Prompt Emission from Tidal Disruptions of WDs by IMBHs

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Objects of tidal disruptions

MS (post-MS) + IMBH/SMBH

- Big star => large tidal radius
- Slow timescale 1week – 1 yr
- Low peak accretion rate 0.1-1M_{sun}/yr

➡ Slow weak events

WD + IMBH

Presentation by Pablo Laguna on Wednesday

- Small star and small BH
- Fast timescale 1 min – 1hr
- High peak accretion rate $10^4 M_{sun}$/yr

➡ Fast powerful events

Lots of energy within a small volume,
but need to convert into radiation
and break the Eddington limit

➡ Prompt emission from relativistic outflow

Production of relativistic outflows

Ordered magnetic field

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

Blandford & Znajek 1977 | Blandford & Payne 1982

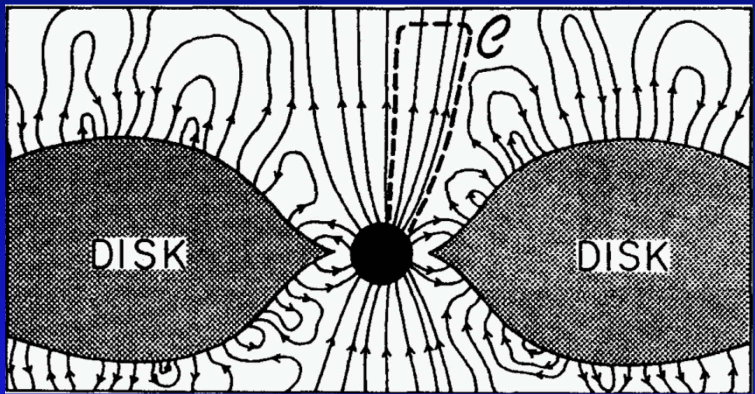

figure: Thorne 1988

- Weak initial B-field in a WD ($B \sim 10^4$ Gs)
- Only random B-field is generated fast via MRI
- However, even toroidal random B-field produces weak jets

McKinney et al. 2012

No ordered magnetic field

Fireball model:
Lots of energy + little bit of matter
= effective acceleration

Meszaros & Rees 1992a,b | Piran et al. 1993

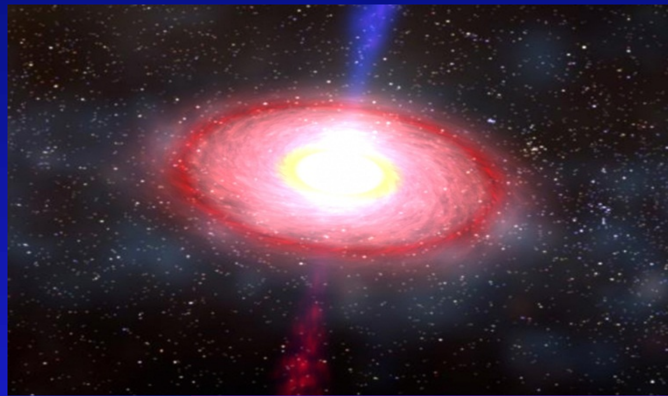

figure: Dana Berry and NASA

- Hard to dump energy into matter
  Neutrinos serve this purpose in GRBs
- Dissipation of random B-field
  dumps some energy => weak jets

WD + IMBHs tidal disruptions likely produce slow weak jets

Emission from relativistic outflows

Blazar modelling

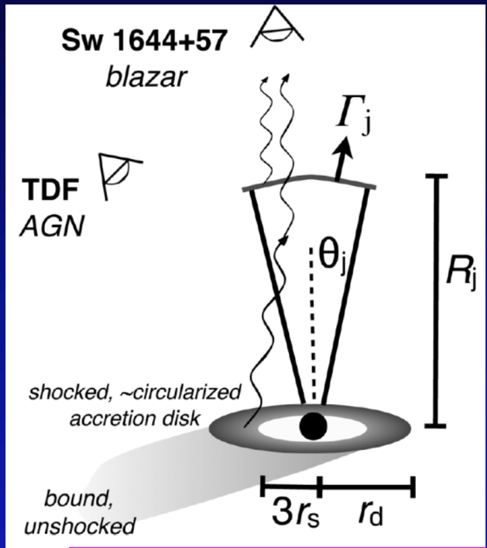

figure: Bloom et al. 2011

Synchrotron + External Comptonization of disk and reflected photons

e.g. Ghisellini & Tavecchio 2009

Scattering optical depth τ_σ <1
photons traverse the flow

GRB modelling

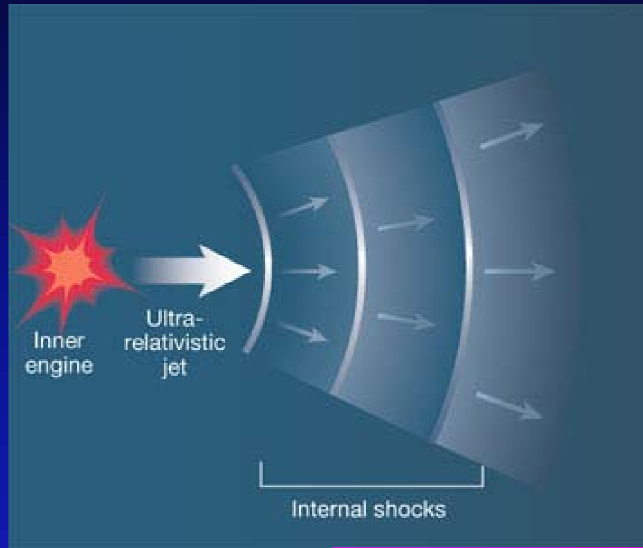

figure: Piran 2003

Synchrotron + internal Comptonization (+ pair physics)

