A New Channel for X-ray Flashes: Tidal Disruptions of White Dwarfs by Intermediate Mass Black Holes

Shcherbakov et al. 2013, ApJ, 769, 85

Haas, Shcherbakov et al. 2012, ApJ, 749, 117

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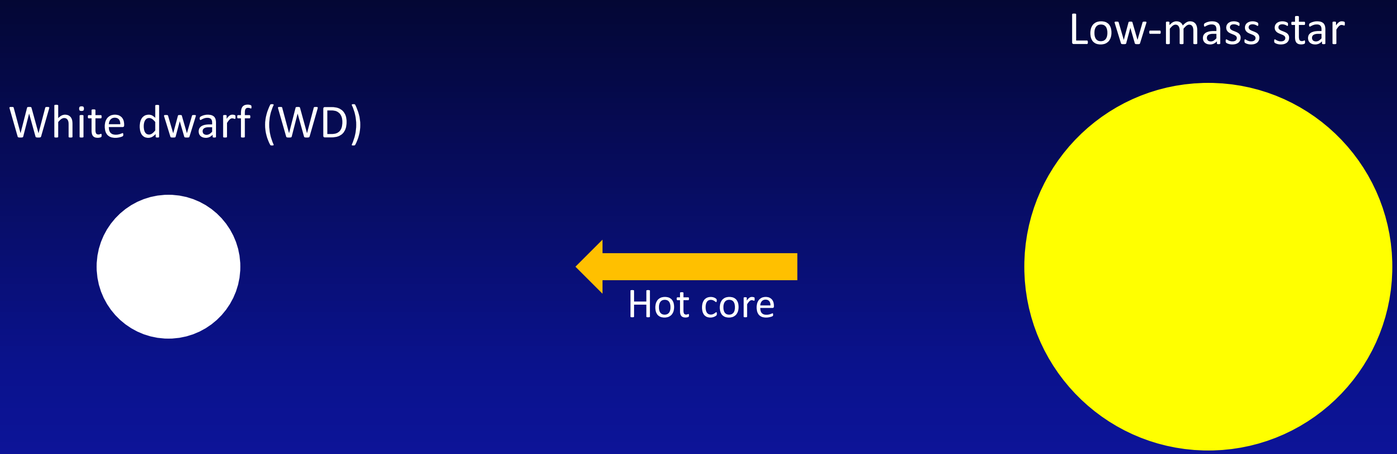
31 May 2013

White Dwarfs



White dwarf (WD)

Hot core

Low-mass star

Facts about WDs

Mass: 0.2-1.4M_{sun}, radius: (2-9)·10^3km.

Supported by electron degeneracy pressure.

WD is a solar mass squeezed within the Earth’s radius

Black holes

Stellar mass BHs

Many established sources w/ masses 5-15M_{sun}

Supermassive BHs

Dozens of established sources w/ masses 10^6-$10^{10}M_{sun}$

Intermediate mass BHs

Candidates w/ masses 10^3-10^4M_{sun}

=> $R_g \sim$ Earth radius

found by stellar dynamics in globular clusters,
nuclear broad lines in dwarf galaxies,
soft luminous blackbody X-ray sources

Lutzgendorf et al. 2013

Dong et al. 2007

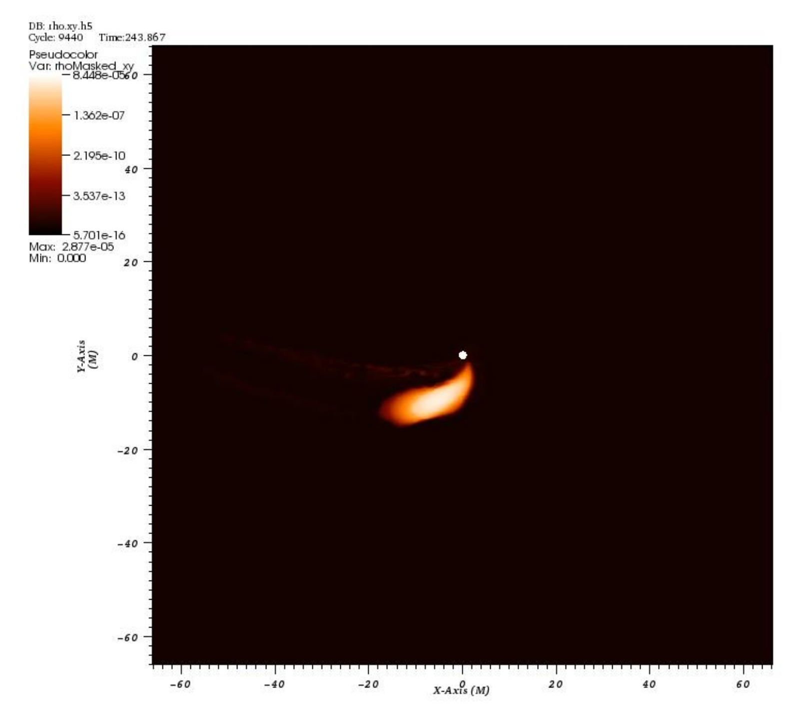
Davis et al. 2012

Is there a definitive proof yet?

Qualitatively new ways to identify sources

Tidal disruptions

(this is actually an "ultra-close" disruption with R_T/R_p=6)

