PENNSTATE
Astronomy & Astrophysics

Cataclysmic Variability of Galactic Nuclei

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Possible cataclysmic events in galactic nuclei

- SNe, GRBs
- Flare from an AGN
- Tidal disruption of a star by a black hole
- Binary supermassive black hole coalescence

Mergers of Binary Supermassive Black Holes

The basics of SBBH coalescence

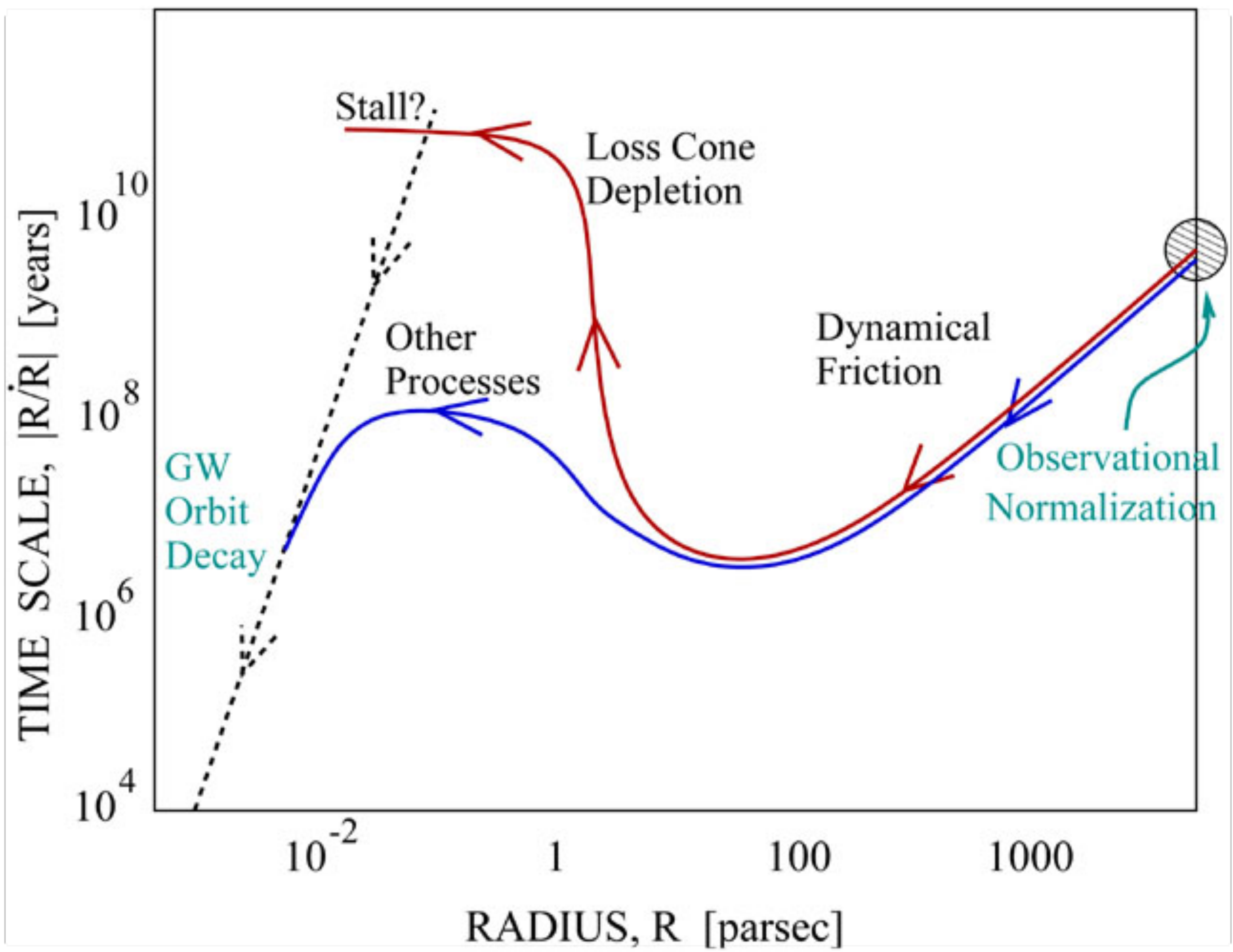
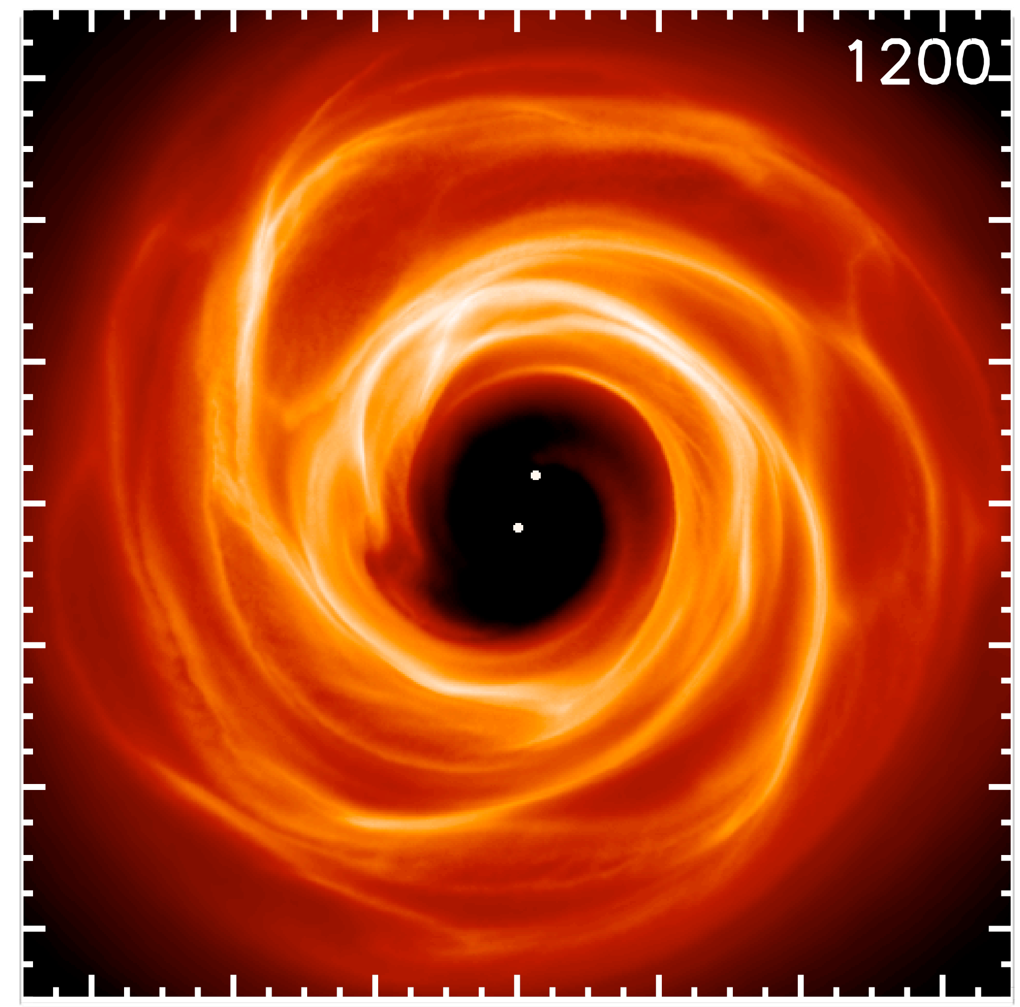


