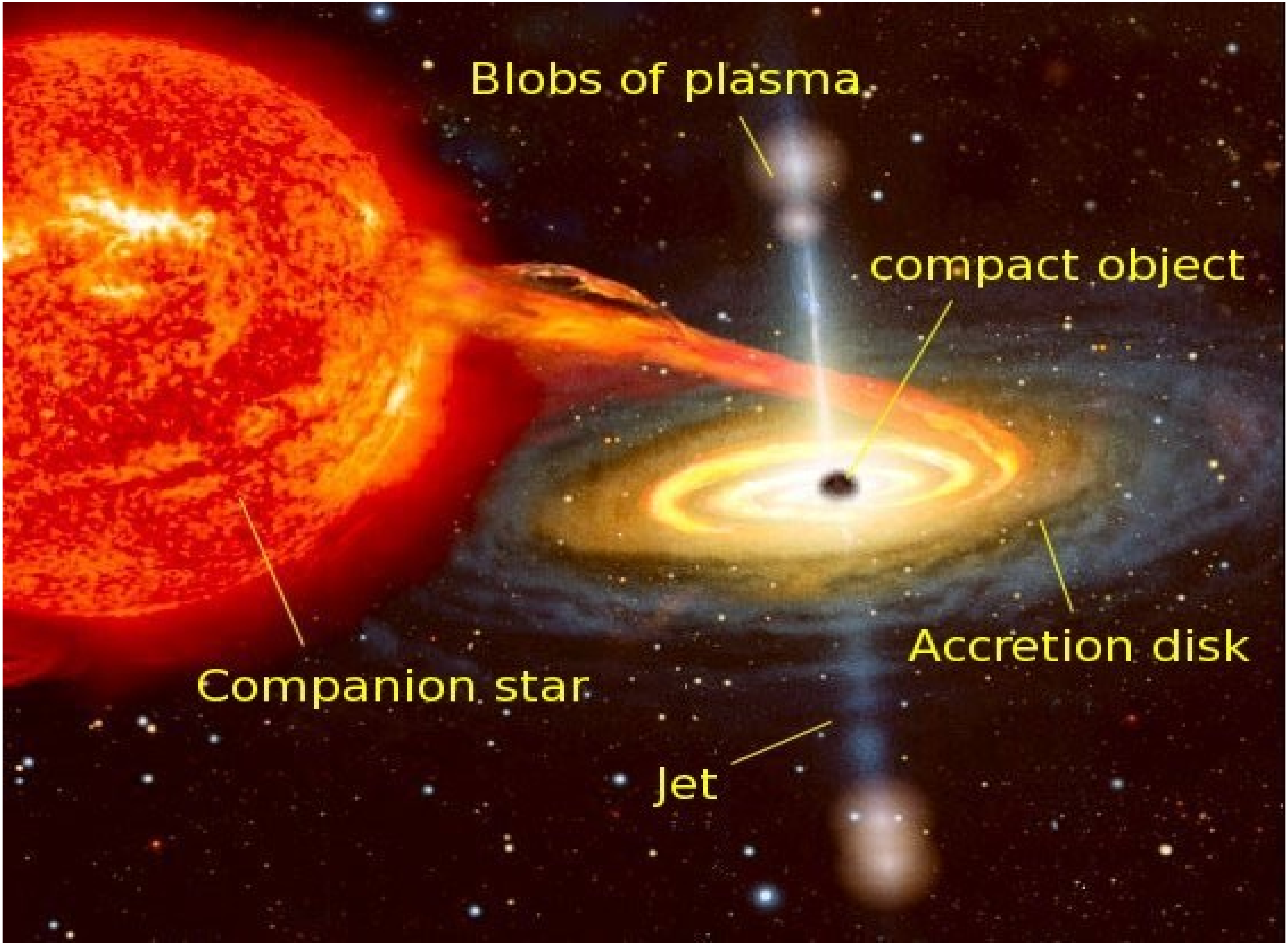




Gandhi+15, Atel 7686 (ULTRACAM fast camera at 4.2-m WHT)



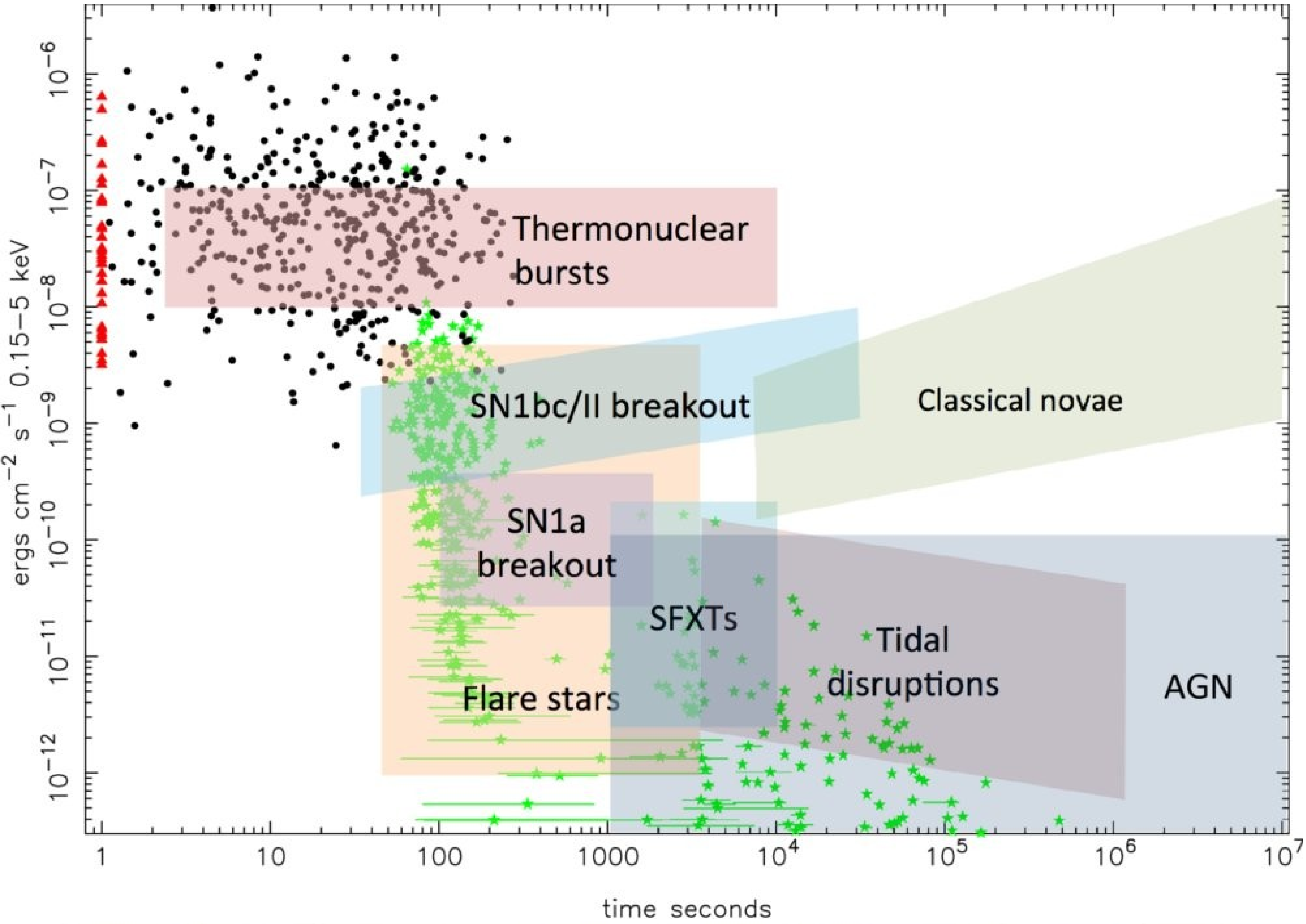



Blobs of plasma
compact object
Accretion disk
Companion star
Jet

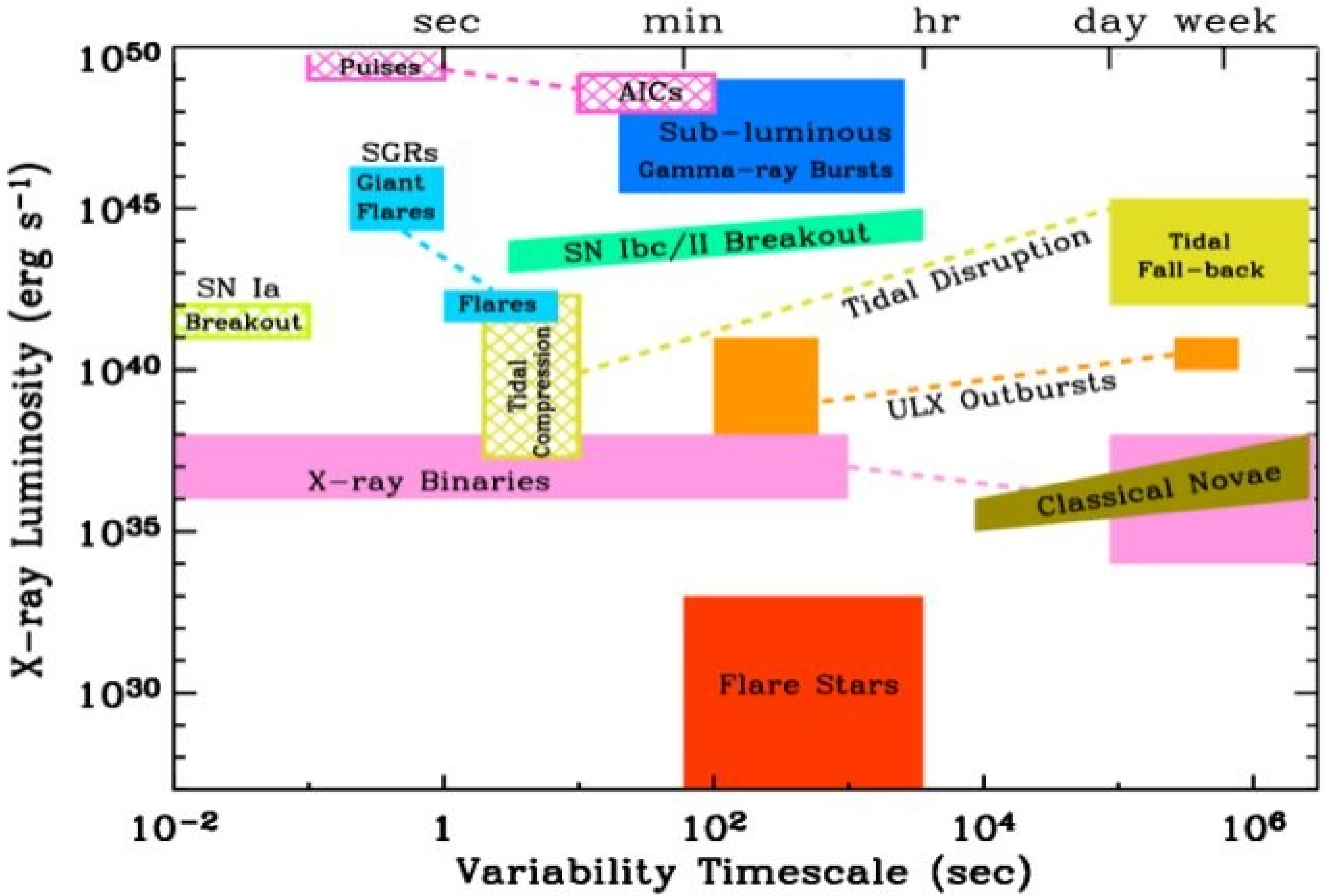
TRANSIENT EVENTS

Our focus is on

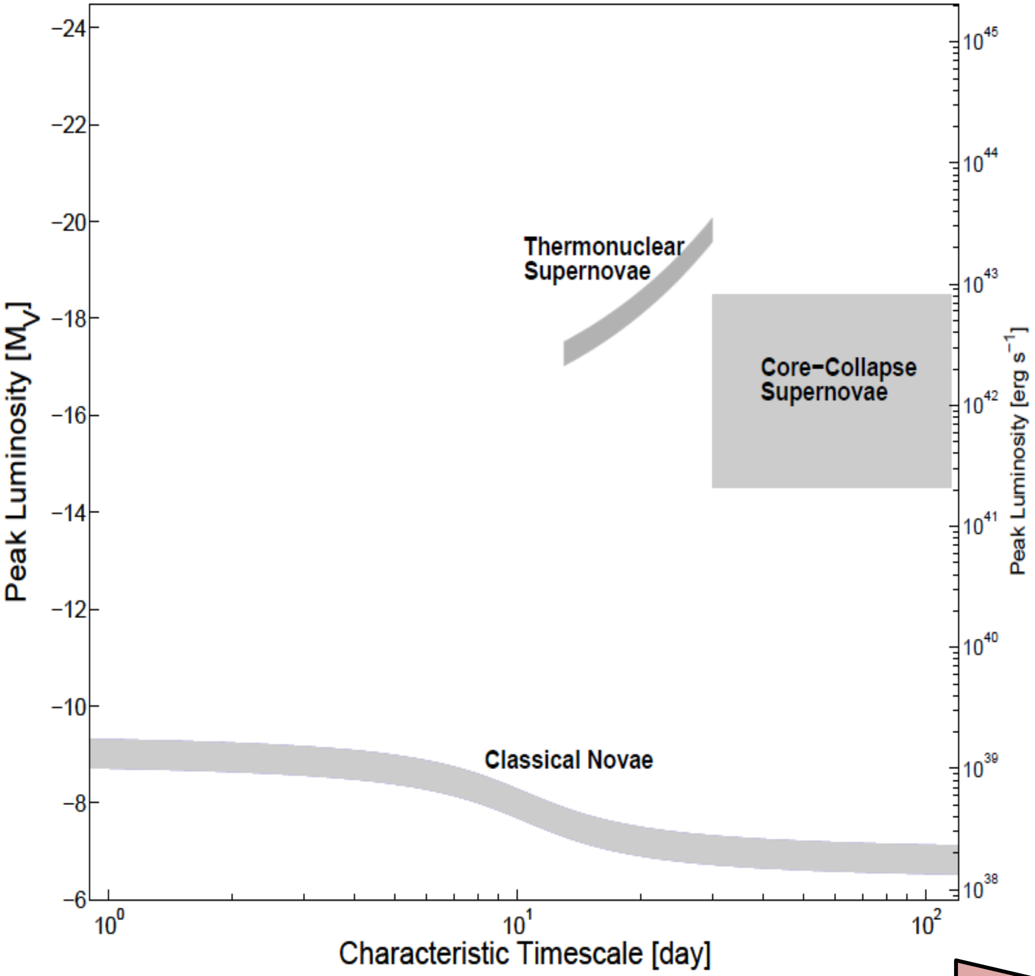
TIME DOMAIN ASTRONOMY

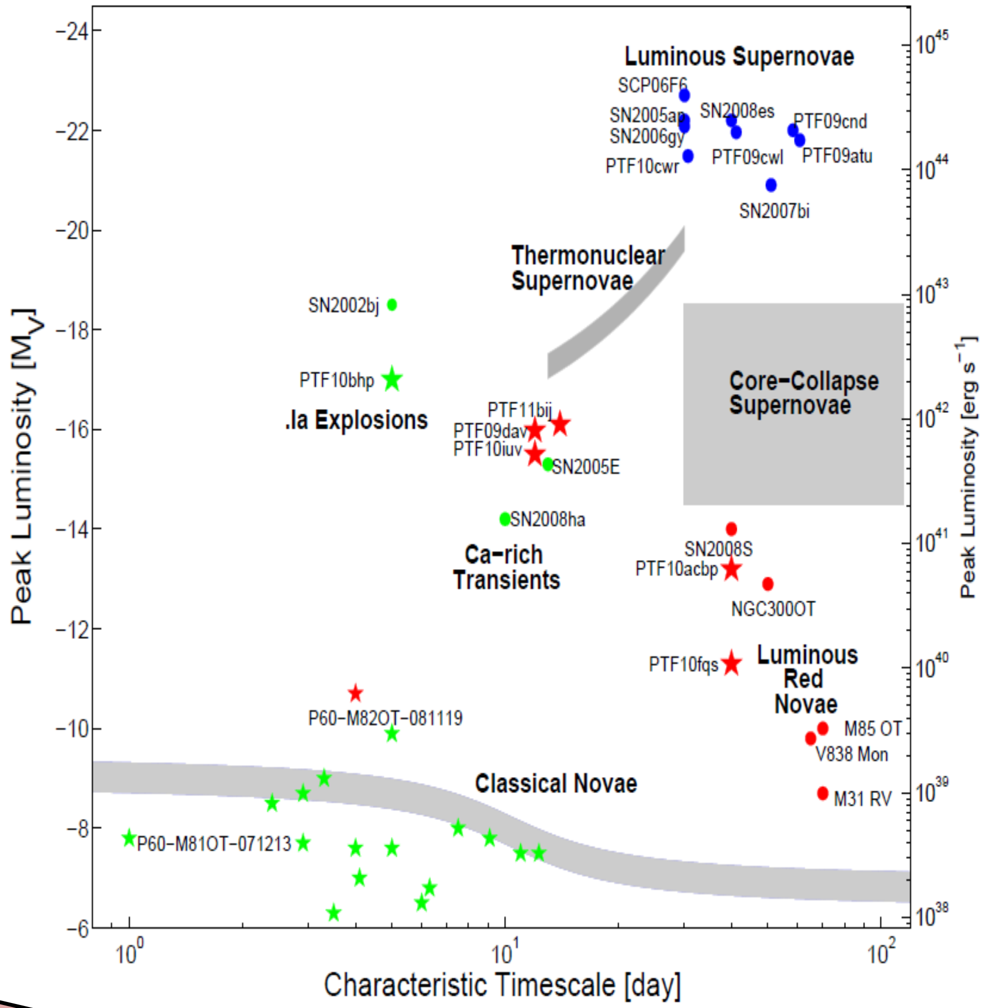


TIME DOMAIN ASTRONOMY



Optical Phase Space: Then and Now





Transients: science drivers

- Traditionally wide-field sky monitoring confined to high-energies or optical (e.g. SNe, novae)
- We can now fill in gaps in the phase space

Transients: science drivers

- Study of physics laws in extreme conditions (e.g., SNe, GRBs, TDEs, neutron stars, stellar BHs, SMBHs)
- Extreme accelerators (SN remnants, relativistic jets)
- Less luminous transients (flaring stars), accretion in our Galaxy, evolution of stars and galaxies
- Transients as probes to constrain cosmology (SNe,GRBs, first stars)

Revolution

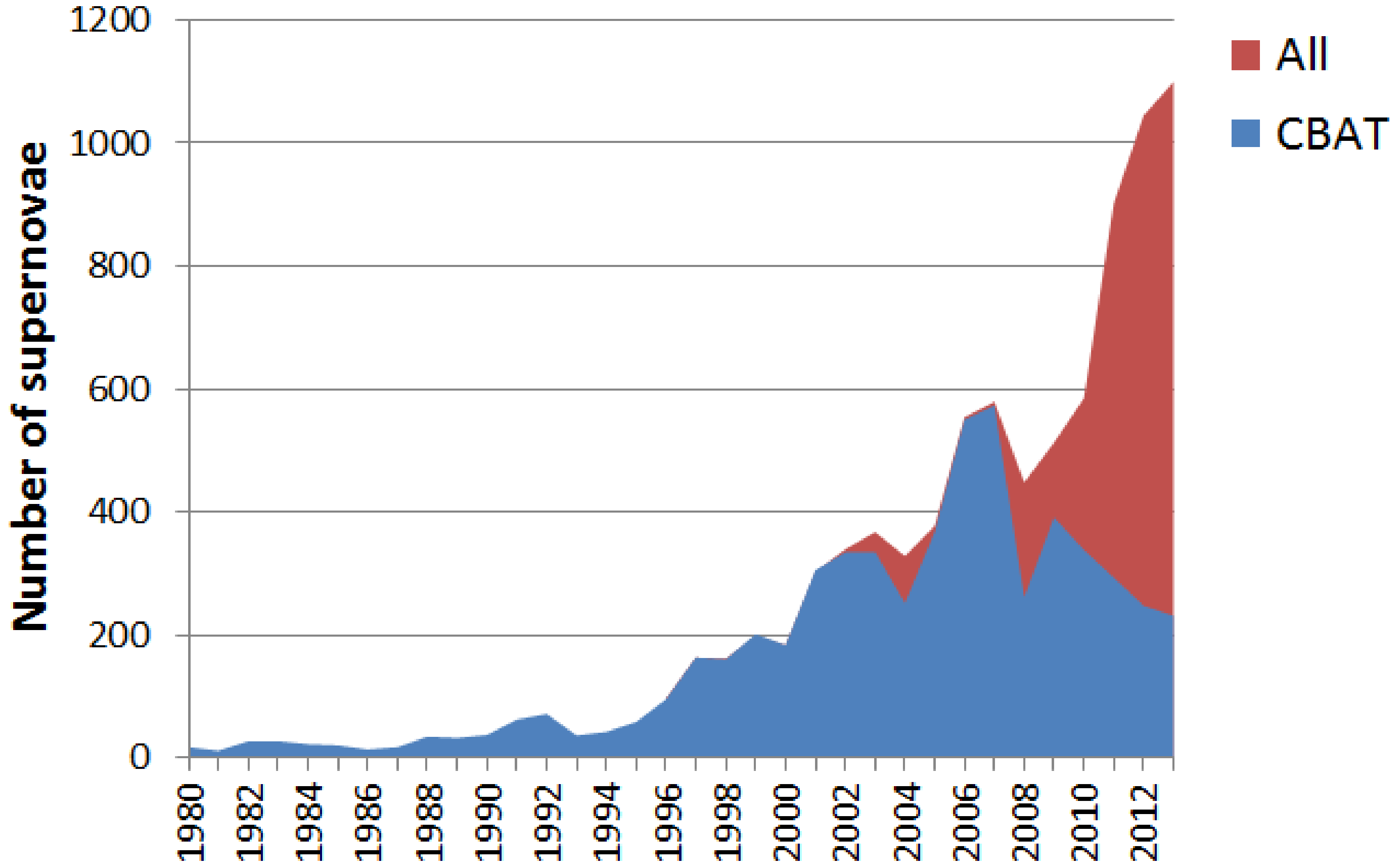
Data poverty → immense exponentially growing data richness (Big Data)