e.g. Kumar & Narayan 2009

τ_σ >1 => photons from disk
can't reach the emission region

WD + IMBHs disruptions have τ_σ >>1, should be modeled as weak GRBs

GRB-like emission from jet

Internal shock model

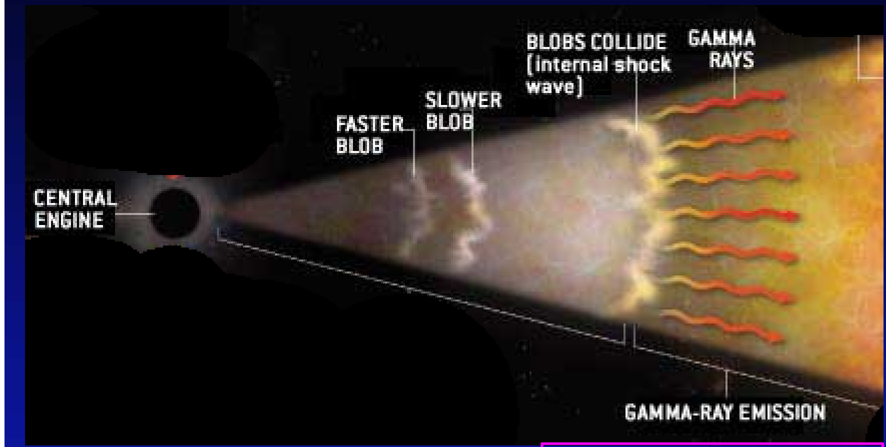

figure: Juan Velasco

Faster blob smashes into the slower blob

↓

Shock accelerates electrons into a power-law

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Electrons emit synchrotron
& Comptonize radiation field

↓

Hard non-thermal spectrum is produced

Photospheric emission model

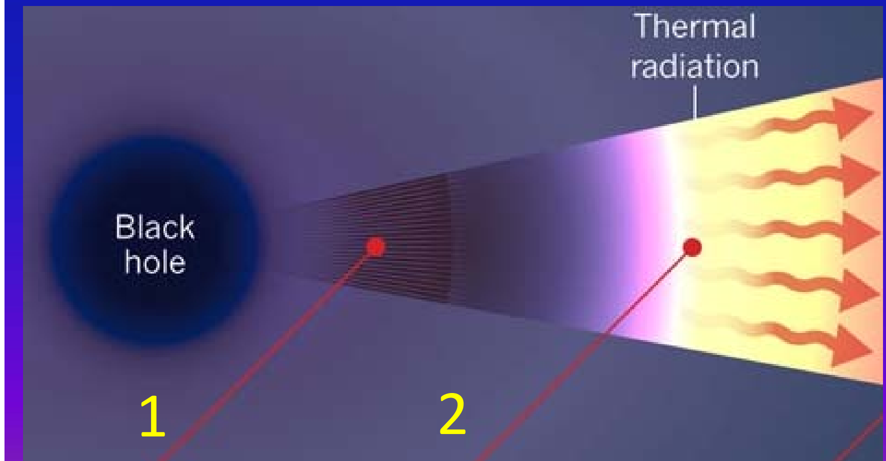


figure: Eric Hand, Nature

Photons are produced near the jet base/along jet

↓

Trapped photons thermalize in dense region (1)

↓

They escape from photospheric radius r_{ph} (2)