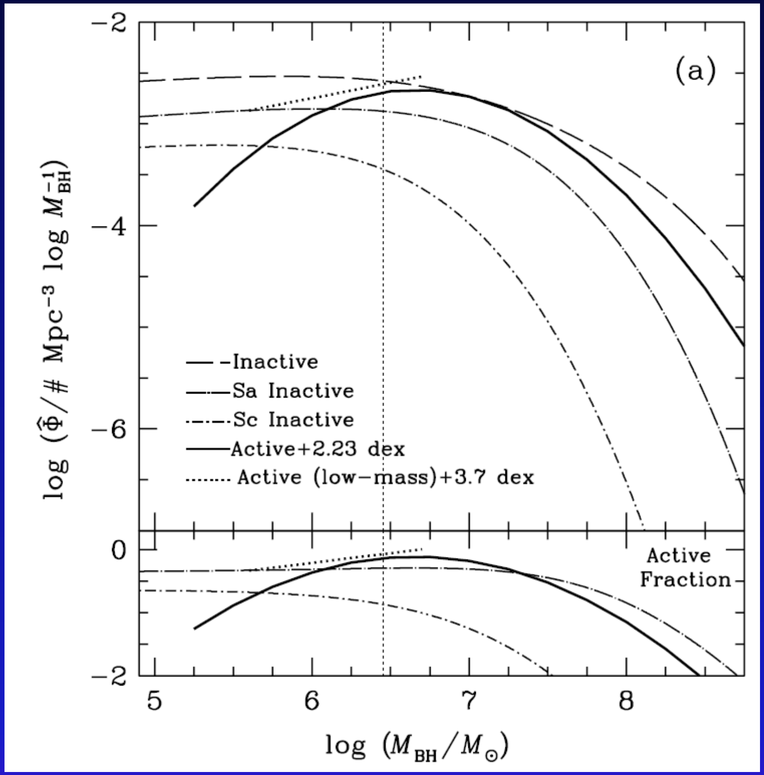


Haas, Shcherbakov et al. 2012

Some debris fall onto the BH
and form accretion disk

How to find IMBHs?

BH mass function



SDSS DR4 data

Greene & Ho 2007

IMBHs may be there in small galaxies, but be mostly inactive

How to illuminate IMBH population?

Tidal disruptions of stars

Normal stars are disrupted too far
=> slow and weak flare

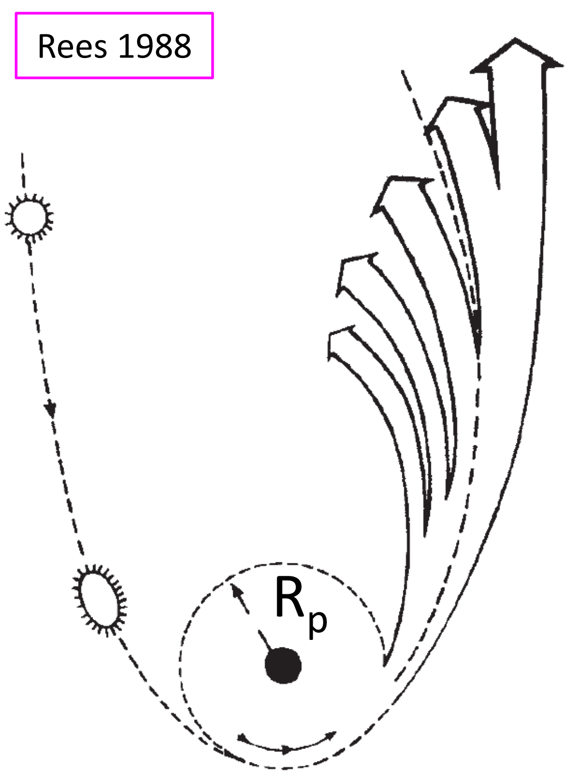
Neutron stars => swallowed as whole

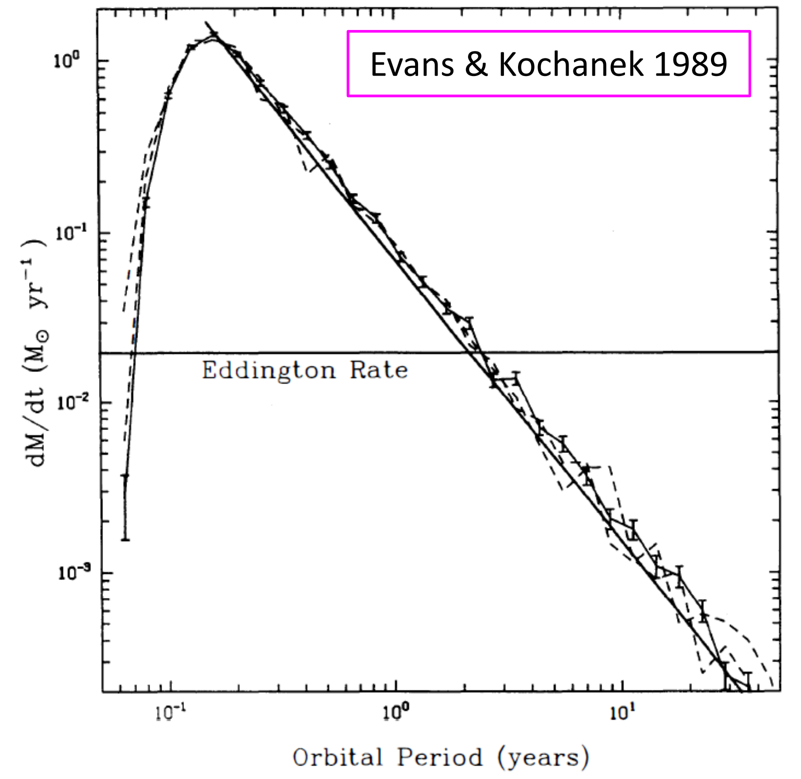
White dwarfs have radius ~ IMBH radius
+ disrupted close to the BH => violent event

Intermediate mass BHs should be effectively illuminated by tidal disruptions of WDs

General features of tidal disruptions

- A star approaches on a parabolic orbit
- Pericenter radius R_p is less than tidal radius R_T => tidal disruption
- 50% of debris fall back and form accretion disk
- Typical event duration is 1hr for IMBH-WD encounter (1mo for SMBH-star)
- Typical accretion rate is $10^3 M_{sun}/yr$ for IMBH-WD ($1 M_{sun}/yr$ for SMBH-star)
- Accretion rate drops w/ time as $\dot{M} \sim t^{-5/3}$


Rees 1988


Evans & Kochanek 1989

Electromagnetic signatures

Infall of material onto a BH releases a lot of energy

↓

How is energy converted into photons, which we observe?

