星系宇宙学重点实验室系列讲座

超大质量黑洞撕裂恒星事件

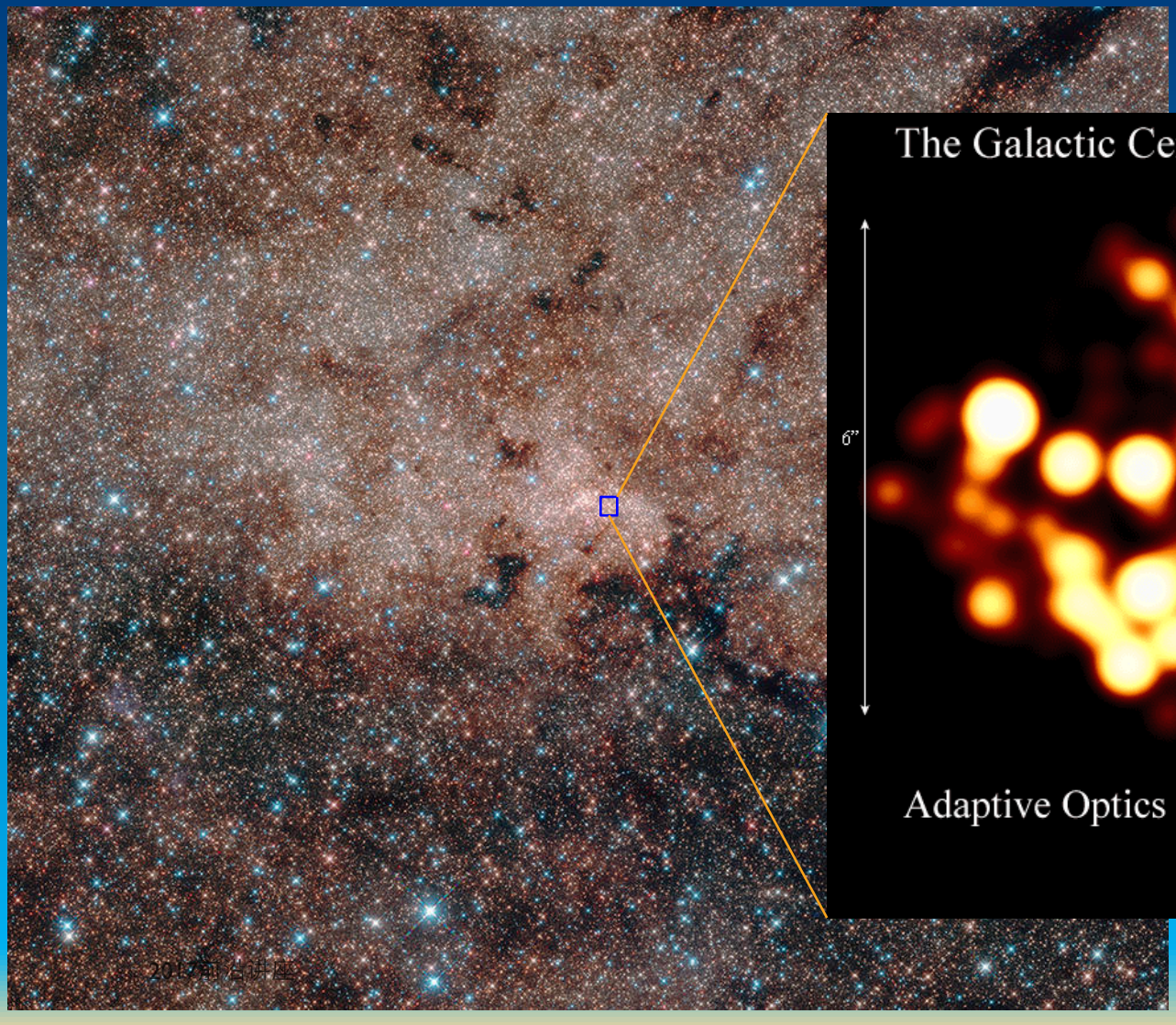
Wang Tinggui (王挺贵）

中国科学技术大学

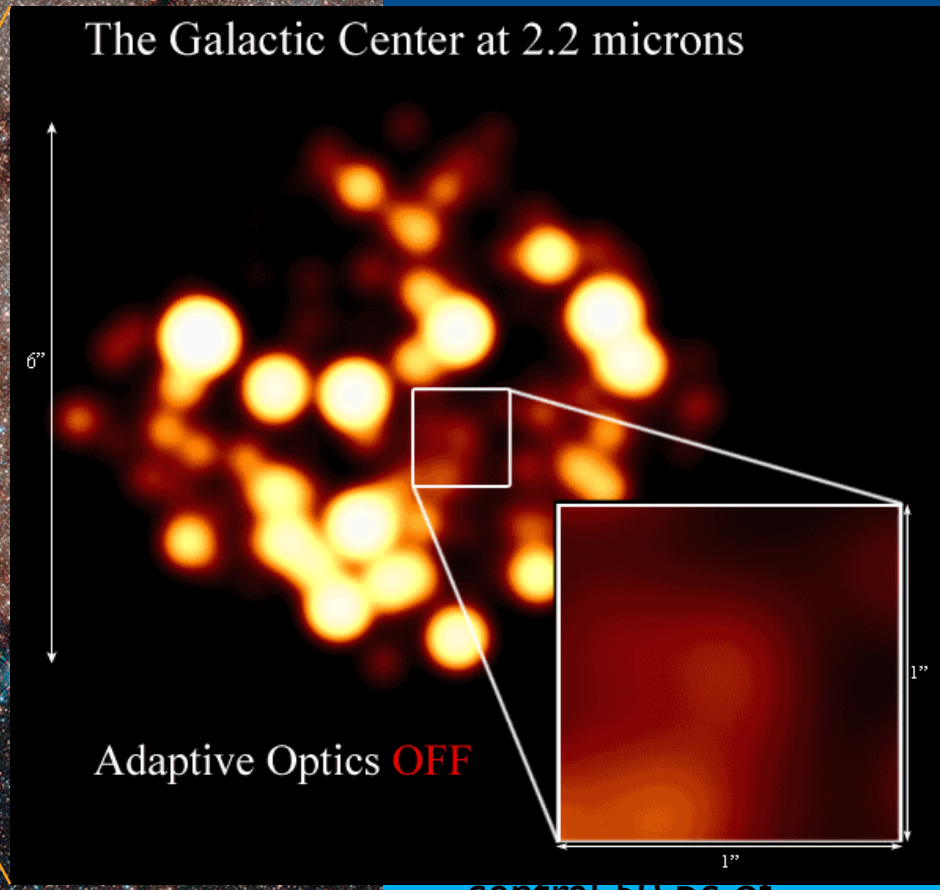
OUTLINES

1. **Definition**
2. **What can TDEs tell us**
3. **A brief history overview**
4. **Classical model and predictions**
5. **Basic observational characteristics**
6. **Confrontation between observations and theories**
7. **Diversity or ImpoSERS ?**
8. **Other physics processes**
9. **Perspective**

银河系中心



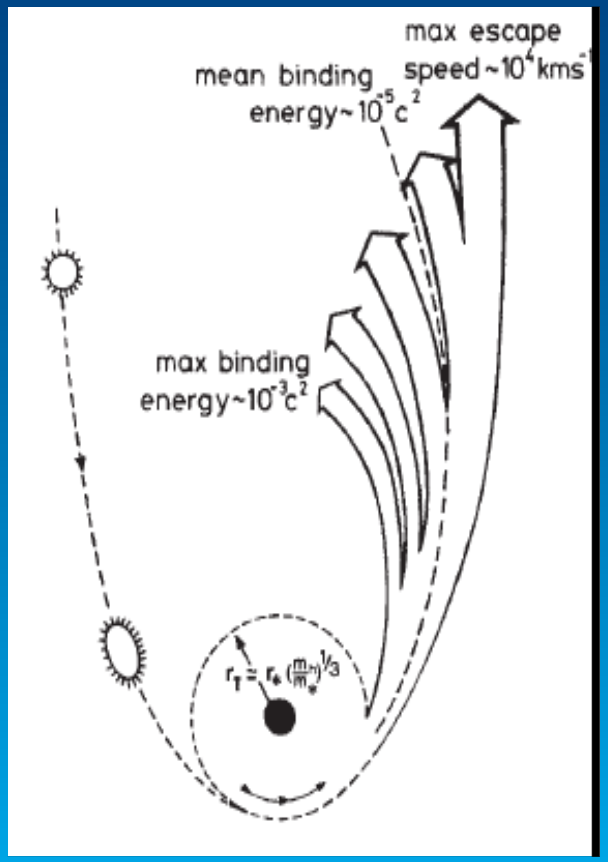
Credit: Ghez



central 50 pc of MW/HST

WHAT IS A TDE?

- A star is tidally disrupted when $r < r_t$
- (hills 1975). ~ half debris falls back, forming an accretion disk, the other half escapes. transient accretion will give rising to optical/uv to soft x-ray flares.



Rees 1988

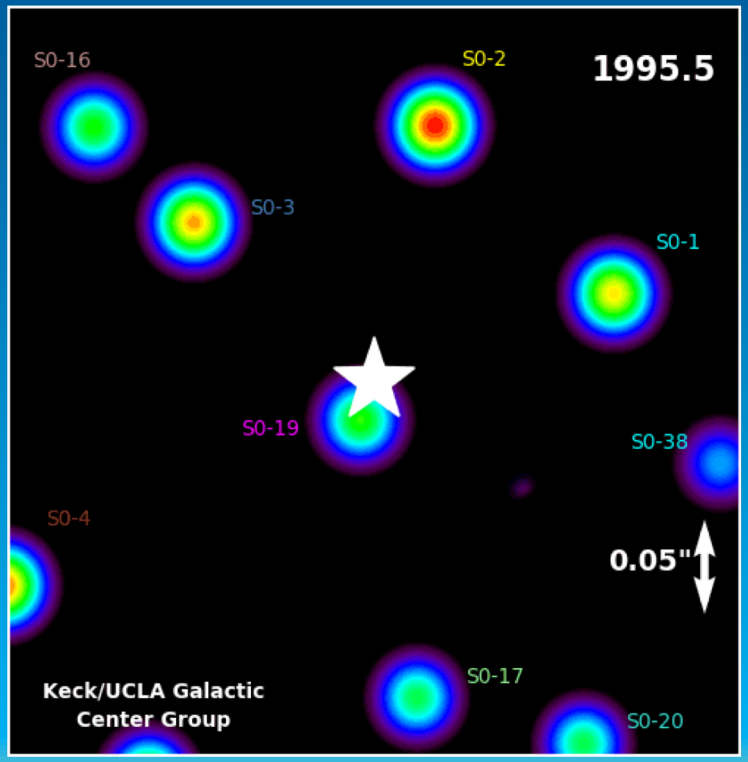
TIDAL RADIUS

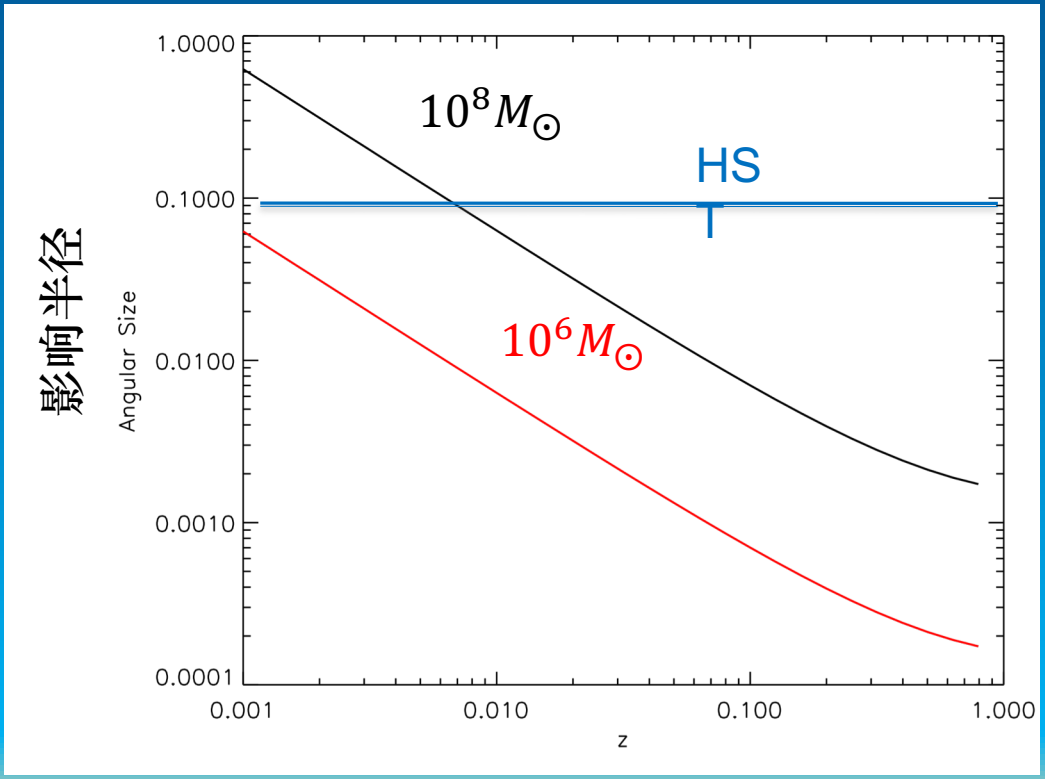
- According to the definition of tidal radius
- $$g_t = \frac{GM_{BH}}{r_t^2} \times \frac{R_*}{r_t} = \frac{GM_*}{R_*^2} = g_*$$
- $$\boldsymbol{r_t \approx 23.6 r_s M_{\bullet,6}^{-2/3} \left(\frac{M_\odot}{M_*}\right)^{1/3} \left(\frac{R_*}{R_\odot}\right)}$$
- For solar type star, $M_{BH} \approx 1.1\times10^8 M_\odot, r_t \approx r_s$. i.e, star will entirely fall into the black hole, rather than be disrupted. Mass larger than this can still disrupt giant star or high mass star.