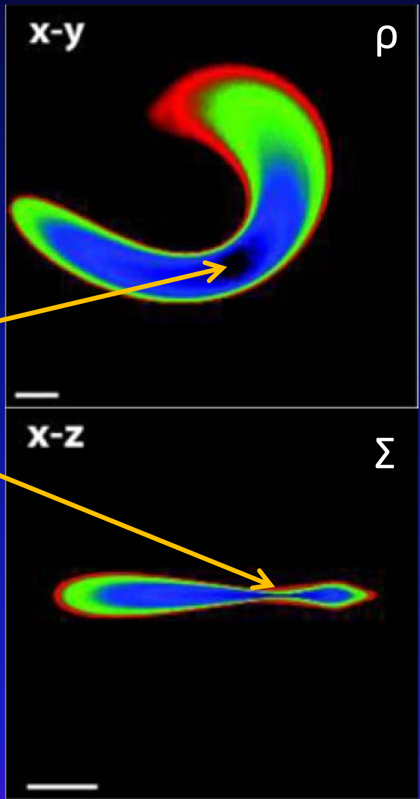
↓

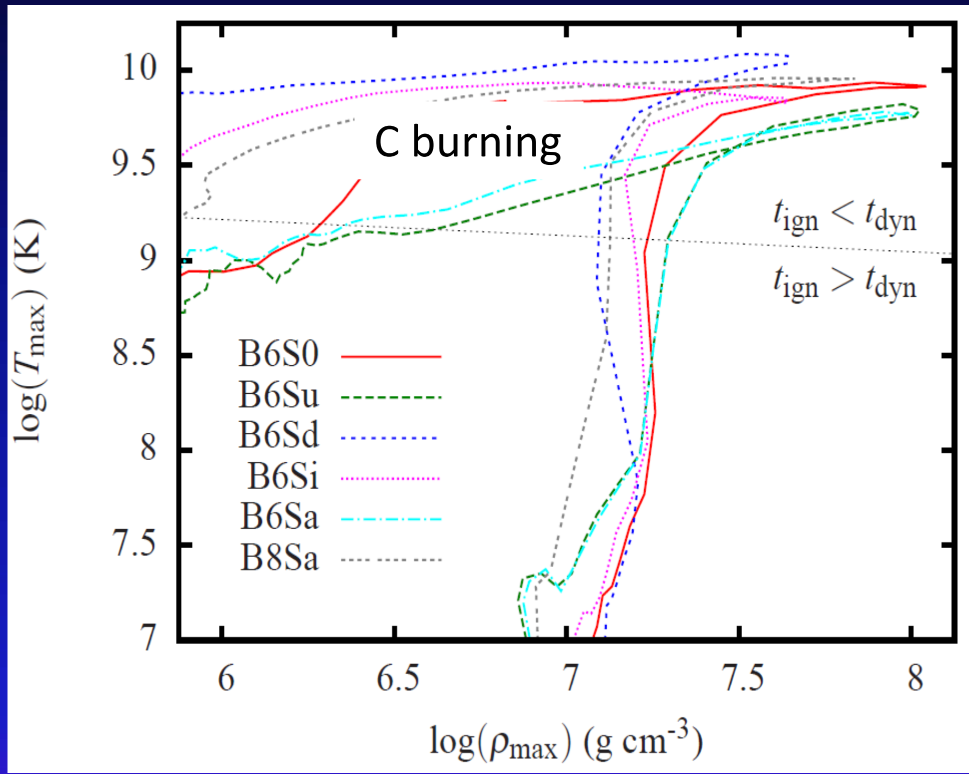
Soft thermal spectrum is produced

No radiation comes from inside of r_{ph}

Supernovae from tidal disruptions

If density and temperature are high enough for long enough
=> nuclear reactions / supernovae ignition





Tidal compression
in perpendicular direction
(tidal pinching)