Photons are trapped in dense debris

↓

Eddington limit $L_{Edd} = 10^{41}$ erg/s for $10^3 M_{Sun}$ BH

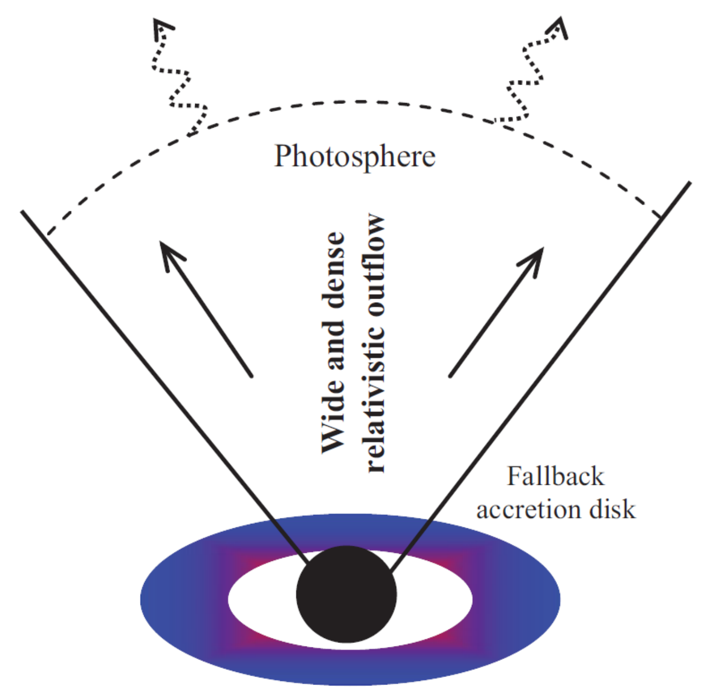
But gas infall generates heat at rate

$$P \sim 0.1\dot{M}c^2 \sim 10^{49}\ \mathrm{erg/s} \sim 10^8\, L_{Edd}$$

Outflow/jet allows
to release trapped photons faster
and achieve high luminosity

↓

Photons are advected with the outflow
and released in lower density region
with optical depth τ_σ=1 (photosphere)

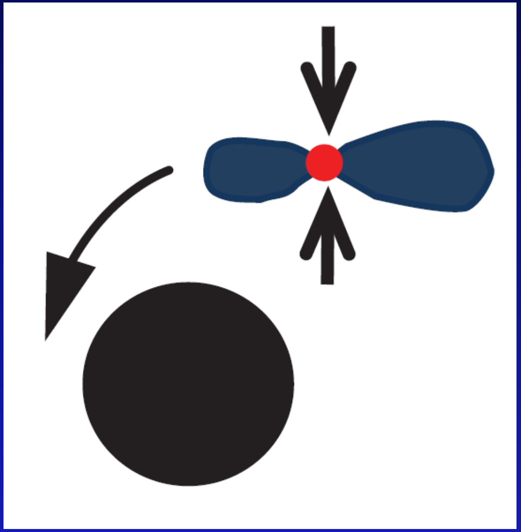


Nuclear ignition

Tidal pinching:

WD is squeezed to orbital plane

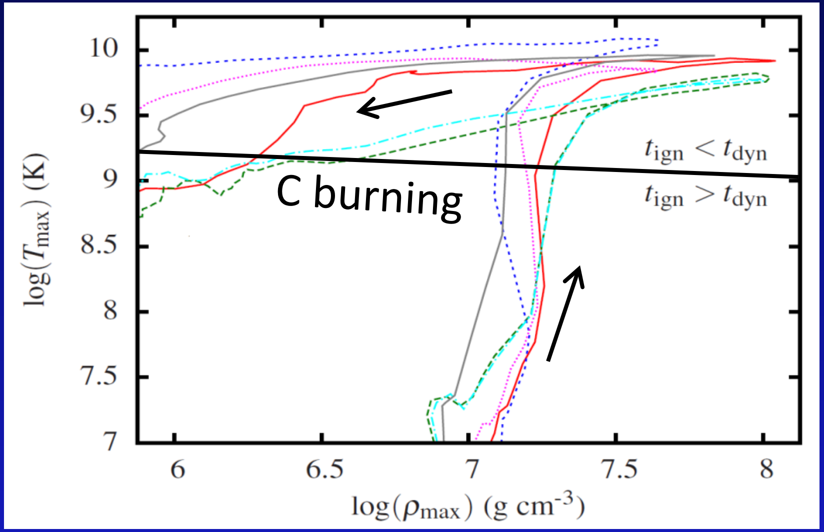
Carter & Luminet 1982; Rosswog et al. 2009