Be aware the limits of newtonian gravitation model

WHAT CAN WE LEARN FROM TDES

- Probe quiescent massive black holes, especially of low mass or in relatively far galaxies, or star clusters





WHAT CAN WE LEARN FROM TDES

- Learn essential physics around supermassive black holes through the formation and evolution of accretion flows, outflows and jets.
- Environment of quiescent supermassive black holes
- Seeds of supermassive black hole by IMBH
- Probe Stellar populations in the center nucleus

A BRIEF OVERVIEW OF HISTORY: 70S-80S

- **1970s-90s theoretical works**
- **TDEs as energy sources of AGNs**
- Hills '75/78, Young et al. 77
- **tidal disruption rate**
- Bahcall & Wolf 76, Young et al'77, Lightman & Shapiro 77, Young '80
- **disruption of binaries and hyper-velocity stars**
- Hills, 88
- **physical process and observational signatures**
- Carter & Luminet '82; Ulmer 1991 ..
- **Rees 1988 Nat article**

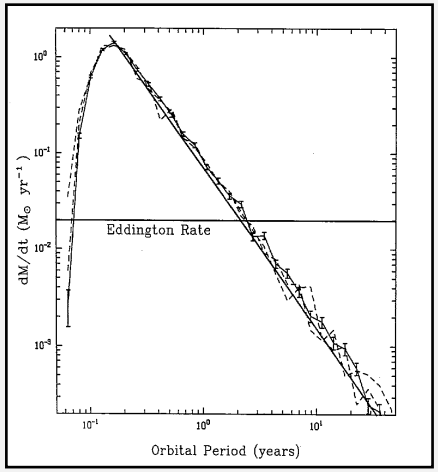
THE CLASSICAL MODEL

Rees 1988, Nature,

- **assumption: fast dissipative circularization i.e., accretion rate = fall-back rate**

$$\dot{M}(t) = \frac{dM}{dE}\frac{dE}{dt} = 2\pi(GM_{BH})^{2/3}\frac{dM}{dE}t^{-5/3}$$

Rees assumes dM/dE=const, so he yields $\dot{M} \propto t^{-5/3}$ (typo in original paper, corrected by Phinney; Evans & Kochanek 1989;Laoda et al. 2010)



accretion rate is highly super-Eddington if black hole mass is smaller than

$$\dot{m} = 133 M_6^{-3/2} m_{*,\odot}^2 R_{*,\odot}^{-3/2} \eta_{-1} t^{-5/3}$$

THE CLASSICAL MODEL

Rees 1988, Nature,

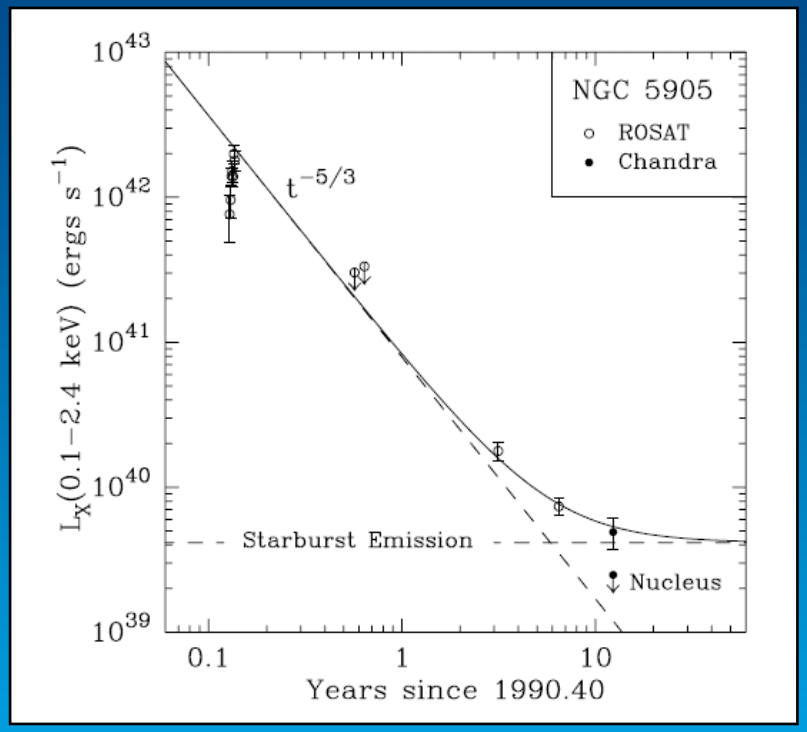
Angular momentum conservation suggests that disk will be very compact if circularization is efficient. Specific angular momentum at pericenter is $l_c = vr_p \approx \sqrt{2}v_c r_p$. By noting $l_c \propto r^{\frac{1}{2}}$, circularization radius: $r_d = 2r_p \sim 10^1 r_s$

For comparison, an AGN disk has $r_d \sim 10^4 r_s$

PREDICTIONS OF CLASSICAL MODEL

- **Light curve:** $L \propto t^{-5/3}$
- **Flare SED peaks in UV to soft X-ray :**
- $$T_{eff} \approx 4\times10^{5}K(\dot{m}/\eta_{0.1})^{1/4}M_{6}^{-1/4}$$
- **event rate: 10^{-4} to 10^{-5} gal^{-1} yr^{-1},**
- **important for growth of IMBH**
- **High probability of misaligned inner disk with BH spin**

HISTORICAL DISCOVERY



Komossa et al. 1999; Halpern Baad Komossa 2004

- 1996, Komossa et al. noticed large amplitude X-ray flares in the center of some galaxies
- 持续到10年的后续观测，证实非活动，行为和TDE理论预言一致

$T_{bb} = (6 - 15) \times 10^5$ K

$L_x = 10^{42} - 10^{44}$ ergs s^{-1}

$t_{flare} \sim$ months- 1yr

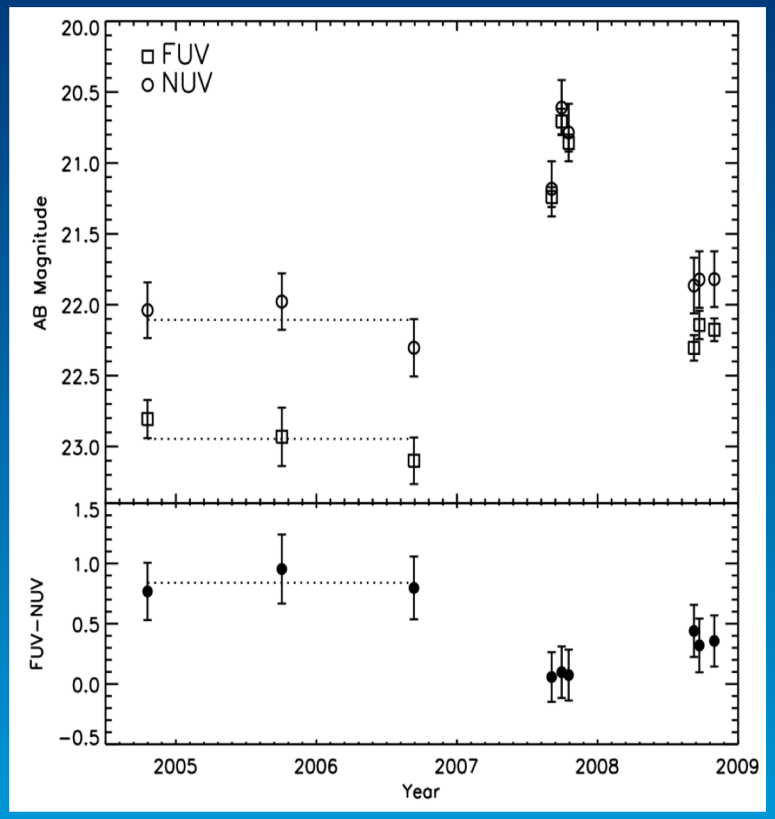
supersoft X-ray spectrum at initial discovery, and hardens significantly at late stage.

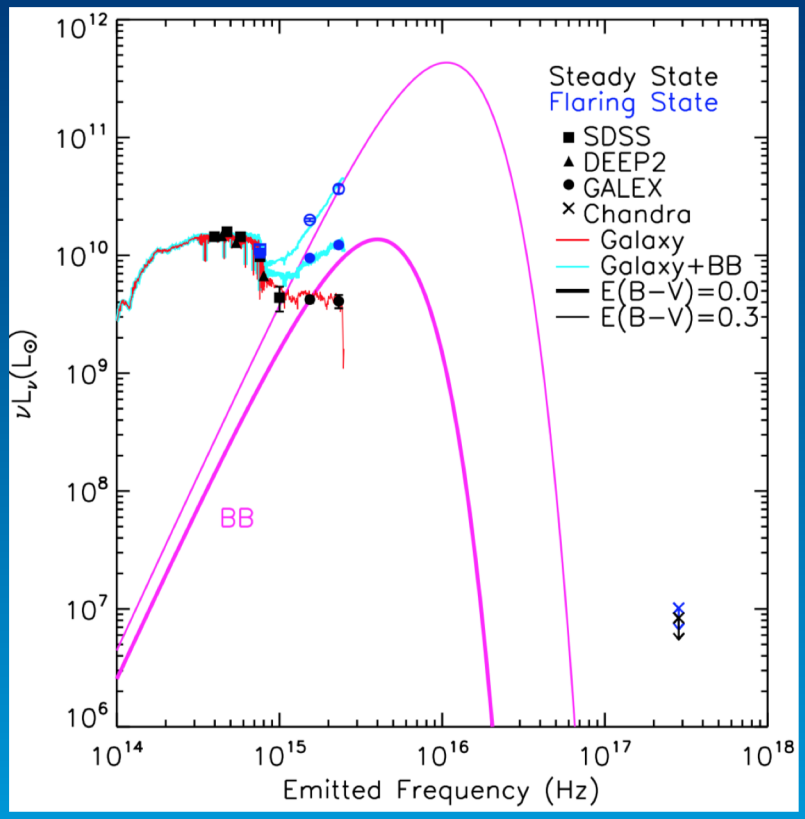
MORE DISCOVERIES IN SOFT X-RAYS

NGC 5905	0.011	*ROSAT*	Bade et al. (1996), Komossa and Bade (1999)
RX J1242-1119	0.050	*ROSAT*	Komossa and Greiner (1999)
RX J1624+7554	0.064	*ROSAT*	Grupe et al. (1999)
RX J1420+5334	0.147	*ROSAT*	Greiner et al. (2000)
NGC 3599	0.003	*XMM-Newton*	Esquej et al. (2007, 2008)
SDSS J1323+4827	0.087	*XMM-Newton*	Esquej et al. (2007, 2008)
TDXF 1347-3254	0.037	*ROSAT*	Cappelluti et al. (2009)
SDSS J1311-0123	0.195	*Chandra*	Maksym et al. (2010)
2XMMi 1847-6317	0.035	*XMM-Newton*	Lin et al. (2011)
SDSS J1201+3003	0.146	*XMM-Newton*	Saxton et al. (2012b)
WINGS J1348	0.062	*Chandra*	Maksym et al. (2013), Donato et al. (2014)
RBS1032	0.026	*ROSAT*	Maksym et al. (2014b), Khabibullin and Sazonov (2014)
3XMM J1521+0749	0.179	*XMM-Newton*	Lin et al. (submitted for publication)
3XMM J150052.0+015452	0.145	XMM-newton	Lin et al. 2017
2XMM J123103.2+110648	0.118	*XMM-Newton*	Lin et al. 2016
GSN 069	0.018	*XMM-Newton*	Shu et al. 2018
J2150−0551	0.055	*XMM-Newton*	Lin et al. 2018