Rosswog et al. 2009

Variety of compositions
and explosion energies,
NOT just SN type Ia

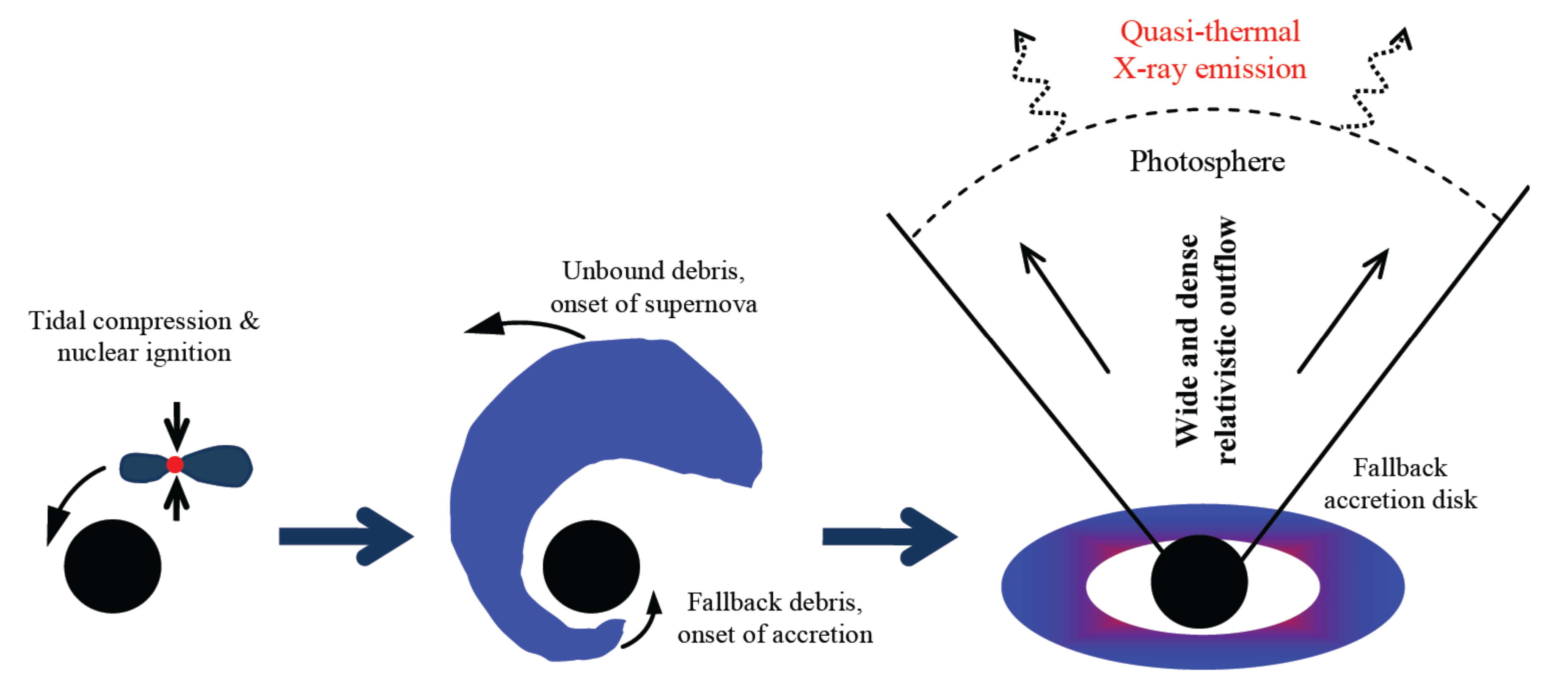
Haas, Shcherbakov, Bode, Laguna, 2012

White dwarfs should explode

Nuclear energy release < 0.01mc^2, thus dynamics are often unchanged

Both supernova & GRB signatures

General picture

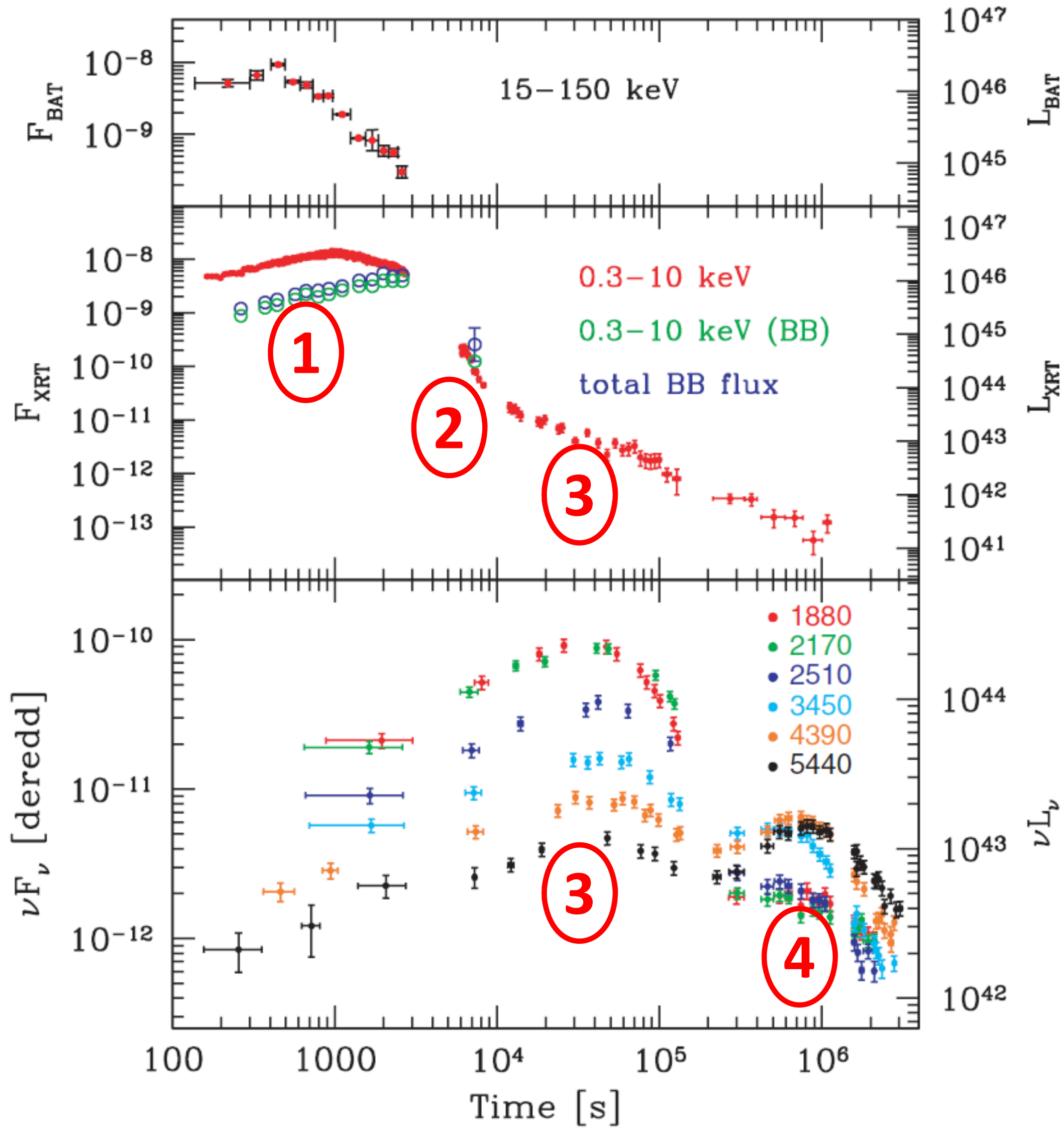


- Transient with timescale ~1000s
- Weak and soft GRB (low-luminosity GRB)
- Accompanying fast supernova with low ejecta mass (since $M_{WD}<1.4M_{sun}$)

Let's look at *Swift* GRB catalog → **GRB 060218**

GRB 060218: observations

Normalized count rates & fluxes in different bands



Ghisellini et al. 2007b

Redshift z=0.033

1. Thermal photospheric emission + Comptonization by accelerated electrons
2. Steep decay: intrinsic /or/ absorption
3. Optical afterglow peak: external shock /or/ long-term engine activity
4. Optical supernova peak