Thermonuclear ignition

Track of density/temperature

Haas, Shcherbakov et al. 2012



Nuclear burning may happen during tidal pinching

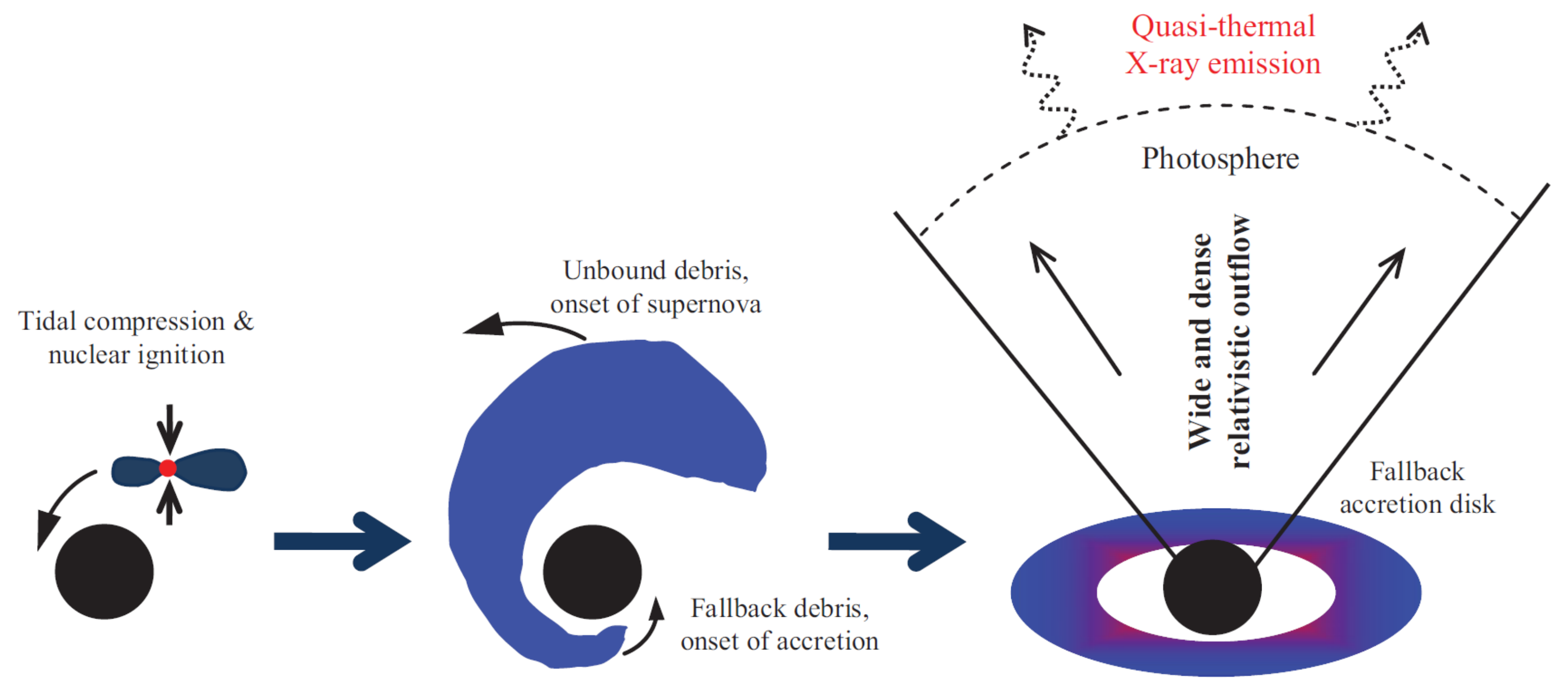
Similar to supernova Type Ia?
(when the WD burns after getting too heavy)

Different from Type Ia:
wide range in final composition,
energy release E_{kin}, and ejecta mass M_{ej};
mostly underluminous explosions w/ small M_{ej}.

Rosswog et al. 2009

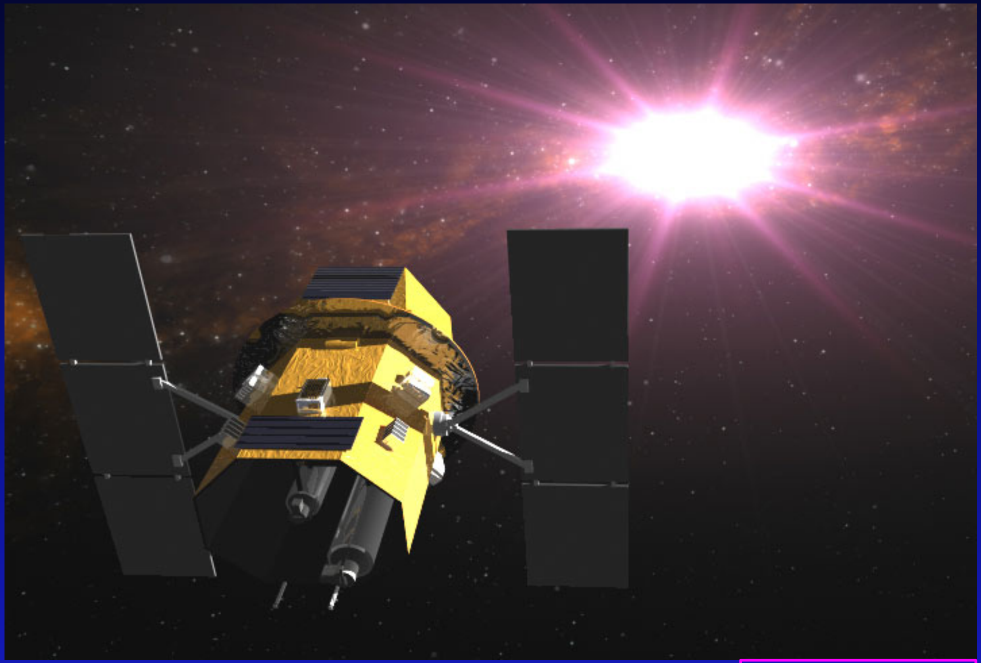
General picture of WD disruption by IMBH

- Nuclear explosion leads to unbound debris fraction of >50%
- Photons thermalize before escaping from photosphere, and reach soft X-ray energies



Search for 1hr long X-ray (blackbody) transients accompanied by weak supernovae

Swift satellite



Credit: NASA

- Designed to search for gamma-ray bursts:
  short (0.1-1000s) powerful “bursts” of hard X-rays/gamma-rays
- Sees 10% of the sky simultaneously
- In orbit since 2004
- Can take simultaneous hard X-ray/soft X-ray/UV/optical spectra
- Discovered almost 1000 bursts with a wide range of properties

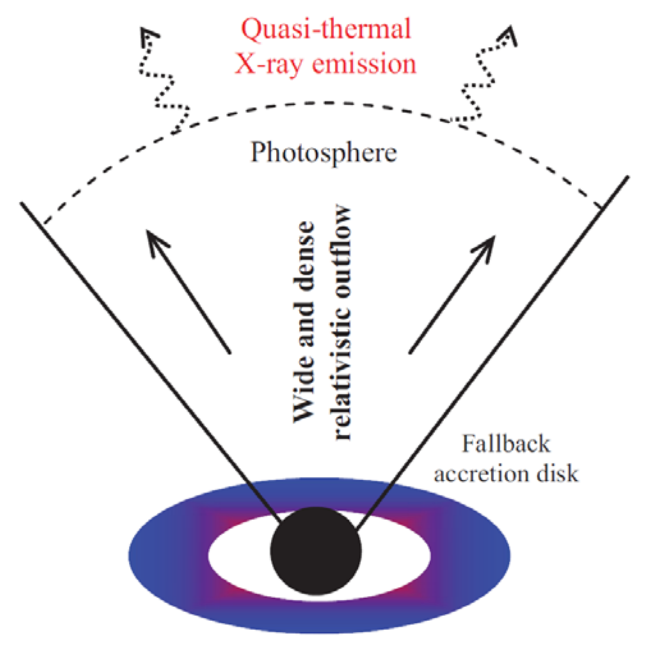
GRB060218: observational facts

- One of the longest (t_{90}=2600s) gamma-ray burst observed w/ *Swift* (out of 859)
  (another ultra-long GRB is an “established” tidal disruption *Swift* J1644+57)
- Soft spectrum: X-rays <5keV, typical GRB is dominated by >100keV photons
- Accompanied by a peculiar supernova SN2006aj
  with estimated low ejecta mass M_{ej}=1-2M_{Sun}
- Supernova position is consistent w/ the center of the host galaxy
- Was extensively observed in radio/optical/UV/X-rays by various instruments