DISCOVERY IN UV

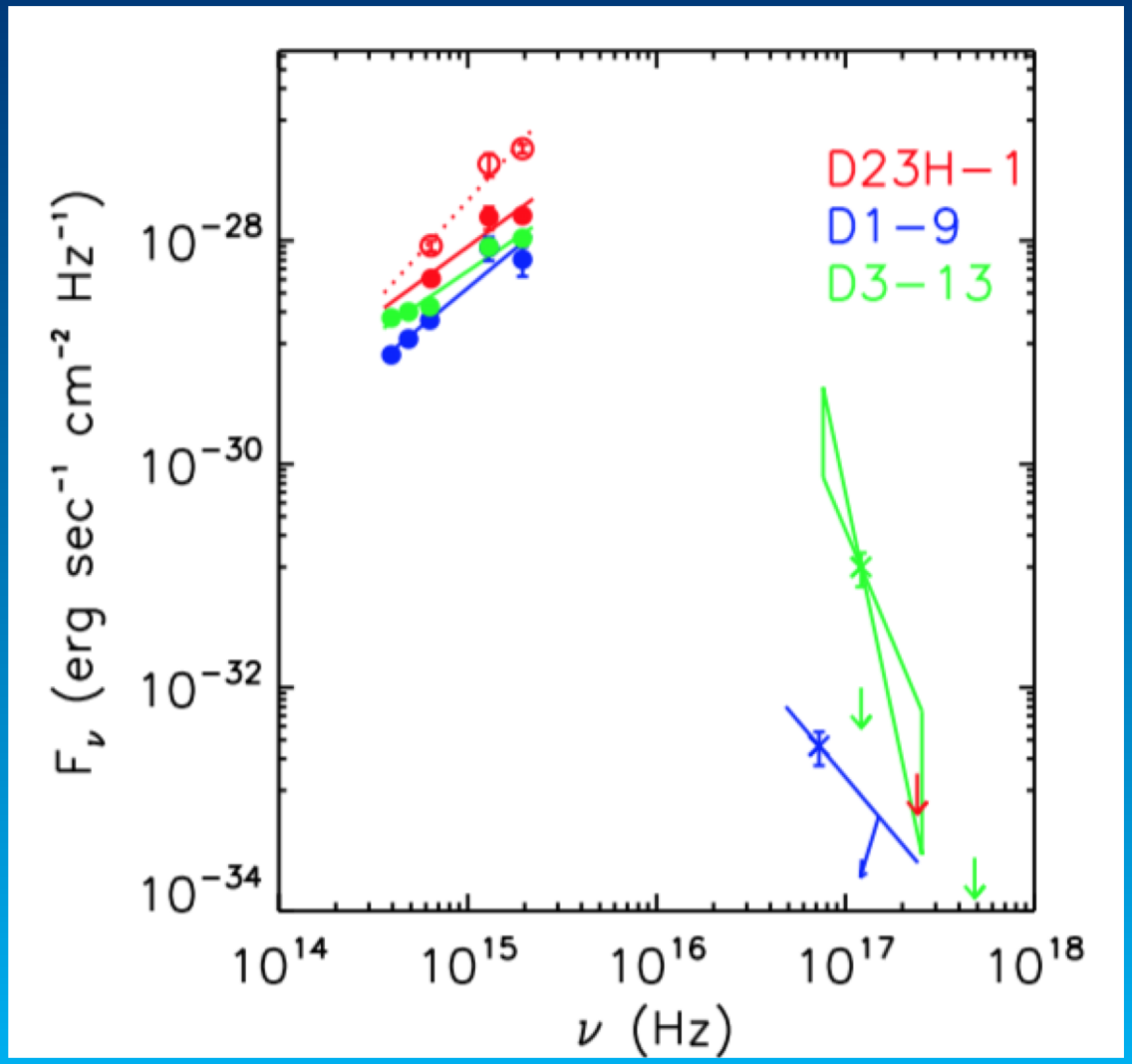
Gezari+09





GALEX discovered large amplitude UV flares in 3 normal galaxies (BPT diagram, spectra taken after flares was discovered)

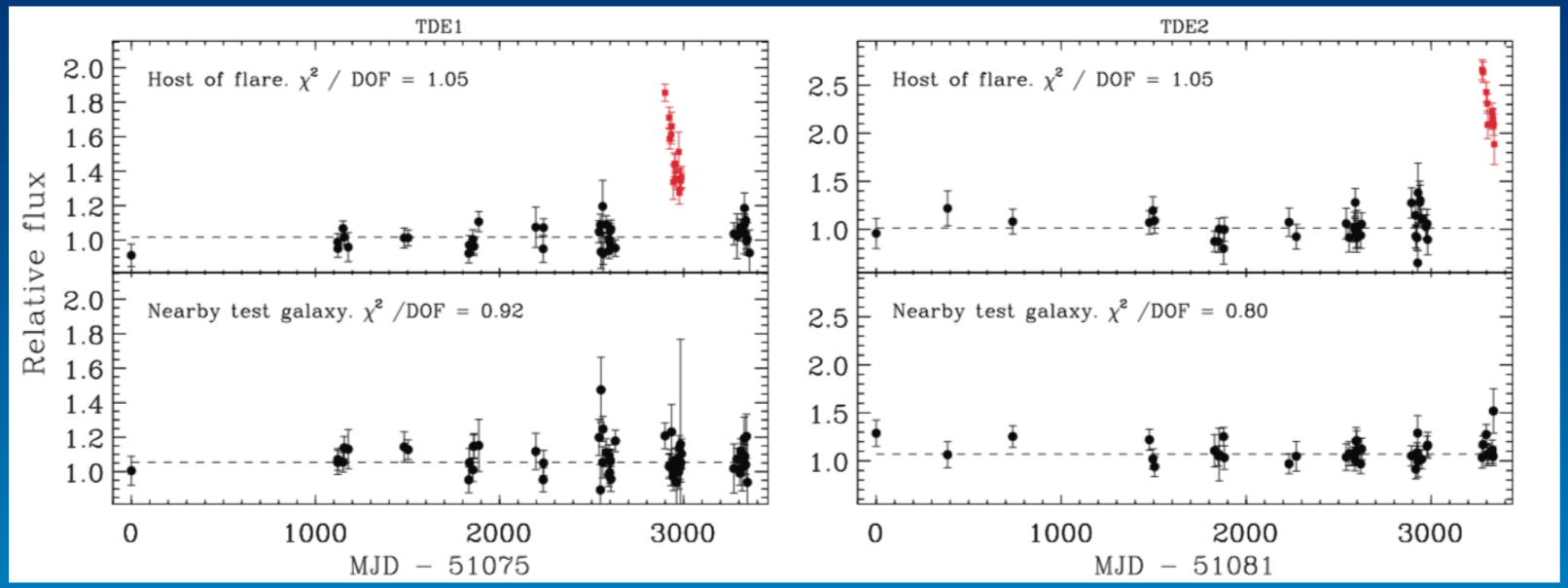
UV DISCOVERED TDES

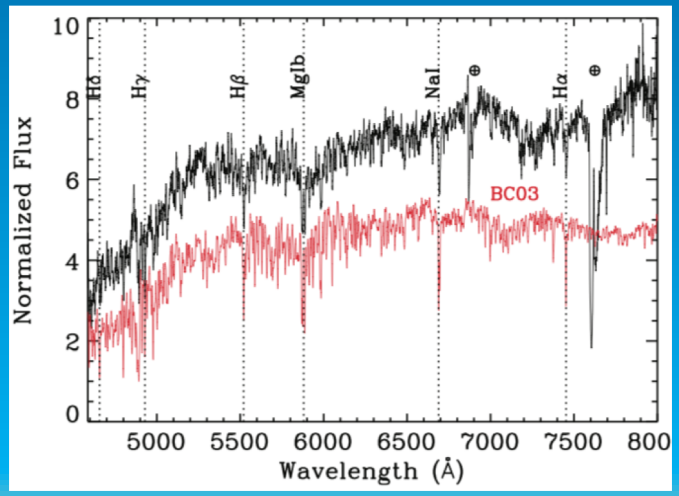


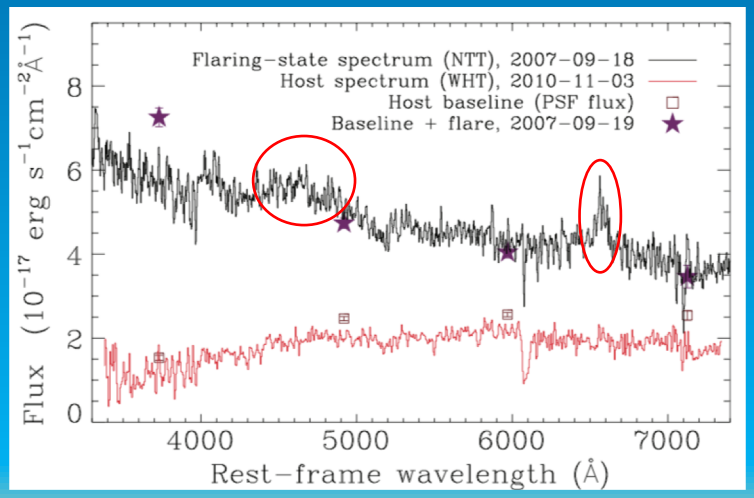
X-ray can be weak in UV TDEs

Gezari+09

TWO OPTICAL TDES FROM SDSS SURVEY



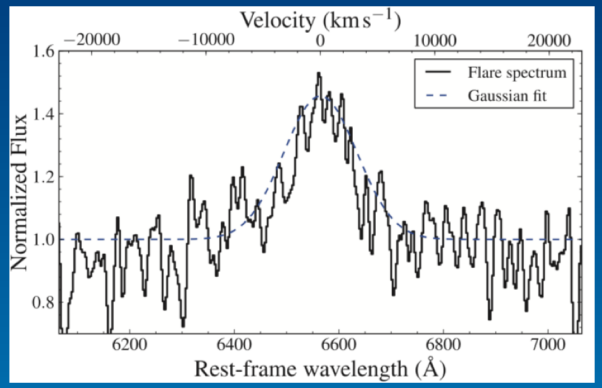


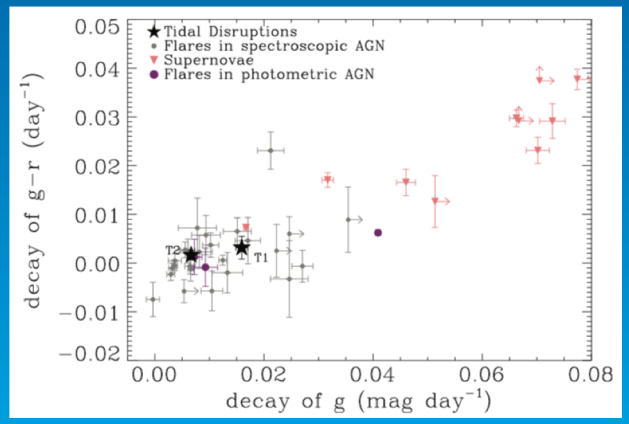


van Velzen+12

IMPLICATIONS OF SDSS TDES

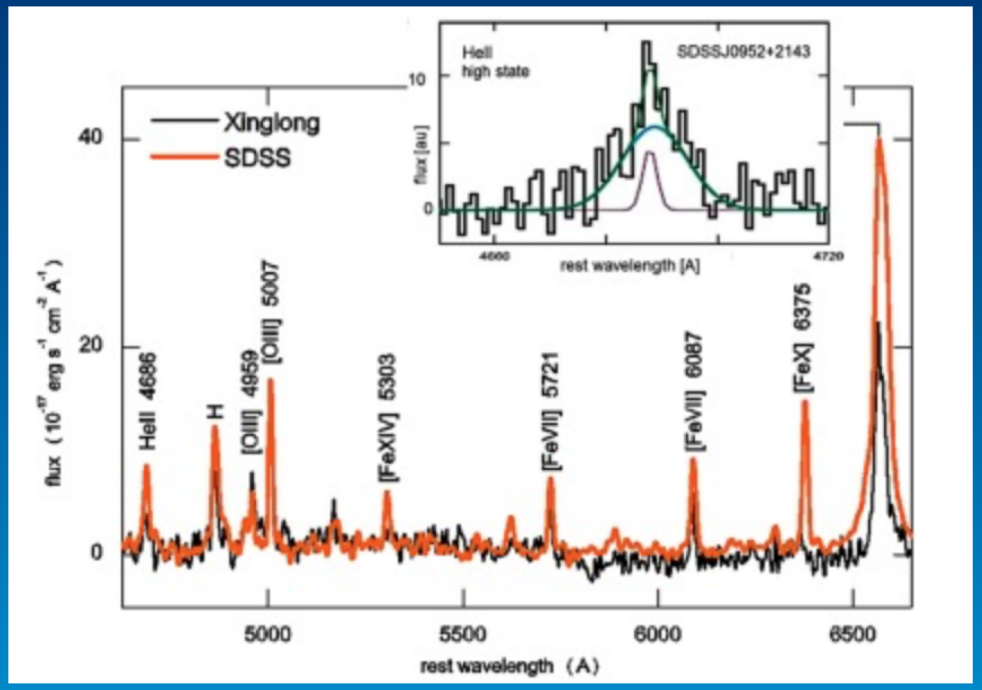
- We learn
  - optical TDEs can be as common as X-rays
  - Little color changes
  - Optical luminosity is order of magnitude higher than theoretical prediction (Strubbe, L. E., & Quataert 2009)
  - Serendipitously obtained spectrum shows broad Halpha line