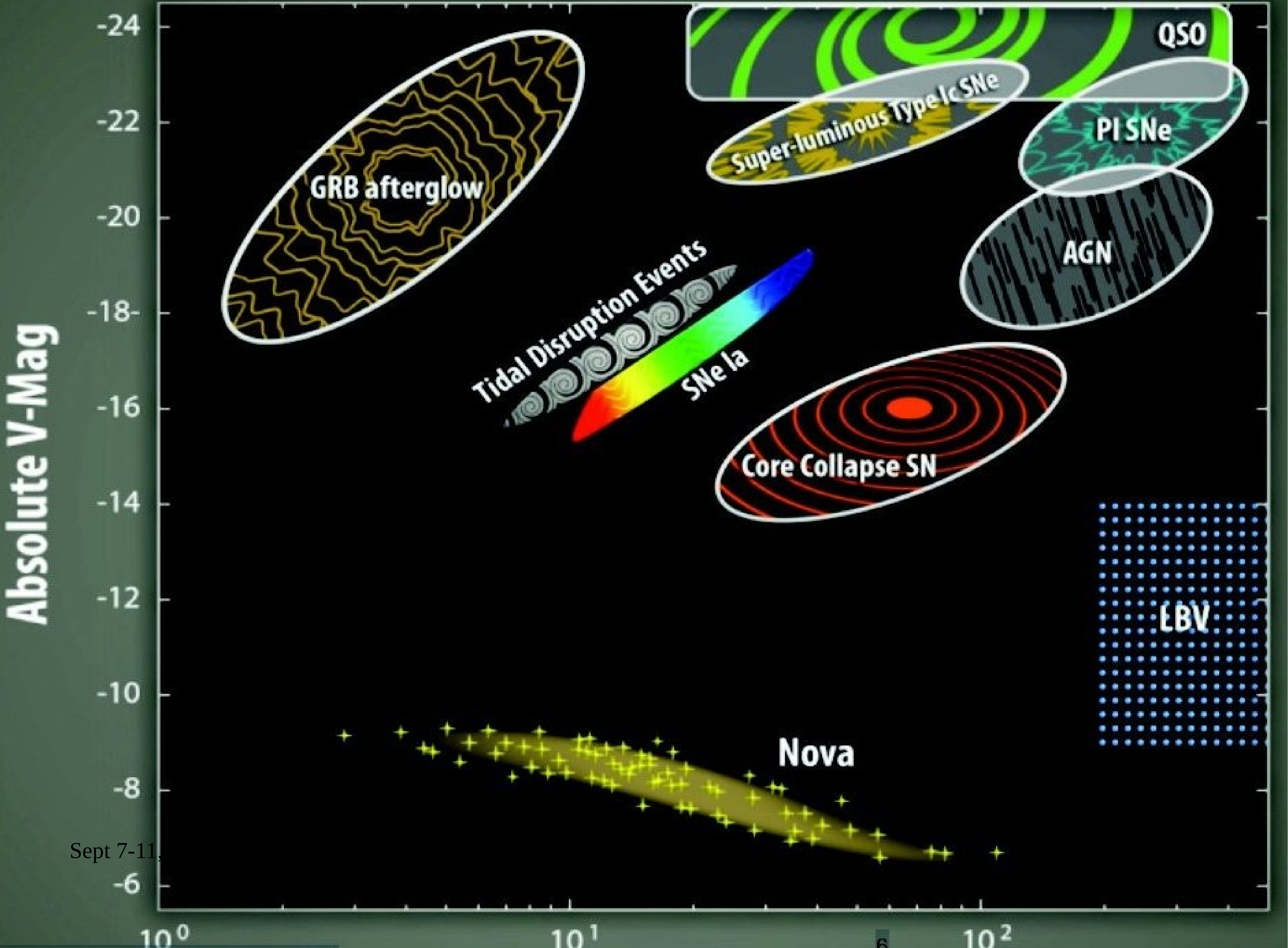
Recent discoveries:
- Predicted and sought-after
- Unexpected

→ New discovery space

Astronomy has just entered the Time Domain and Synoptic Sky Survey Era

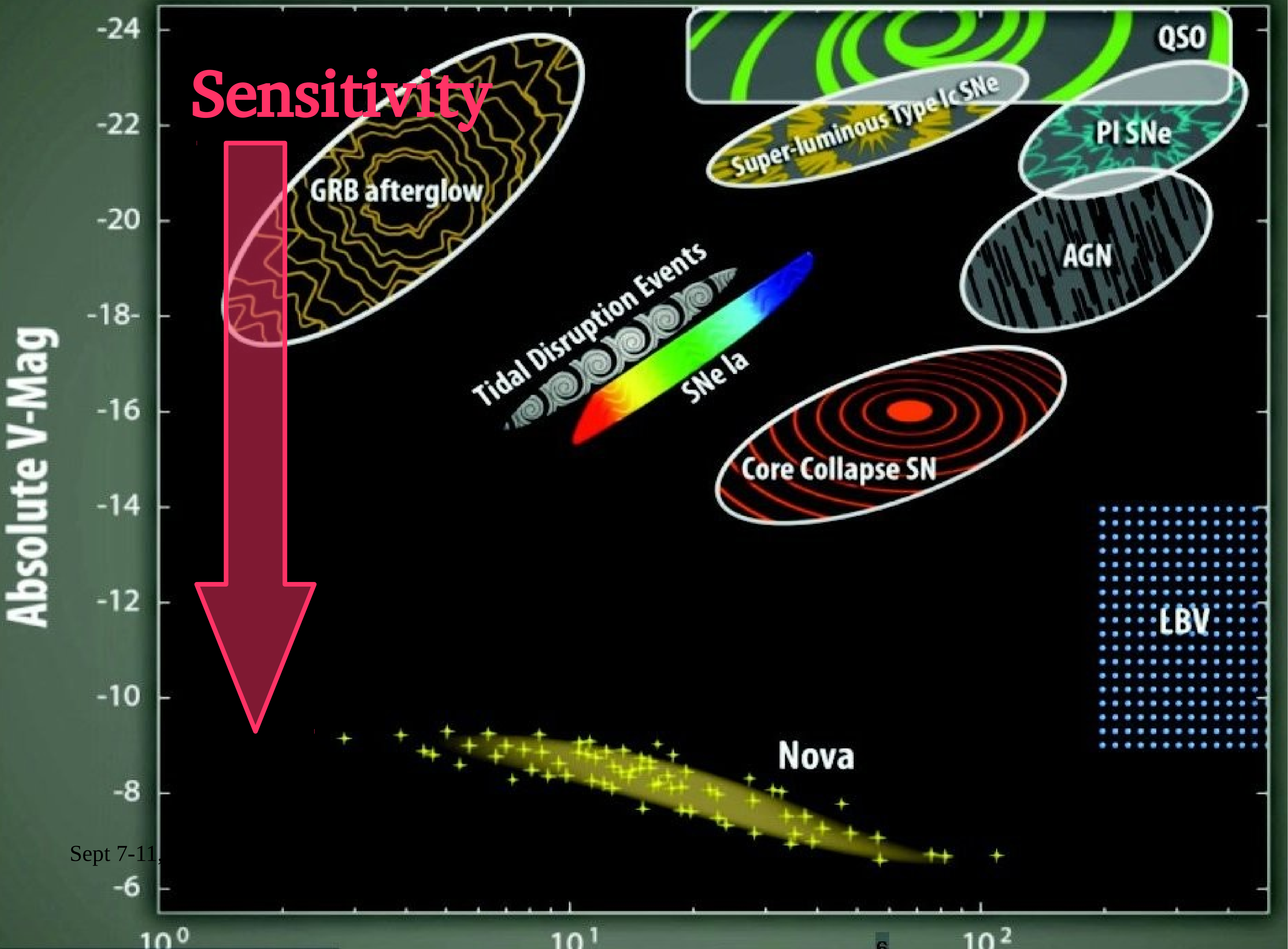
SNe: discovery rate



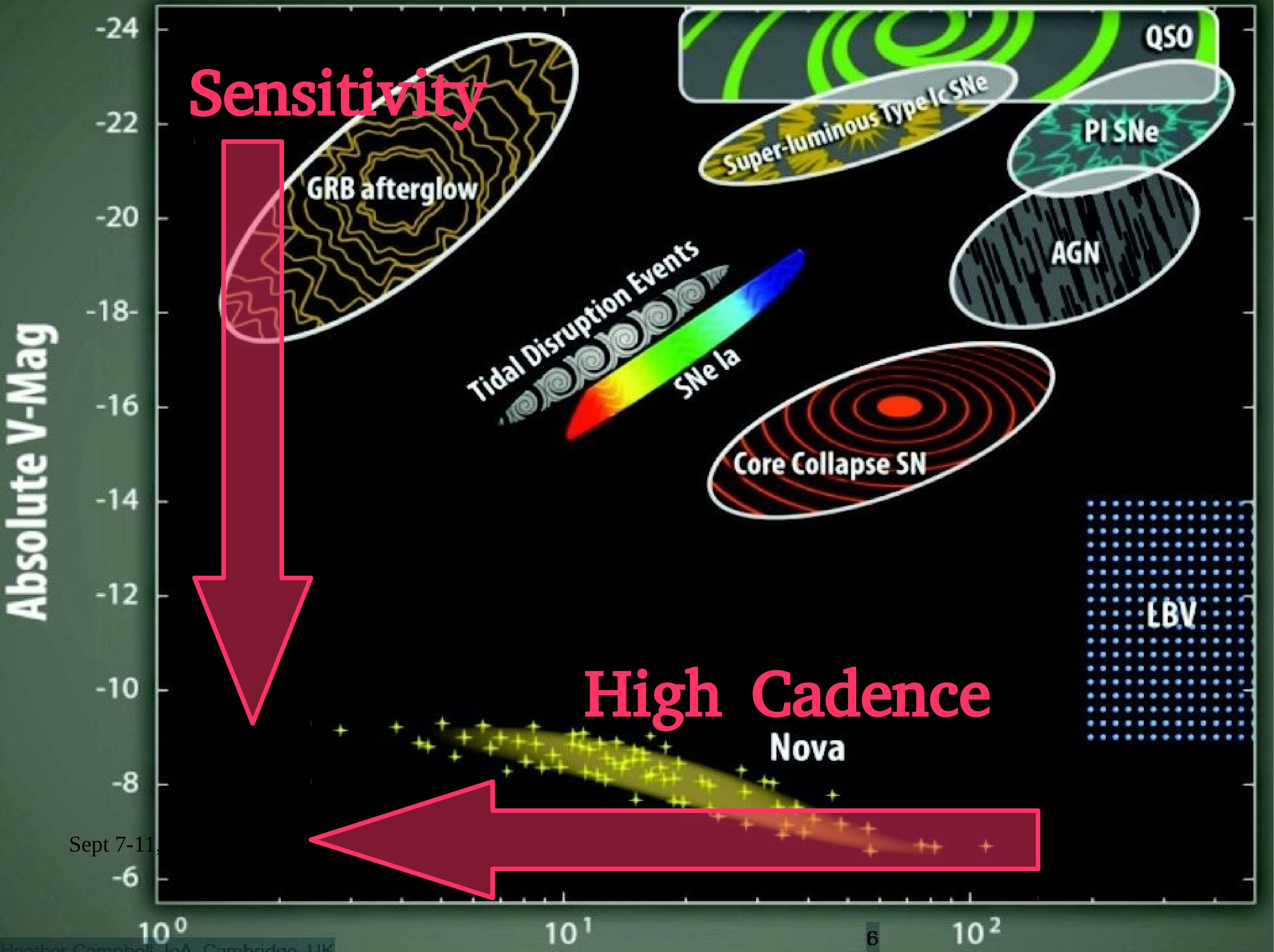


Sept 7-11,

Heather Campbell, IoA, Cambridge, UK



Sensitivity



Sensitivity

High Cadence

TIME DOMAIN ASTRONOMY

- Revolution in our ability to monitor the Universe

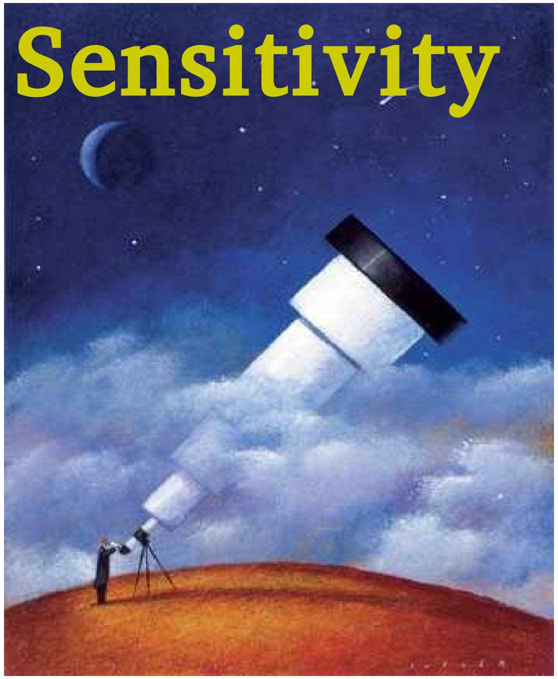
- Capture the **behaviour of the temporal sky** with **high cadence** **across the e.m. spectrum** and through **neutrino and gravitational wave** physics.

- Census of the transient sky

Summing up, keys are…

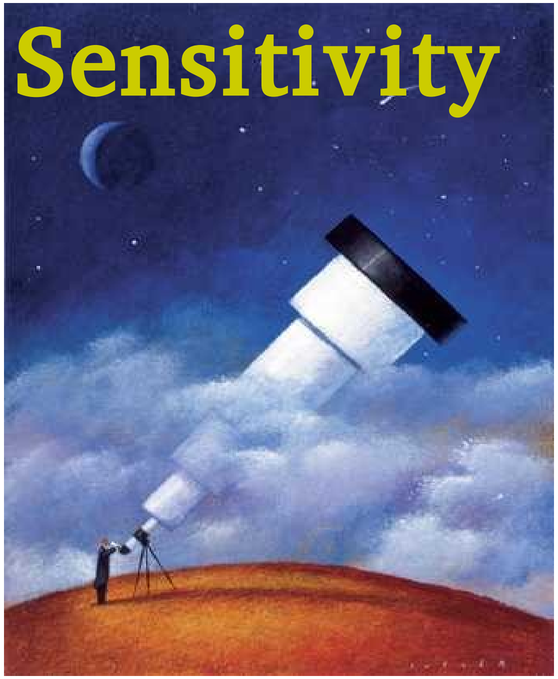
Time domain (high cadence)

Time domain (high cadence)

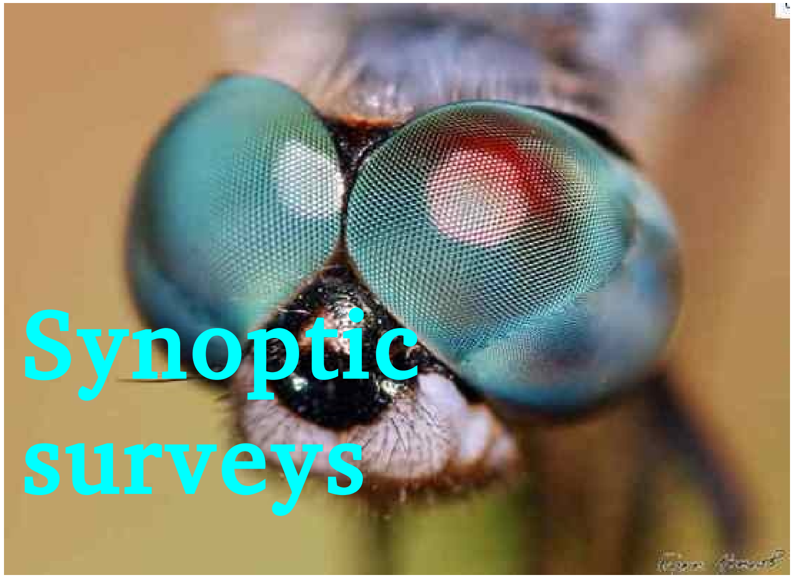


Sensitivity

Time domain (high cadence)



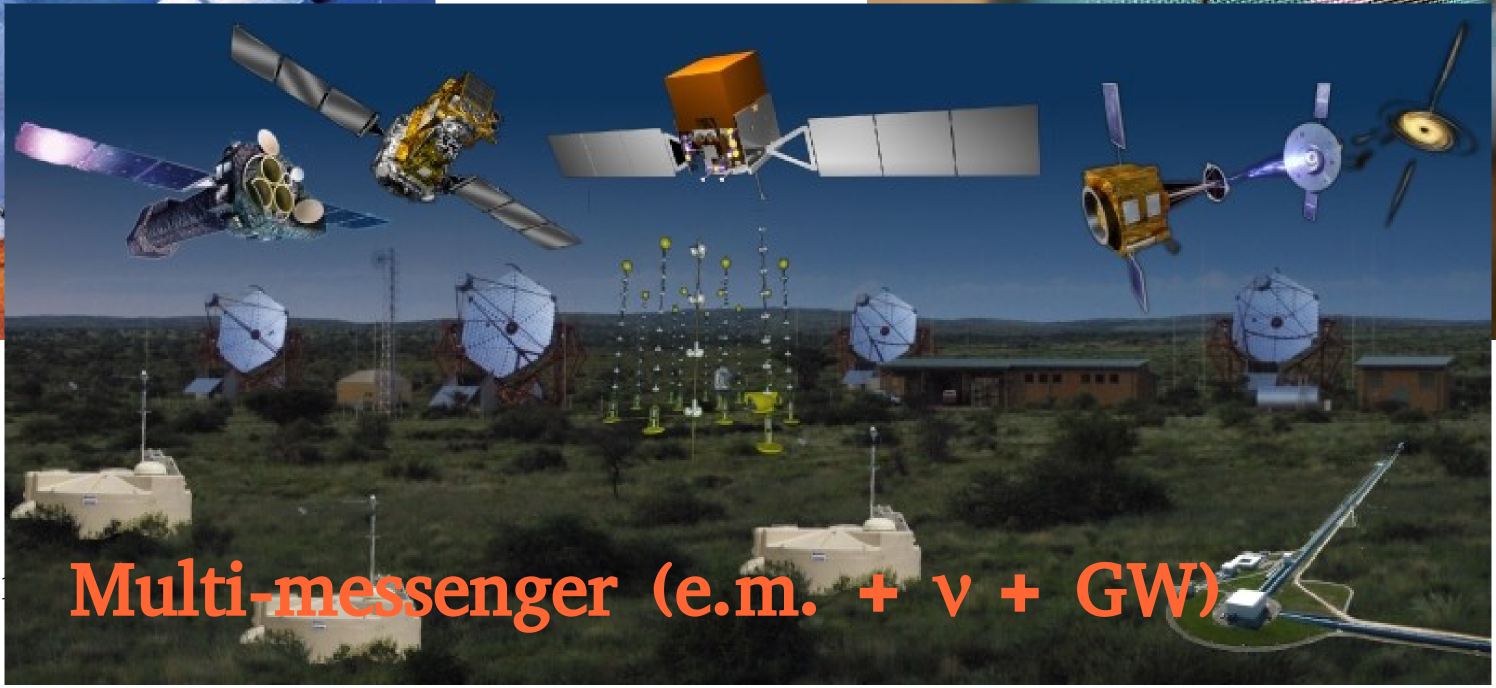
Sensitivity



Synoptic surveys

Time domain (high cadence)

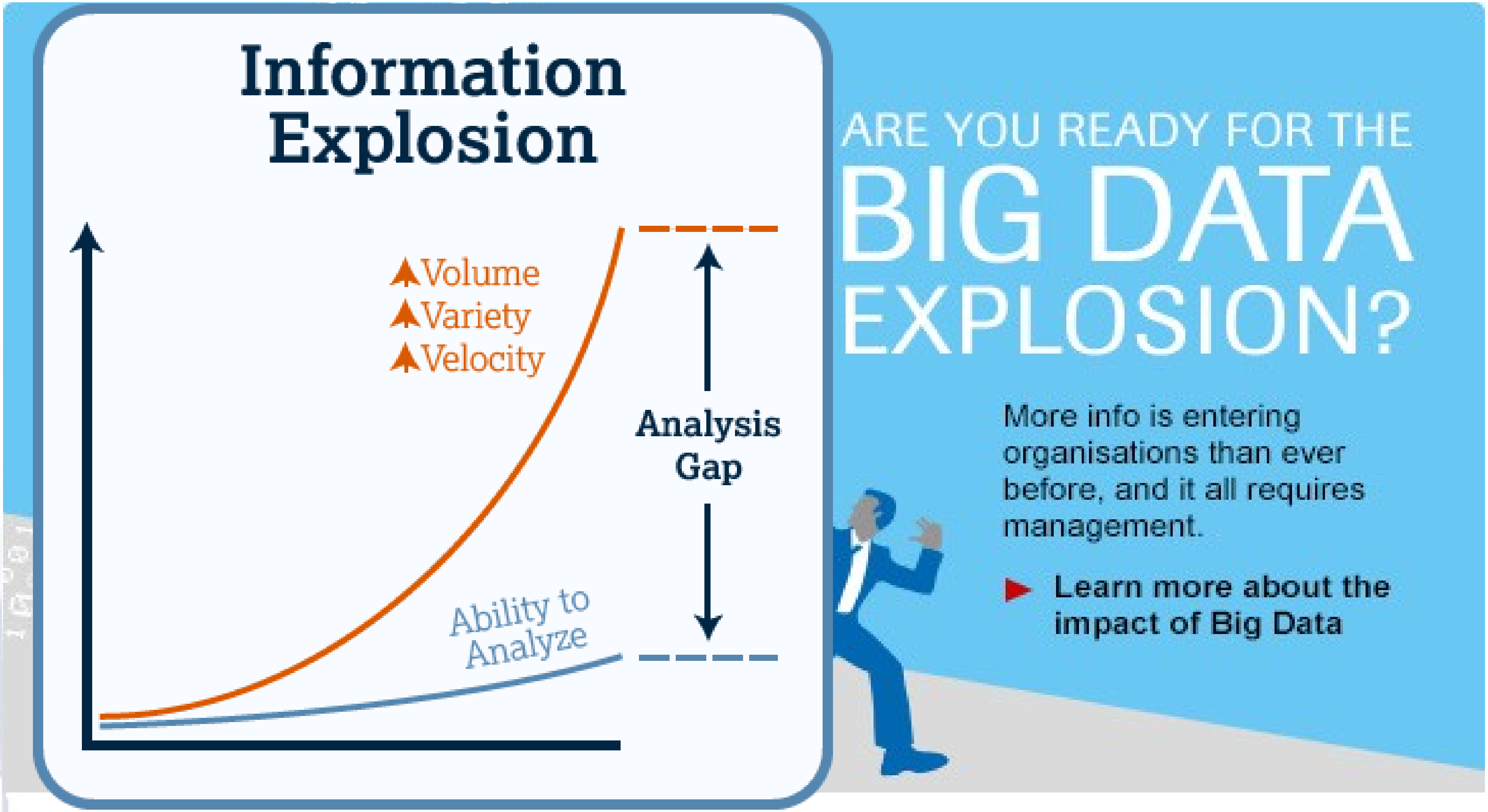
Sensitivity



Multi-messenger (e.m. + ν + GW)

More info is entering organisations than ever before, and it all requires management.