GRB 060218: fitting early XRT data

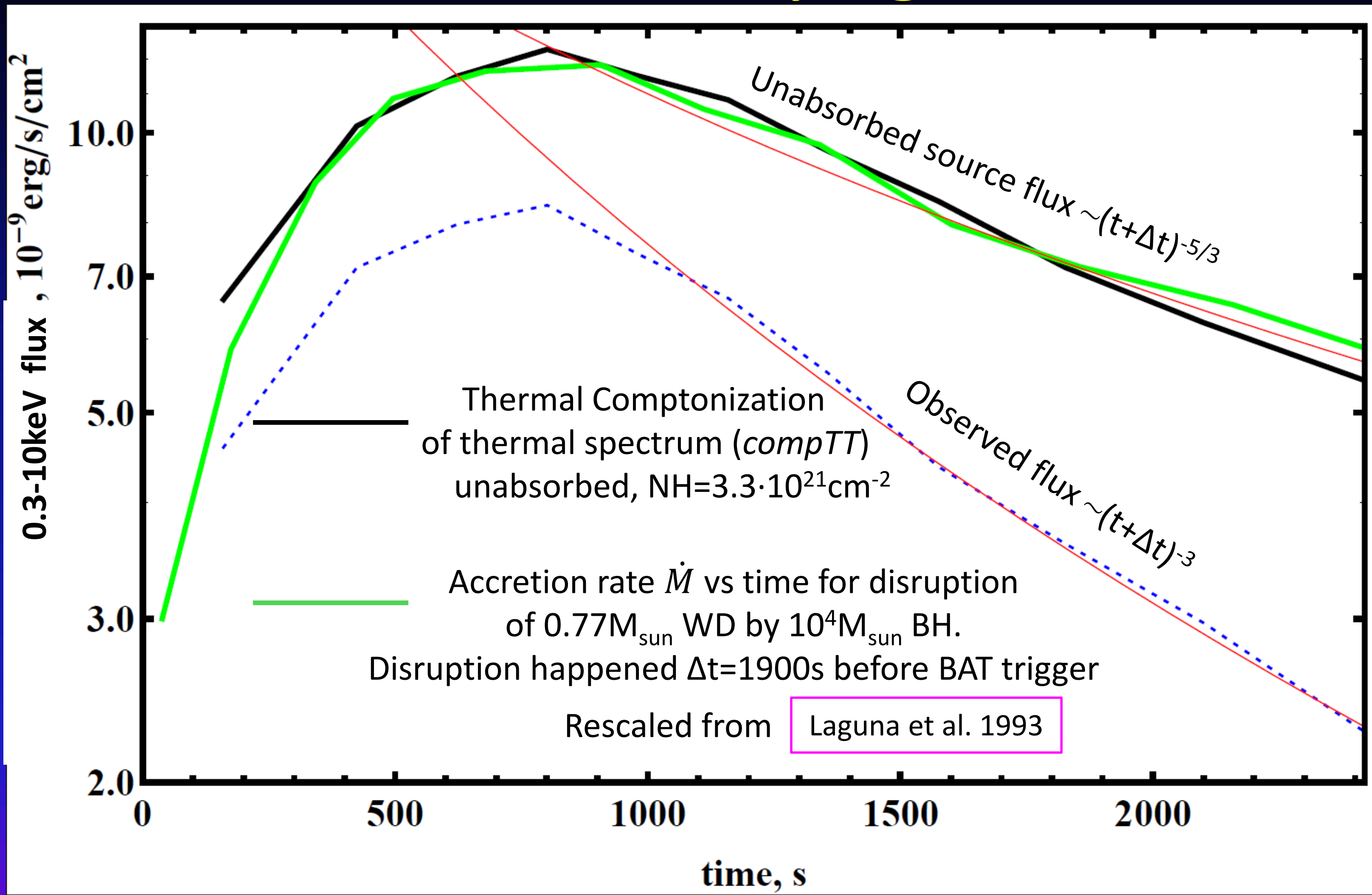
1. Cut into time slices with ~16,000photons in each
2. Define a model: *bknpower* /or/ *compPS* (thermal Comptonization of thermal emission)
3. Joint fit for all time slices with low-Z absorber (NH = $1.1 \cdot 10^{22}$cm^{-2} , Z = $0.07Z_{\odot}$)
4. Find the model parameters for that NH (and galactic NH=$0.94 \cdot 10^{21}$cm^{-2})

TIME-RESOLVED SPECTROSCOPY OF GRB 060218 SOFT X-RAY SPECTRUM. FITTING WITH THERMAL EMISSION COMPTONIZED BY THERMAL ELECTRONS.

Number	Time period t [s]	Photon temperature T_0[keV]	Electron temperature T_e[keV]	Absorbed flux $F_{abs}[10^{-9}$erg s^{-1} cm$^{-2}]$	Unabsorbed source flux $F_s[10^{-9}$erg s^{-1} cm$^{-2}]$	black body source flux $F_{bb}[10^{-9}$erg s^{-1} cm$^{-2}]$
1	164-478	0.103889	262.29	4.5859	6.6131	2.6308
2	478-691	0.105175	297.624	7.159	10.165	4.0328
3	691-875	0.0994212	258.846	7.9645	11.493	4.4652
4	875-1049	0.105797	230.162	8.3529	12.288	5.0203
5	1049-1226	0.0966514	176.625	7.4236	11.523	4.7628
6	1226-1414	0.100756	145.849	6.6358	10.842	4.8484
7	1414-1620	0.111926	119.479	5.5168	9.5569	4.7838
8	1620-1854	0.111573	93.0945	4.3687	8.4317	4.6858
9	1854-2119	0.132391	80.8674	3.6139	7.1626	4.4116
10	2119-2404	0.148928	65.9304	2.9701	6.2465	4.2841
11	2404-2756	0.142105	55.275	2.2676	5.4125	3.9627

- (Observed) photon temperature is T_0~0.10-0.15keV
- Electron temperature T_e~50-300keV, goes down with time
- Reduced χ^2=1.11 in a joint fit with *compPS*
- Unabsorbed/absorbed flux ratio goes up rapidly with time

GRB 060218: early lightcurve



Source flux perfectly matches $\dot{M}$ vs t for tidal disruption!
M_{BH}~$10^4 M_{sun}$; absorption is the key