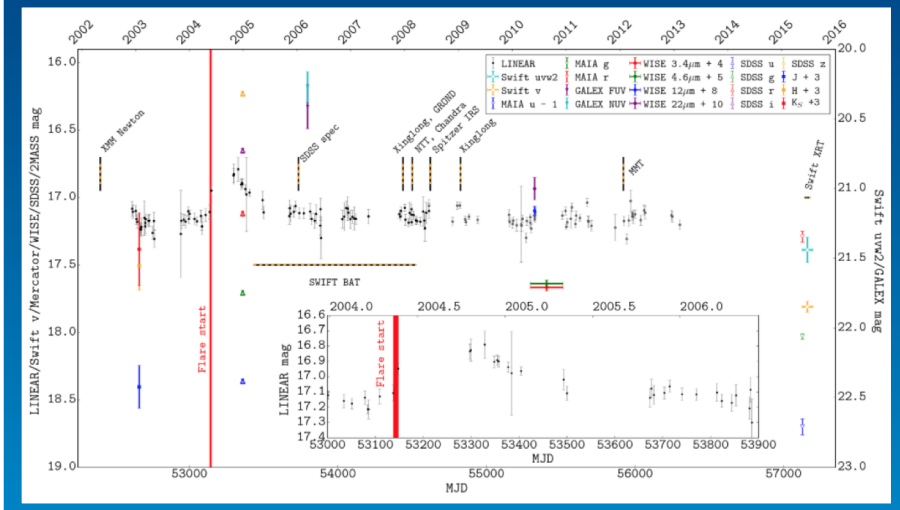




van Velzen+12

TRANSIENT BROAD LINES IN TDE CANDIDATES: ECLES





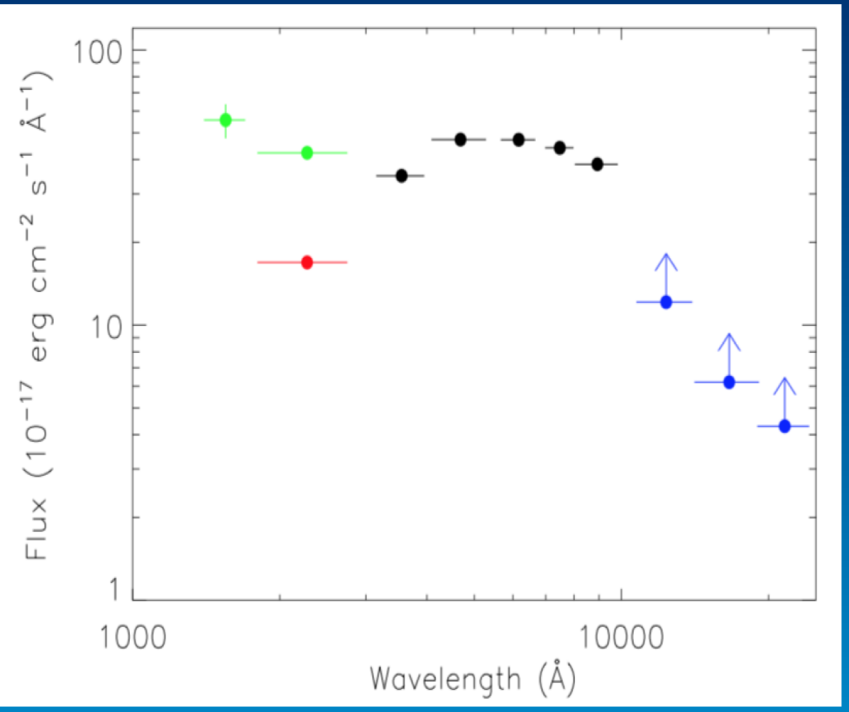
Palaversa+, 2015

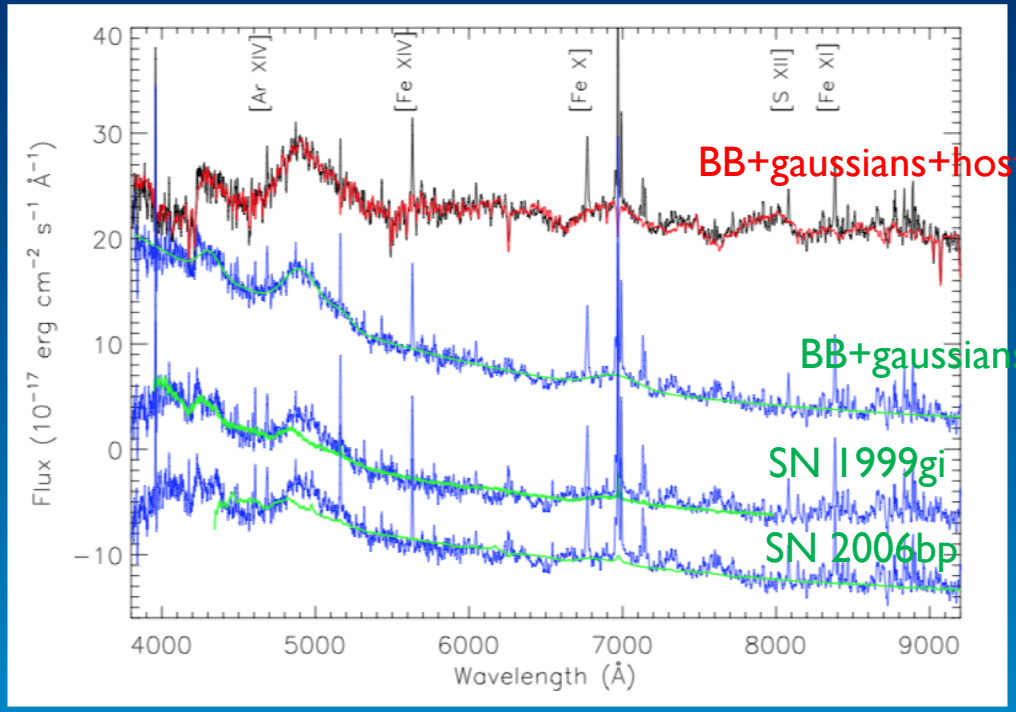
CLs are produced by the soft X-rays:
transient CLs → transient soft X-rays
Rate: 10^{-5} gal^{-1} yr^{-1} for $-21.5<M_g<-18.5$

Komossa et al. 2008; Wang et al. 2012, Yang et al. 2013

SDSS J0748+4712

Wang+ 2011



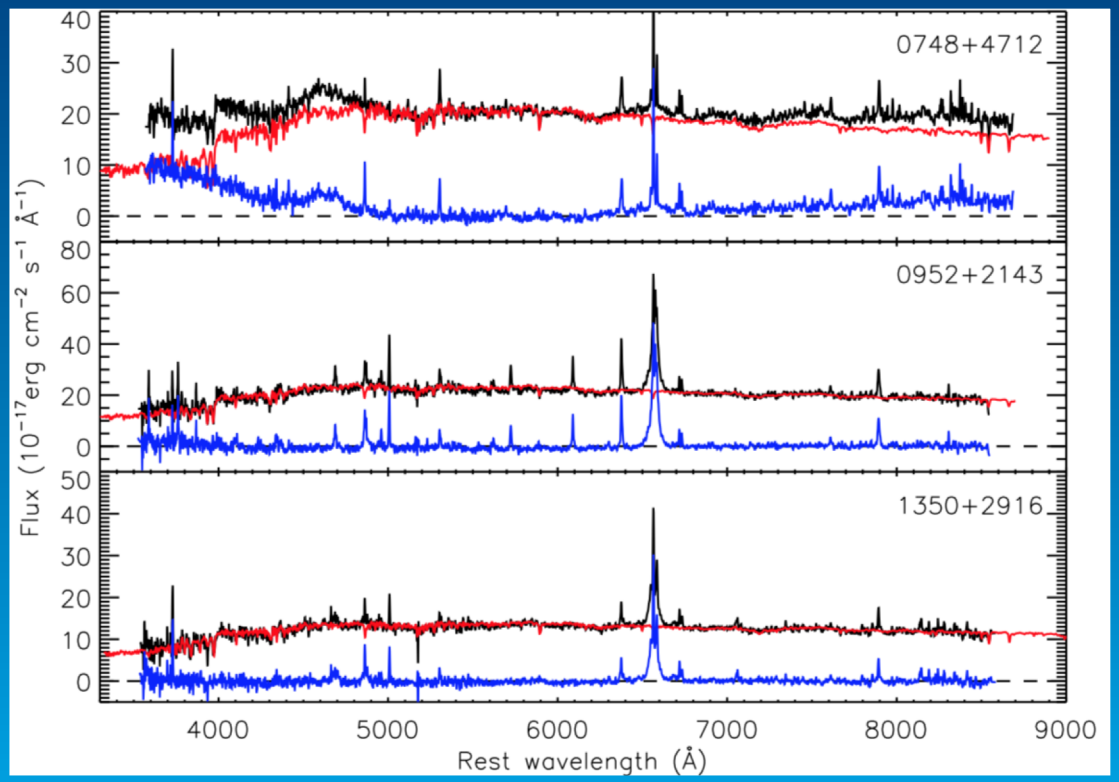


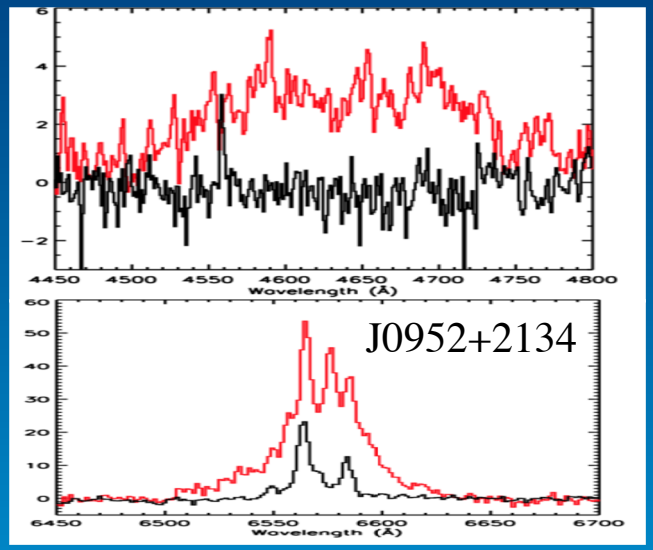
Transient high ionization CLs, accompanying by UV declining brightening [O III], long infrared echo

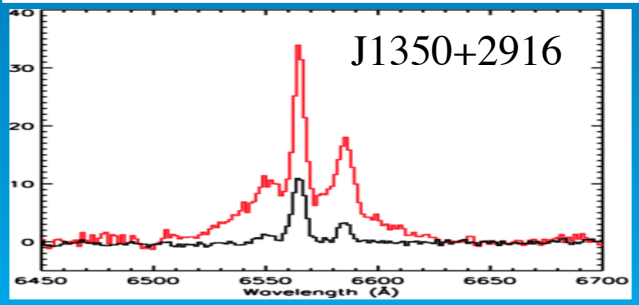
Broad HeII and weak Halpha -- become a bench-mark of TDE spectrum