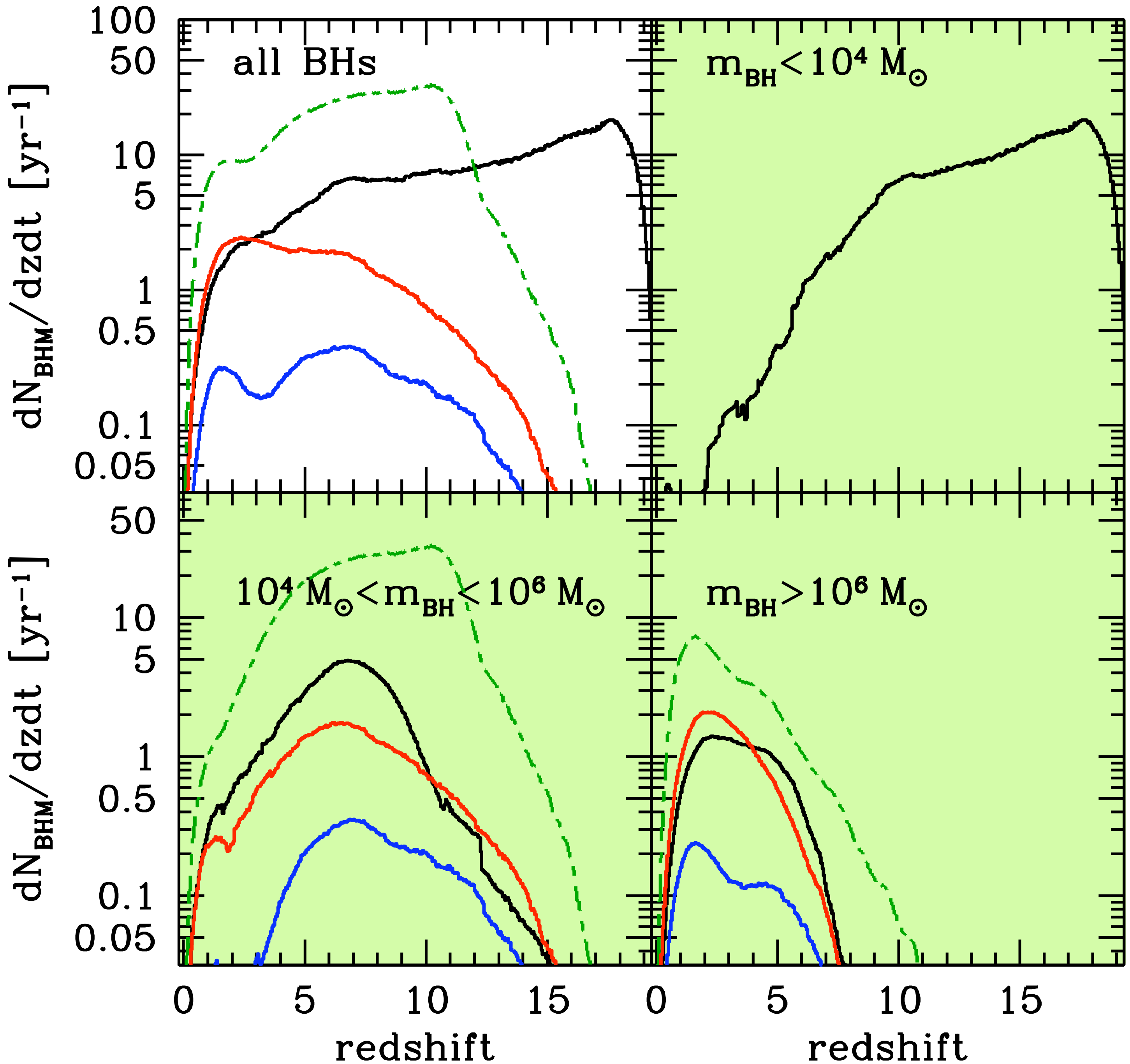
figure from Backer et al. (2003), based on the work of Begelman et al. (1980)



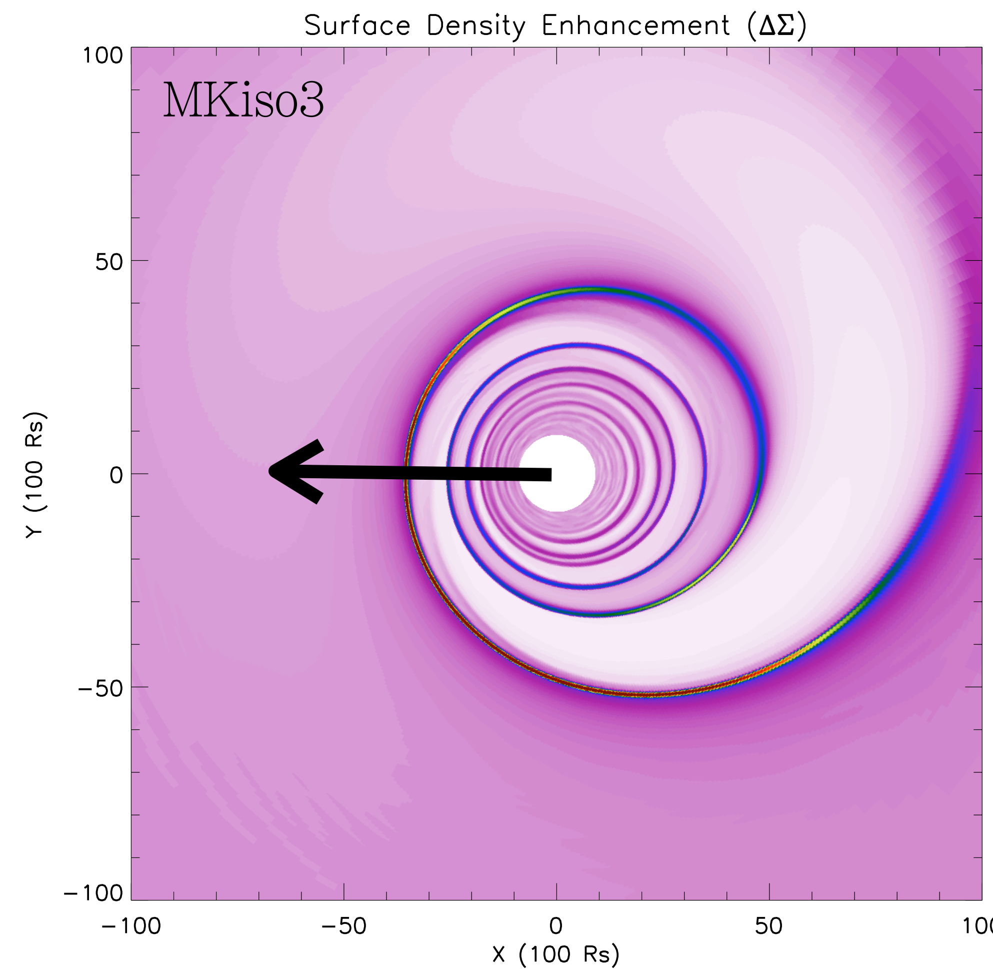
(from Cuadra et al. 2009)

Event rates and observational consequences

from Sesana et al. (2009)



from Corrales et al. (2010)
see also Rossi et al. (2010)



$t=210$ d, $r_{in}=10^3$ R_s

$\upsilon_K=530$ km/s, $M_\bullet=10^6$ $M_\odot$

$L\sim2\times10^{43}$ erg/s

LISA detection rate: 10 – few x 100 yr^{-1}

Tidal Disruption of Stars by a Supermassive Black Hole

The basics of tidal disruption

» Tidal disruption condition: $a_\mathrm{T} > g_\star$

$$R_\mathrm{T} = \eta \left(\frac{M_\bullet}{m_\star}\right)^{1/3} r_\star \quad \Leftrightarrow \quad \frac{R_\mathrm{T}}{M_\bullet} = \eta \left(\frac{M_\bullet}{m_\star}\right)^{-2/3} \frac{r_\star}{m_\star}$$

- strength of tidal encounter (a.k.a. penetration factor) $\beta = (R_\mathrm{p}/R_\mathrm{T})^{-1}$
- for a 1 M⊙ main-sequence star,

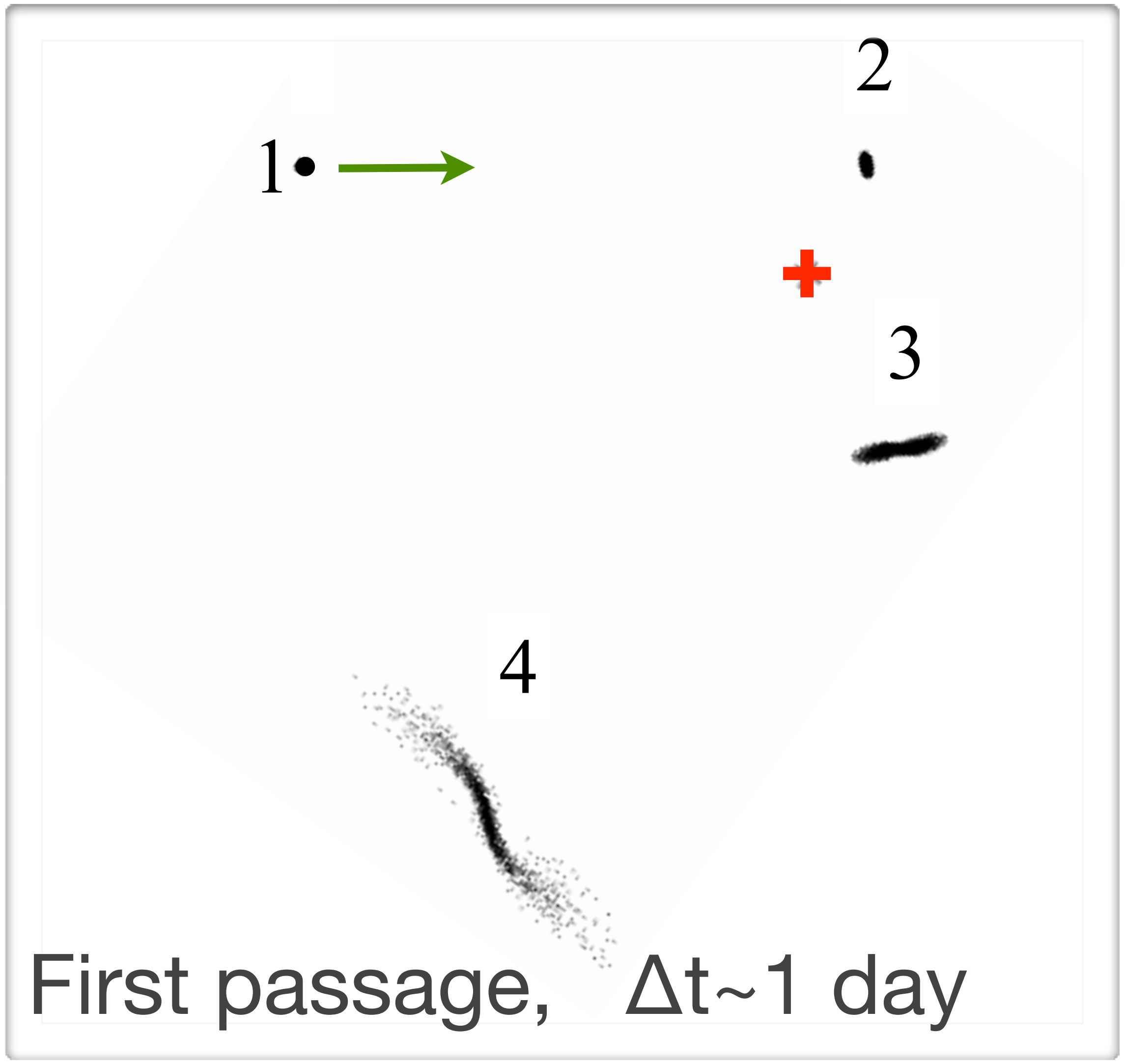
$$R_\mathrm{T} = R_\mathrm{S} \quad \text{when} \quad M_\bullet \approx 10^8\ \mathrm{M}_\odot$$