⬇

Consistent with a WD disruption by an IMBH

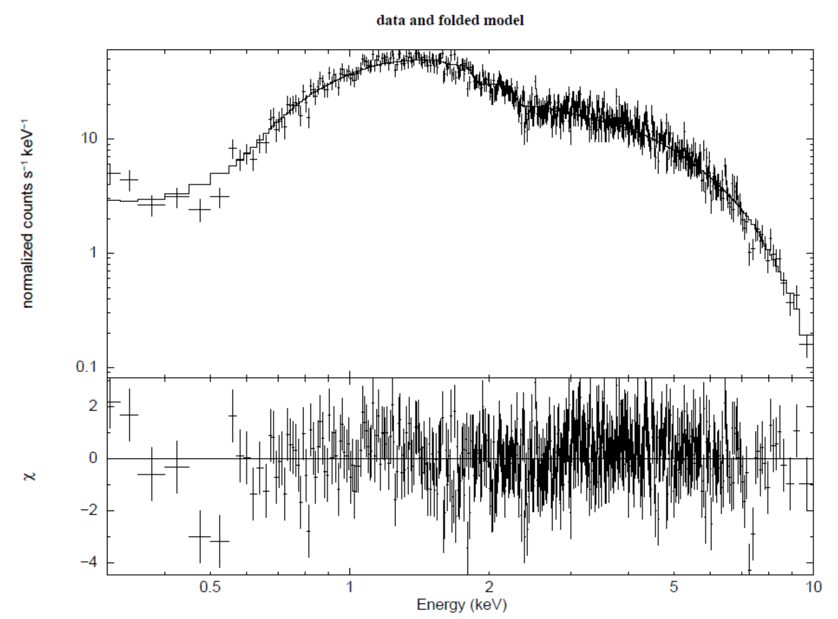
GRB060218: X-ray spectrum



- Blackbody (BB) component from thermalized photons.
- Compton upscattering by relativistic electrons in photosphere.
- Soft spectrum is influenced by absorption in host galaxy.
- Spectrum may change w/ time => divide into 11 time intervals and model them jointly.

Model in X-ray data analysis package XSPEC

- *compPS* model – blackbody Compton scattered by hot thermal electrons => joint χ^2/dof =1.10.
- BB temperature T=0.11keV, flux F~$5\cdot10^{-9}$erg/s/cm^2.
- Low-Z constant absorption NH~10^{22}cm^{-2}.
- Spectrum is heavily absorbed at late times as it becomes softer and softer.