COMMON BROAD LINES IN TRANSIENT ECLES

Yang+ 13



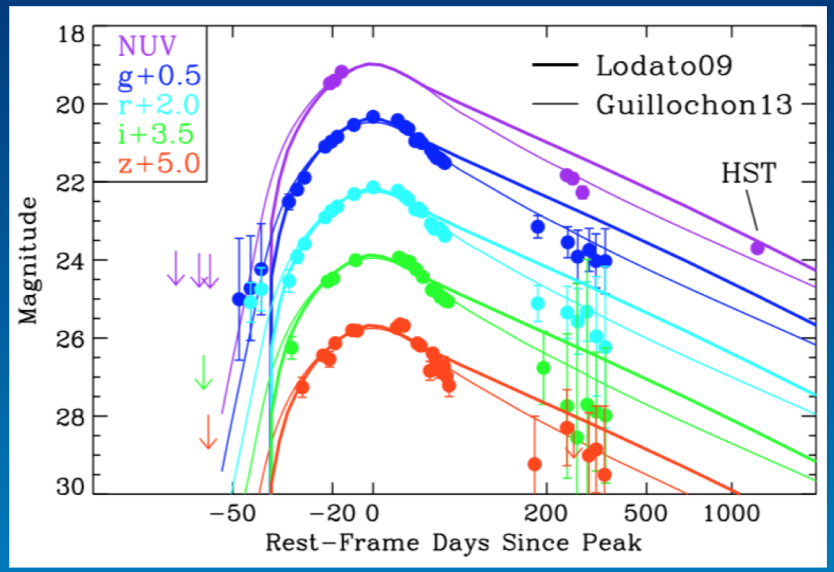




¾ show broad lines

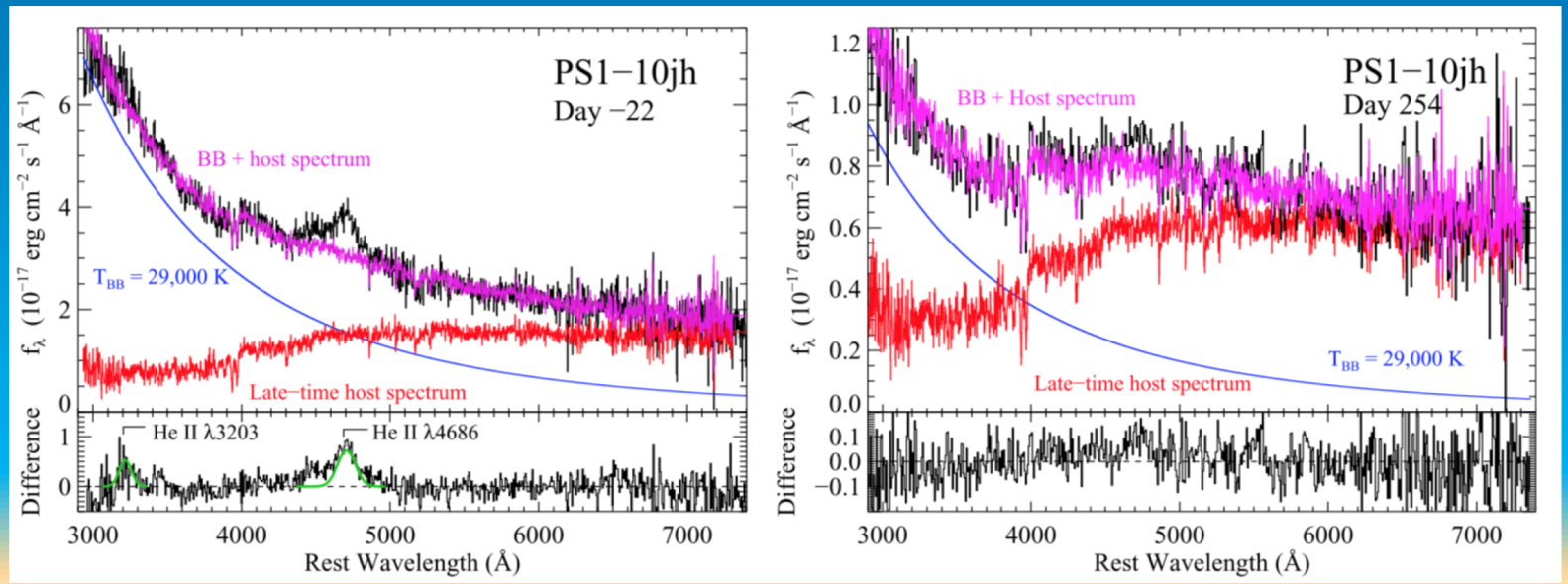
often double peaked

PS1-10JH @ Z=0.1698



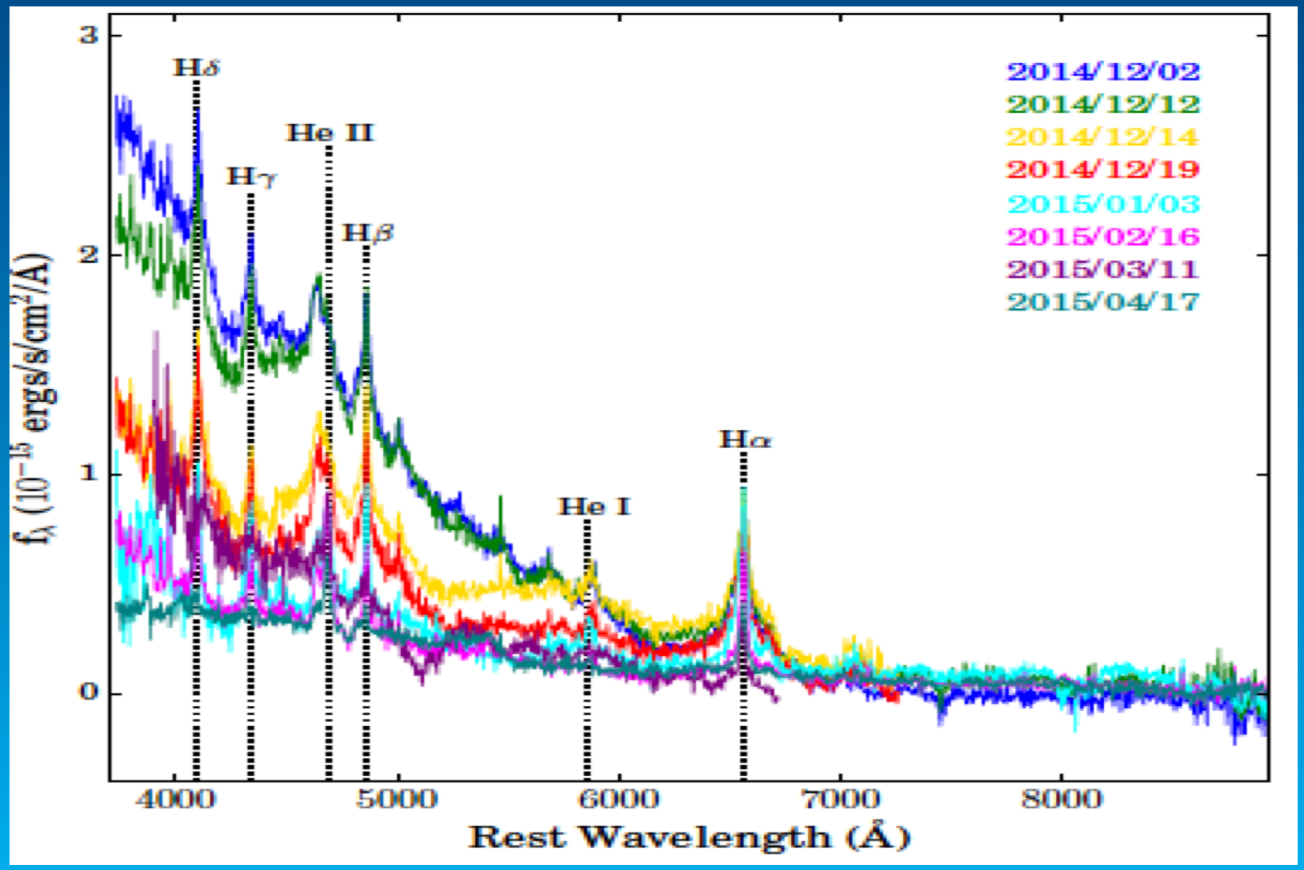
- Good coverage to the rising phase
- Strong broad HeII and weak H alpha also true a year later
- no color evolution

Gezari et al. 12; Gezari et al. 2015



RAPIDLY EVOLVING BROAD LINES

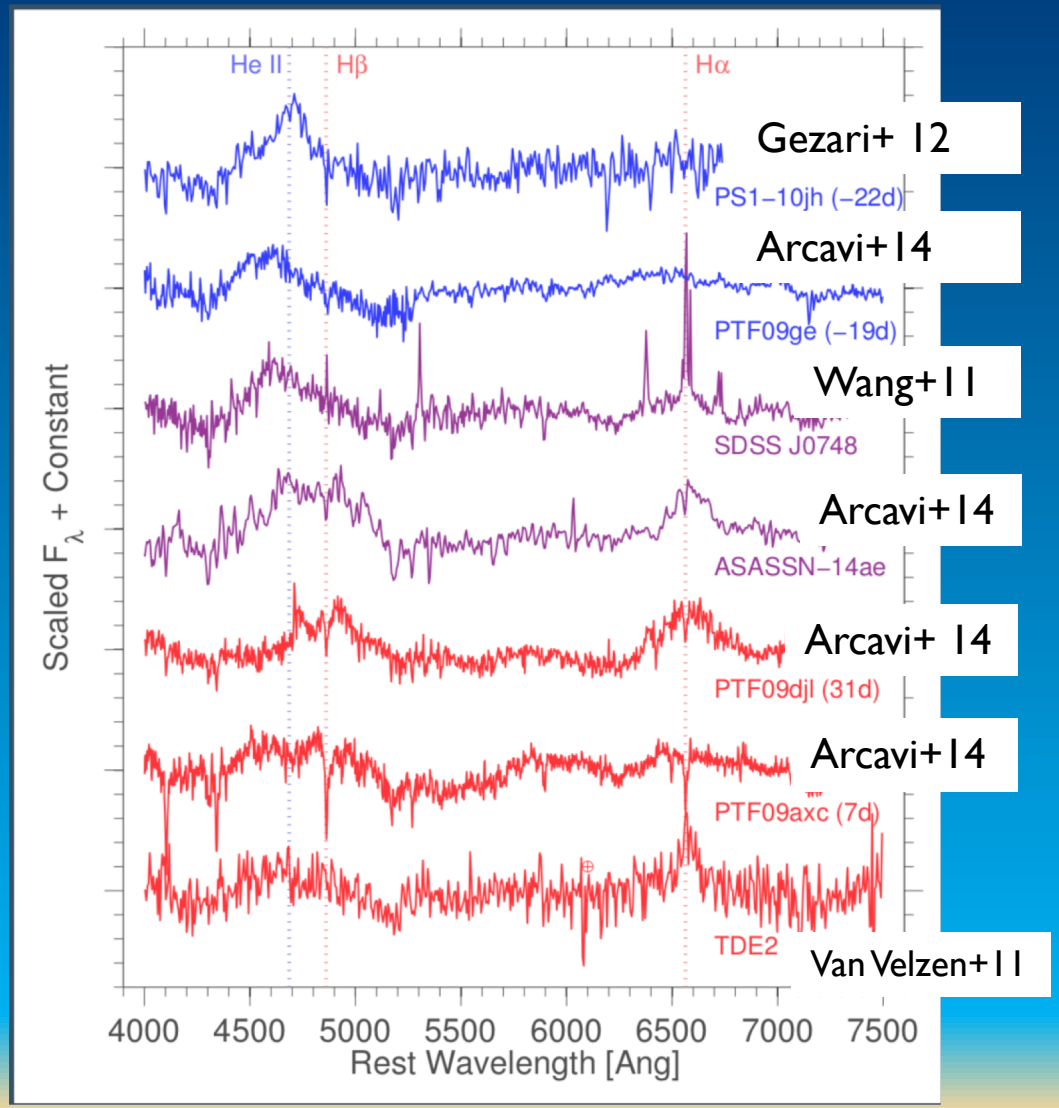
HeII and H lines change strengths and profiles on time scale of months