- for a 0.6 M⊙ white dwarf,

$$R_\mathrm{T} = R_\mathrm{S} \quad \text{when} \quad M_\bullet \sim 10^5\ \mathrm{M}_\odot$$

$$R_\mathrm{T} = R_\mathrm{LSO} \quad \text{when} \quad M_\bullet \sim 10^4\ \mathrm{M}_\odot$$

The disruption: play-by-play



(figures from Lee & Kim 1996)

time scales for

$m_\star$=1 $M_\odot$, $M_\bullet$=10^6 $M_\odot$, $\beta \simeq 1$

Accretion of returning debris

- Accretion rate ∝ $t^{-5/3}$
  - Rees (1988), Evans & Kochanek (1989), Lodato et al. (2009), +many others
- Early times: blackbody spectrum with T ~ 10^5 K
  - Loeb & Ulmer (1997); Ulmer (1999), Strubbe & Quataert (2010)
- Late times: illumination of debris by soft-X/UV photons and line emission
  - Bogdanović et al. (2004) Strubbe & Quataert (2010)

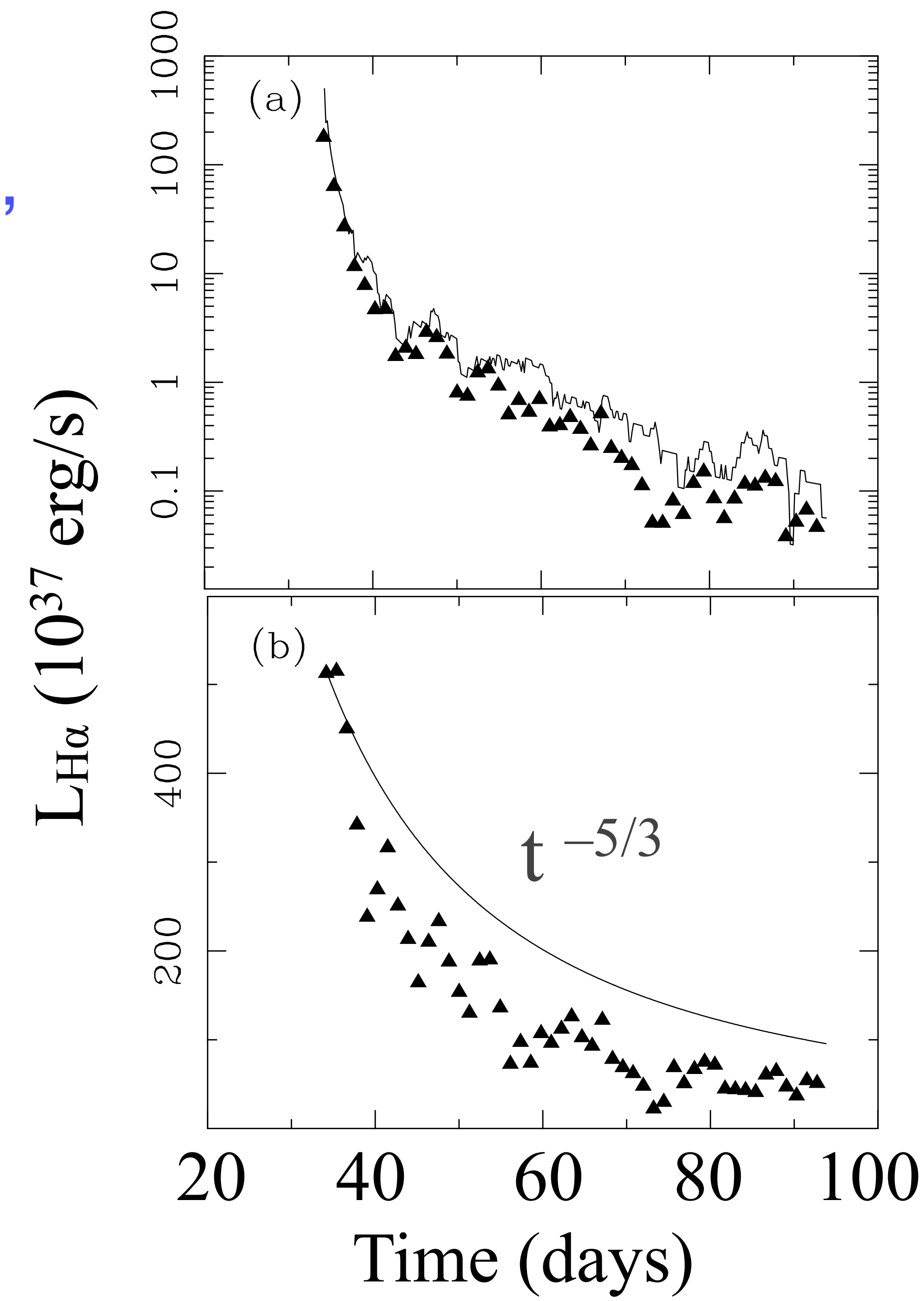


figure from Bogdanović et al. (2004)

What can we learn by observing such events?

- Identification of “dormant” black holes in galactic nuclei,
  - including IMBHs, which can disrupt WDs.
- Constraints on stellar dynamics in galactic nuclei, via event rates
  - mass segregation (compact objects)
  - isotropy of stellar orbits (i.e., triaxiality)
- Black hole and galaxy co-evolution
  - event rates depend on BH mass spectrum and host luminosity distribution, and their relation

Recent predictions of event rates

- Magorrian & Tremaine (1999)
  $\Gamma \sim 10^{-4}$ galaxy $^{-1}$ yr $^{-1}$ for MS stars in $L < 10^{10} L_\odot$ galaxies with steep density cusps ($\Gamma \sim 10^{-5}$ galaxy $^{-1}$ yr $^{-1}$ for giants)

- Wang & Merritt (2004)
  $d\Gamma(M_\bullet)/dM \approx 10^{-4} M_6^{-0.25}$ galaxy $^{-1}$ yr $^{-1}$ (implied)
  $\Rightarrow \Gamma(10^6 - 10^8 M_\odot) \approx 10^{-5}$ yr $^{-1}$ Mpc $^{-3}$

- $\dot{M} \sim 10^{-3} M_\odot$ yr $^{-1}$ ($\Rightarrow 10^6 M_\odot$ in 10^9 years)

  important for growth of small BHs
  (Magorrian & Tremaine 1999; Merritt & Poon 2004)

More on event rate predictions

» Rates depend on BH mass spectrum, galaxy luminosity distribution, and relation between the two.

» Loss cone assumed to be re-populated via 2-body relaxation.

Triaxiality leads to faster re-filling of loss cone

» Chen et al. (2009)
Enhanced rate in case of a q≪1 binary BH

$\Gamma \sim 1$ galaxy $^{-1}$ year $^{-1}$, for ~10 ^{4} years

Observations: serendipitous discoveries

- The basic idea in past searches:
  - Abrupt changes in UV/X-ray flux (x 10 or more)
  - Followup observations: X-ray and emission-line variability; rule out other explanations (AGN, SNe)
- ~9 X-ray events (Komossa, Greiner, Grupe, Brandt)
  - 4 events show: $L(t) \sim t^{-5/3}$ over > 10 years
- 1 UV event: NGC 4552 (Renzini et al.1995)
- 4 Emission-line events:

  NGC 1097, Pic A, IC 3599 (also X-ray), SDSS J 0952+2143 (SN?)
  (Storchi-Bergmann et al. 1993, Halpern & Eracleous 1994, Sulentic et al 1995, Grupe, Komossa et al 2009)

X-ray flares: active *vs* inactive galaxies

- Variability of a weak AGN will compicate our identification of tidal disruption events.
- Possible cataclysmic variability of AGNs not well known; must assume the worst...
- We do know that LLAGNs can vary by factors of several in the UV over a few years.