Caveat: only 0.3-10keV flux is considered, will include BAT data soon

Thermal photospheric emission model

Thermal flux F_{BB} (at known distance) + observed temperature T_{BB}

⬇

Thermal emission in Fireball model

Pe'er et al. 2007

⬇

Bulk Lorentz factor Γ and jet base radius r_0,
then BH mass assuming r_0=several*r_g

GRB 060218 at peak: $F_{BB}=5\cdot10^{-9}$erg/s/cm^2, z=0.033; T_{BB}=0.1keV;
total emitted flux $F_{tot}=1.2\cdot10^{-8}$erg/s/cm^2, assume radiation efficiency 10%

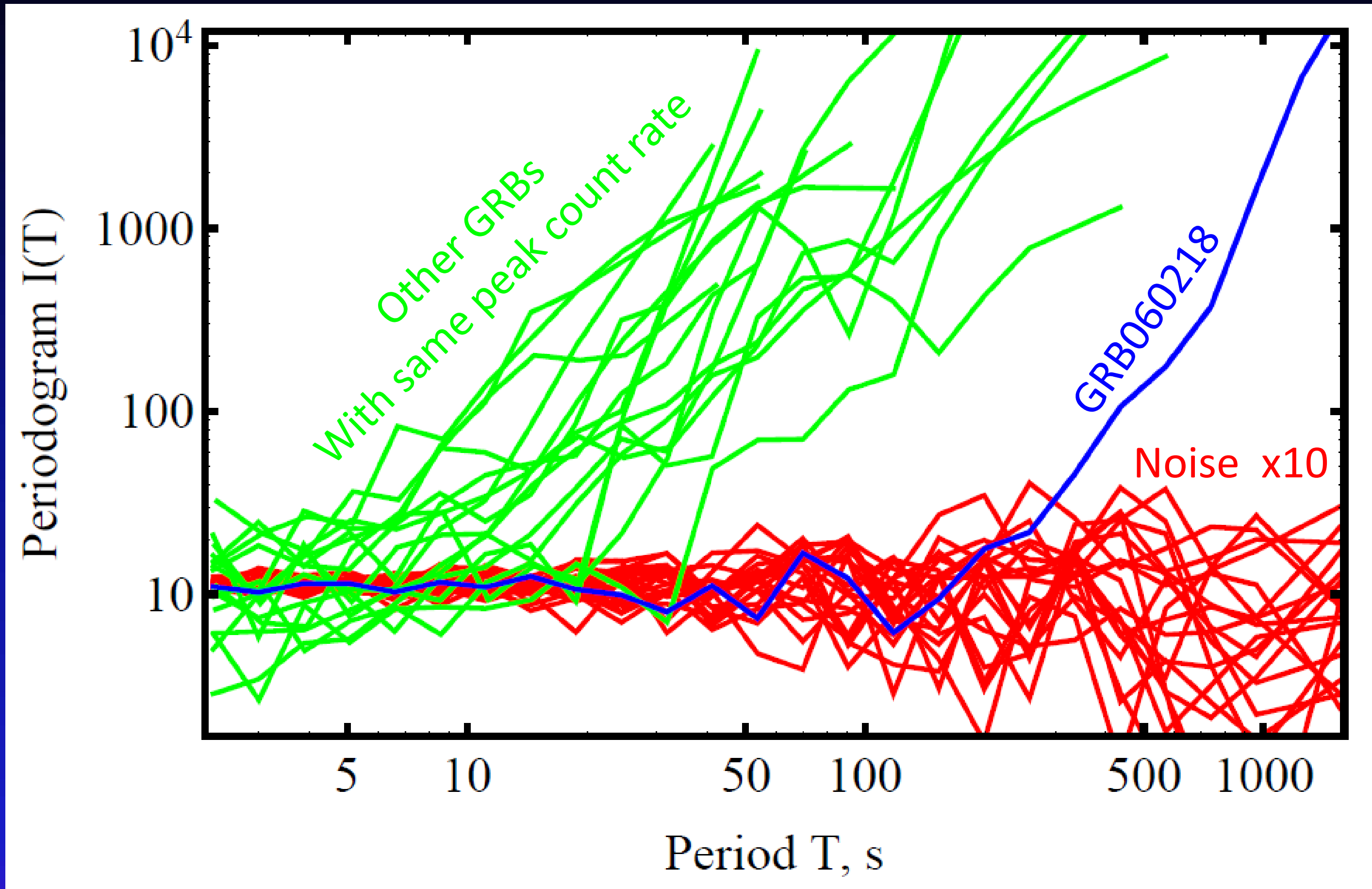
⬇

Lorentz factor Γ=2.8, while base radius $r_0=1.3\cdot10^{10}$cm,
BH mass $M_{BH}\approx15{,}000M_{sun}$ for $r_0=5r_g$

Entirely independently arrive at the same $M_{BH}\sim10^4M_{sun}$(!)