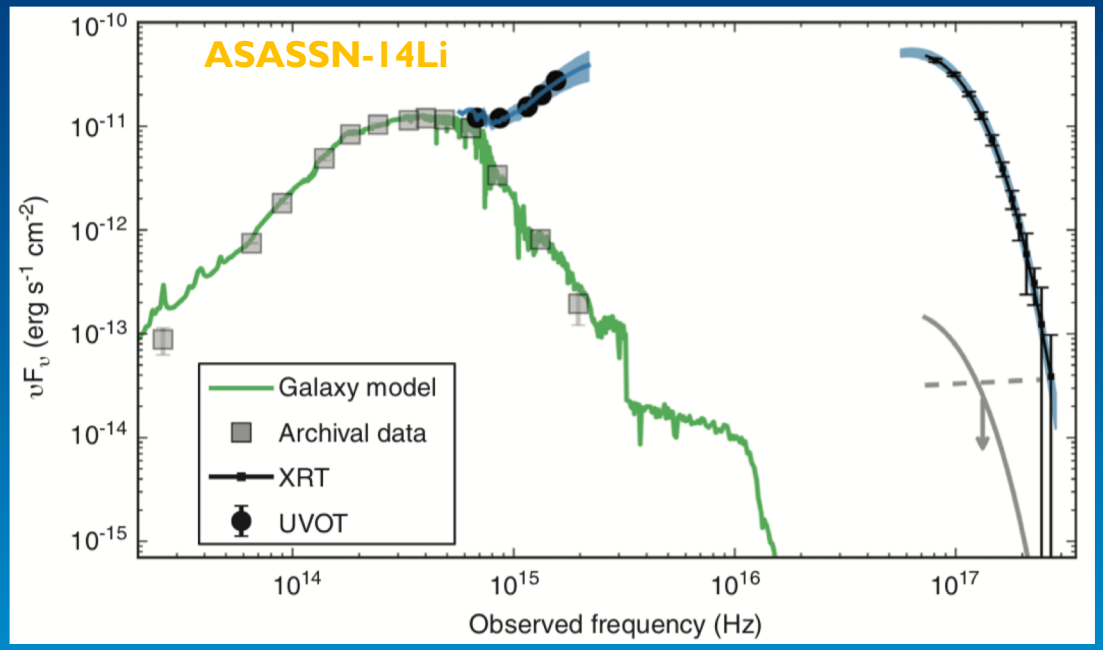
ASASSN-14li

Holoien et al. 2015

COLLECTION OF STRONG HEII EMITTER



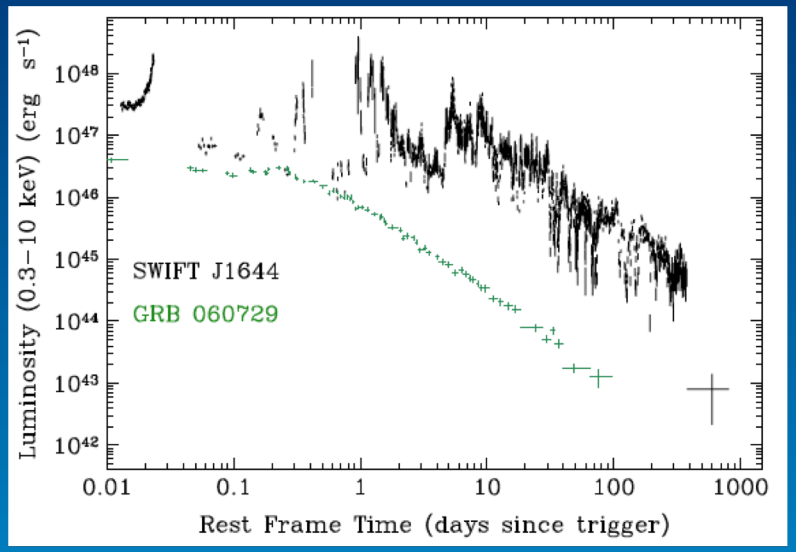
SPECTRAL ENERGY DISTRIBUTIONS



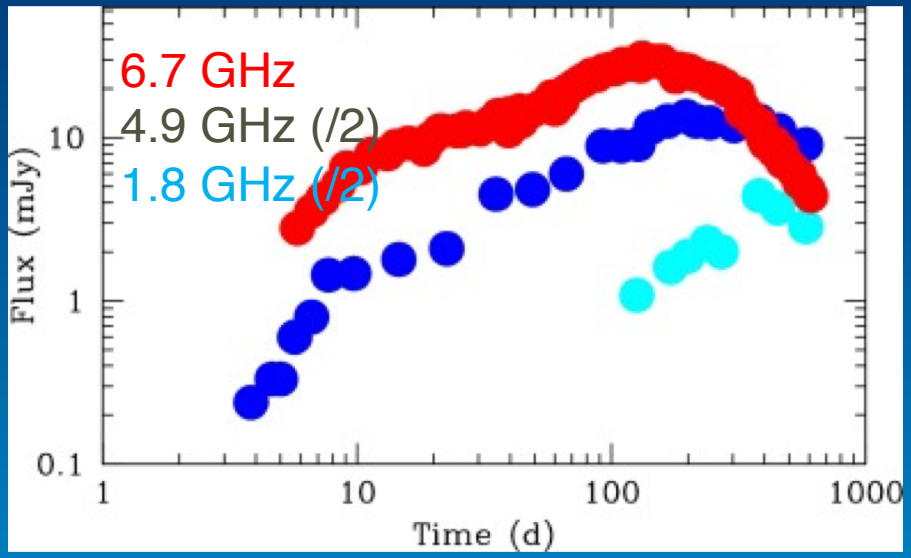
van Velzen+16

two single black bodies: with T = 7.7 × 10^5 K and T = 3.5 × 10^4 K
with pretty diversity in soft X-ray component

JETTED TDE



Burrows et al. 2011

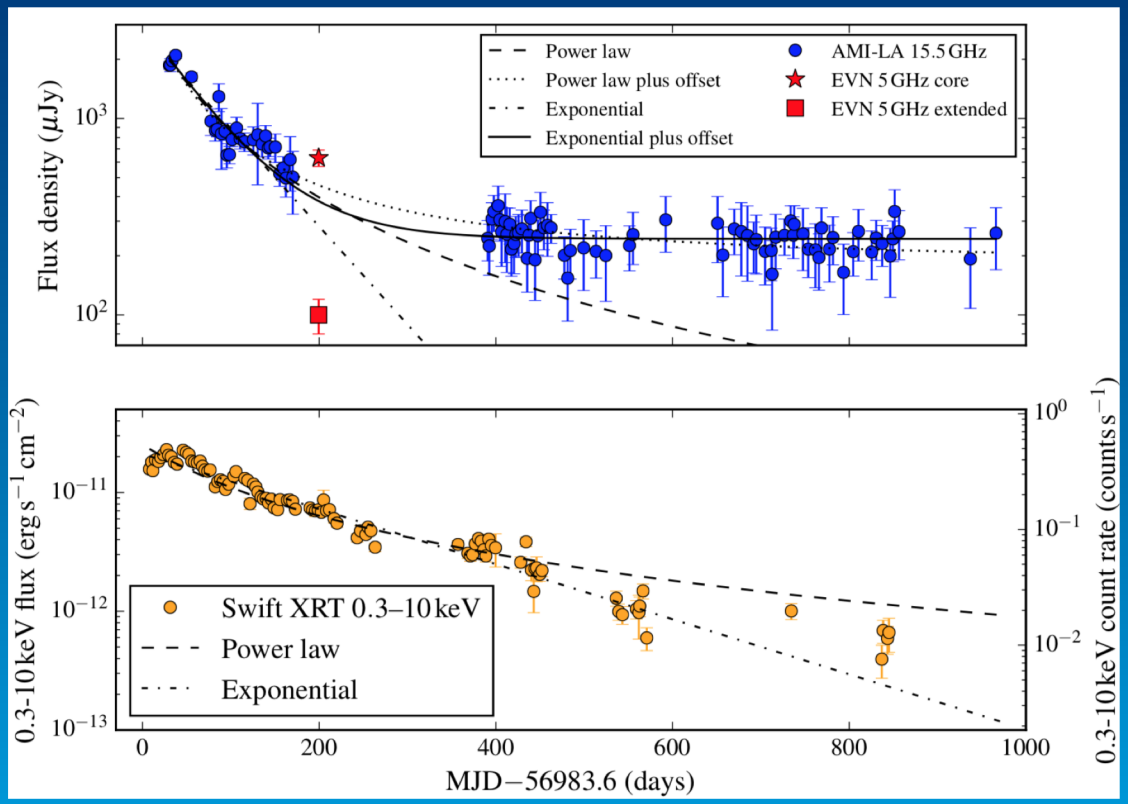


Zauderer et al. 2013

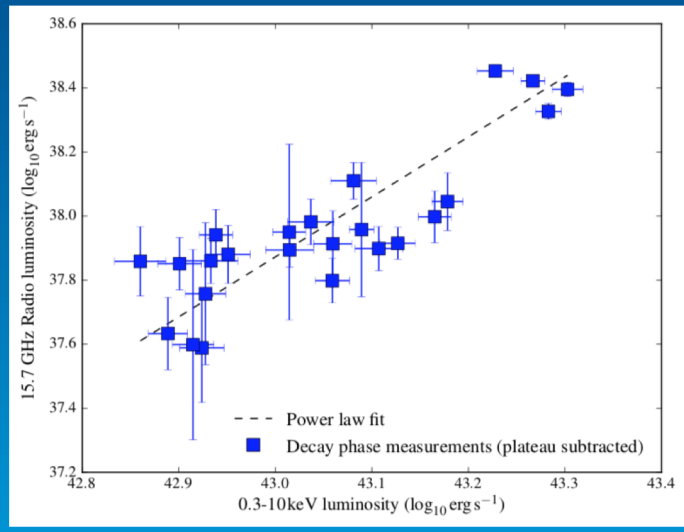
3 on axis + 1 offset Jetted TDEs

Gamma and radio detected, short term flickers

LOW POWER RADIO EMISSION: JETS OR OUTFLOWS

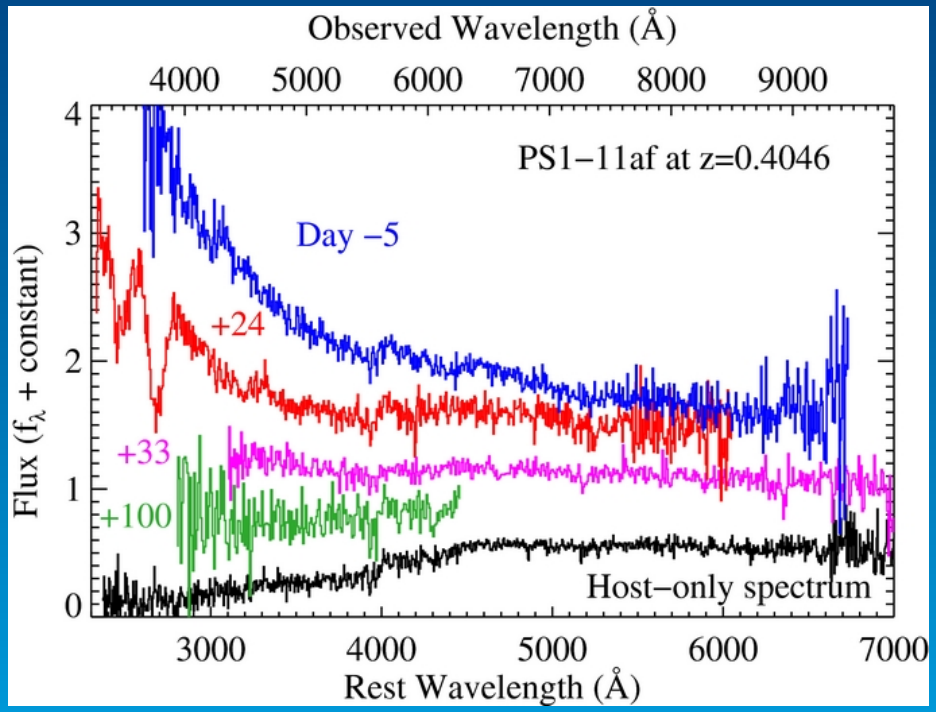


ASASSN-14Li



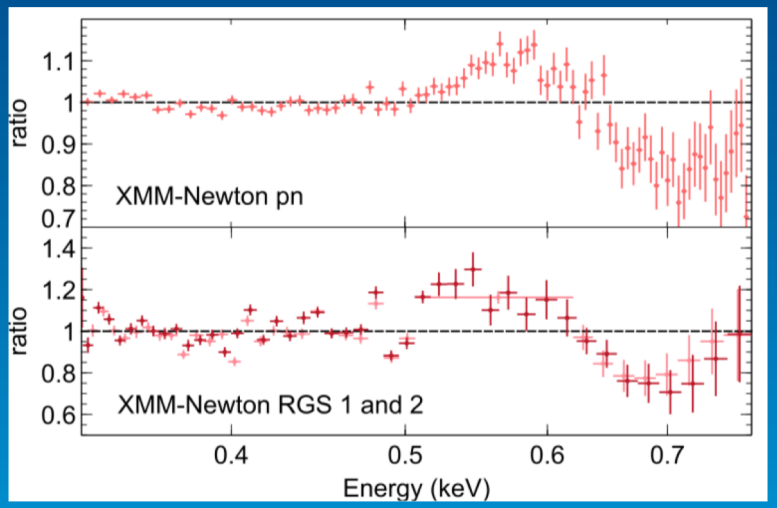
- Alexander+16: non-relativistic outflow with a kinetic energy of ≈(4-10) × 10^{47} erg, a velocity of ≈12,000-36,000 km s^{-1}
- van Velzen+16: synchrotron shock emission is produced as the transient ejecta decelerate upon interacting with dense gas; a total jet energy of Ej ~ 10^{48} erg