► Learn more about the impact of Big Data



Information Explosion

ARE YOU READY FOR THE BIG DATA EXPLOSION?

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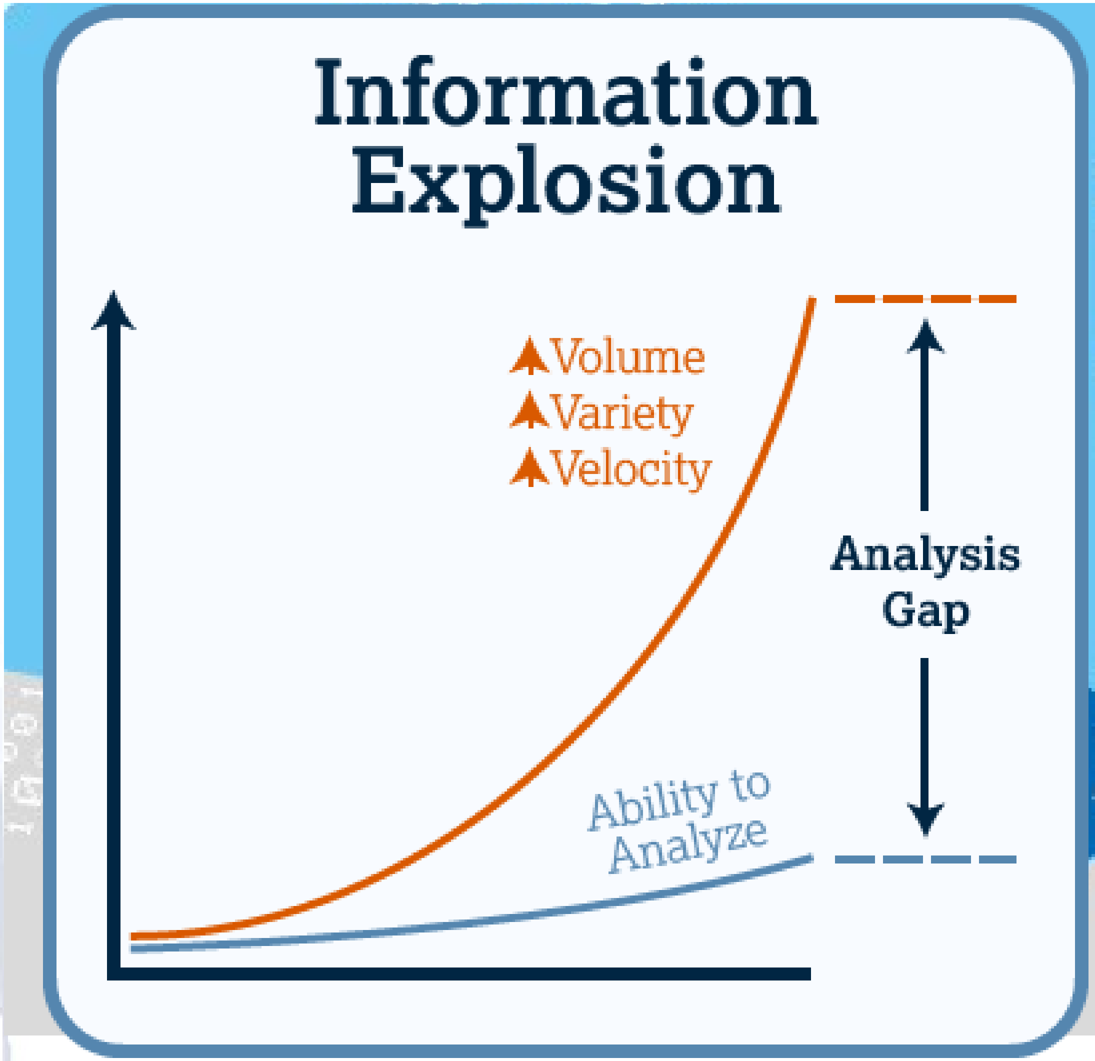

Information Explosion
Volume
Variety
Velocity
Analysis Gap
Ability to Analyze


ARE YOU READY FOR THE
BIG DATA
EXPLOSION?
More info is entering


HELP

Data Mining

Journey through Transients and Present/Future related Science

- Swift review of a *very selected sample* among the hottest kinds of transients (lectures 1+2)

- Review of current and future surveys and related issues/strategies (lecture 2)

Observational perspective: mind-boggling variety!

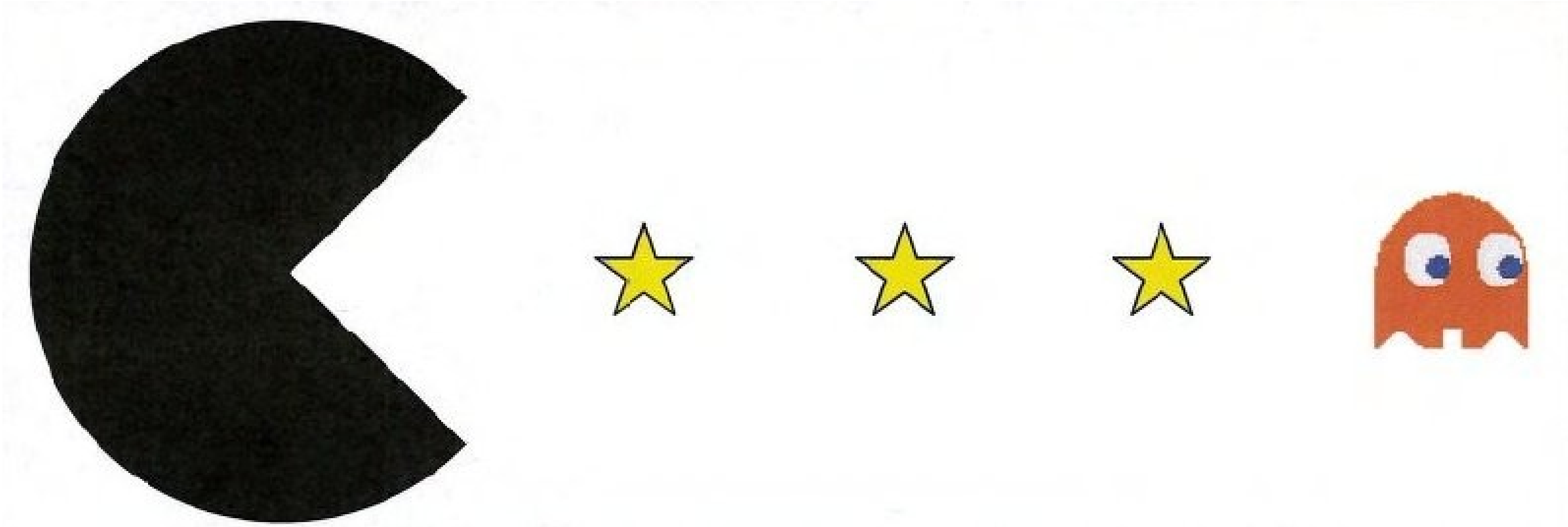
- Asteroids, comets, **NEO**
- Occultations by trans-Neptunian objects
- Exoplanets via microlensing/transits
- T Tauri outbursts, episodic accretion
- X-ray transients, X-ray binaries
- Novae, Supernovae, high-z Quasars
- Gamma-Ray Bursts (GRBs)
- Tidal Disruption Events (TDEs)
- Fast Radio Bursts (FRBs)
- SuperLuminous Supernovae (SLSNe)
- Luminous Blue Variables (LBVs) – SN Impostors
- Ultra-Luminous X-ray sources (ULXs)

Observational perspective: min boggling variety

- Asteroids, comets
- Occultatio
- Ex
-
-
- S
- Lu s) – SN Impostors
- Ul sources (ULXs)

- Superflares from solar-type stars
- SN shock break-outs
- Radio Transients
- Unclassified Transients
- Unknown (often the most exciting side of future)
- Expected in the future:
  - Gravitational waves (binary mergers, asymmetric exploding SNe)
  - Neutrino astronomy (particle accelerators, core collapses)
  - Very high-energy gamma-rays (30 GeV-100 TeV)

Tidal Disruption Events (TDEs)



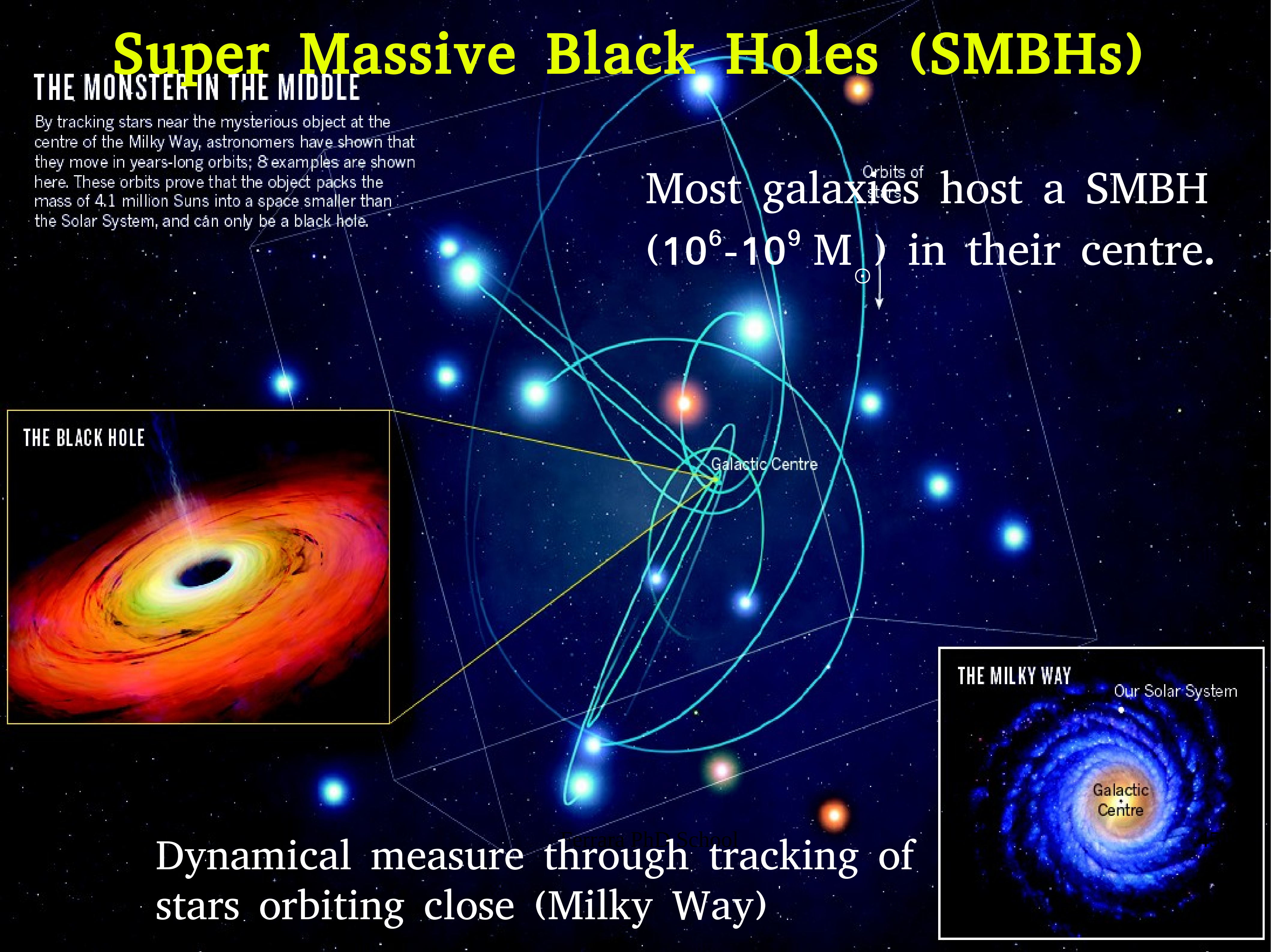
a long-predicted tale that turned real

Super Massive Black Holes (SMBHs)

Most galaxies host a SMBH (10^6-10^9 $M_\odot$) in their centre.

Copious amount of radiation due to accreted matter

Super Massive Black Holes (SMBHs)



THE MONSTER IN THE MIDDLE

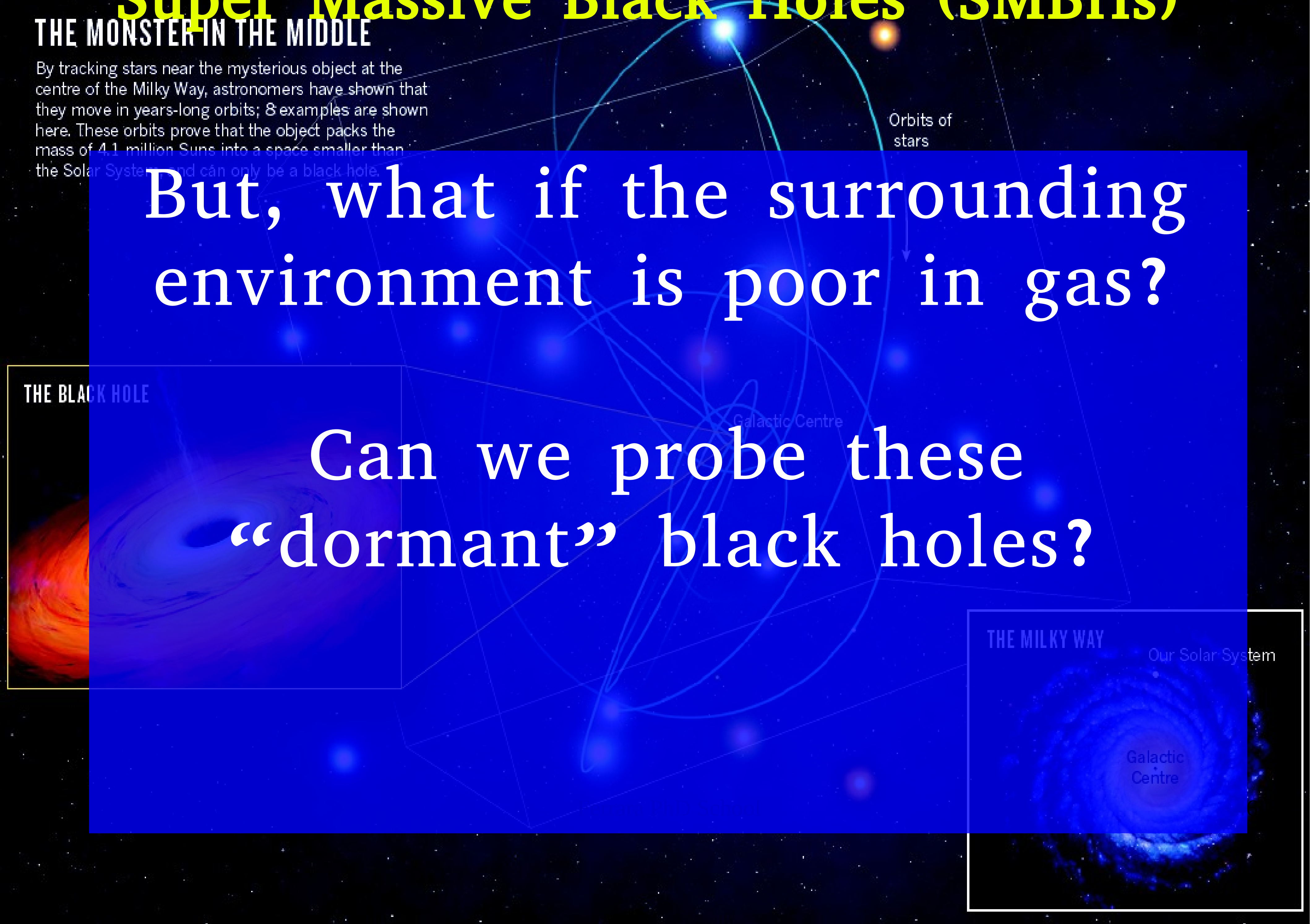
By tracking stars near the mysterious object at the centre of the Milky Way, astronomers have shown that they move in years-long orbits; 8 examples are shown here. These orbits prove that the object packs the mass of 4.1 million Suns into a space smaller than the Solar System, and can only be a black hole.

Most galaxies host a SMBH (10^6-10^9 $M_\odot$) in their centre.

Dynamical measure through tracking of stars orbiting close (Milky Way)

Ferrara PhD School

Super Massive Black Holes (SMBHs)



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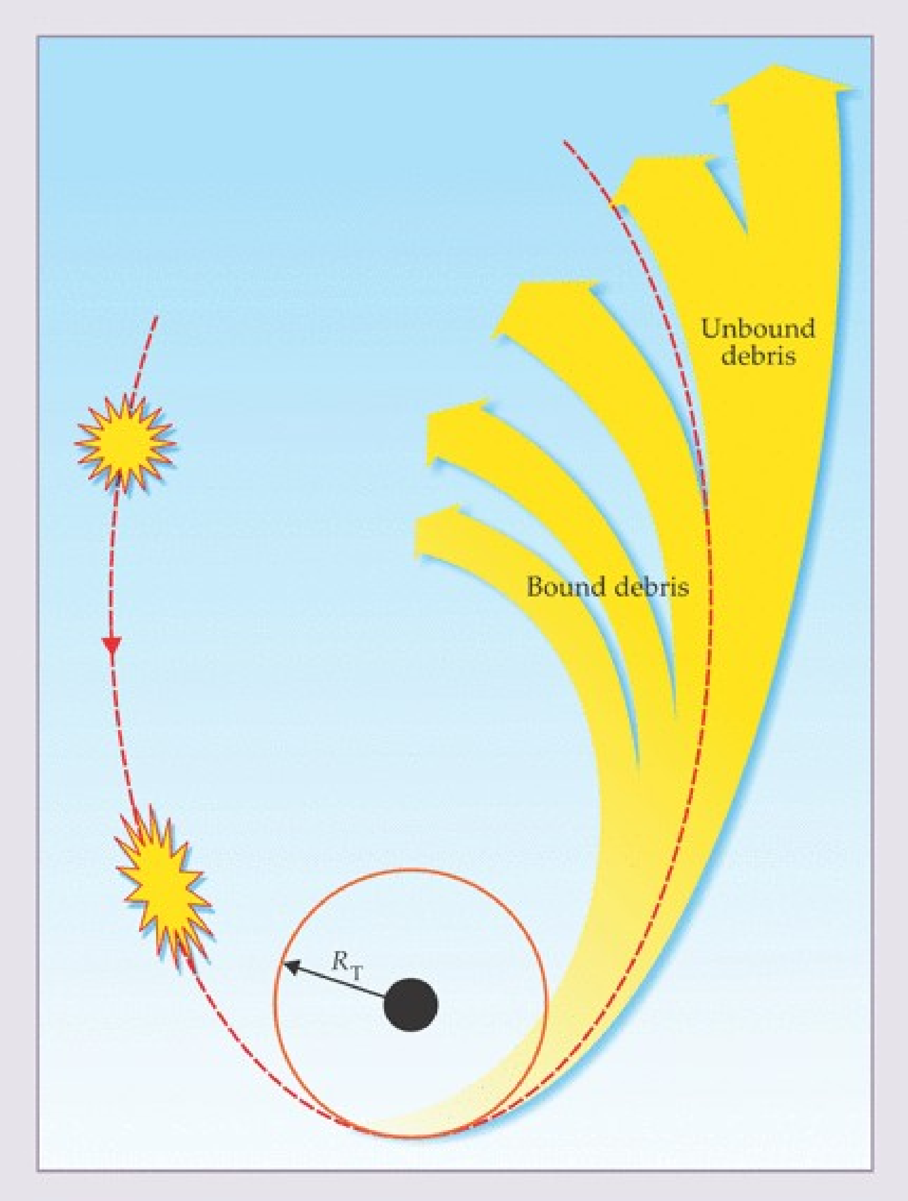
But, what if the surrounding environment is poor in gas?