Non-thermal flux – Comptonization by continuously-heated electrons

Timing analysis



Log-smoothed periodogram following Papadakis & Lawrence 1993

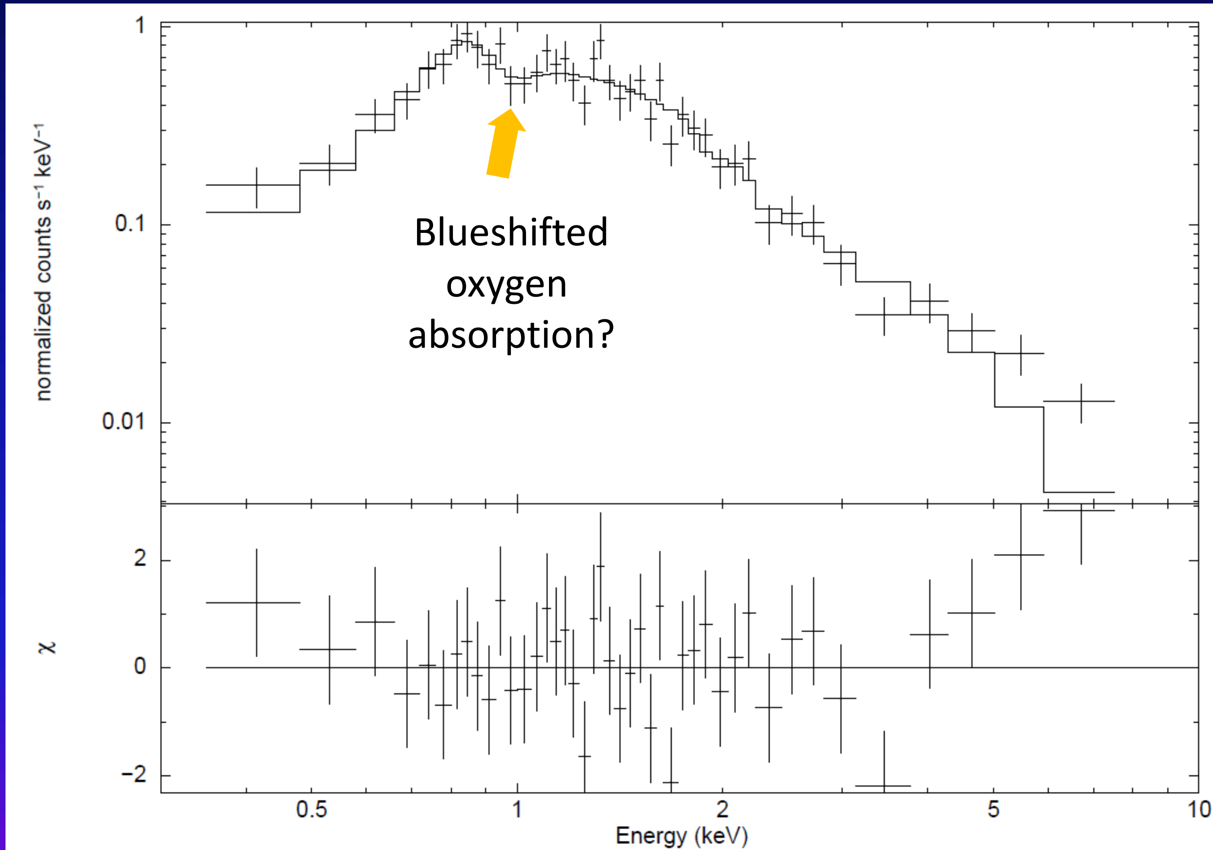
Characteristic timescale ~500s –
clearly different from GRB population

Steep decay (t~6300s)

Absorbed *bbody* + *powerlaw* with extra absorption by blueshifted oxygen.

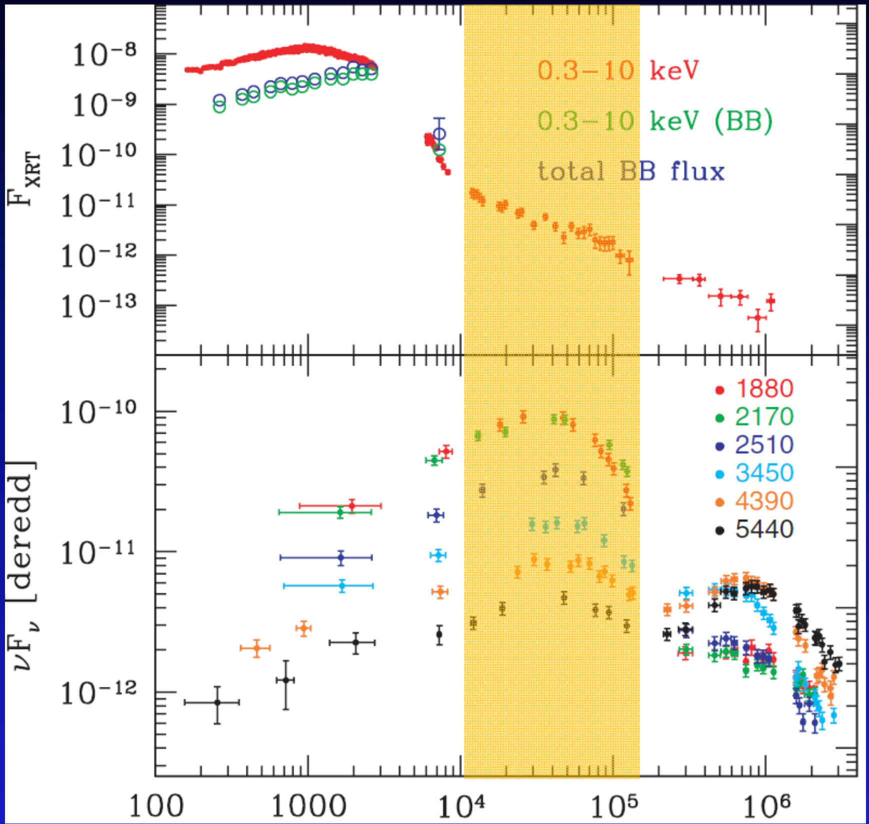
Absorbed flux $F_{abs}=2.9\cdot10^{-11}$erg/cm^2/s, source flux $F_S=1.1\cdot10^{-9}$erg/cm^2/s – 40 times larger!