Observations: systematic X-Ray surveys

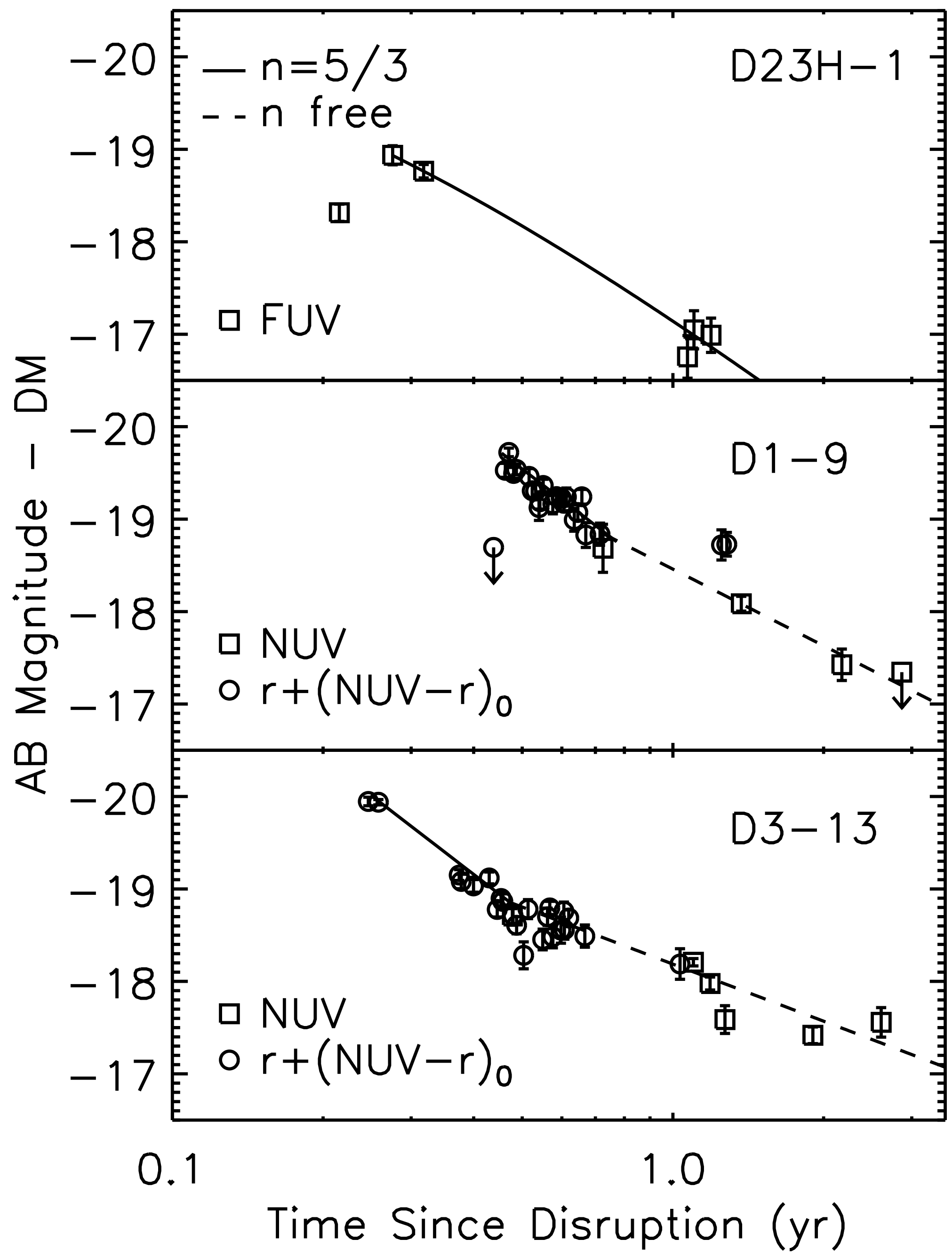
- ROSAT all-sky survey *vs* later, pointed observations (3 events) (Donley et al. 2002)
  $\Gamma \sim 10^{-5}$ galaxy $^{-1}$ yr $^{-1}$
- ROSAT all-sky survey *vs* XMM slew survey (2 events) (Esquej et al. 2002)
  $\Gamma \sim$ few x 10^{-4} galaxy $^{-1}$ yr $^{-1}$
- Multiple observations of *Chandra* deep fields (0 events) (Luo et al. 2008)
  $\Gamma < 10^{-4}$ galaxy $^{-1}$ yr $^{-1}$
- Multiple observations of galaxy clusters (1 event so far) (Maksym & Ulmer in progress)

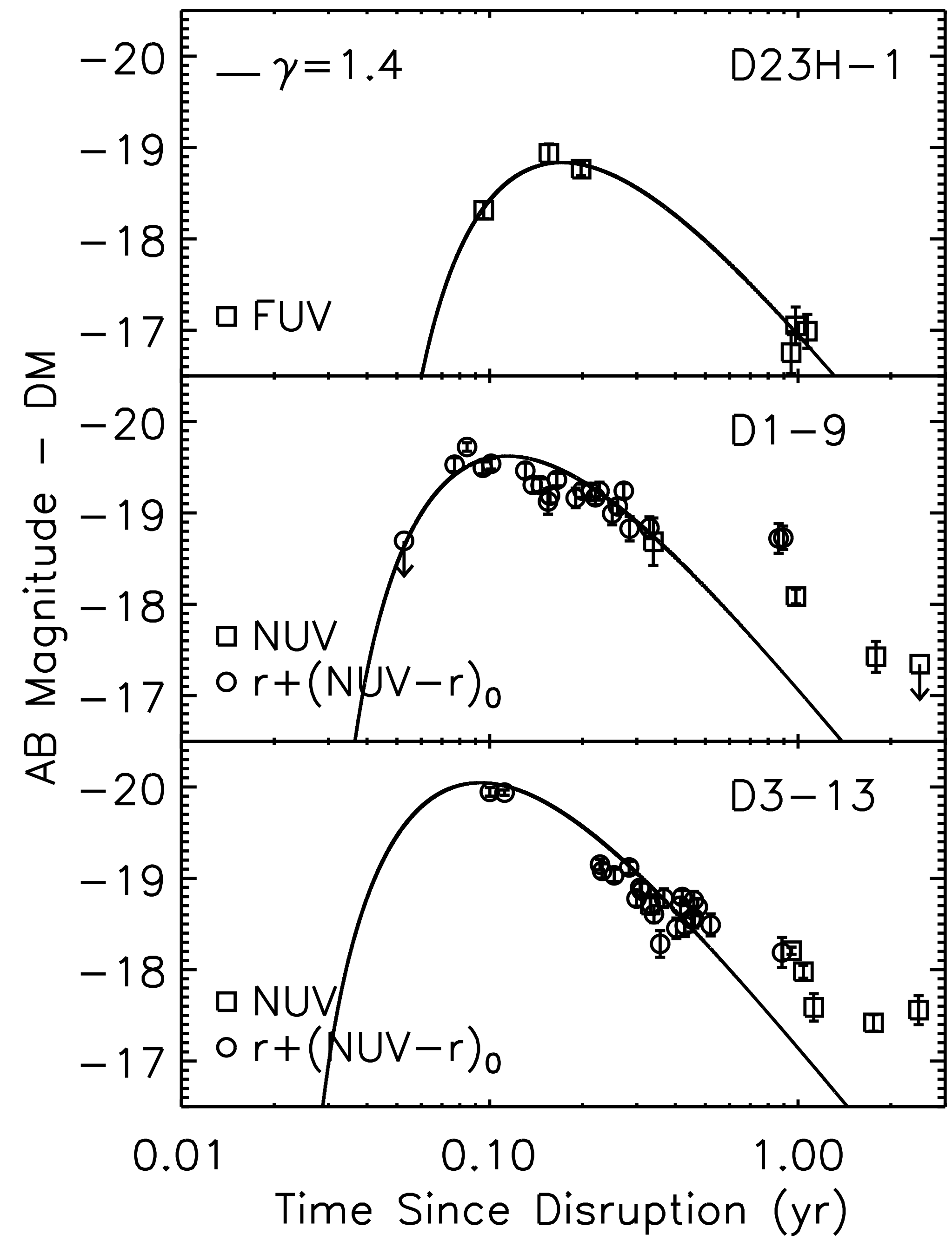
Observations: systematic UV surveys

Gezari et al. (2006, 2008, 2009)

- Comparison of multiple *GALEX* exposures of the same fields in search of UV flashes.
  x 10–100 increase in UV flux
- Followup observations:
  - optical spectroscopy and photometry
  - X-ray “spectroscopy”
- 3 events found so far with very similar properties
- Rate consistent with few x 10^{-4} galaxy $^{-1}$ yr $^{-1}$