Can we probe these "dormant" black holes?

Tidal Disruption: basics



When a star passes too close, it is torn apart by the BH tidal forces:

$$\frac{GM}{R_T^3}R_* = \frac{Gm_*}{R_*^2}$$

- M = BH mass
- R_T = tidal disruption radius
- R_* = star radius
- m_* = star mass

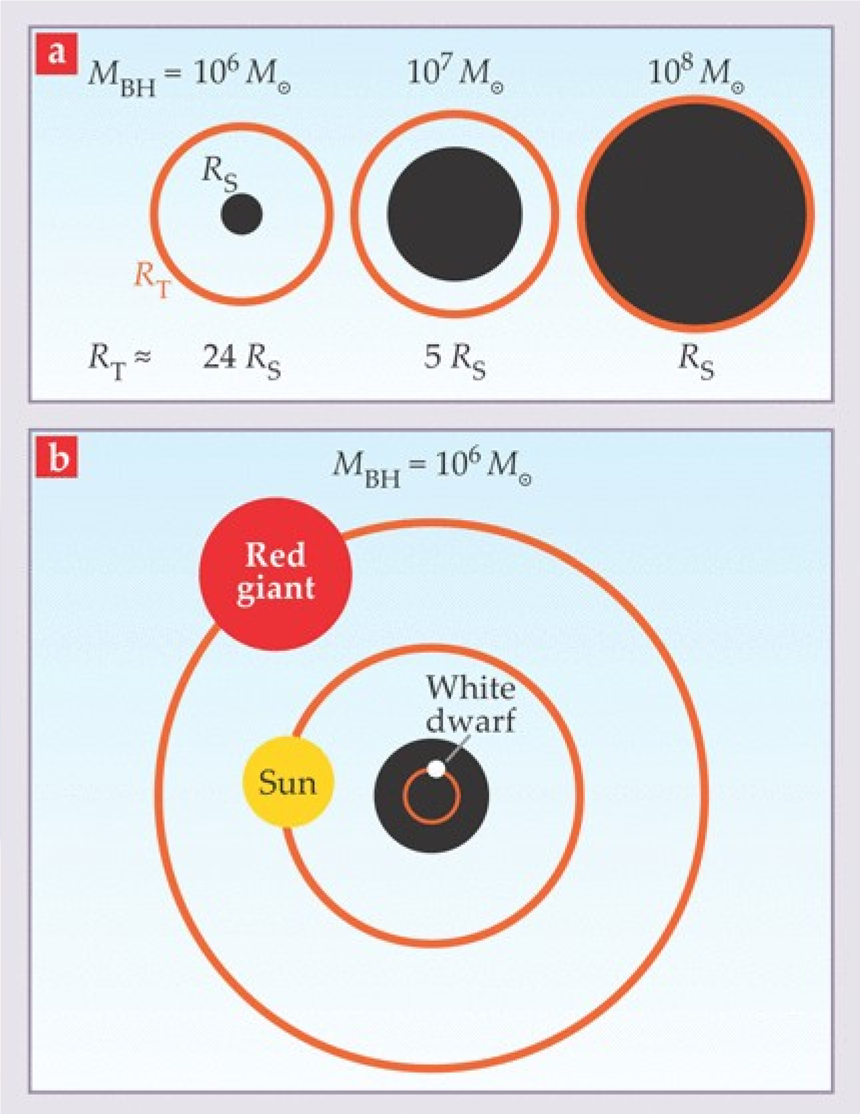
$$R_T = \left(\frac{M}{m_*}\right)^{1/3} R_*$$

- Example:

M = 4×10^6 m_*; R_* = $R_\odot$

$\Rightarrow R_T \approx 1$ AU

Disrupted or swallowed?



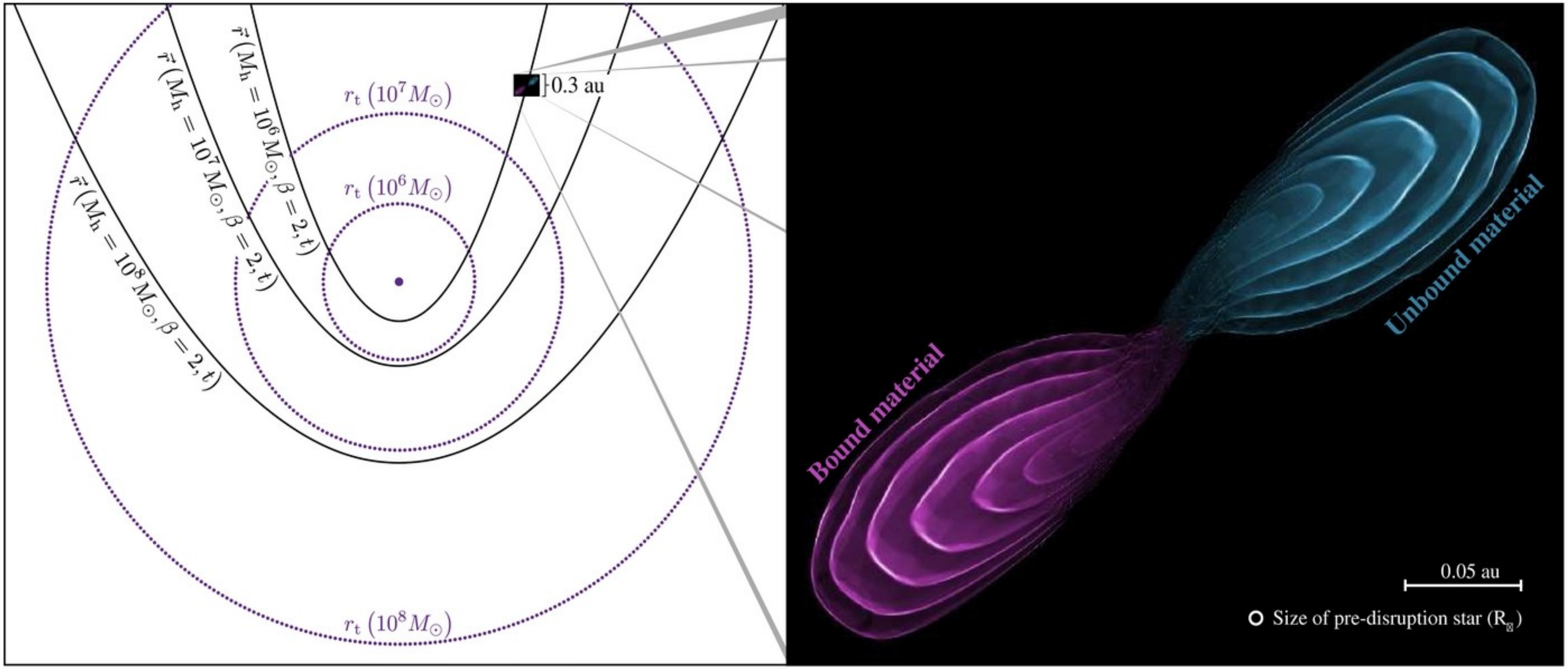
When BH Schwarzschild radius is too large, the star gets swallowed. To avoid this:

$$R_T = \left(\frac{M}{m_*}\right)^{1/3} R_* > R_s = \frac{2GM}{c^2}$$

$$M_{crit} \approx 10^8 \left(\frac{R_*}{R_{sun}}\right)^{3/2} \left(\frac{m_*}{m_{sun}}\right)^{-1/2} m_{sun}$$

For a given BM mass M, R_T depends sensitively on stellar size

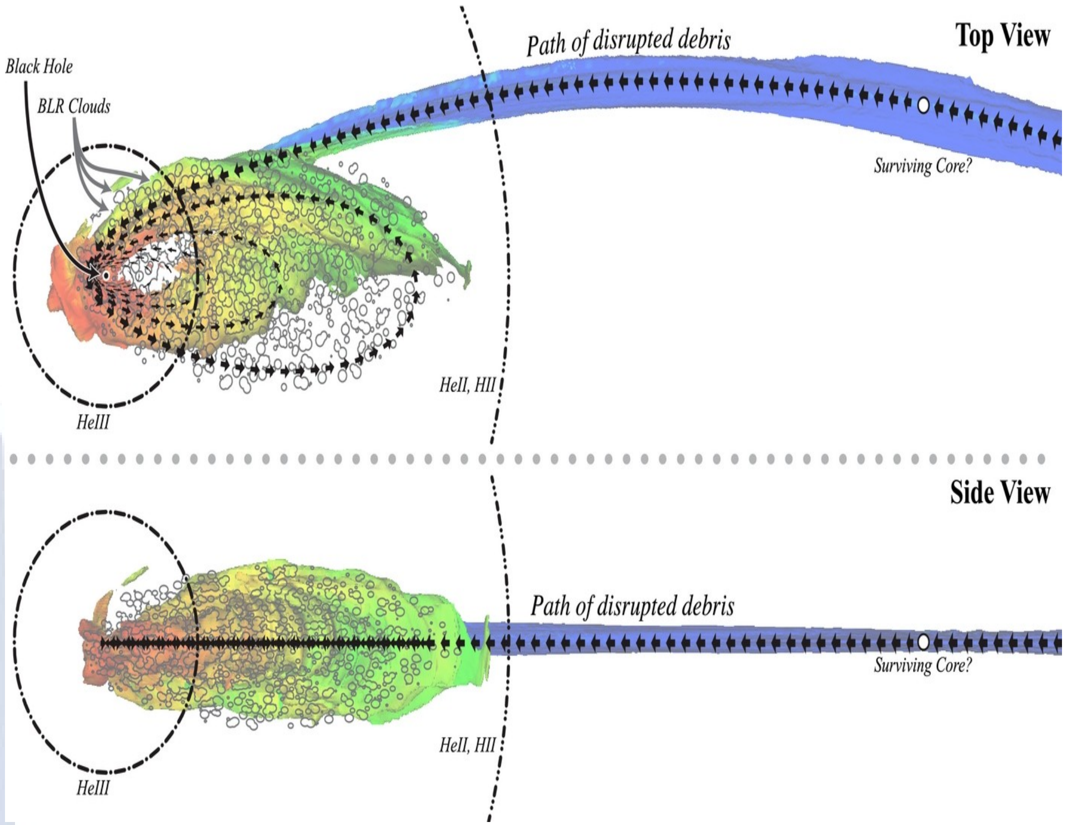
Half bound, half unbound



De Colle+12

Penetration factor: $$\beta = \frac{R_T}{R_p}$$

Mass accretion rate of bound debris



Spread in grav potential energy (Rp = periastron distance):

$$\Delta E \approx \pm \frac{GM}{R_p^2} R_* \simeq \frac{GM}{a}$$

where $a \simeq \frac{R_p^2}{R_*}$

Orbital timescale (3rd Kepler's law):

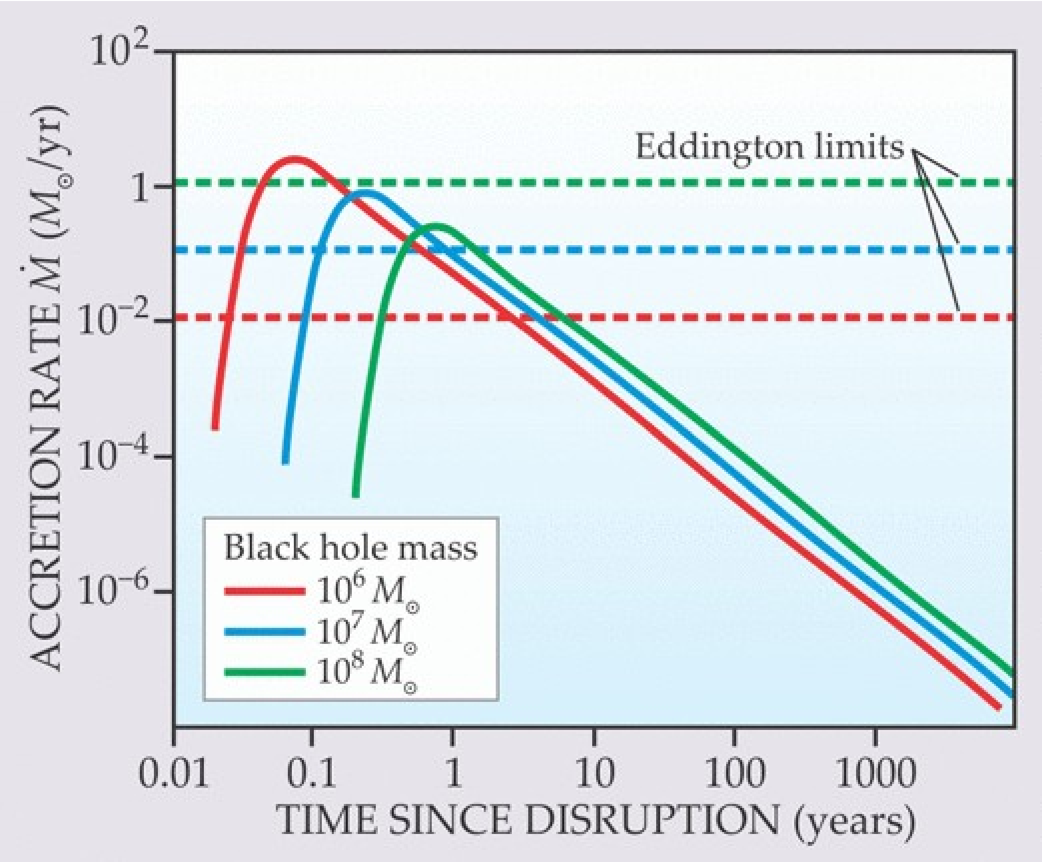
$$t_p \simeq \left(\frac{a^3}{GM}\right)^{1/2} \simeq \left(\frac{R_p^6}{GMR_*^3}\right)^{1/2}$$

$$t_p \simeq \beta^{-3}\left(\frac{R_*^3}{Gm_*}\right)^{1/2}\left(\frac{M}{m_*}\right)^{1/2} \simeq \frac{\beta^{-3}}{\sqrt{G\rho_*}}\left(\frac{M}{m_*}\right)^{1/2} \approx 10^3\, s \left(\frac{M}{m_*}\right)^{1/2}\beta^{-3} \approx 40\, d$$

Sun

$\beta \simeq 1\, ;\, M/m_* \simeq 4\text{x}10^6$

Mass accretion rate of bound debris



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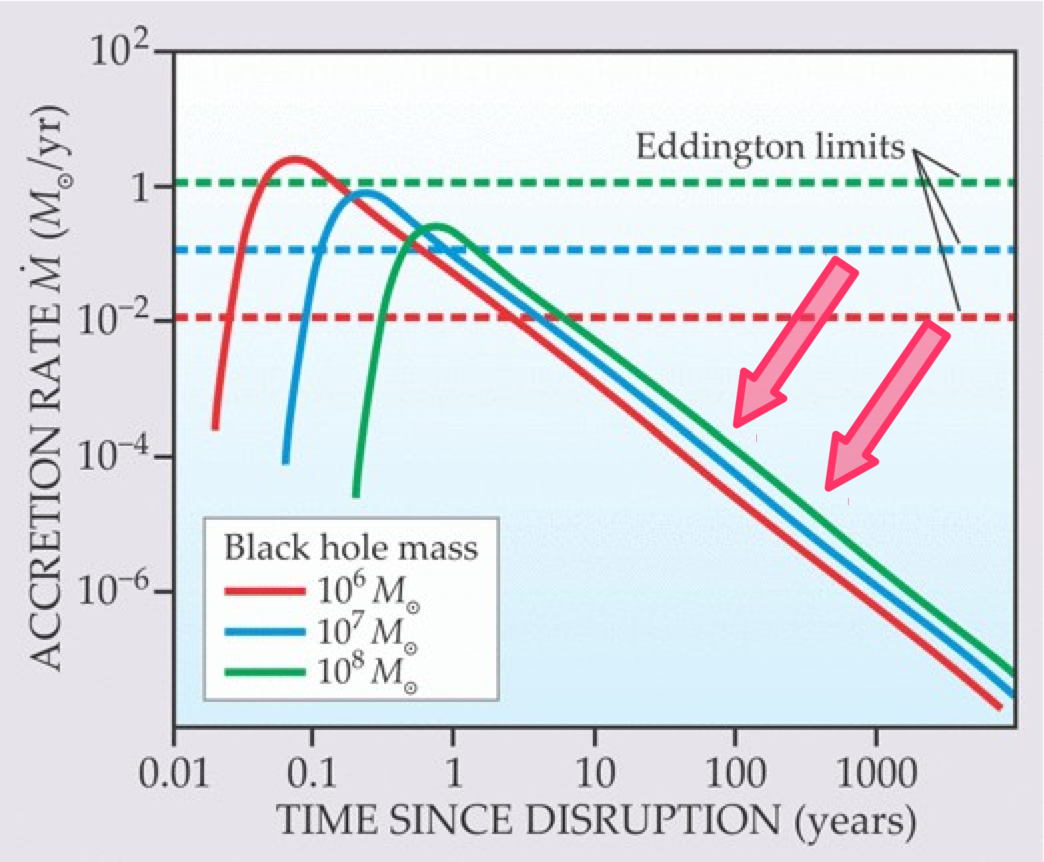
Fallback rate at $t>t_p$ scales as $t^{-5/3}$



The accretion rates exhibit the $t^{-5/3}$ decay expected for the range of eccentric Keplerian orbits:

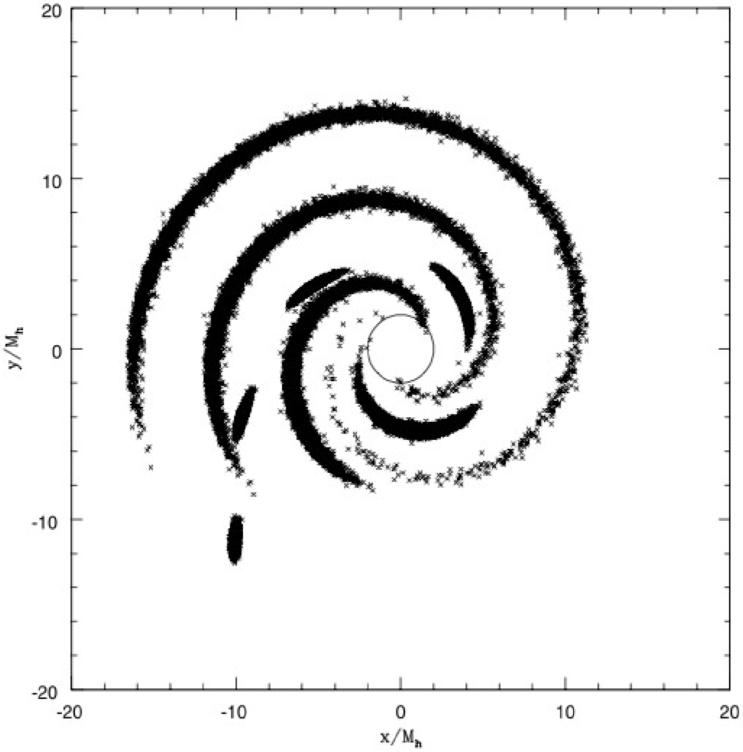
$$\frac{dm}{dt}=\frac{dm}{dE}\frac{dE}{dt}$$

Assuming dm/dE ~ constant, in agreement with simulations within a factor of a few:

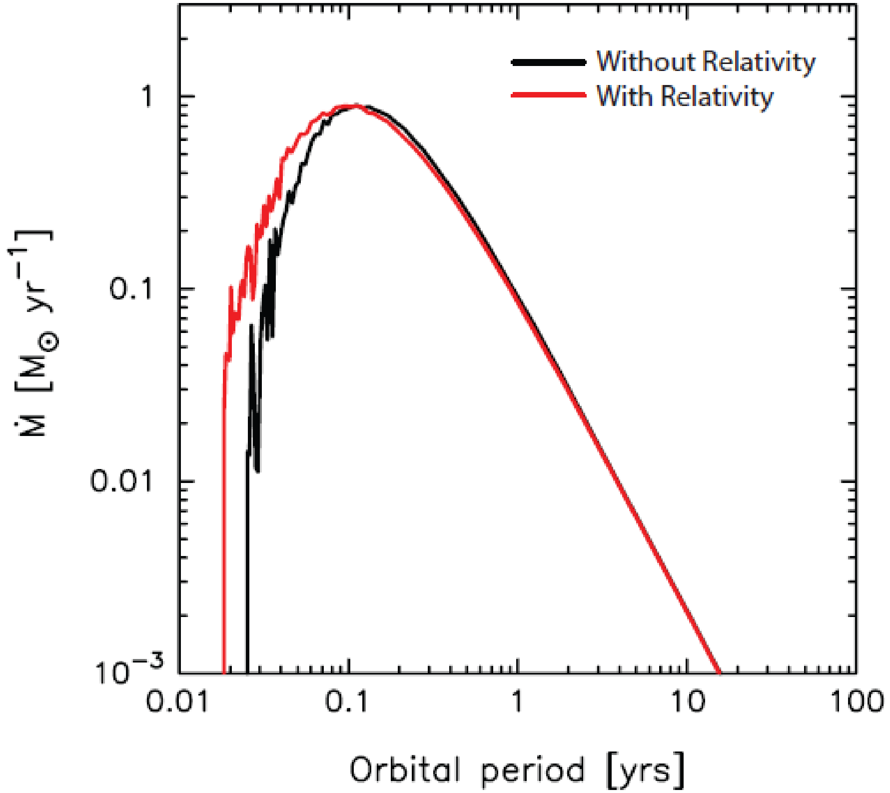
$$a\propto t^{2/3};\, E\propto\frac{Gm}{a}\propto Gm\,t^{-2/3}\rightarrow\frac{dE}{dt}\propto t^{-5/3}$$

(Rees88;
Evans+Kochanek89;
Lodato+09)

When GR is taken into account



Because of relativistic precession, debris distribution in angle is somewhat different (circularization may be affected).