System properties from X-ray spectrum

Model BB temperature T and BB flux F, know the distance d

Source isotropic luminosity L

Standard jet acceleration model

Pe'er et al. 2007

Jet Lorenz factor Γ and base radius R_{base}

$\Gamma \sim 2.7$, $R_{base} \sim 1.3 \cdot 10^{10}$cm

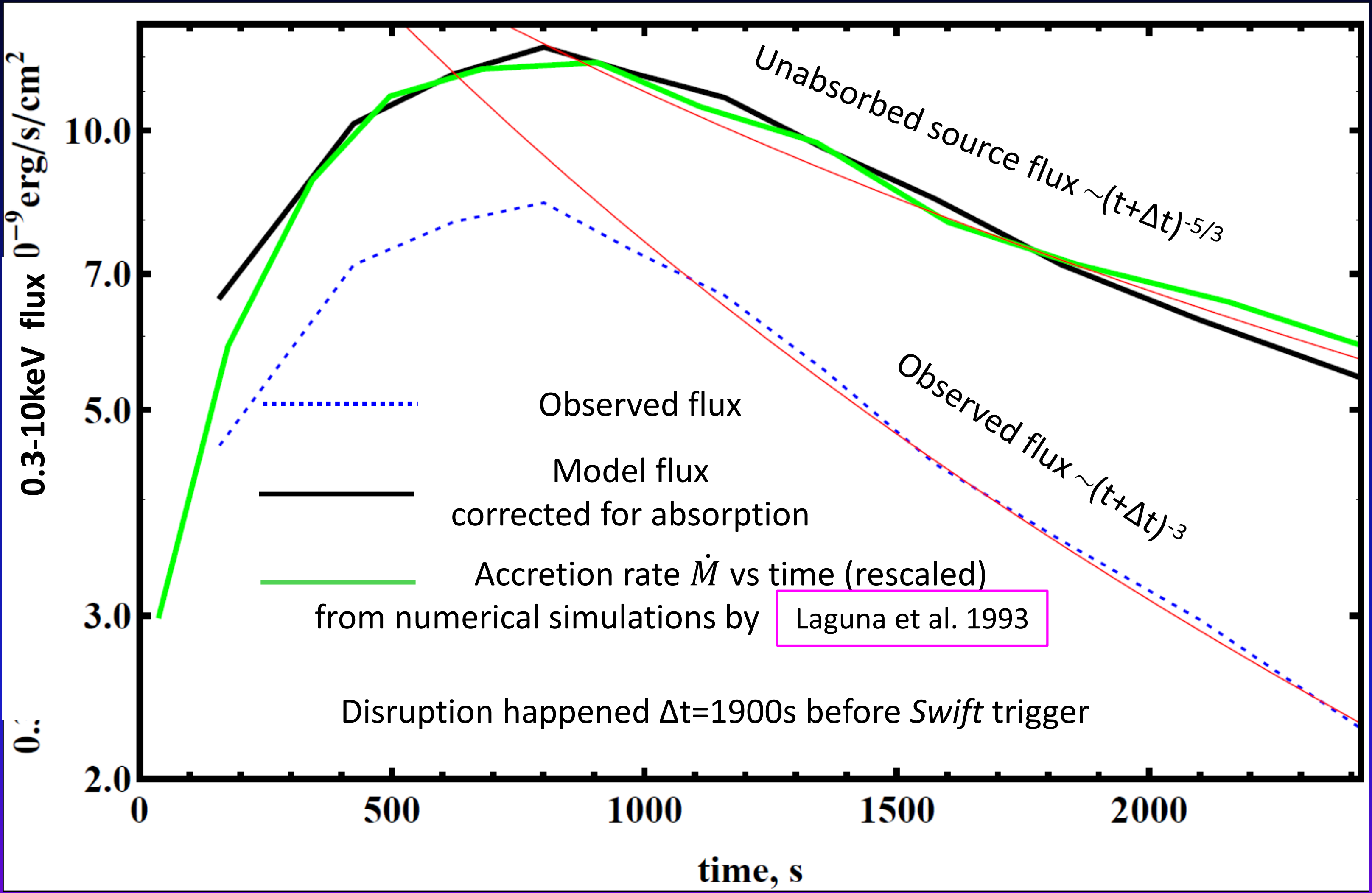
Assume jet base at several R_g

BH gravitational radius $R_g \sim 2 \cdot 10^9$cm,

BH mass $\boxed{M_{BH} \sim 10^4 M_{Sun}}$

GRB060218: lightcurve

Constant NH, spectrum softer w/ time => larger absorbed fraction



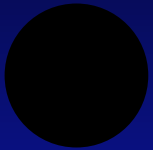
Disruption happened Δt=1900s before *Swift* trigger

Source flux perfectly matches $\dot{M}$ vs *t* for tidal disruption!

M_{BH}~$10^4 M_{sun}$, heavy WD, absorption is the key

Smoothness of lightcurve

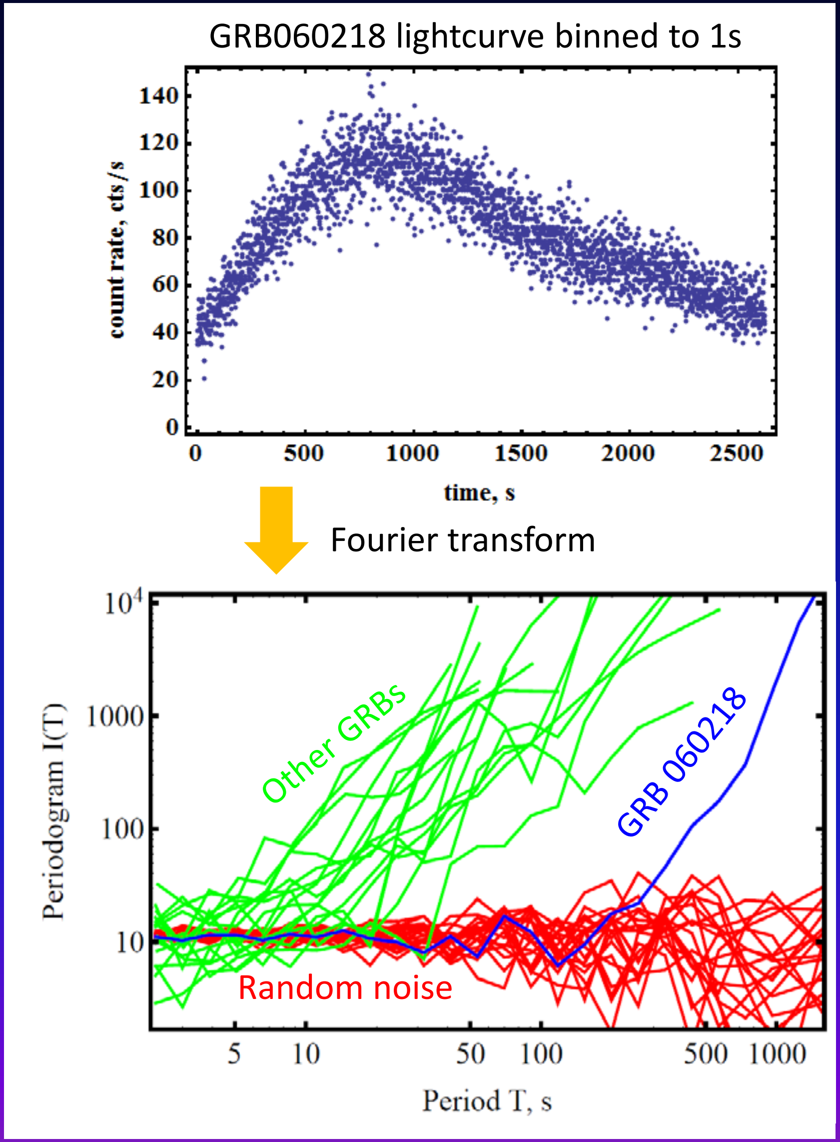
Large BHs
have large variability timescales



GRBs are associated with $\sim 10 M_{Sun}$ BHs
Our tidal disruption has $\sim 10^4 M_{Sun}$ BH

GRB060218 is expected to be
not only longer, but also smoother

Characteristic timescale ~500s –
clearly different from GRB population



Other GRBs selected to have same peak count rate

Late lightcurve – afterglow

Early times

Material falls back as $\dot{M} \sim t^{-5/3}$,
spends little time in disk,
quickly spirals onto the BH