Light curves of GALEX events

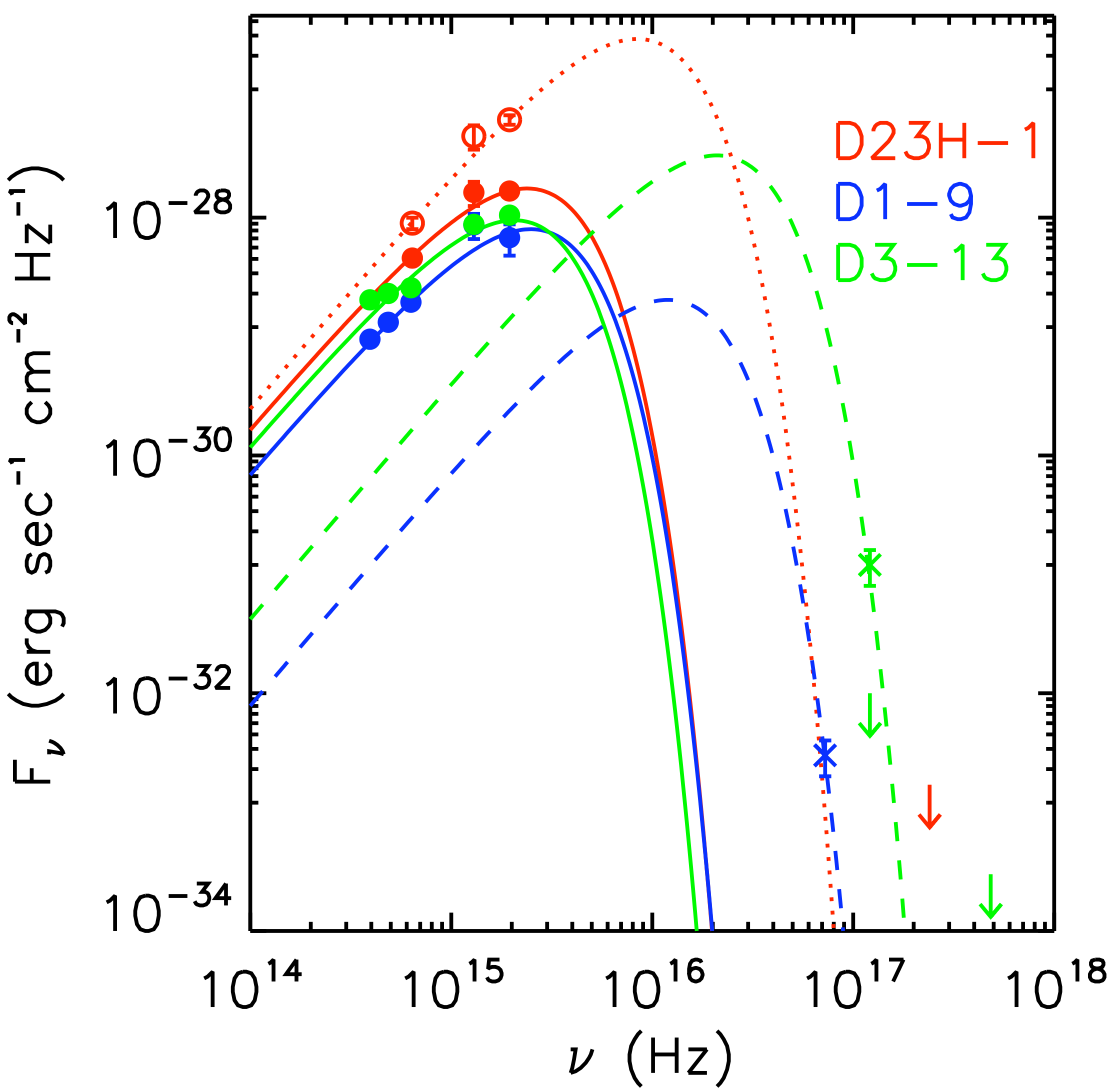




Power-Law Fit ~ $t^{-5/3}$
from Gezari et al. (2009)

Model of disruption of polytropic star $M_\bullet \sim 10^7 M_\odot$

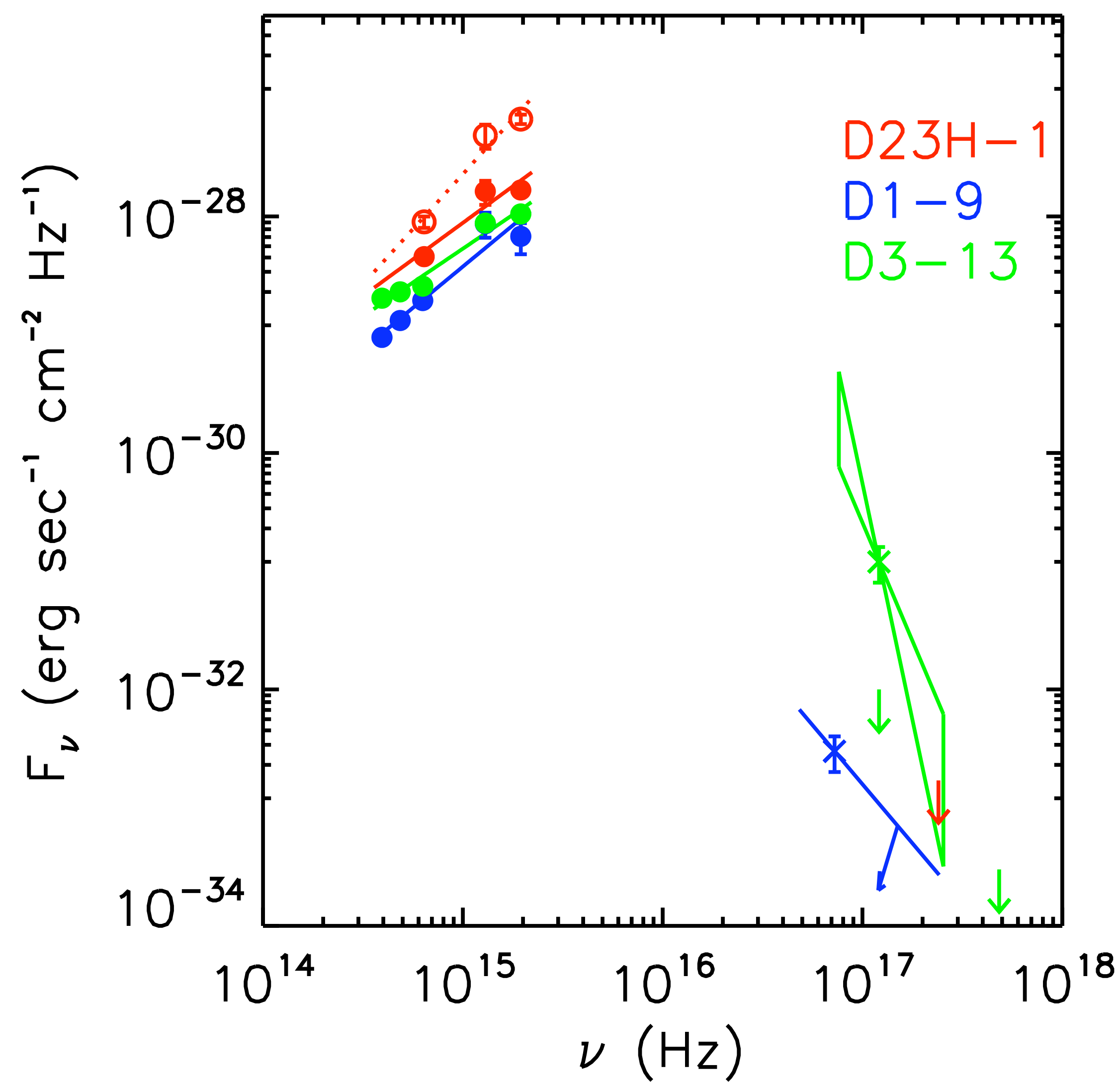
Spectral energy distributions of GALEX events



Blackbody Fit

$T \sim 10^5$ K

from Gezari et al. (2009)



Double Power-Law Fit

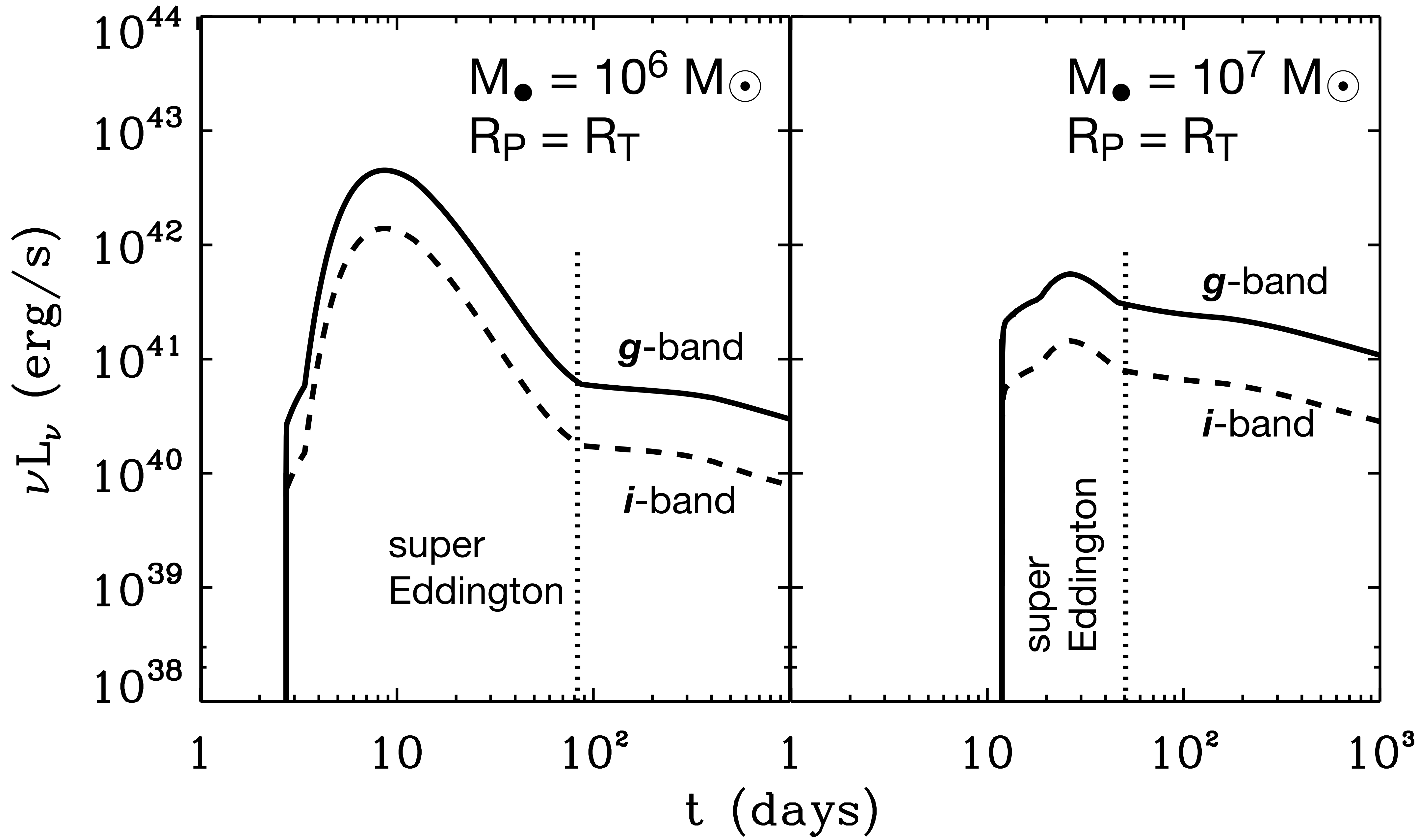
Observations: what we have learned so far