Oxygen column density NO=$5\cdot10^{19}$cm^{-2} at bulk $\Gamma=1.73$ – easily provided by cooling jet



Even if $t^{-5/3}$ continues, absorption can produce steep decay!

Afterglow



X-ray flux $F_{XRT} \sim t^{-1.2}$ – typical
Optical emission peaks at 8 hours
There is radio

Shell with energy $E_{kin} \sim 10^{49}$erg produces an external shock with an outer medium

Campana et al. 2006

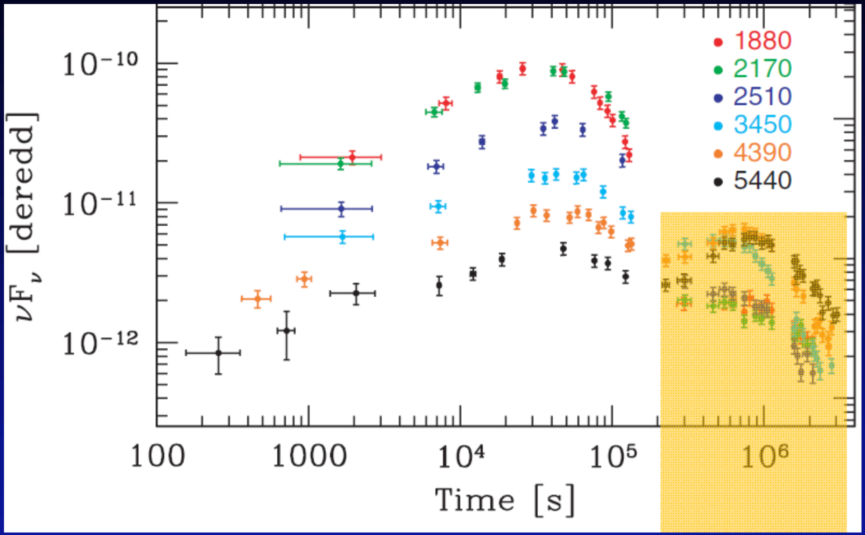
Late activity of the central engine may dominate the afterglow, outer medium density $n \sim 100 cm^{-3}$

Fan, Piran, Xu 2006

Lots of late-time central engine activity in tidal disruptions
Outer medium – accretion flow onto IMBH?

Afterglow is qualitatively consistent with tidal disruption

Associated supernova SN2006aj



Mazalli et al. 2006, 2007; Pian et al. 2006; Sonbas et al. 2008

Classification – type Ib/c:
collapse of stripped C/O core
High outflow velocity ~ 30,000 km/s
Strong oxygen lines, little hydrogen/iron
Energy E_K~$2\cdot10^{51}$erg/s, ejecta mass ~$2M_{sun}$
Radioactive nickel mass M_{Ni} ~$0.2M_{sun}$
Short duration ~10 days

Explanation within a tidal disruption paradigm

Haas et al. 2012

1. Velocity spread ~30,000km/s is readily produced via a tidal disruption
2. Variety of SN explosions is produced from tidal pinching: Rosswog et al. 2009
   in particular the ones with little Fe/Ni, most events are not SN type Ia
3. Composition: lack of H, abundance of O suggest C/O white dwarf;
   abundance of Ca, little Ni – SN explosion w/ small nuclear energy release
4. Include late-time engine activity => lower inferred ejecta mass
   Normally, optically thin capture of Ni decay products => ejecta mass,
   but accretion disk with $\dot{M}\sim t^{-4/3}$ at late times can inject most of radiated energy
   Cannizzo et al. 2009 (in fact, SN radiated less than afterglow!)

Supernova is qualitatively consistent with tidal disruption

WD-IMBH disruption rates

In globular clusters

Space density of globular clusters: ~ $10 Mpc^{-3}$

McLaughlin 1999

Brodie & Strader 2006

Event rate ~ 10^{-8}/yr/cluster ($10^3 M_{sun}$ IMBH)

Baumgardt et al. 2004

Total ~ 100/yr within Gpc^3 (WD-IMBH) for 1 IMBH per cluster

Then ~ 1 event per SWIFT mission within 200Mpc assuming wide outflow

In centers of small/dwarf galaxies

Some black holes have mass $M=10^4$-$10^5 M_{sun}$

Recent Arxiv: Edri et al. 2012; Dong et al. 2012

Such galaxies may have higher white dwarf numbers compared to GCs

Higher BH mass => higher disruption cross-section

GRB 060218 comes from a small galaxy

Wiersema et al. 2007

Event rates have huge uncertainties, but are generally consistent

Alternative explanations of GRB 060218

Each explanation (incl. ours) has weaknesses, and we do not know which one is better

Supernova shock breakout

Campana et al. 2006

↓

Can't transport that much energy outwards through the star

Ghisellini et al. 2007a,b

↓

Relativistic shock breakout and asymmetric SN explosion

Waxman et al. 2007

Powered by a magnetar

Fan et al. 2011

↓

Magnetar spin down time is too short

Bufano et al. 2011

(Potential) problem with tidal disruption:

Need to model supernova energy balance and derive low ejecta mass

Conclusions

- Weak jet from WD-IMBH tidal disruption
- Long soft quasi-thermal ll-GRB likely follows
- Associated supernova should be fast/have low mass
- GRB 060218/SN2006aj is a good candidate from multiple prospectives:

Spectrum + lightcurve + timing + afterglow + supernova