UBIQUITOUS OUTFLOWS



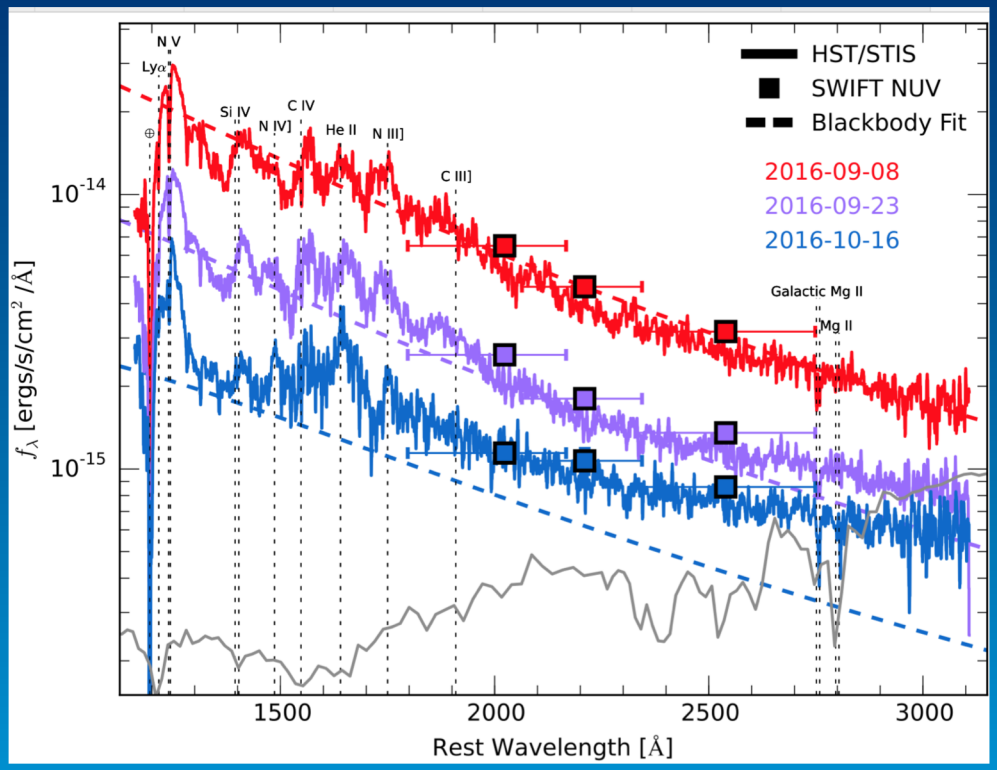
Chornock et al. 2014

X-ray UFO in ASASSN-14li



Kara+ 17

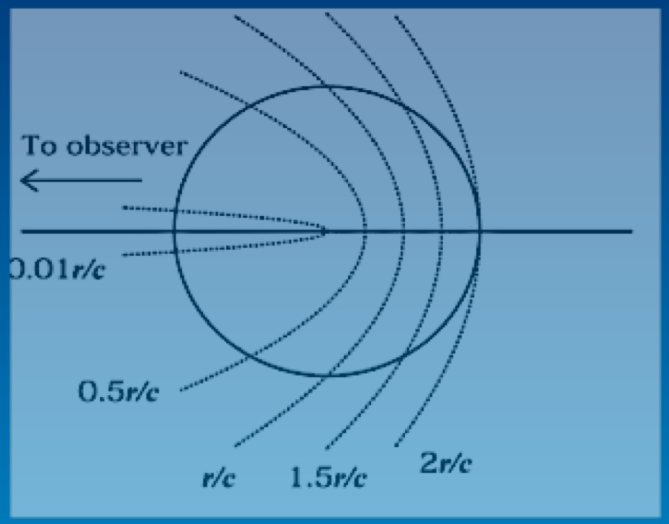
BROAD ABSORPTION LINES

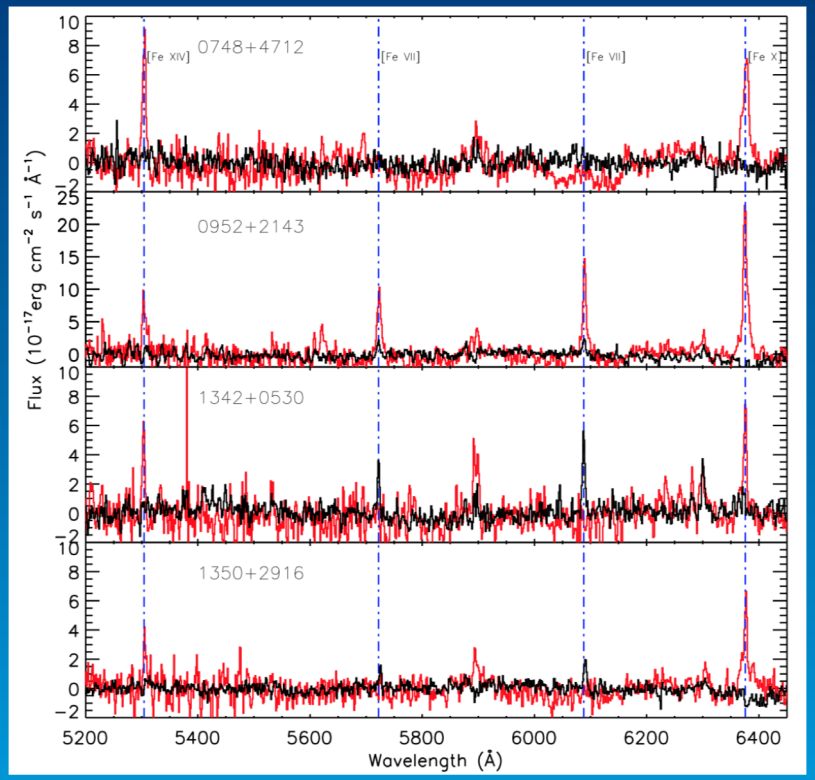


Brown+17

UV BALs are common (3/4) among TDEs (Yang et al. 2017)

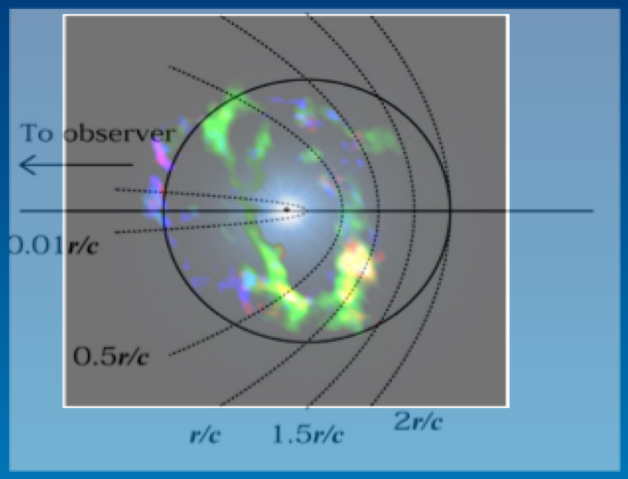
NARROW EMISSION LINES

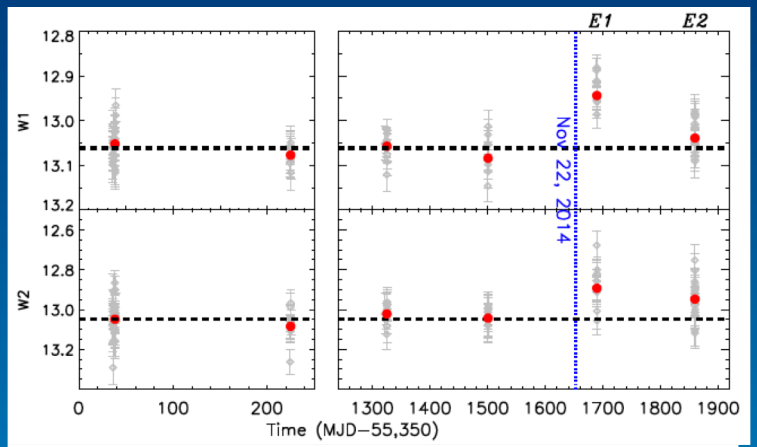


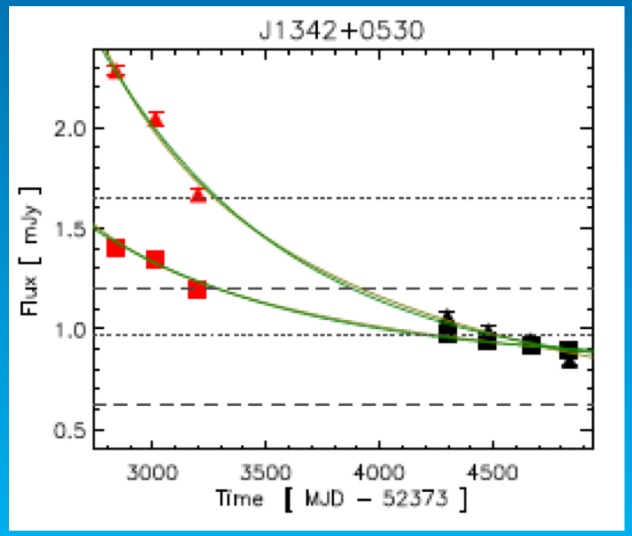


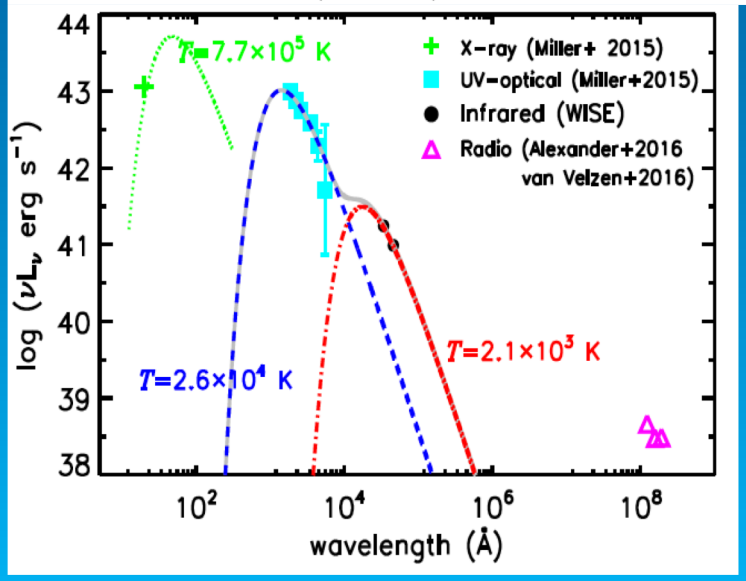
Reverberation effect: a lagged response of emission lines from distant gas, mainly high ionized coronal lines, recombination lines such as HeII, and also [O III]