- 12-17 candidate events known
- Event rates broadly consistent with predictions but with large uncertainties
- Some of the predicted signatures seen in each case (but not all signatures seen in same case)
- The most simple models do the best job explaining light curves and SEDs...

Need to identify a few events with confidence to test the theory but we cannot be confident about our identifications without a good theory.

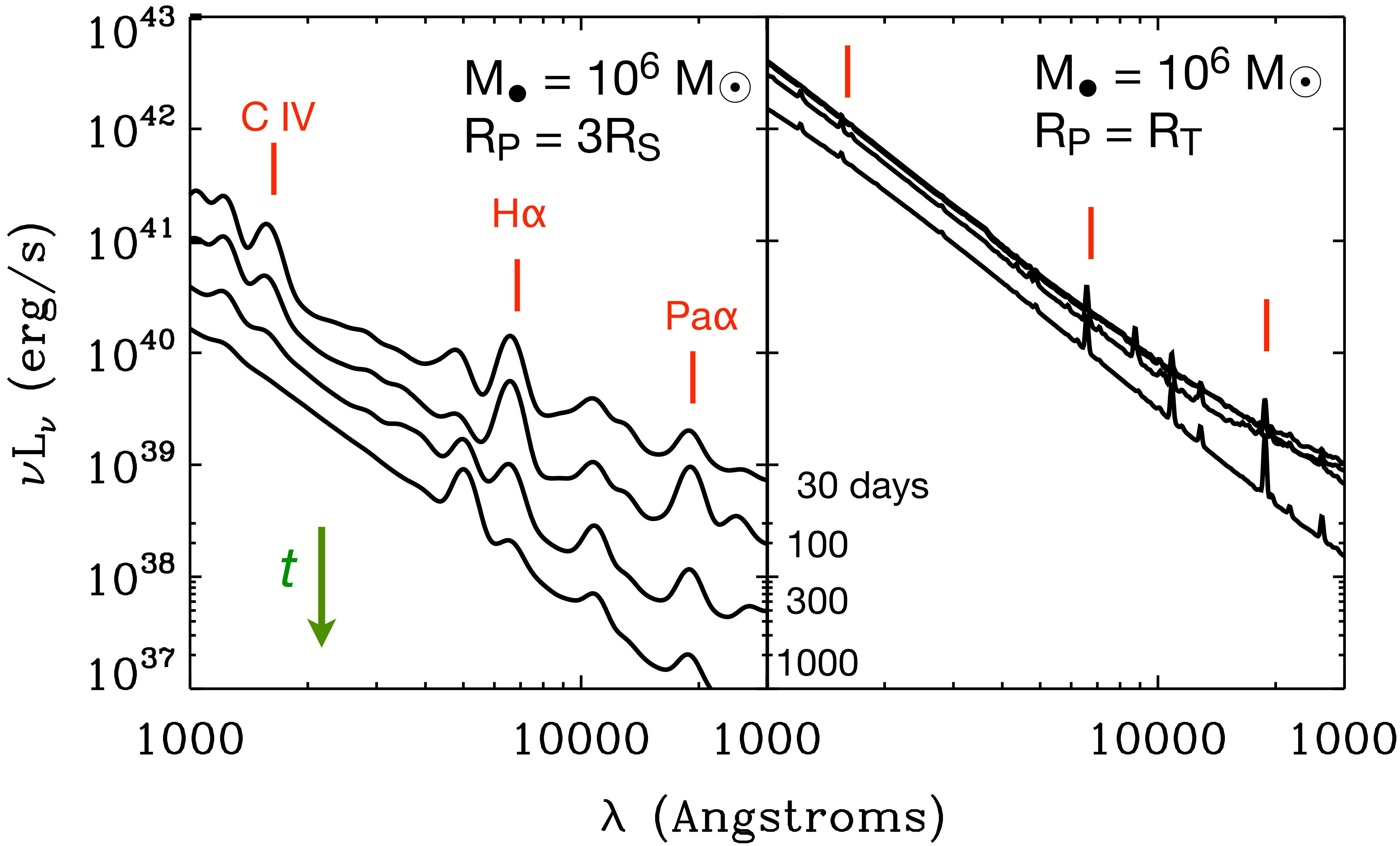
Signatures to look for: light curves

from Strubbe & Quataert (2010)



Signatures to look for: late-time spectra

from Strubbe & Quataert (2010)



How do we tell them apart from SNe?

- Must coincide with center of host galaxy
- Decay rate: $t^{-5/3}$ (or shallower)
- Continuum is blue: starts at $g-r \approx -1$ and gets bluer with time (negative K correction)
- AGN-like ionizing continuum should lead to **high-ionization**, AGN-like emission lines, especially at late times.
  FWHM ~ few x 1000 km/s

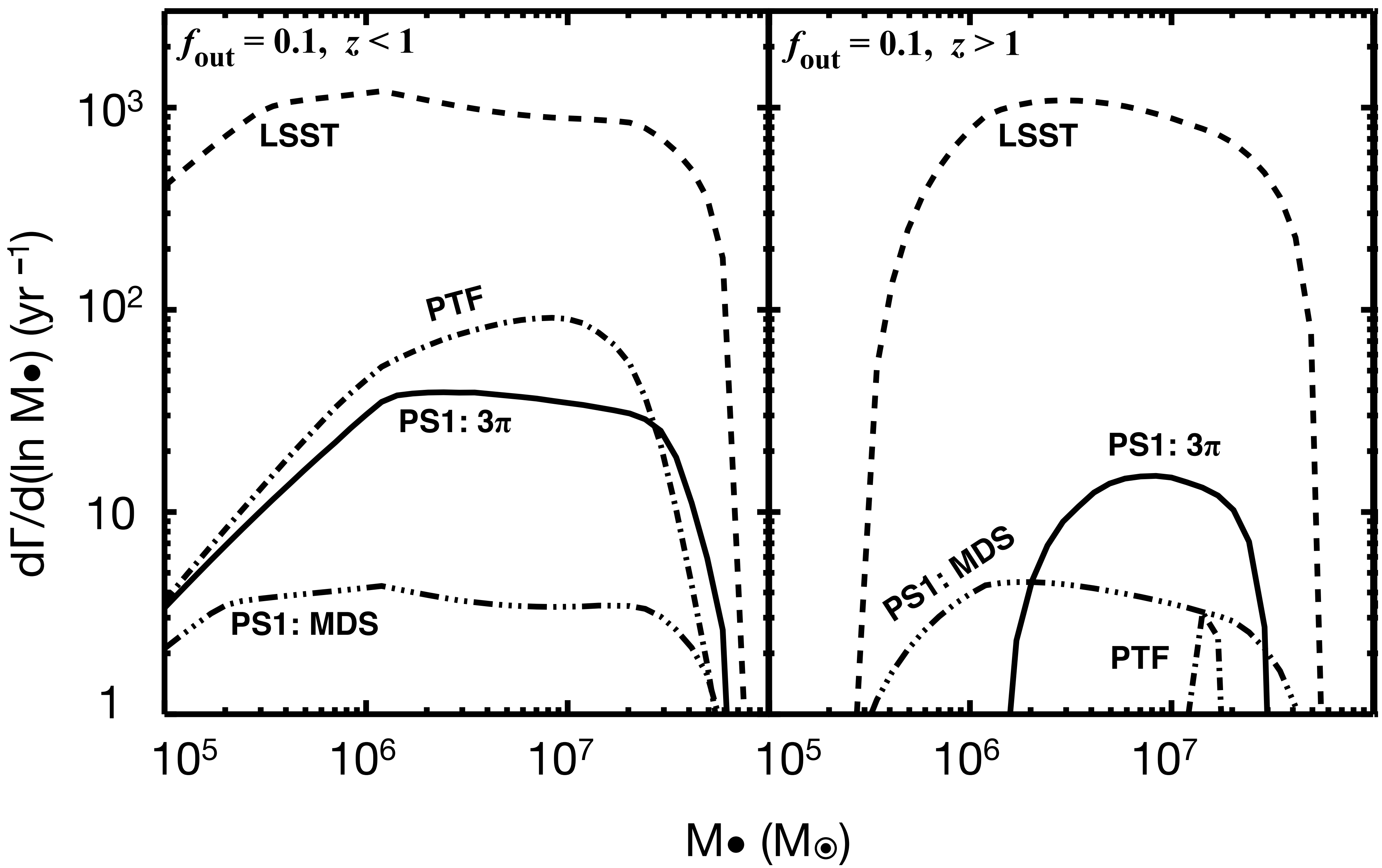
Predictions for ongoing and upcoming surveys