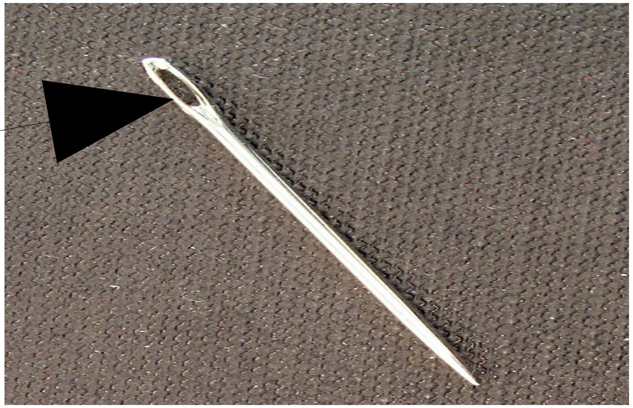
However, dm/dt is very similar! (factors of ~2, Kesden+ 2012)

TDEs are rare events

- The tidal radius for main sequence (MS) stars is only ~ 1 AU.
- Stars that fall into the SMBH likely come from its sphere of influence, ~ 1 pc.
- Per star, the disruption rate is very low:

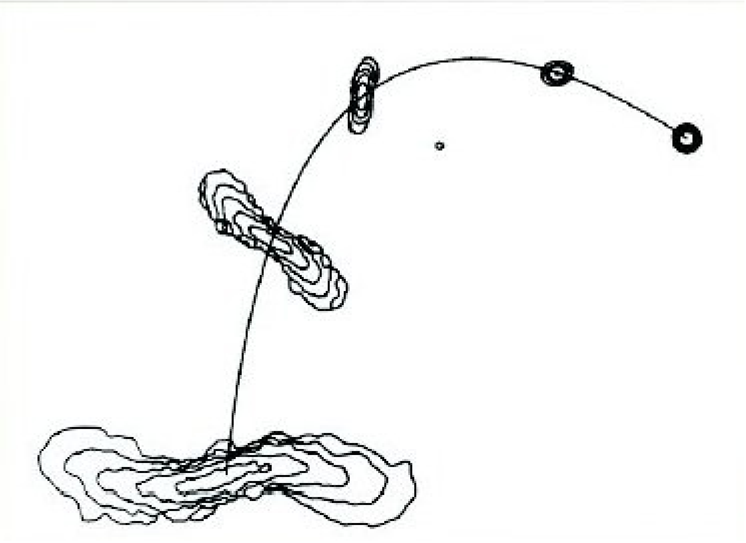
1 every 10,000 years per galaxy!

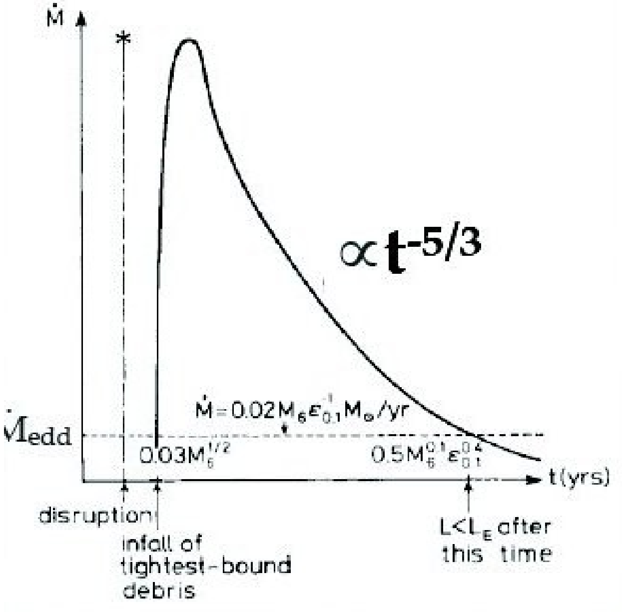
Throwing a star into the tidal radius is like throwing a grain of salt through the eye of a sewing needle a km away.



Credits: Guillochon

Basic predictions



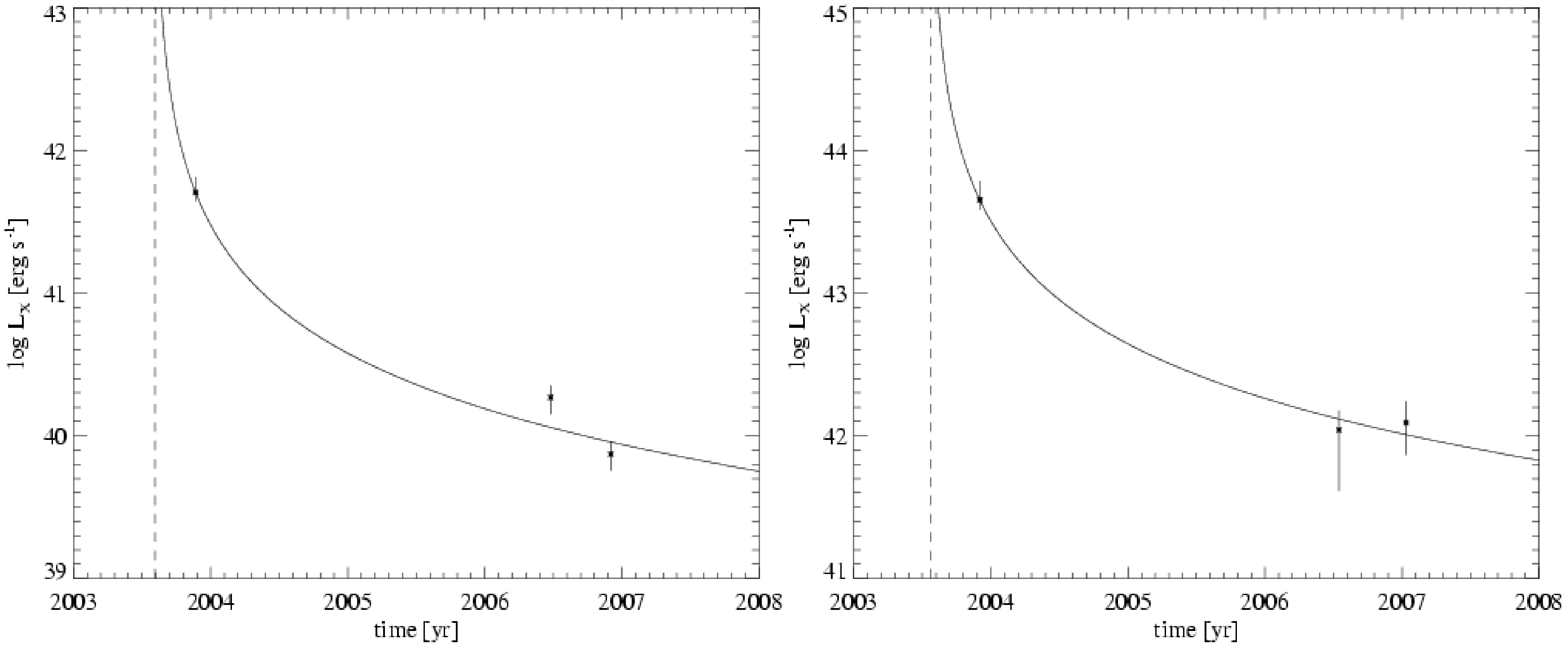


- Thermal, Bright in UV/soft X-rays
- $T_{BB} > 2x10^5$ K

(Rees88; Evans+Kochanek89; Lodato+09)

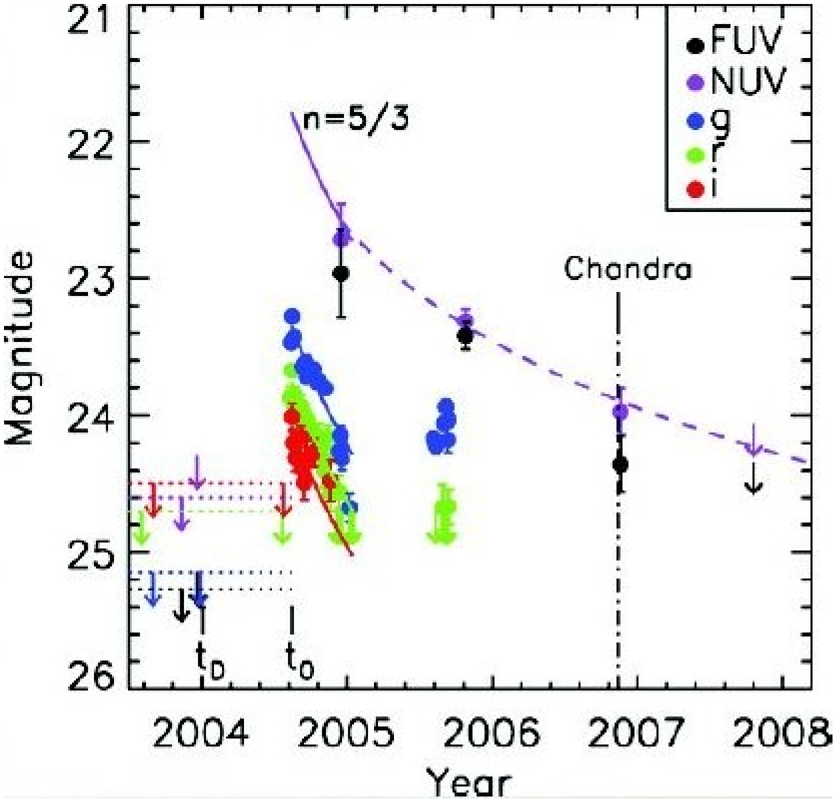
First soft X-ray TDE Candidates

Until **2011** a few candidates with X-ray declining curves in agreement with predictions, poorly constrained though (Komossa**+99+04**, Esquej**+08**)

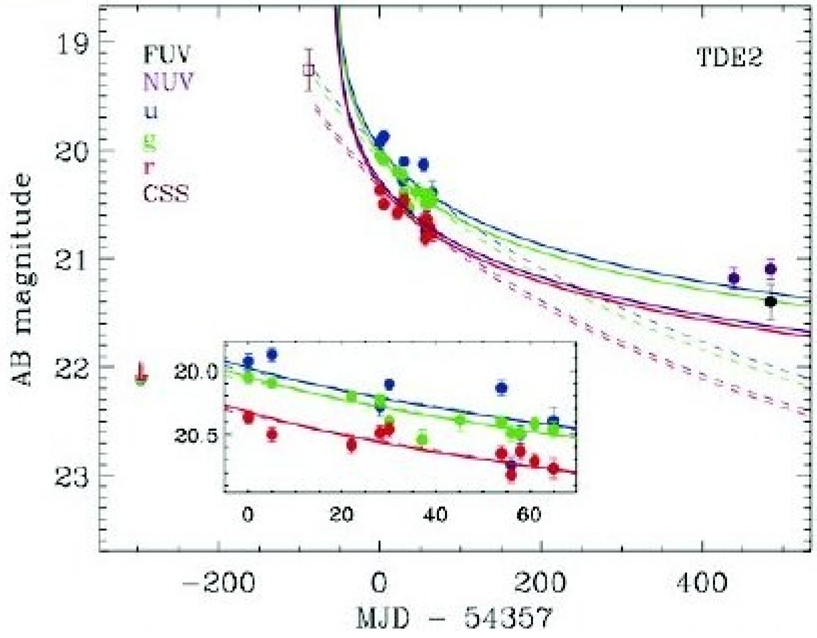


XMM light curves (Esquej**+08**)

+ optical TDE Candidates

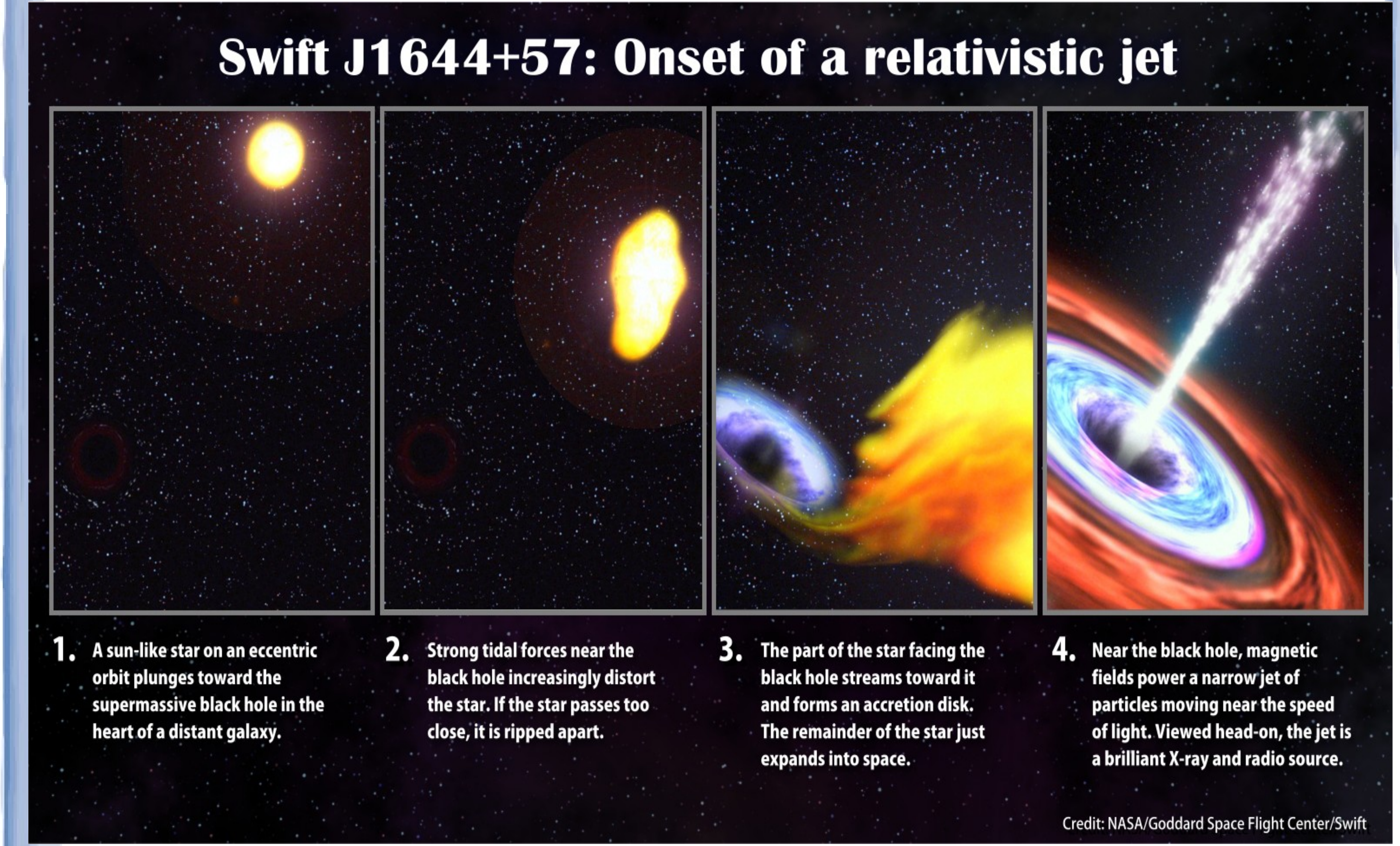


Gezari+09



vanVelzen+11

March 28, 2011: Sw J1655+57



Swift J1644+57: Onset of a relativistic jet

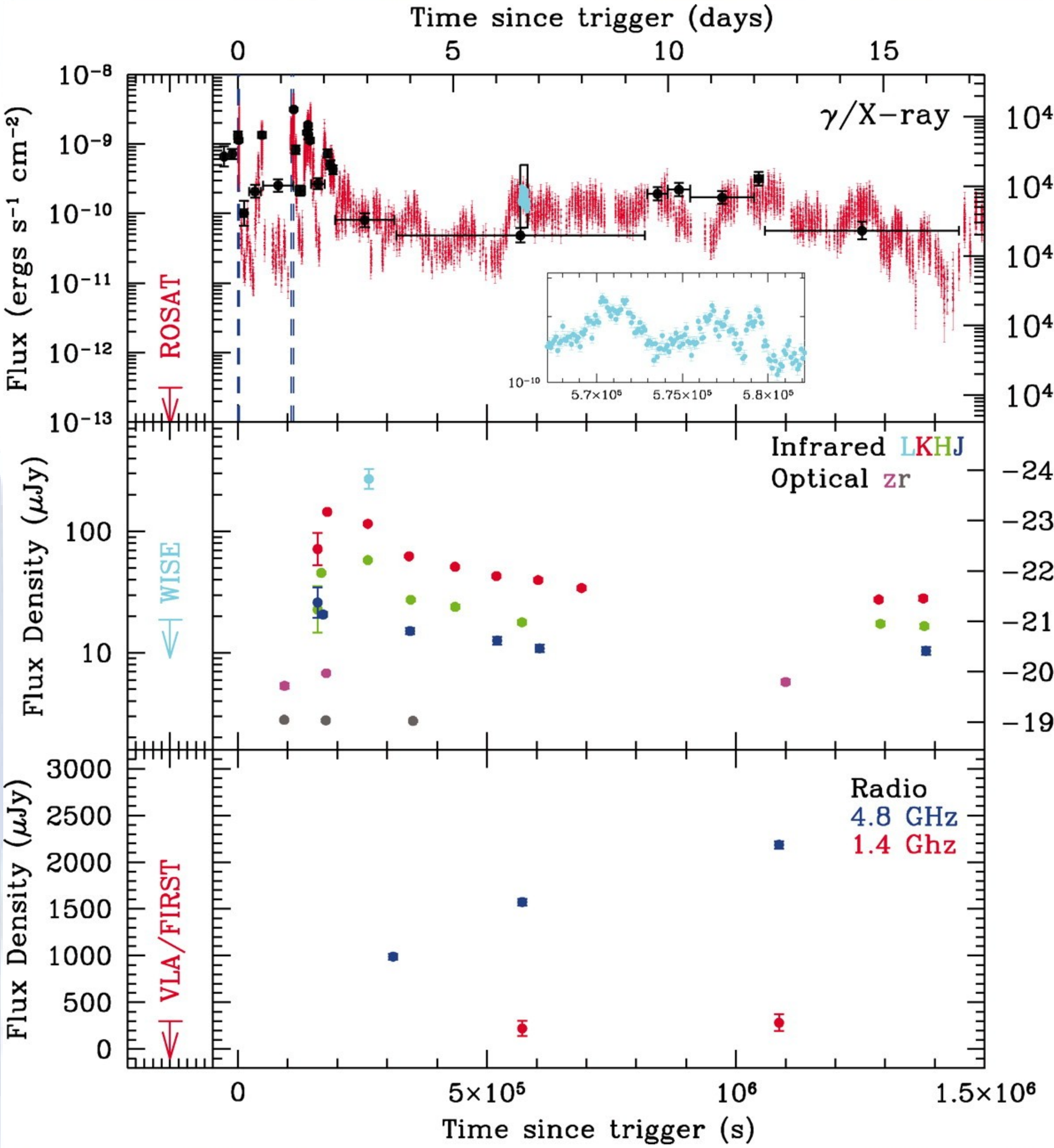
1. A sun-like star on an eccentric orbit plunges toward the supermassive black hole in the heart of a distant galaxy.
2. Strong tidal forces near the black hole increasingly distort the star. If the star passes too close, it is ripped apart.
3. The part of the star facing the black hole streams toward it and forms an accretion disk. The remainder of the star just expands into space.
4. Near the black hole, magnetic fields power a narrow jet of particles moving near the speed of light. Viewed head-on, the jet is a brilliant X-ray and radio source.