Accretion rate $\dot{M} \sim t^{-5/3}$

Late times

Disk grows in size and mass,
less and less debris fall back onto disk

Disk slowly drains into the BH

Accretion rate $\dot{M} \sim t^{-4/3}$

Kumar et al. 2008

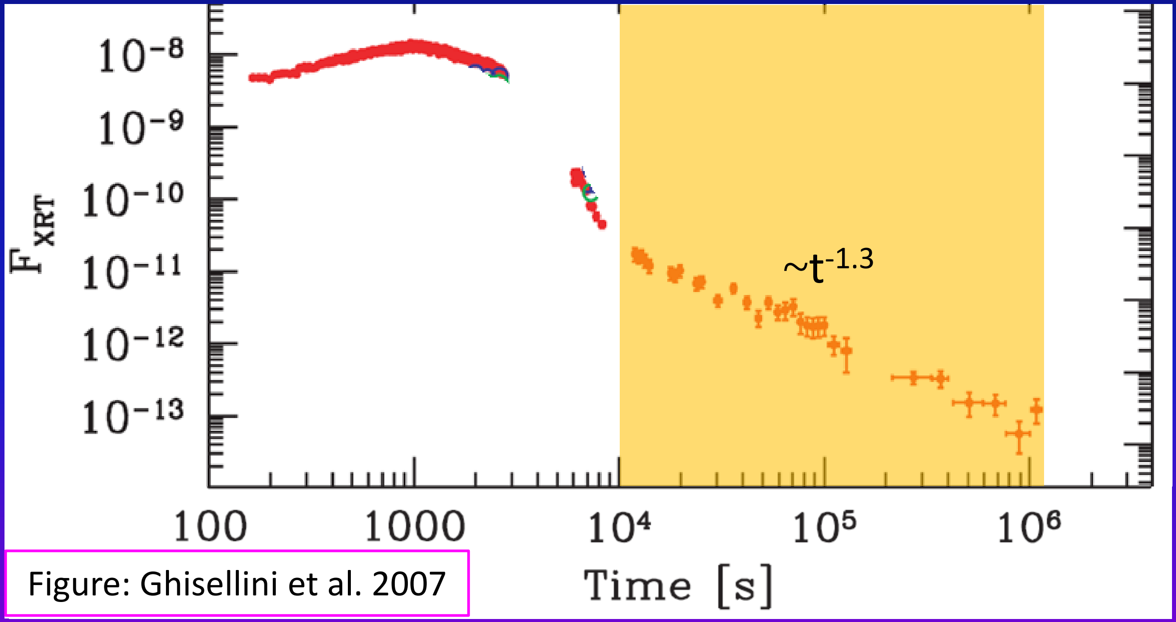
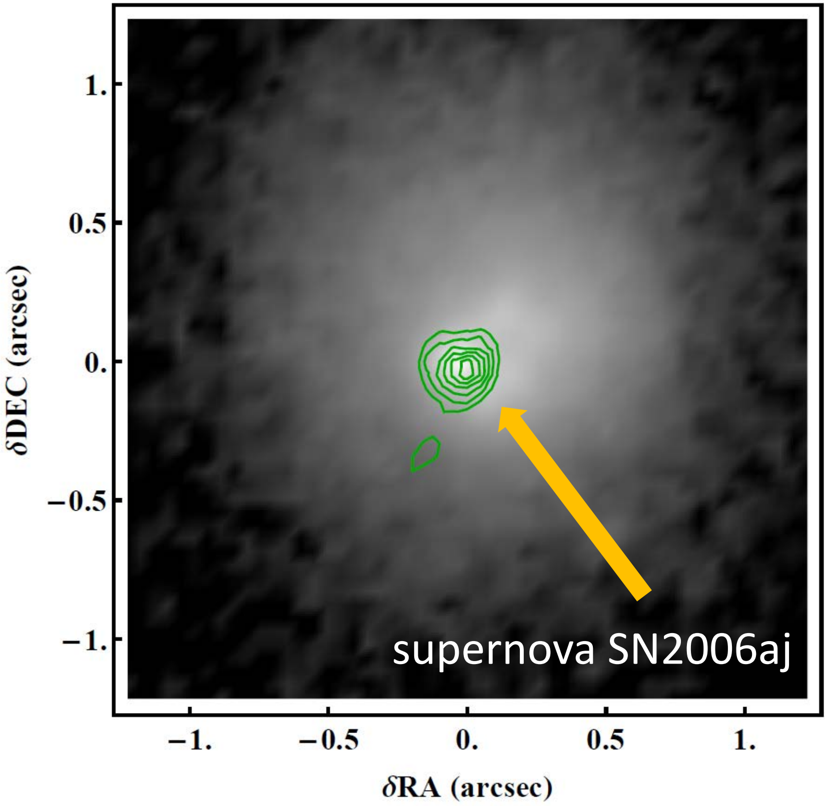


Figure: Ghisellini et al. 2007

Shallow $\sim t^{-1.3}$ decay is consistent
w/ accretion rate behavior at late times

Supernova & host galaxy

Host dwarf galaxy with a supernova



Hubble ACS (814W band)

Supernova – subtraction (early-late) image
Host galaxy – late image
Early=5mo, late = 8mo after supernova

Position of a supernova is consistent with the center of the dwarf host galaxy

Host galaxy stellar mass

$M_{st} \sim 10^{7.2} M_{Sun}$ Ferrero et al. 2007

consistent w/ central BH mass

$M_{BH} \sim 10^{4} M_{Sun}$

Marconi & Hunt 2003

Schramm & Silverman 2012

Jet launching & jet power

Ordered magnetic field of equipartition strength (B~10^{11}G) is needed to launch a strong jet $P_{jet} \sim 0.1\dot{M}c^2$

McKinney et al. 2005+

Energy extraction
by spinning black hole or rotating disk:
slingshot acceleration by magnetic field lines

Blandford & Znajek 1977

Blandford & Payne 1982

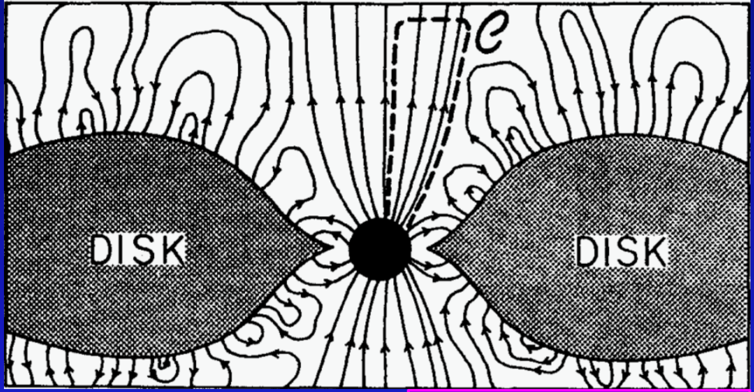


figure: Thorne 1988

Weak Initial B-field in a WD (B~10^4G),
very low jet power for that field

$$P_{jet} \sim B^2$$

B-field is amplified in accretion flow
via MHD instabilities and dynamo,
but typically to sub-equipartition values