Survey	Disk+ Debris (yr^{-1})	Super Eddington (yr^{-1})
PanSTARRs 3π	4–12	200
PanSTARRs MDS	0.2–1	20
PTF	0.3–0.8	300
LSST	60–250	6000

Numbers from Strubbe & Quataert (2010),
In agreement with Gezari et al. (2008)

Breakdown by BH mass

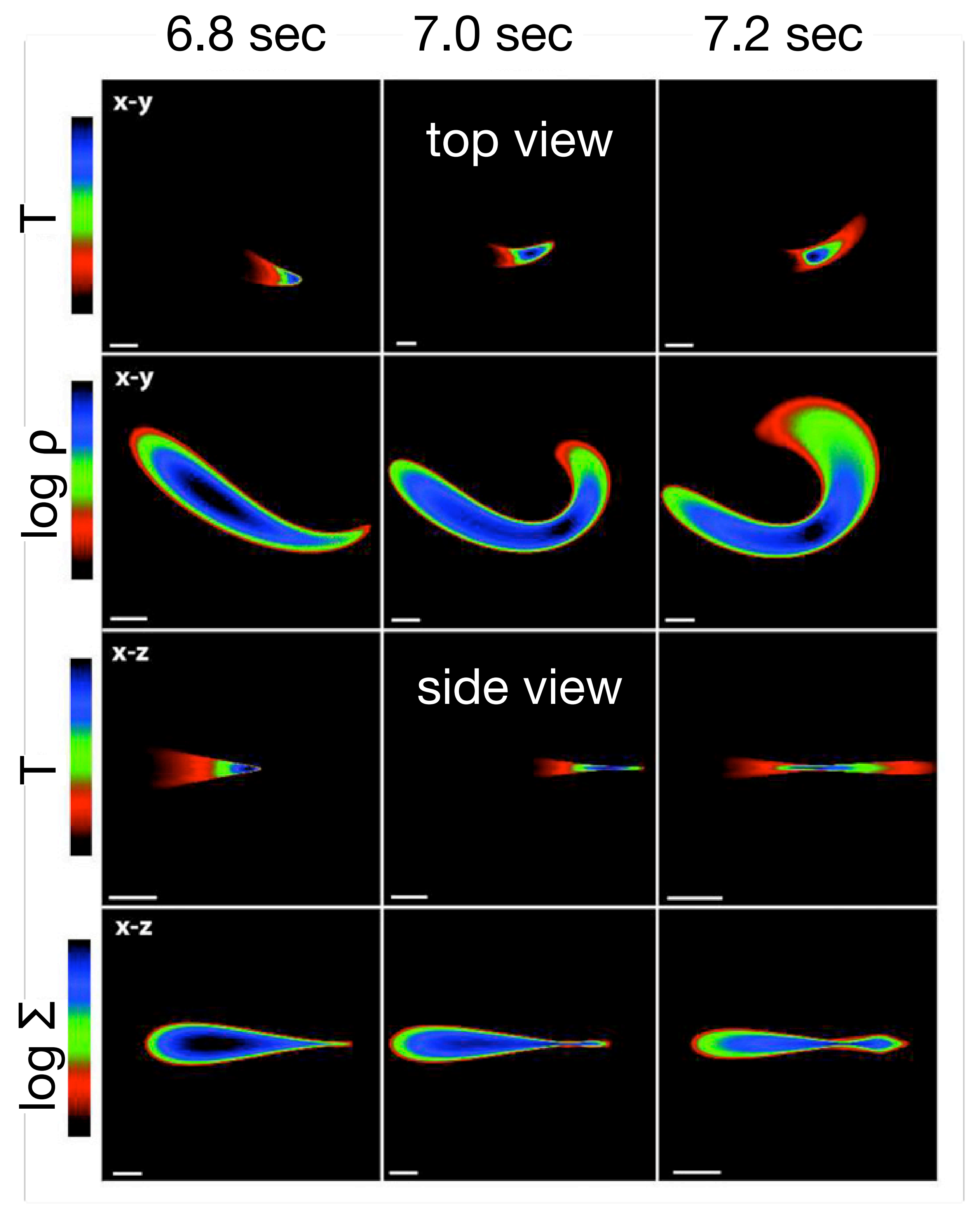
from Strubbe & Quataert (2010)



Disruption of WDs

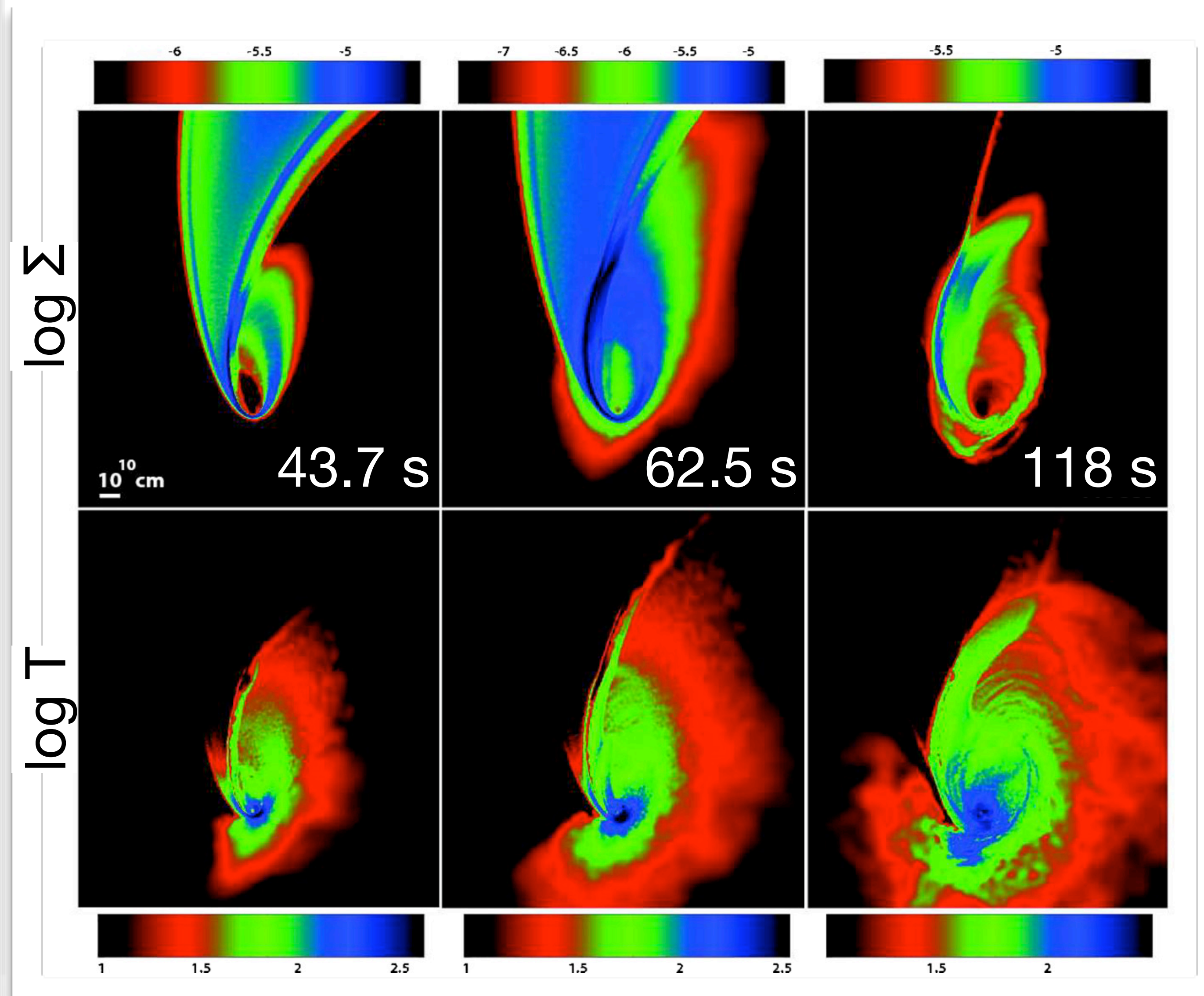
- Thermonuclear reactions possible in strong encounters (Rosswog et al. 2008, 2009)
  Resembles SN at early times
- Accompanied or preceded by gravitational wave signal
  (detectable up to 100 Mpc if in bound orbit)
  Kobayashi et al. (2004); Sesana et al. (2008)
- Unambiguous inferences
  - Confirmation of event (and determination of redshift) from fairly unique emission-line signature
  - **Only BHs with $M_\bullet < 10^5\ M_\odot$ can disrupt WDs**