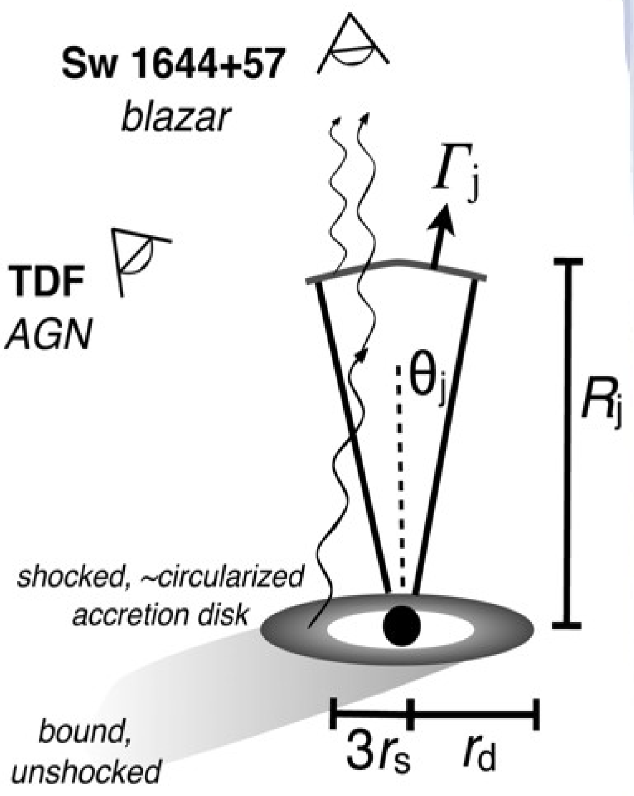
Credit: NASA/Goddard Space Flight Center/Swift

Sw J1655+57

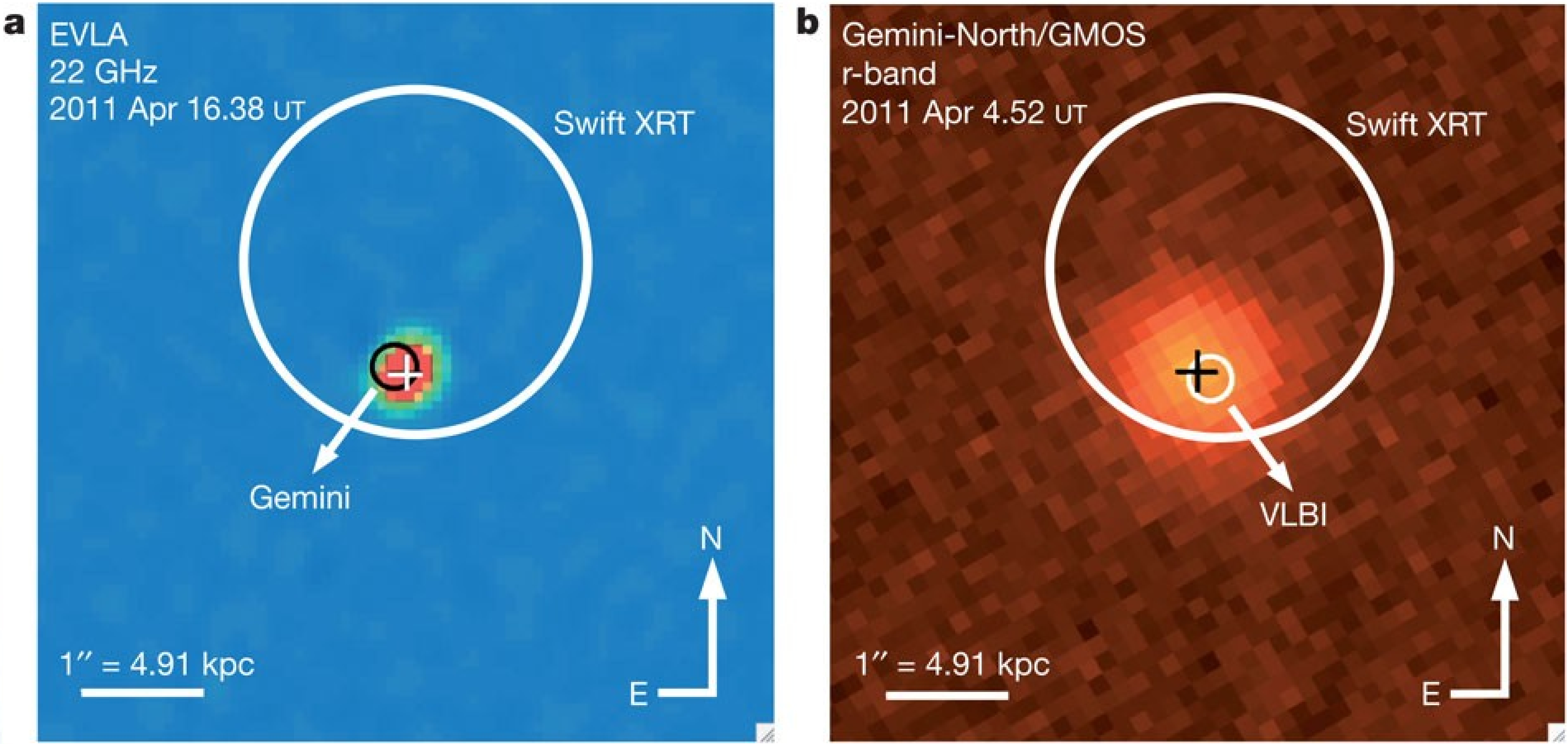
$L_X \sim 10^{45}\text{-}10^{48}$ erg/s

$\Delta t \sim 100$ s





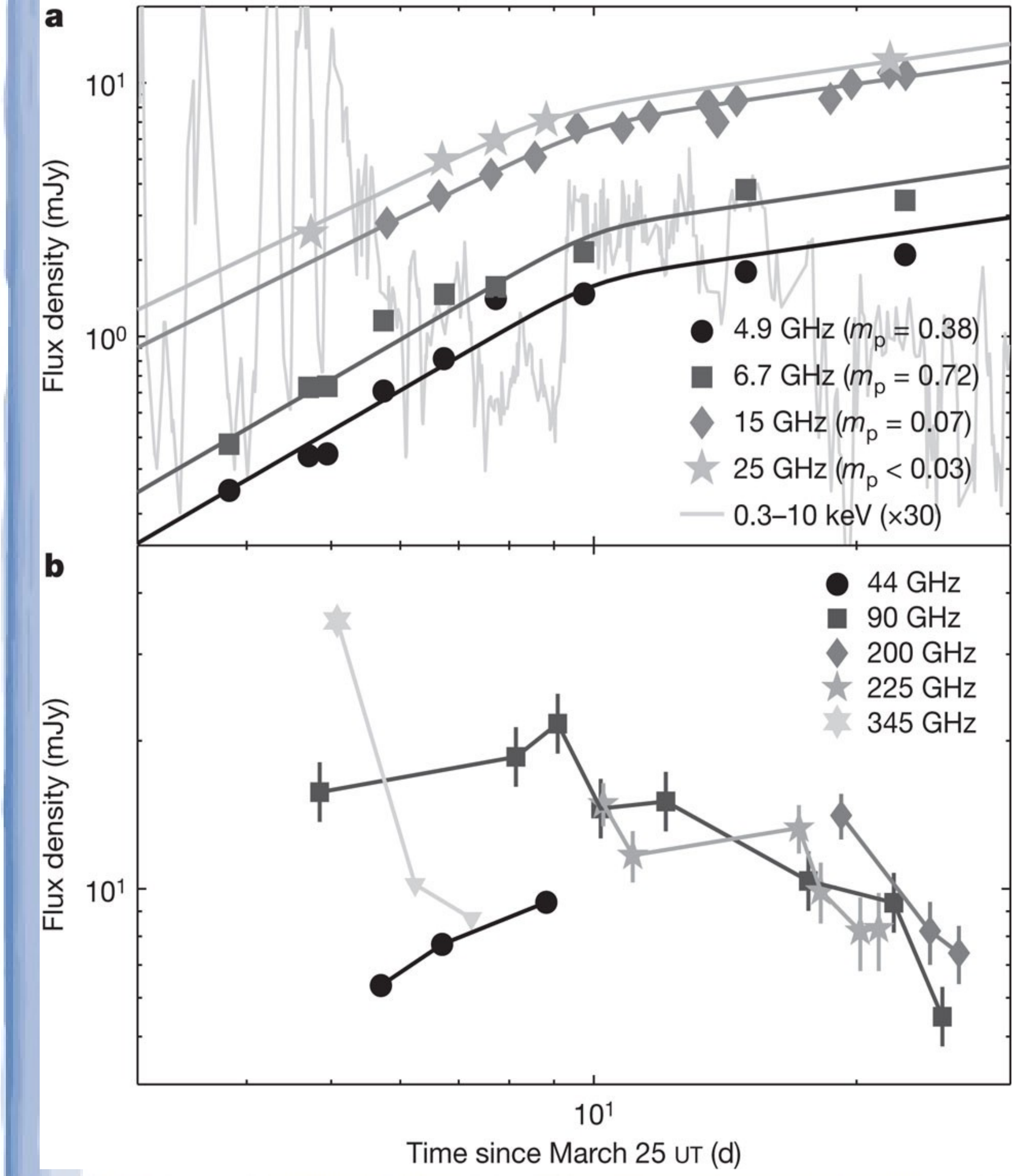
Sw J1655+57: at the centre of its host galaxy at z=0.354

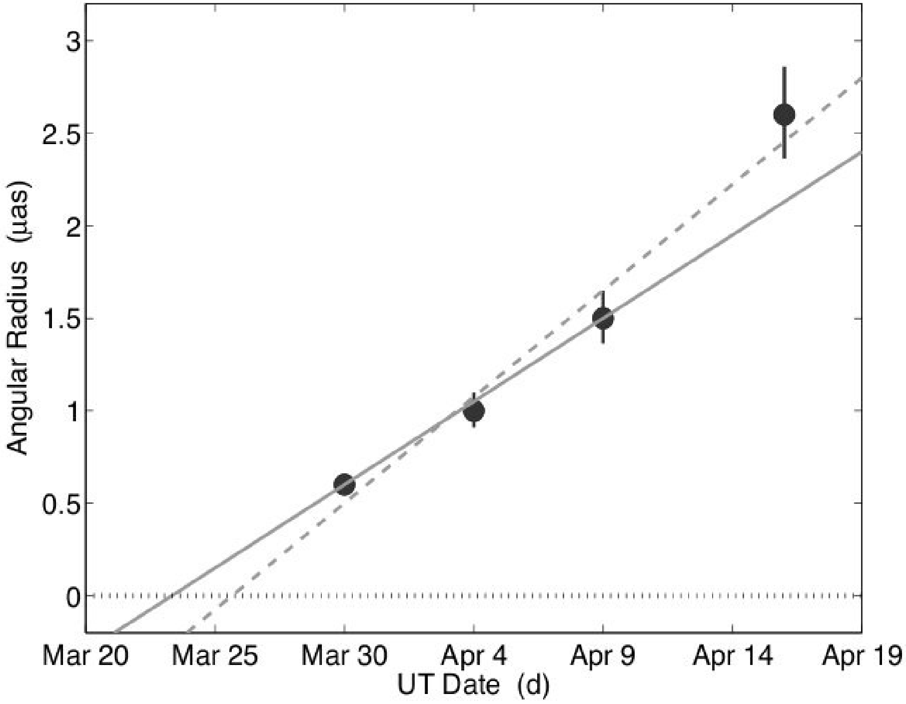


Zauderer+11

Offset: 0.5+- 0.9 kpc

Birth of a relativistic jet: scintillation



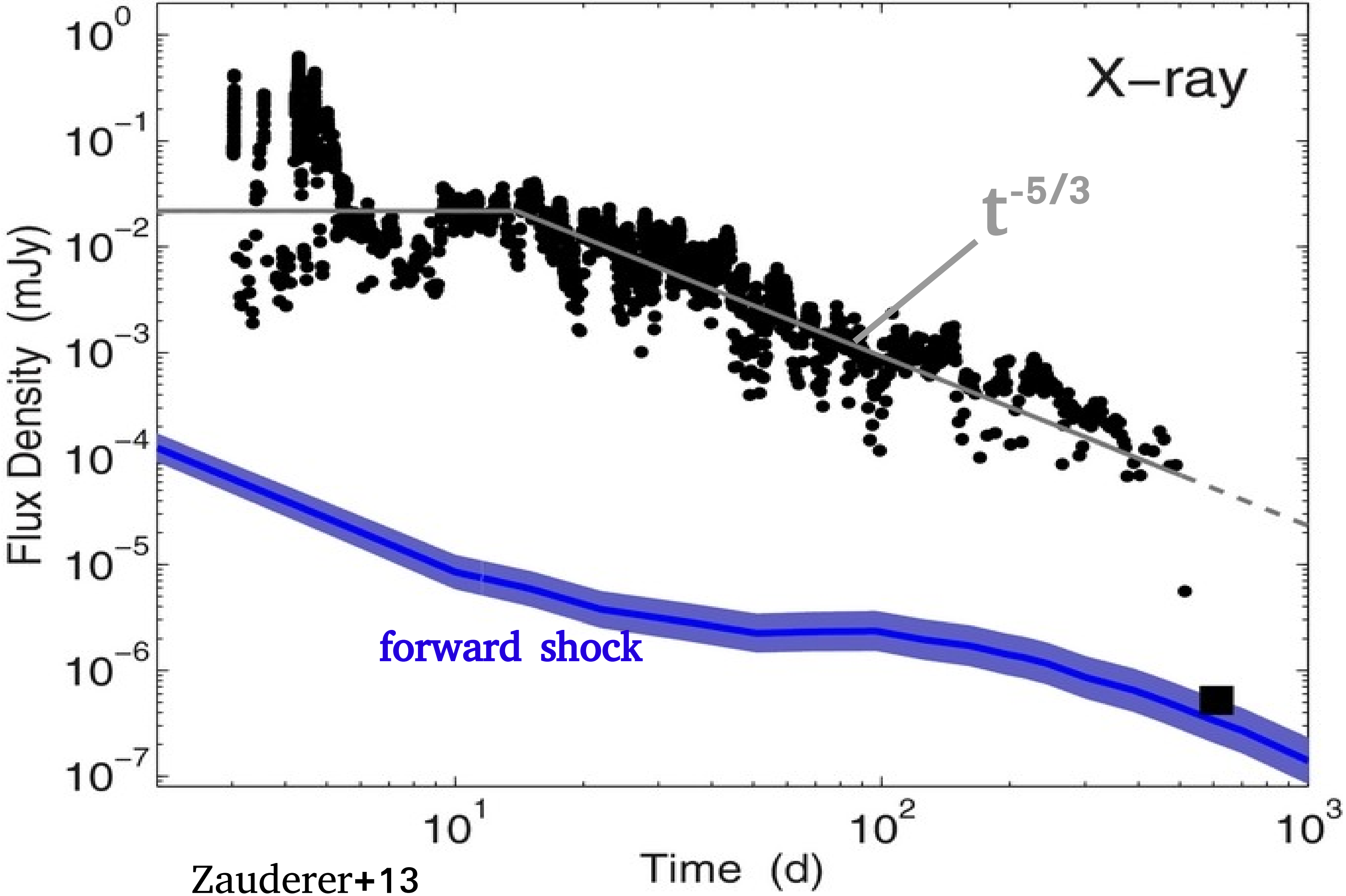


$$m_p \propto \left(\frac{\nu}{\nu_0}\right)^{-17/12} \left(\frac{\theta_s}{\theta_F}\right)^{-7/6} \quad (\nu > \nu_0 = 10\,GHz)$$

$\Gamma \sim$ a few

Zauderer**+11**

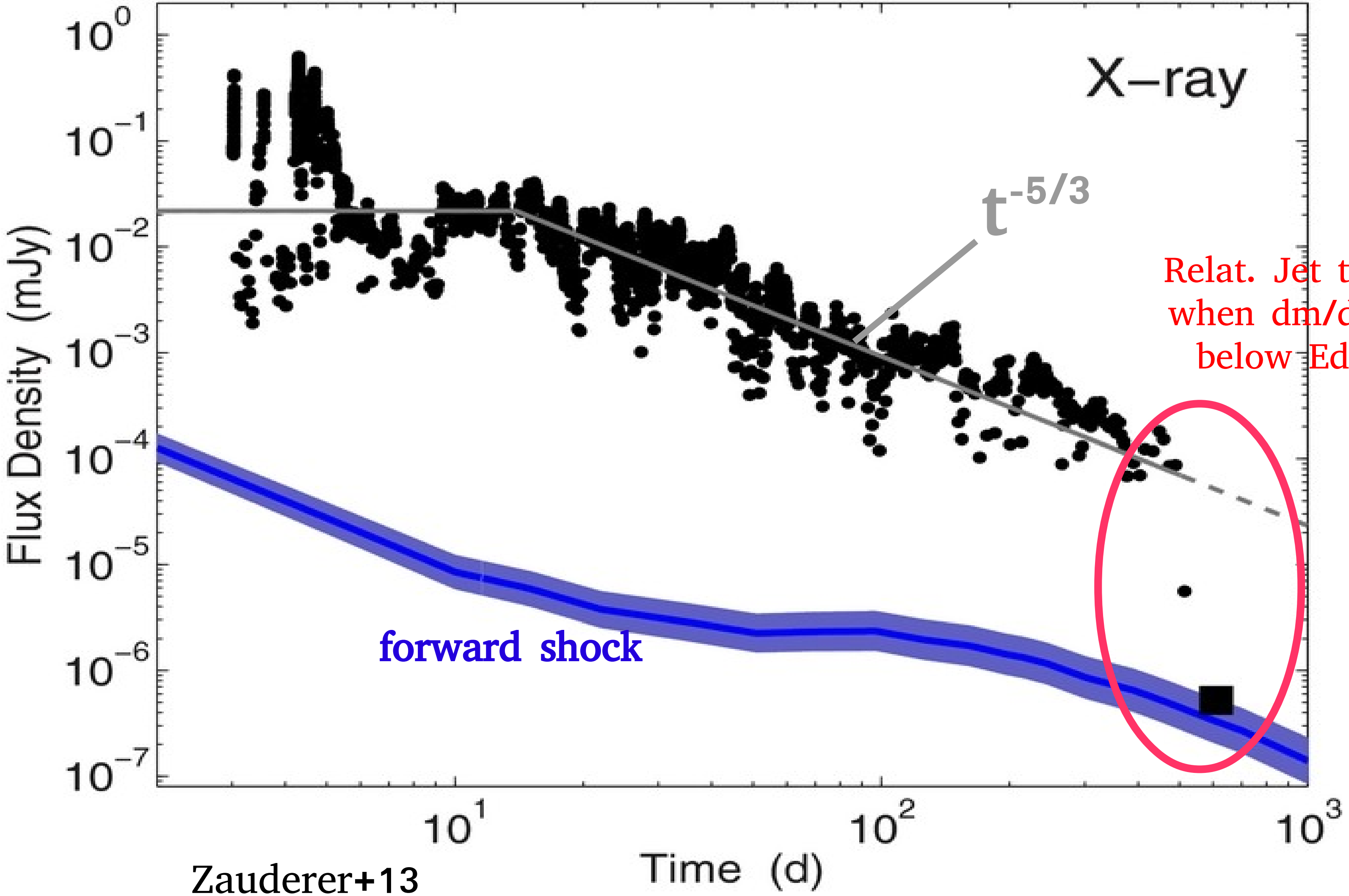
Sw J1655+57: 2-year X-ray light curve



Zauderer+13

radio+NIR+optical: evolving synchrotron

Sw J1655+57: 2-year X-ray light curve



$t^{-5/3}$

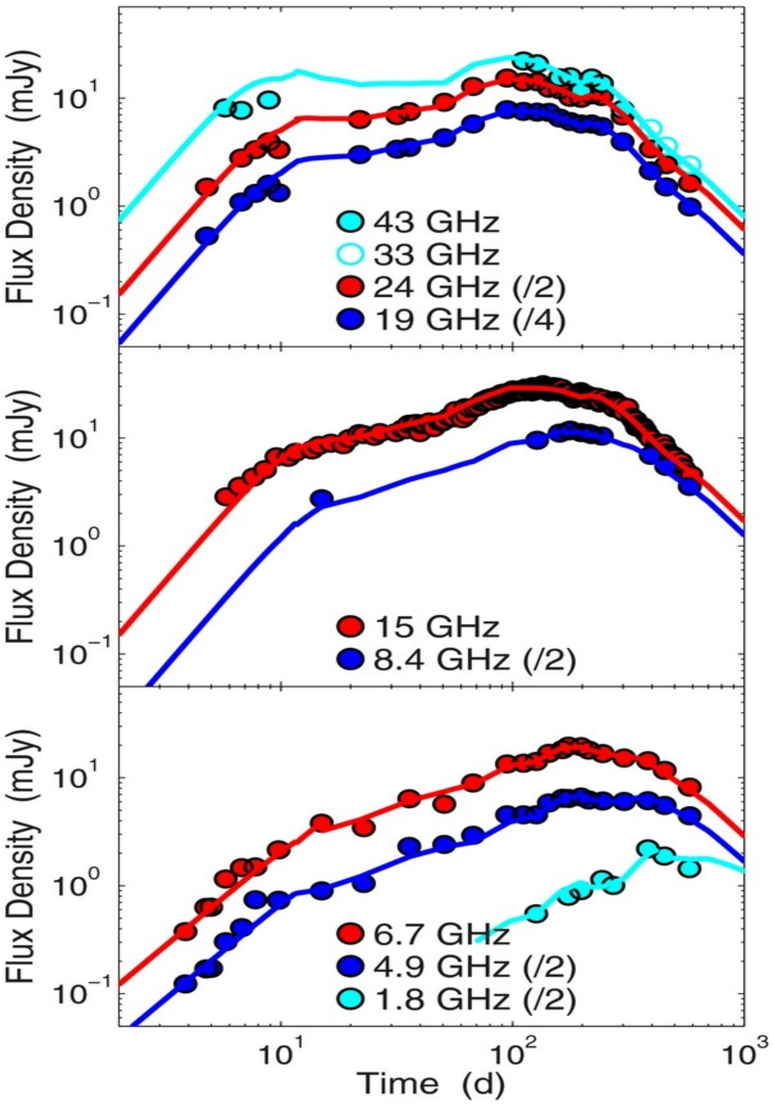
Relat. Jet turns off when dm/dt drops below Edd Lim