McKinney et al. 2012

Consistent with low GRB060218 jet power

$$P_{jet} \sim 10^{-4}\dot{M}c^2$$

Alternative theories for GRB060218

Supernova shock breakout

(launched by collapse of a star
shock heats outer stellar envelope)

Soderberg et al. 2006,
Waxman et al. 2007

↓

Shock cannot carry
10^{49}-10^{52} erg of energy;
Progenitor star would be too big

Ghisellini et al. 2007

Standard gamma-ray burst

(accretion onto small BH
following collapse of a star => jet)

↓

Should have same duration,
+ be from same population

↓

Bromberg et al. 2011

Standard GRB population
does not smoothly extend
to long/soft/weak sources

Jet launched by a magnetar

(neutron star with very large B-field)

Toma et al. 2007; Fan et al. 2011

→

Event would be shorter

Bufano et al. 2012

↑

While other models cannot be reliably excluded
Our tidal disruption hypothesis is probably the most natural

Event rate

Knowing GRB060218 is observed:

- 1 event per 7 yrs of *Swift*
- *Swift* sees 10% of all GRBs
- Distance to source 140Mpc

Theoretical rate in nuclei of dwarf galaxies (DG):
DGs have very tight nuclear star clusters
=> high tidal disruption rate
~10^{-3}/yr/gal

Wang & Merritt 2004

Mass segregation =>
WDs move towards the center,
15% of disrupted stars are WDs

Baumgardt 2004

Assume every dwarf galaxy hosts an IMBH
n_{DG}=0.01/Mpc^3

Observational rate 500evt/yr/Gpc^3

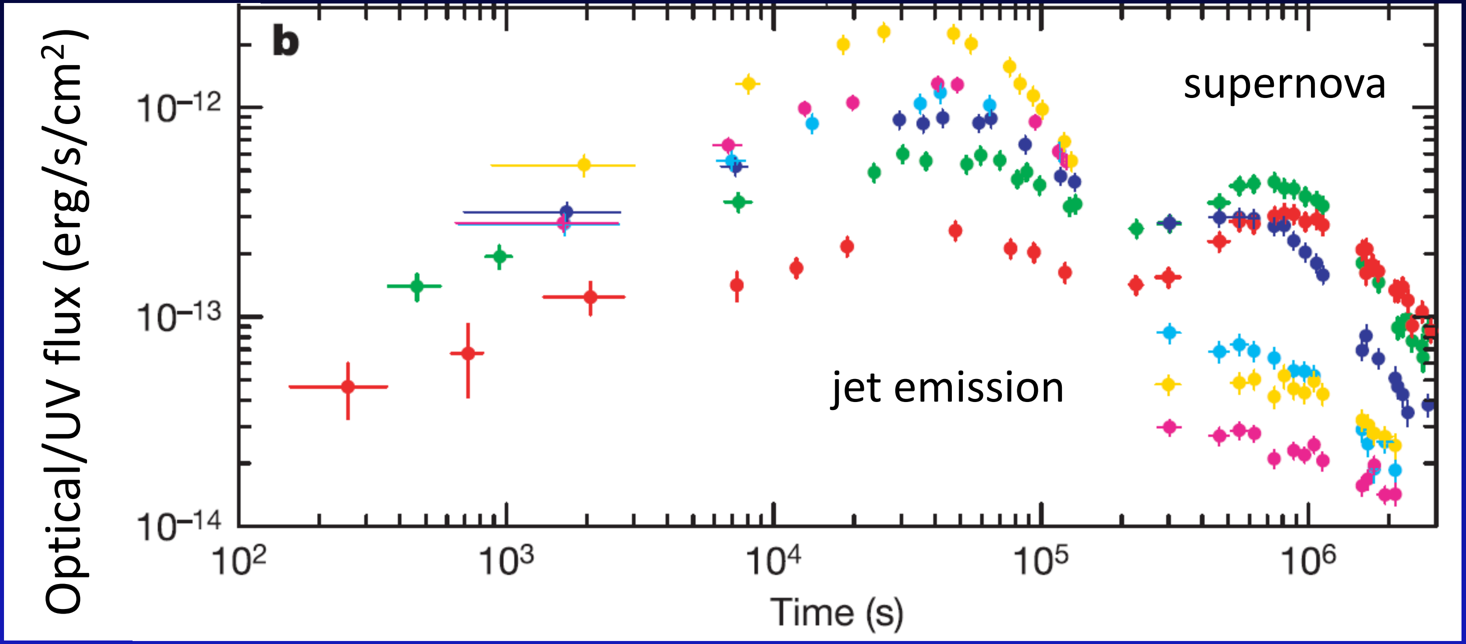
Theoretical rate 1500evt/yr/Gpc^3

Supernova rate ~6·10^4 evt/yr/Gpc^3:
1-3% of supernovae may be of tidal disruption origin!

Search among underluminous supernovae
with low ejecta mass in DG centers (to be performed)

Potential for optical searches

GRB060218 – double-hump optical transient coincident w/ galactic nucleus



Emission from slowly expanding jet fireball (different from GRB afterglow)

Search PanSTARRs & Palomar Transient Factory data
for double-hump supernovae

Conclusions

- Tidal disruptions of WDs illuminate IMBH population
- Produce a jet with correspondent prompt jet emission
- Manifests as long soft weak X-ray transient 1hr in duration
- Associated supernova should be fast/have low ejecta mass
  + be located near the center of host galaxy
- GRB060218/SN2006aj is a good candidate
  from multiple prospectives:

spectrum + lightcurve + timing + afterglow + supernova + host galaxy

Three independent estimates of BH mass $\sim 10^4 M_{\rm Sun}$

Searching for more sources