Strong encounter, burning, and accretion



m_{WD}=0.2 M$_\odot$, M$_\bullet$=10^3 M$_\odot$, β=12

Rosswog et al. (2009)

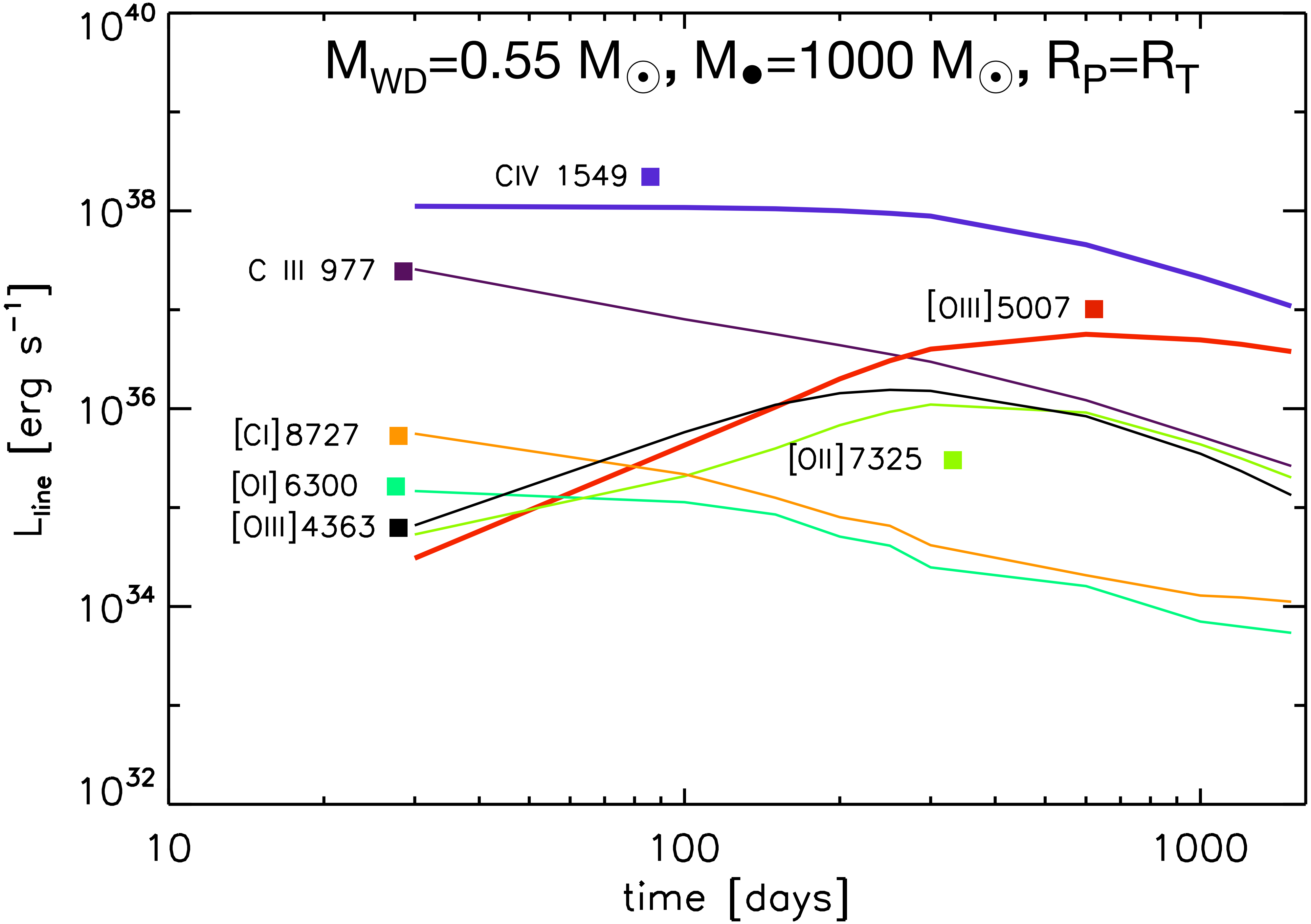


WD capture and disruption rates

- WDs in unbound orbits (Rosswog et al. 2009)
  - ~ 10% of MS star rate
  - sensitive to mass segregation
  - $\Gamma \sim 10^{-5}$ galaxy $^{-1}$ yr $^{-1}$ counting IMBHs in globulars
- WDs in bound orbits: (Sesana et al. 2008)
  - $\Gamma \sim 10^{-8}$–10^{-6} galaxy $^{-1}$ yr $^{-1}$
  - For a Milky Way-like galaxy with $M_\bullet \sim 10^5\ M_\odot$
  - Disruption preceded by strong GW signal

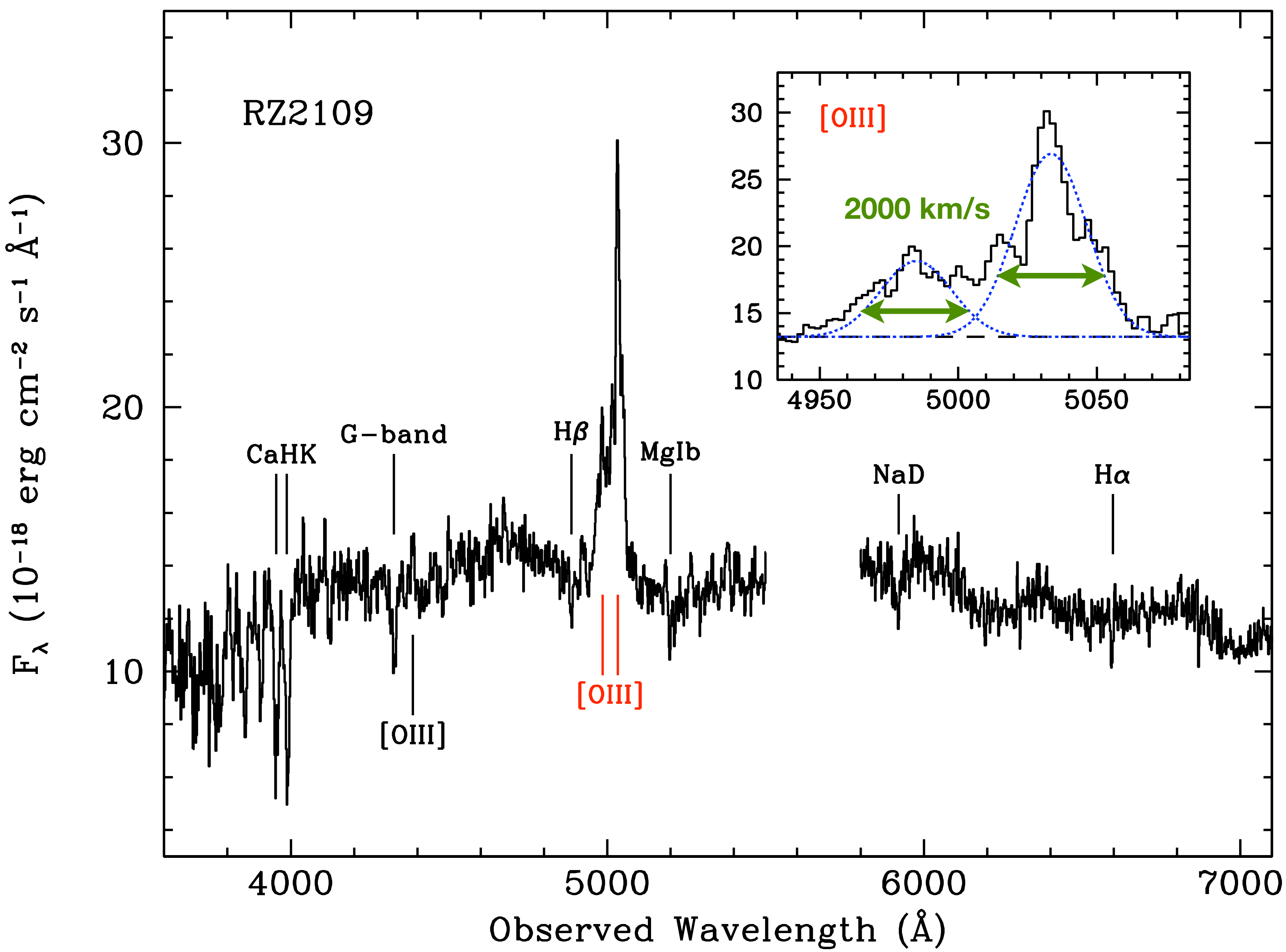
The aftermath of the disruption of a WD

(Clausen & Eracleous 2010, in preparation)



Could this be it?

Spectrum of a globular cluster in NGC 4472 hosting an "ultraluminous X-ray Binary" (Zepf et al. 2008)



We eagerly await gravity to make some waves

The End