forward shock

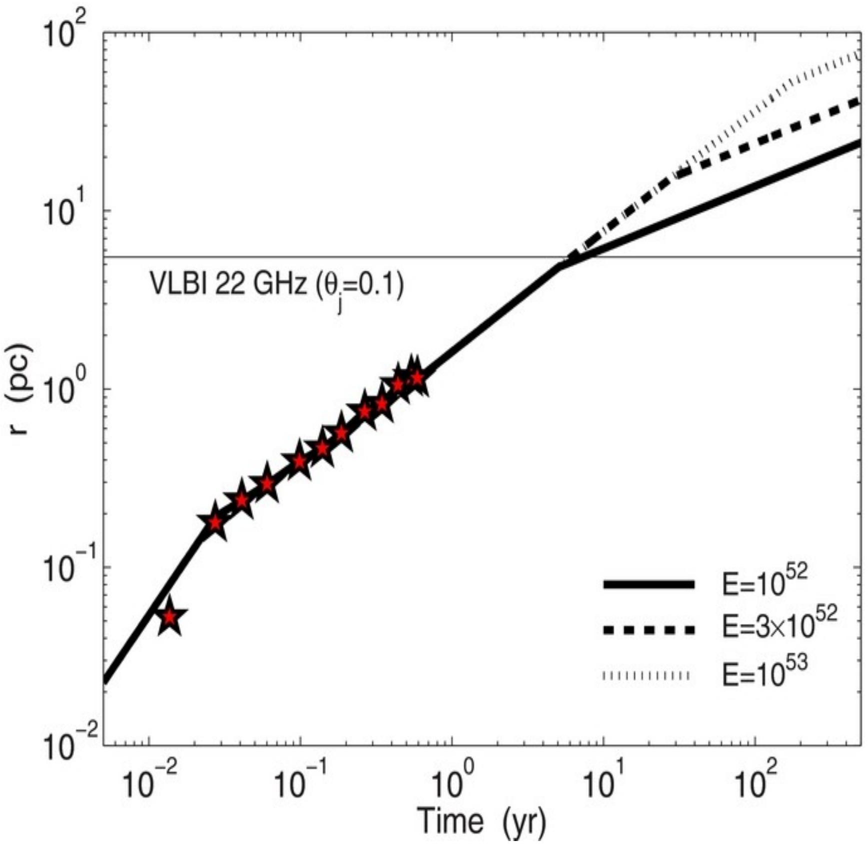
Zauderer+13

radio+NIR+optical: evolving synchrotron

Sw J1655+57: 2-year of radio obs



Zauderer+13

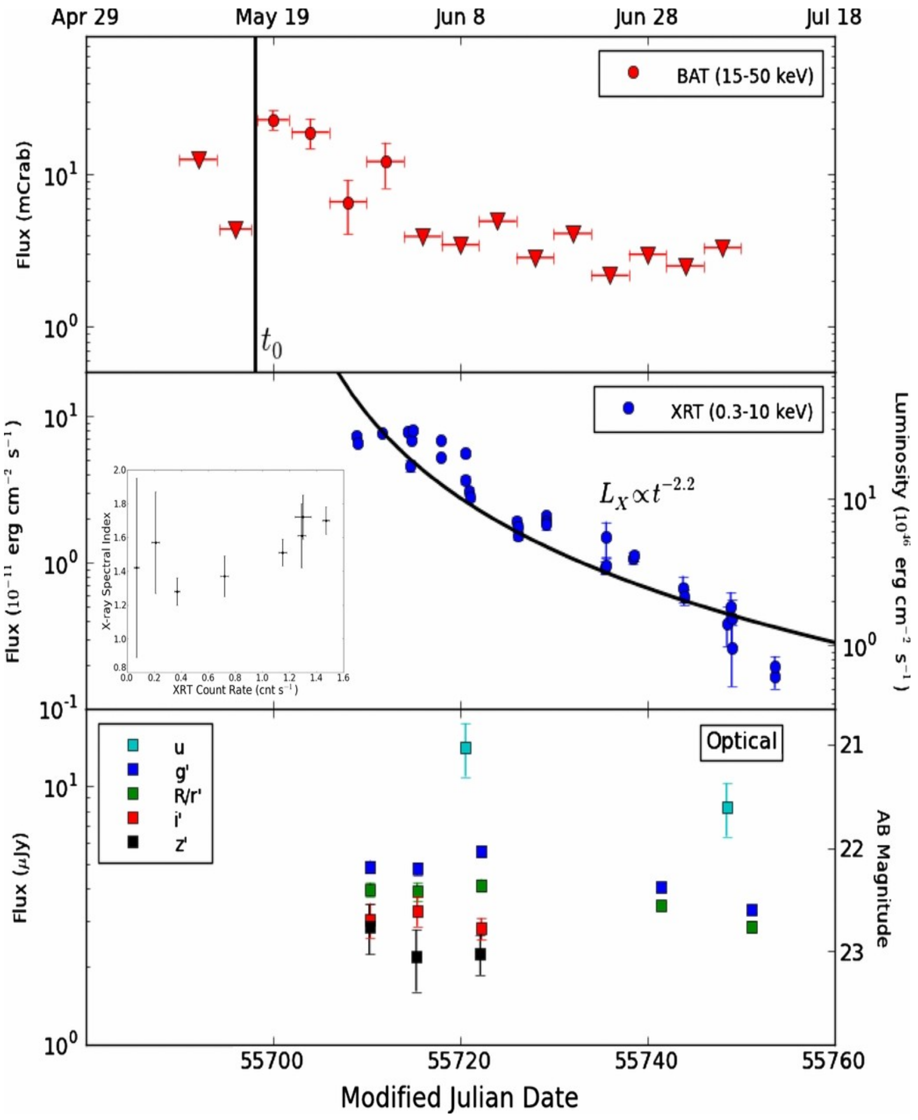


$E_j \sim 10^{52}$ erg ; $M \sim 3\mathrm{x}10^{6}\ M_\odot$

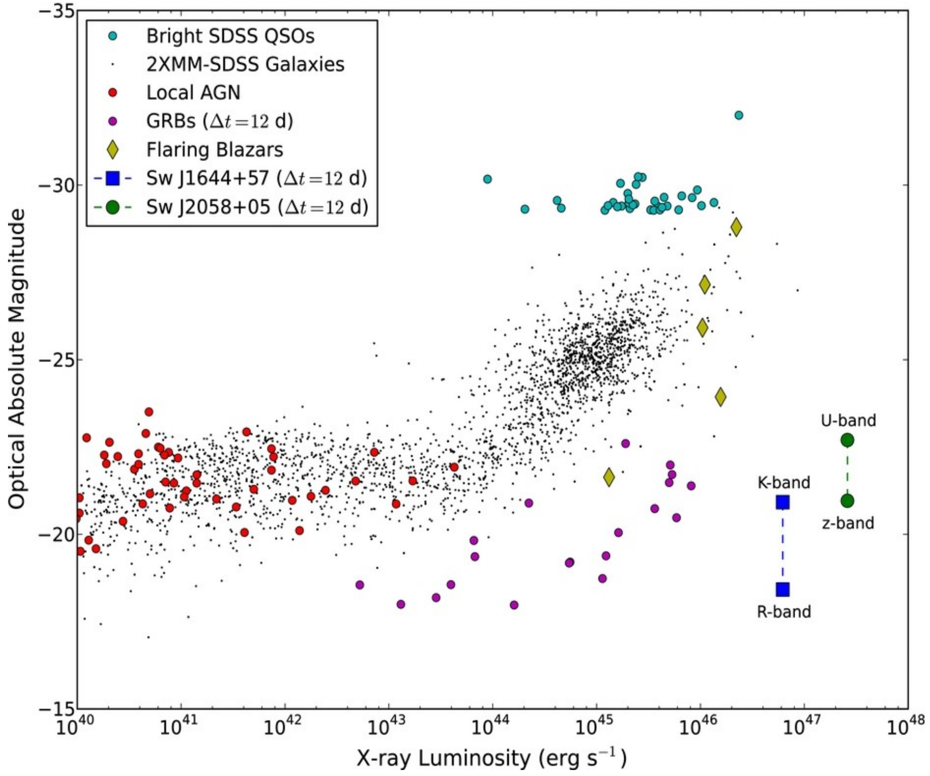
$\vartheta_j = 0.1$ rad

$\Gamma \sim$ a few

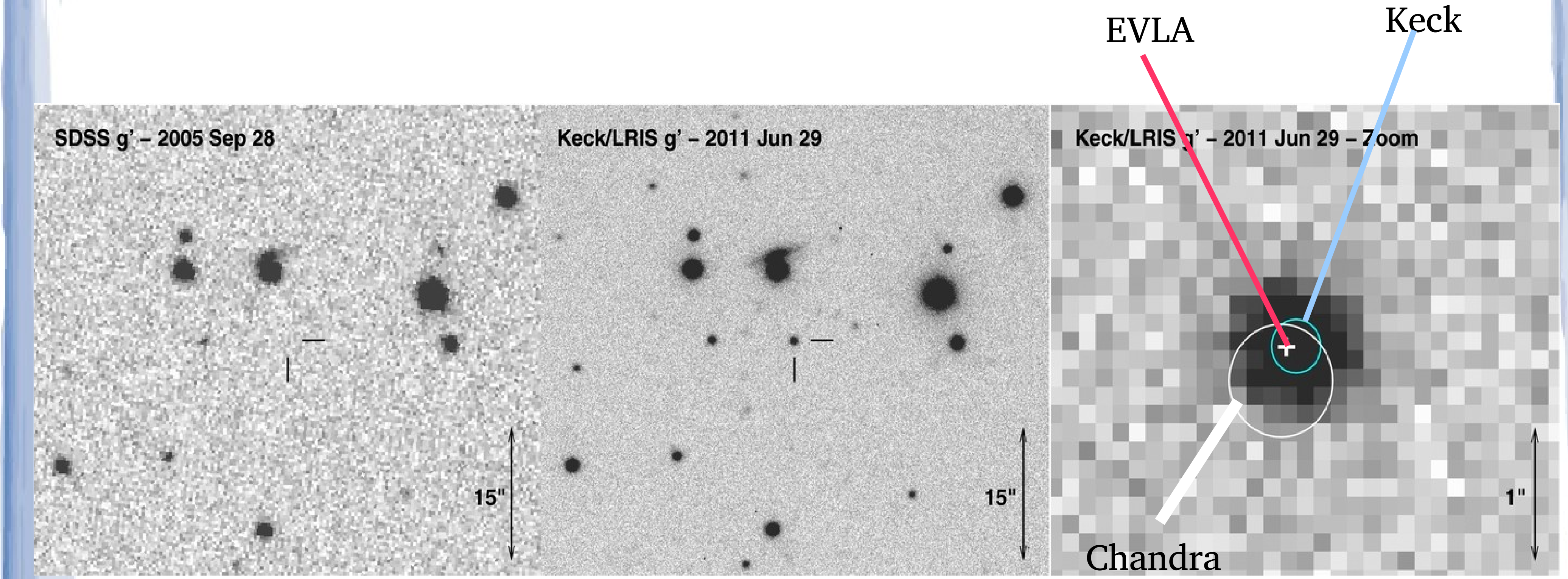
Sw J2058+05: 2nd TDE candidate



Cenko+12

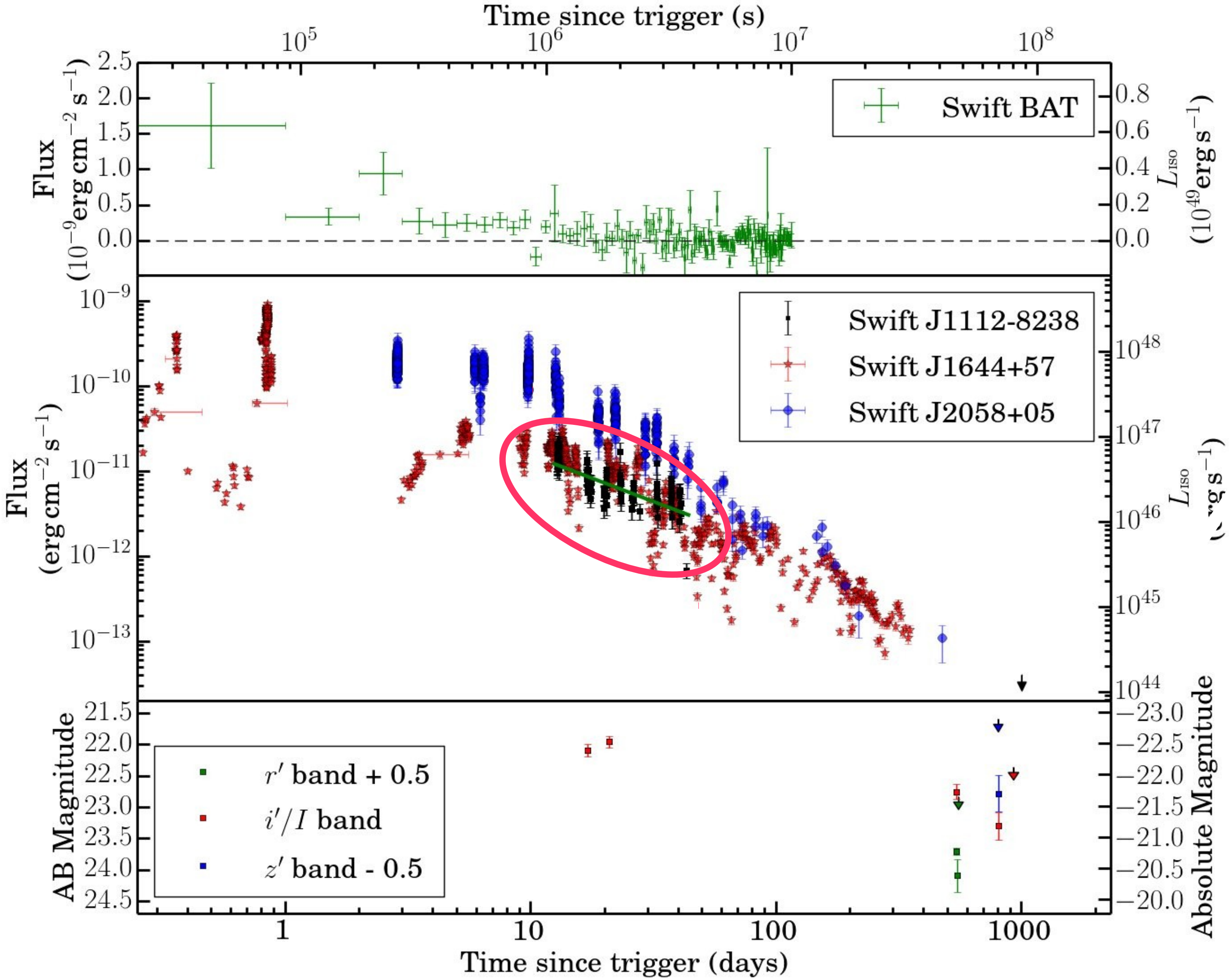


Sw J2058+05: 2nd relativistic TDE candidate



$z = 1.1853$

Sw J1112.2-8238: 3rd relativistic TDE candidate

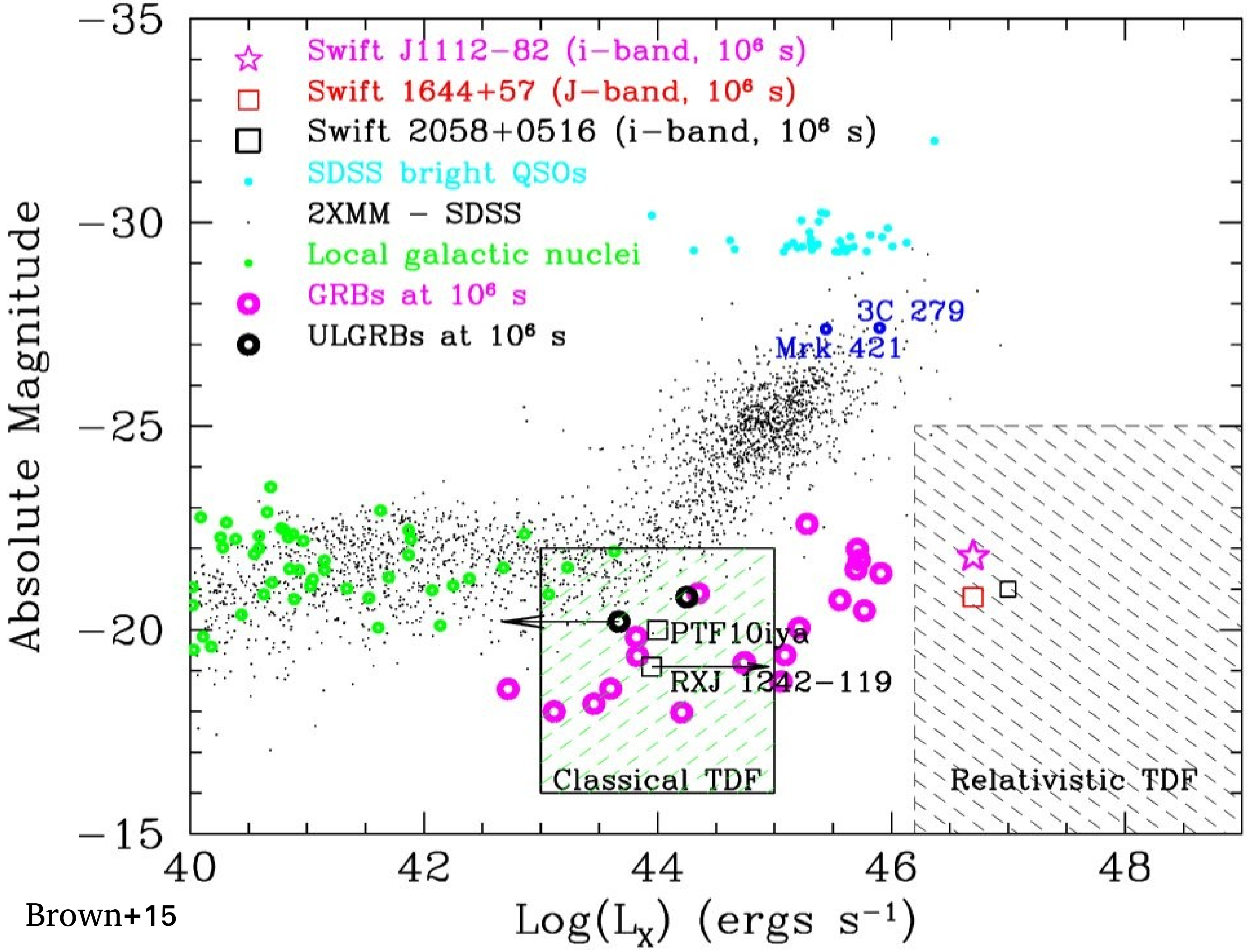


June 2011

Coincident with nucleus of faint gal @ z = 0.89

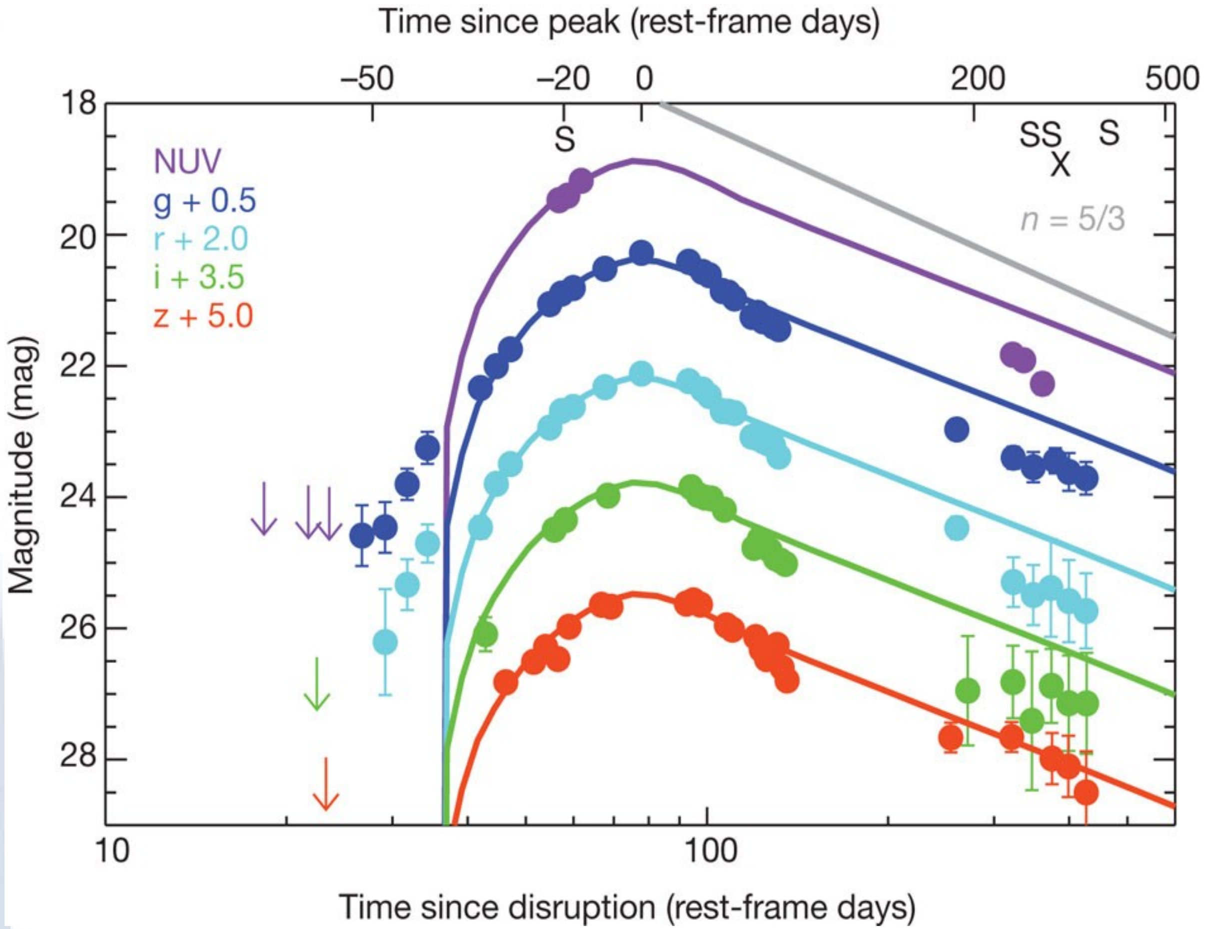
L_x= 10^{47} erg/s

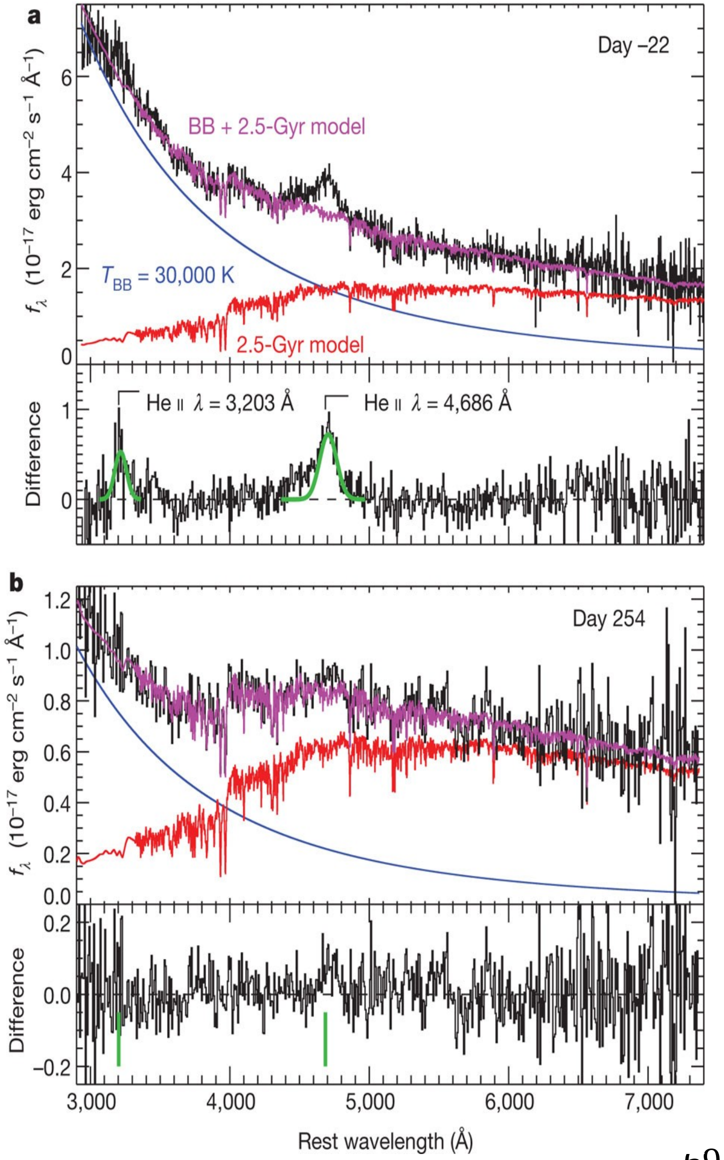
Brown+15


Swift J1112-82 (i-band, 10⁶ s)
Swift 1644+57 (J-band, 10⁶ s)
Swift 2058+0516 (i-band, 10⁶ s)
SDSS bright QSOs
2XMM - SDSS
Local galactic nuclei
GRBs at 10⁶ s
ULGRBs at 10⁶ s
3C 279
Mrk 421
PTF10iya
RXJ 1242-119
Classical TDF
Relativistic TDF
Absolute Magnitude
-35
-30
-25
-20
-15
40
42
44
46
48
Log(L_X) (ergs s⁻¹)

Brown+15

UV-optical flare from a TD of a helium-rich stellar core





At centre of galaxy with M_{stars} = 3.6x10^9 $M_\odot$

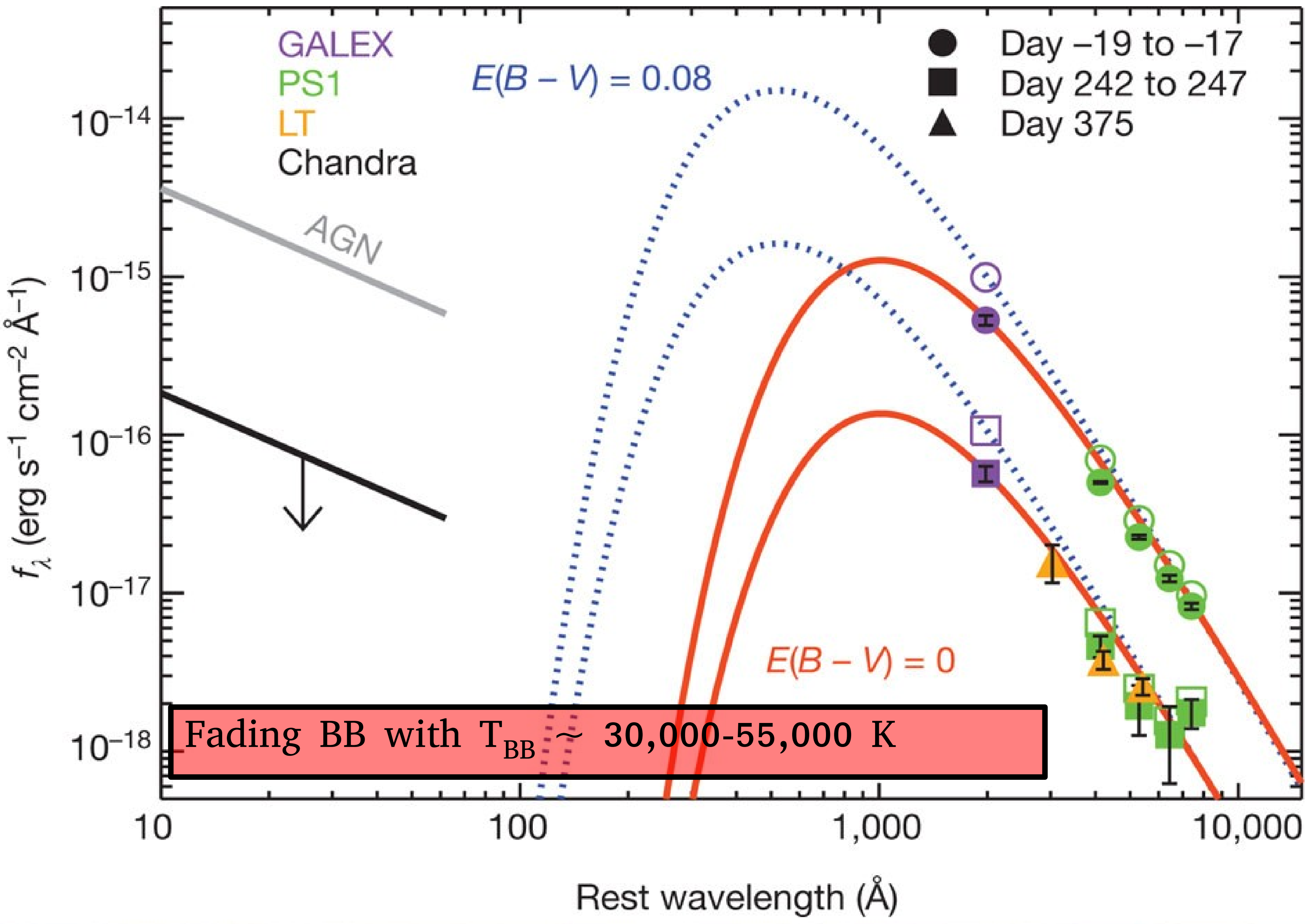
SMBH: M_{stars} = 4(+4,-2) x10^6 $M_\odot$ (scal rel)

z = 0.1696 (LumDist =816 Mpc)

Gezari+12

PS1-10jh

UV-optical flare from a TD of a helium-rich stellar core



Fading BB with $T_{BB} \sim$ 30,000-55,000 K

S

UV-optical flare from a TD of a helium-rich stellar core

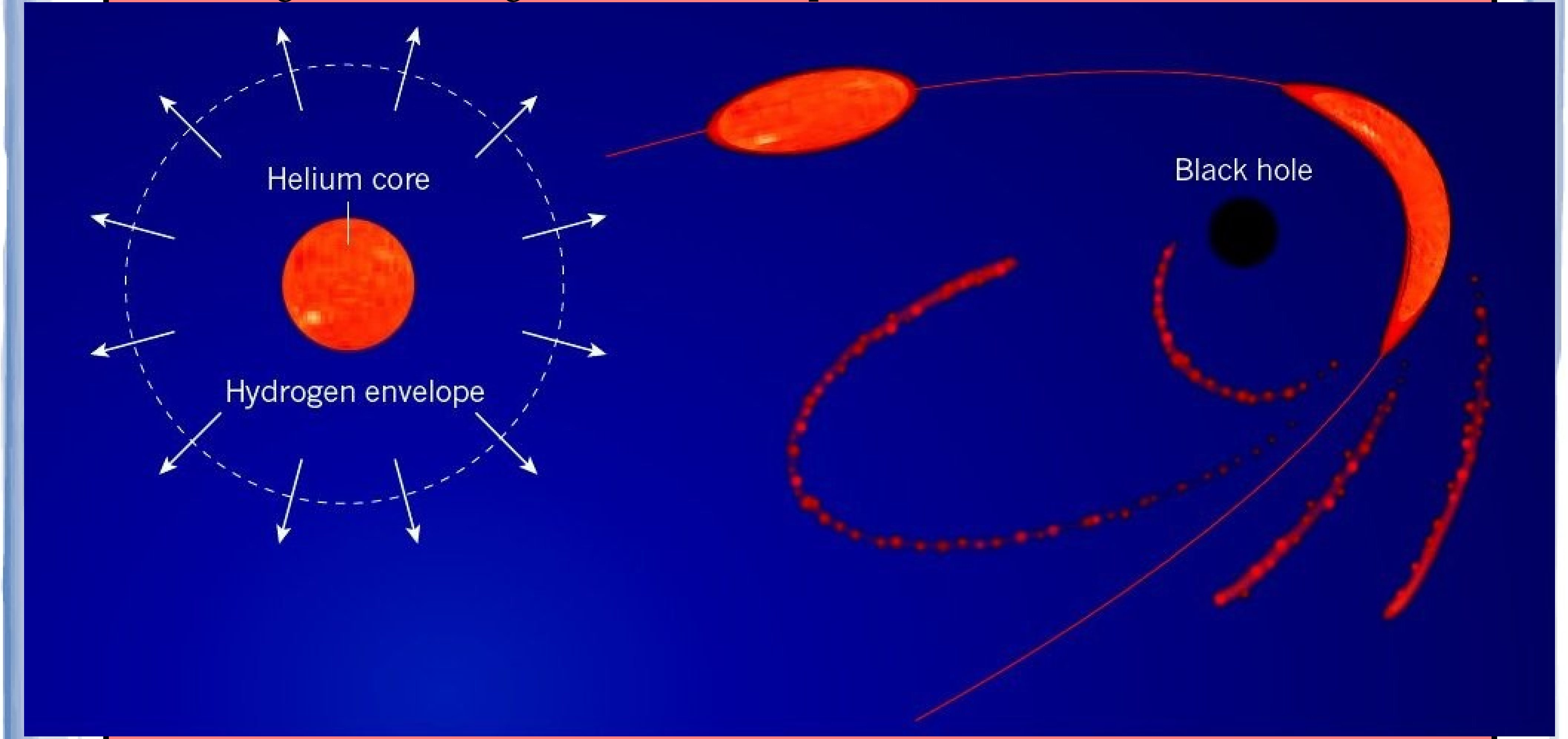
Modelling the TDE light curves and spectra:

- $R_p \sim R_T$
- Polytropic exponent of 5/3 (fully convective star or a degenerate core)
- t_p = 72 ± 2 days
- $M = (1.9 \pm 0.1) \times 10^6\ M_\odot$
- Broad high-ionization HeII emission at 4,686 A
- Lack of Balmer line emission, low H mass fraction: < 0.2
- $L_p \sim 2.2 \times 10^{44}$ erg/s ; $E \sim 2 \times 10^{51}$ erg

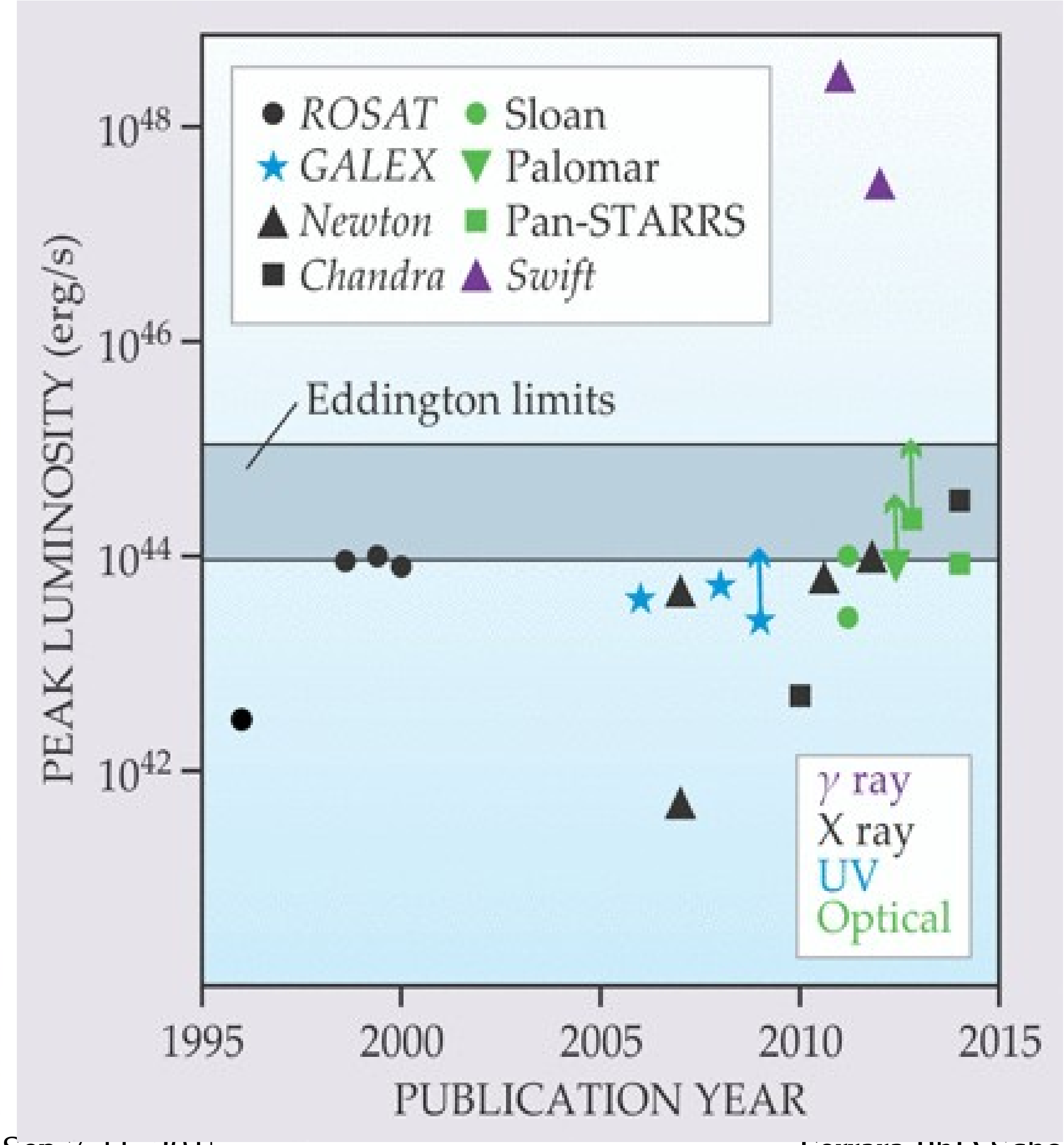
Consistent with a tidally stripped core of a red giant (precursor to helium white dwarf)

UV-optical flare from a TD of a helium-rich stellar core

Modelling the TDE light curves and spectra:



Peak Lum of 20 TDEs (as of 05/2014)

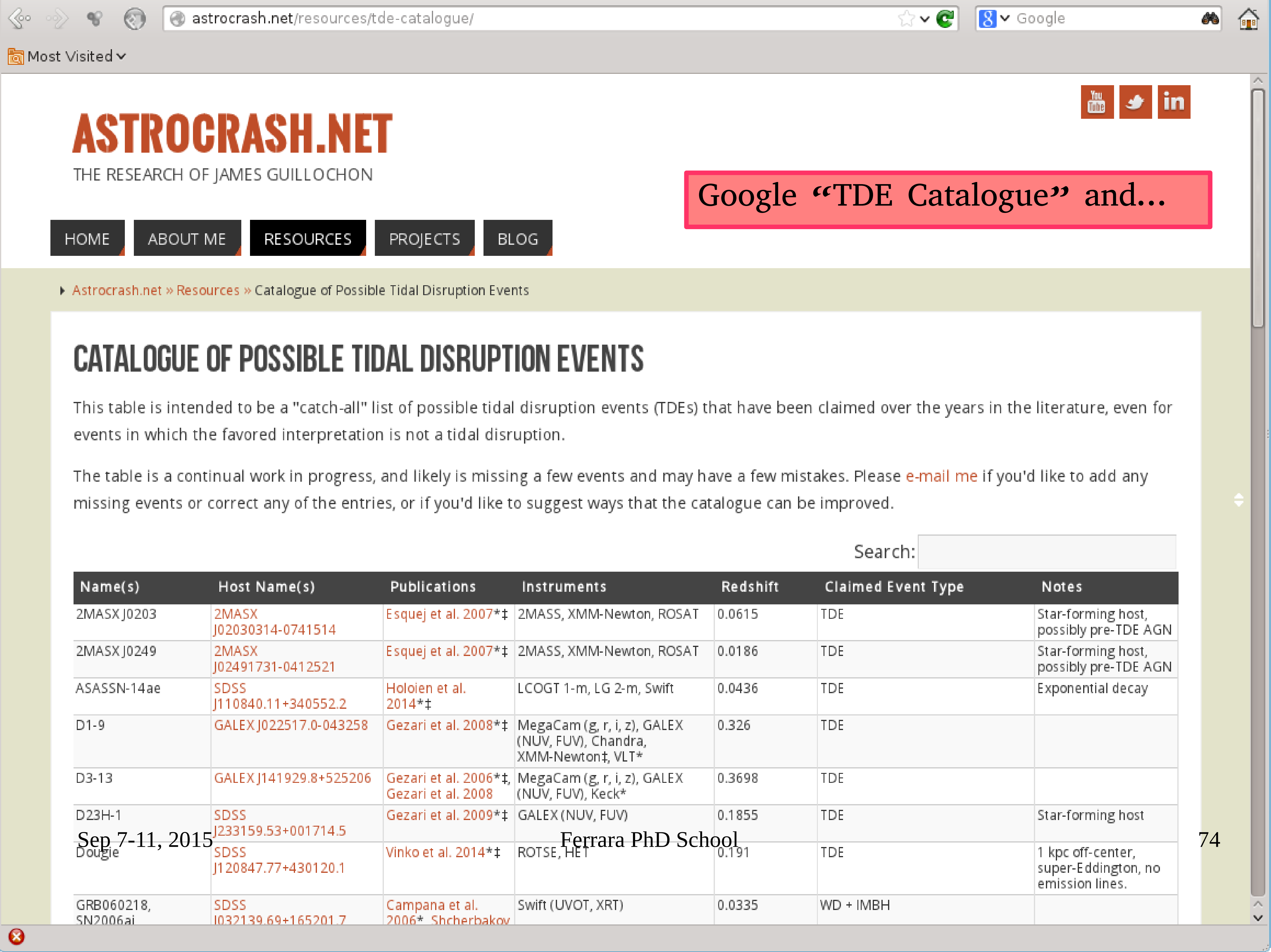


The shaded region shows the range of Eddington upper limits on luminosity for black holes with masses ranging from 10^6 to 10^7 solar masses.

Only three TDE candidates discovered in hard-x-ray flares by the Swift orbiter peak well above the Eddington limits, suggesting highly beamed radiation in our direction from jets of stellar debris boosted to relativistic velocities.

Gezari+14

Google “TDE Catalogue” and…



ASTROCRASH.NET

THE RESEARCH OF JAMES GUILLOCHON

Astrocrash.net » Resources » Catalogue of Possible Tidal Disruption Events

CATALOGUE OF POSSIBLE TIDAL DISRUPTION EVENTS

This table is intended to be a "catch-all" list of possible tidal disruption events (TDEs) that have been claimed over the years in the literature, even for events in which the favored interpretation is not a tidal disruption.

The table is a continual work in progress, and likely is missing a few events and may have a few mistakes. Please e-mail me if you'd like to add any missing events or correct any of the entries, or if you'd like to suggest ways that the catalogue can be improved.

Name(s)	Host Name(s)	Publications	Instruments	Redshift	Claimed Event Type	Notes
2MASX J0203	2MASX J02030314-0741514	Esquej et al. 2007*‡	2MASS, XMM-Newton, ROSAT	0.0615	TDE	Star-forming host, possibly pre-TDE AGN
2MASX J0249	2MASX J02491731-0412521	Esquej et al. 2007*‡	2MASS, XMM-Newton, ROSAT	0.0186	TDE	Star-forming host, possibly pre-TDE AGN
ASASSN-14ae	SDSS J110840.11+340552.2	Holoien et al. 2014*‡	LCOGT 1-m, LG 2-m, Swift	0.0436	TDE	Exponential decay
D1-9	GALEX J022517.0-043258	Gezari et al. 2008*‡	MegaCam (g, r, i, z), GALEX (NUV, FUV), Chandra, XMM-Newton‡, VLT*	0.326	TDE	
D3-13	GALEX J141929.8+525206	Gezari et al. 2006*‡, Gezari et al. 2008	MegaCam (g, r, i, z), GALEX (NUV, FUV), Keck*	0.3698	TDE	
D23H-1	SDSS J233159.53+001714.5	Gezari et al. 2009*‡	GALEX (NUV, FUV)	0.1855	TDE	Star-forming host
Dougie	SDSS J120847.77+430120.1	Vinko et al. 2014*‡	ROTSE, HET	0.191	TDE	1 kpc off-center, super-Eddington, no emission lines.
GRB060218, SN2006aj	SDSS J032139.69+165201.7	Campana et al. 2006*, Shcherbakov	Swift (UVOT, XRT)	0.0335	WD + IMBH	

What do TDEs teach us?

- Demography of low-mass, otherwise-dormant SMBHs
- SMBH growth
- Stellar dynamics around galactic nuclei
- Probes of relativistic effects (emission-line profiles or precession effects in the Kerr metrics)
- Accretion physics near the last stable orbit
- Formation and evolution of radio jets

We just entered the TDE real-time discovery era.


"That's all Folks!"