ECHOES FROM SURROUNDING DUST



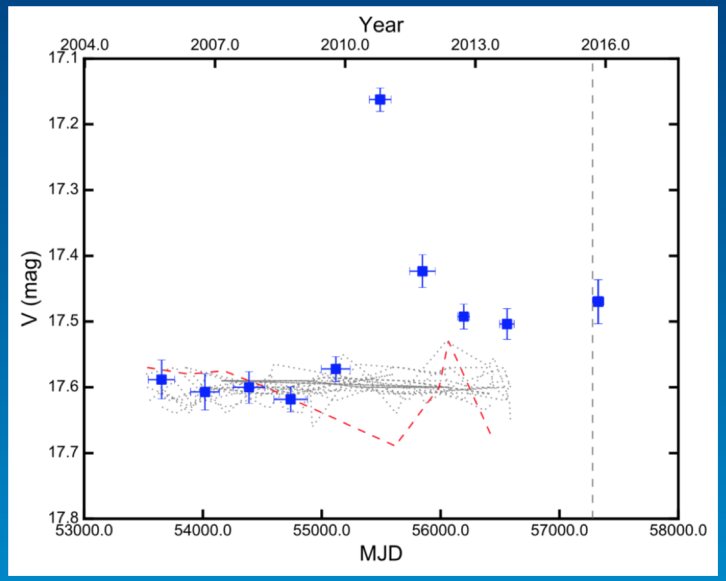


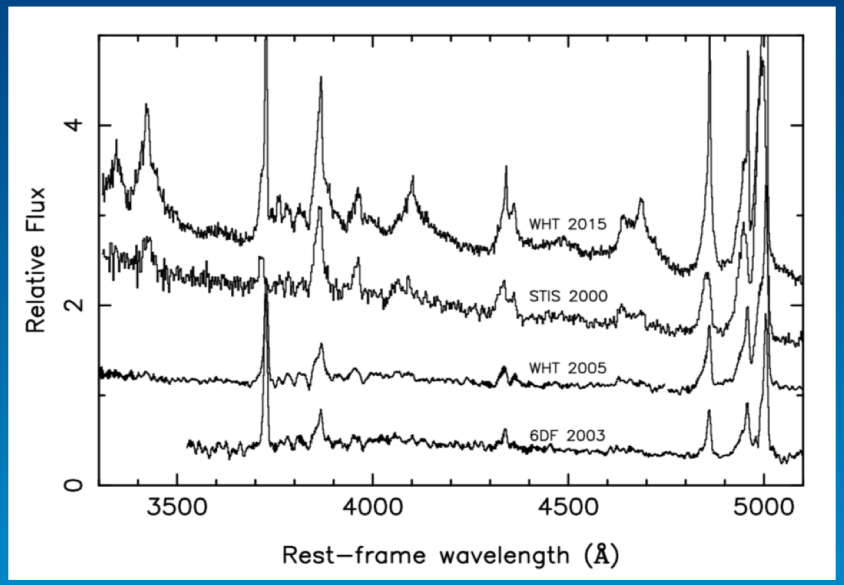




Jiang et al. 2016,2017; Dou et al. 2016,2017

FLARE IN ULIRG F01004-2237





Tadhunter et al 2017

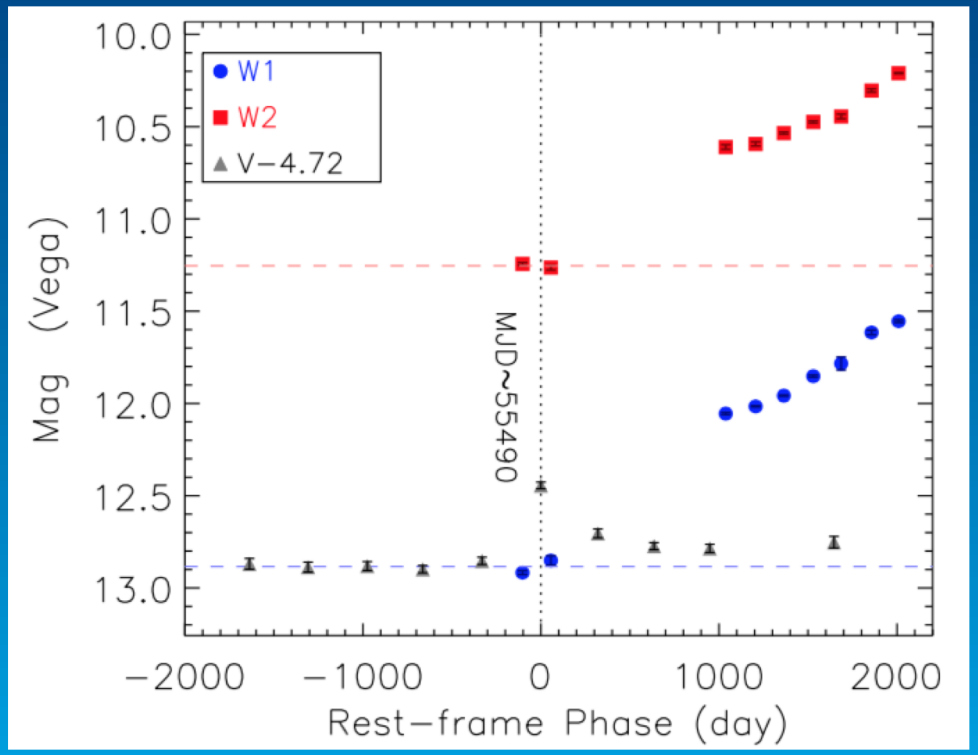
ULIRG with AGN outflow

Brightening broad HeII, Balmer lines and [NeV] after optical flare

Puzzle: rebrightening

MIR ECHO OF THE FLARE

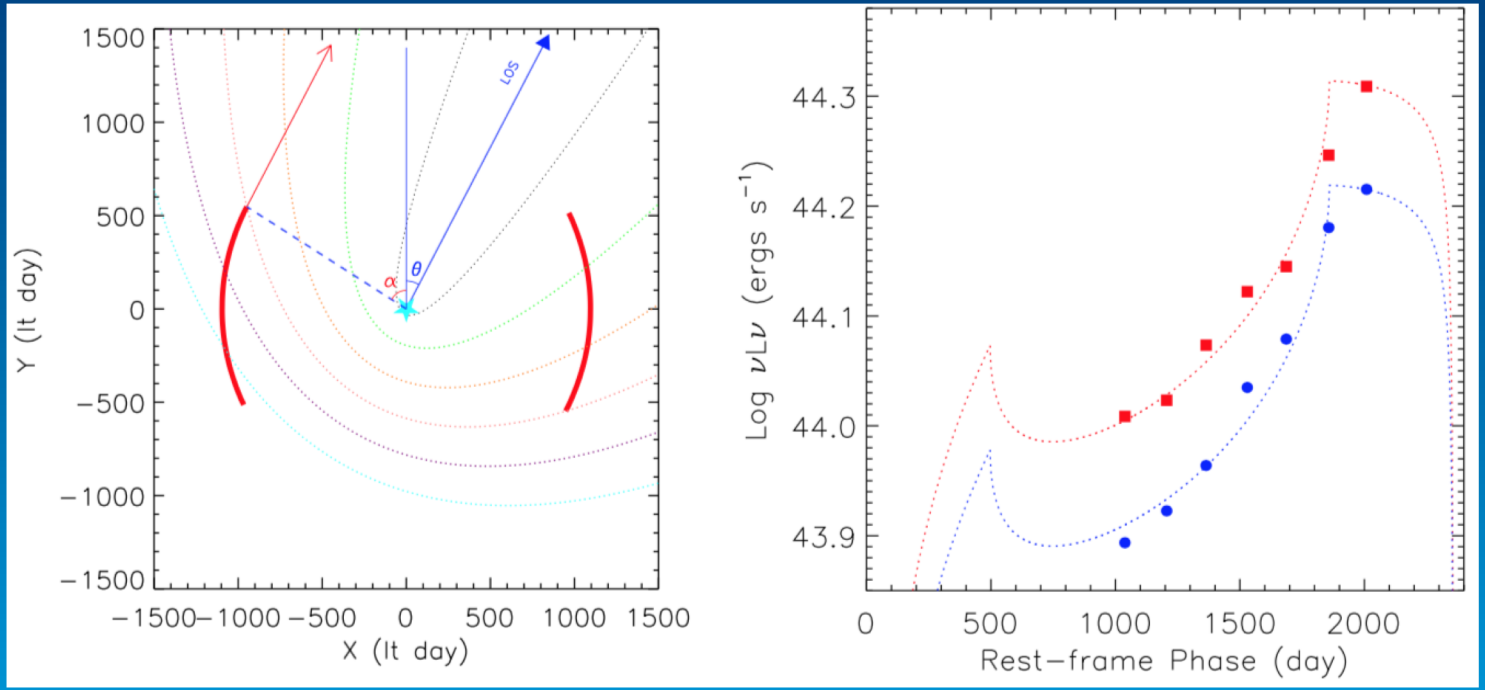
Dou et al 2017



No-instant response,

Puzzle: long term rising MIR light curve

TOY TORUS MODEL



Long MIR brightening is an effect of reverberation

Optical rebrightening is interpreted as dust scattering

The turn down is confirmed by new MIR data

ECHO的可能应用

- Bolometric luminosity：峰值EUV部分不能直接测量

  尘埃颗粒可以作为热光度计，测量温度和离中心距离
- 宁静黑洞的气体、尘埃环境,帮助理解为什么只有一些黑洞活动的
- 探测遮蔽的TDE，全面认识TDE的Population

  红外穿透能力强

PUZZLES AND UNSOLVED PROBLEM

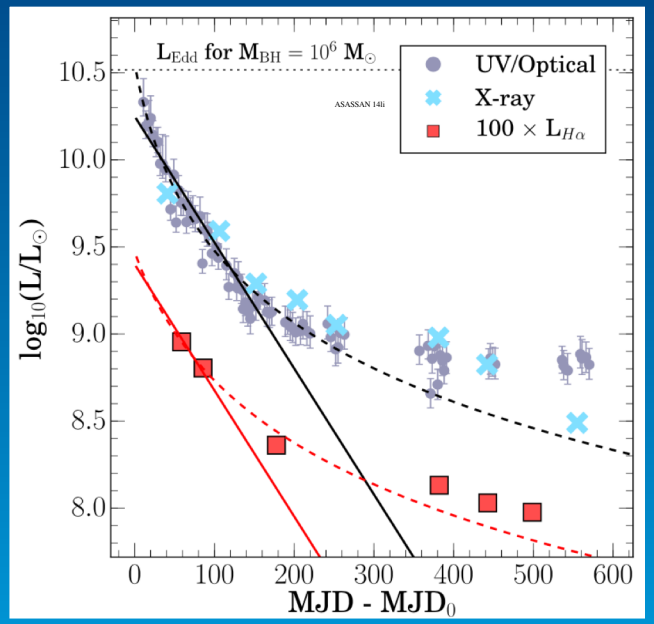
- Too little radiation energy
- Too much optical light and too large OUV emission region
- Too low optical TDE Rate
- Lack of thermal soft X-ray in a large fraction of optically discovered TDE
- Mysterious large HeII/Ha ratio

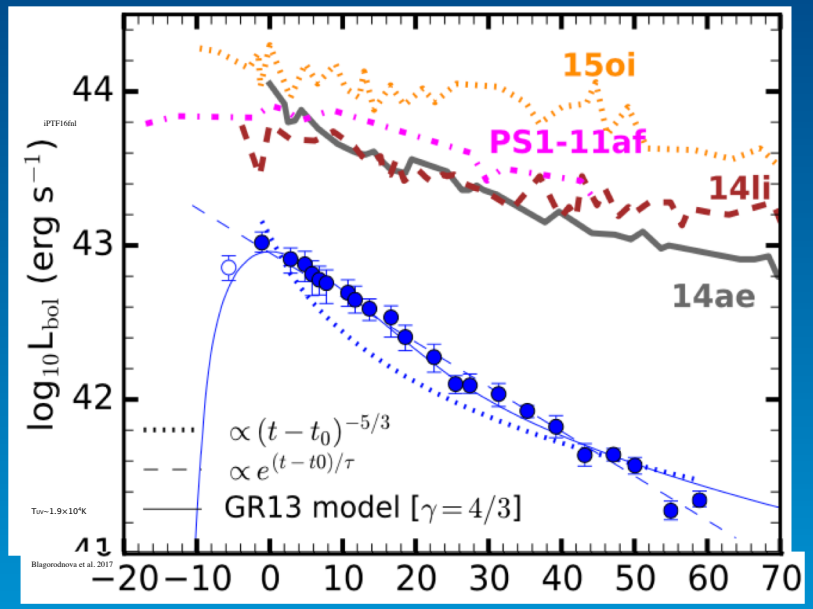
怎么确定真的是TDE?

TOO LITTLE RADIATION

total radiation energy: $10^{49\text{-}51}$erg s; accreted 10^{-4} —10^{-2} $M_\odot$

14li





T_{UV}~3.5×10^4K ; T_X~7×10^5K

Brown et al. 2017

Eint≈ 7 × 10^{50}ergs

$\Delta M \sim 4\times10^{-3} M_\odot$

Eint≈ 2× 10^{49}ergs

$\Delta M \sim 7\times10^{-5} M_\odot$

POSSIBILITIES

A) most bounded mass comes as outflows during super-Eddington accretion phase

Strubbe & Quataert 2009; Guillochon et al. 2014; Strubbe & Murray 2015; Jiang et al., 2014; Dai et al. 2018

outflows as blue-shifted BALs in UV (Yang et al. 2017) or UFO in X-rays (Miller et al. 2016)

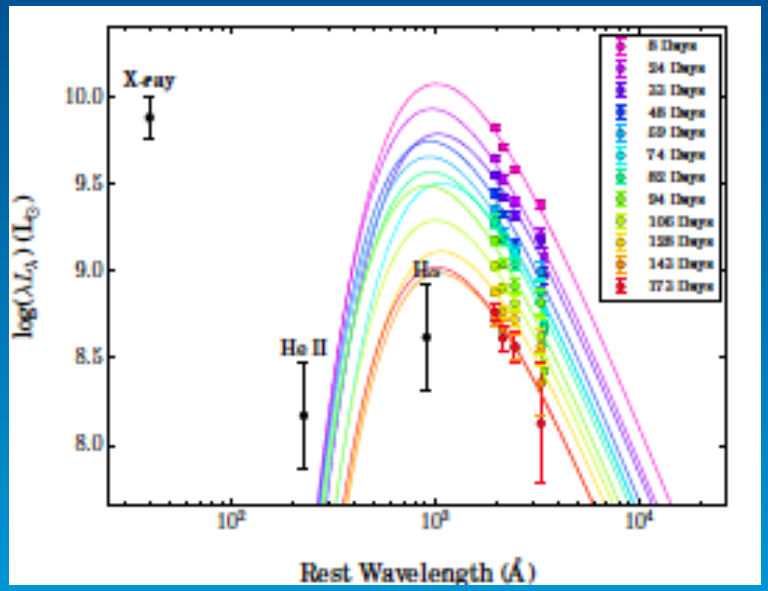
B) collision of elliptical disk with falling debris enhance the eccentricity, causing disk material plunge into black hole (Svirski et al. 17)

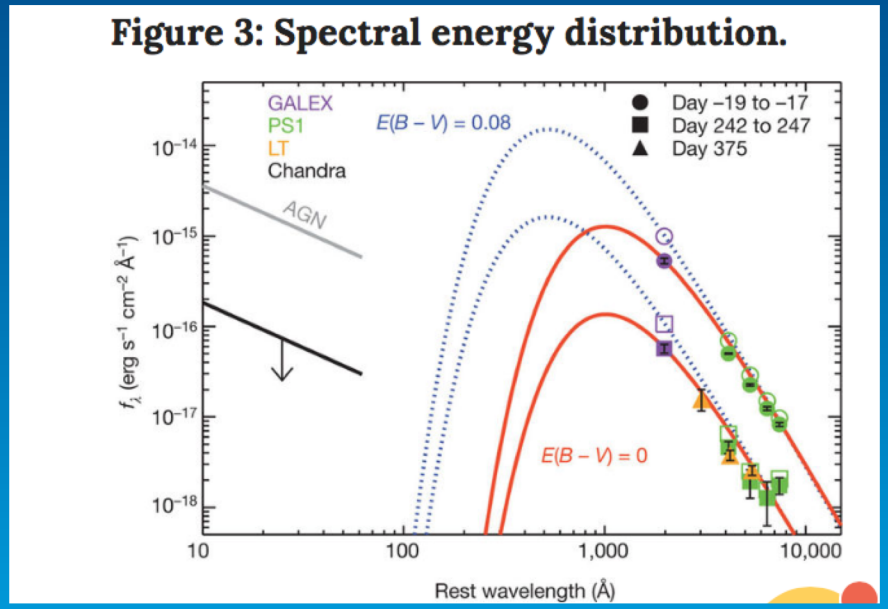
C) wrong estimate of bolometric luminosity. SED peaks at unobservable XUV (Lu et al. 2018; Dai et al. 2018) —> IR echo

X-RAY BIMODALITY

X-ray jetted, Thermal X-ray peak, X-ray Quiet TDEs

AUCHETTL et al. '17





ASASSAN-14li, Holoien et al. '16

Gezari et al 2012

ORIGIN OF X-RAY BI-MODALITY ?

X-ray and optical TDEs: most optical TDEs are soft-X-ray quiet, apparent bimodal; large X-ray TDE LF

clues from UV spectra: X-ray quiet TDEs show BALs and X-ray loud none (Yang et al 17) in analog with BAL and non-BAL QSOs

no apparent differences in BHs (Auchettl et al. 17) or emission lines, in particular, NV (Yang et al. 17), which are created by soft X-rays

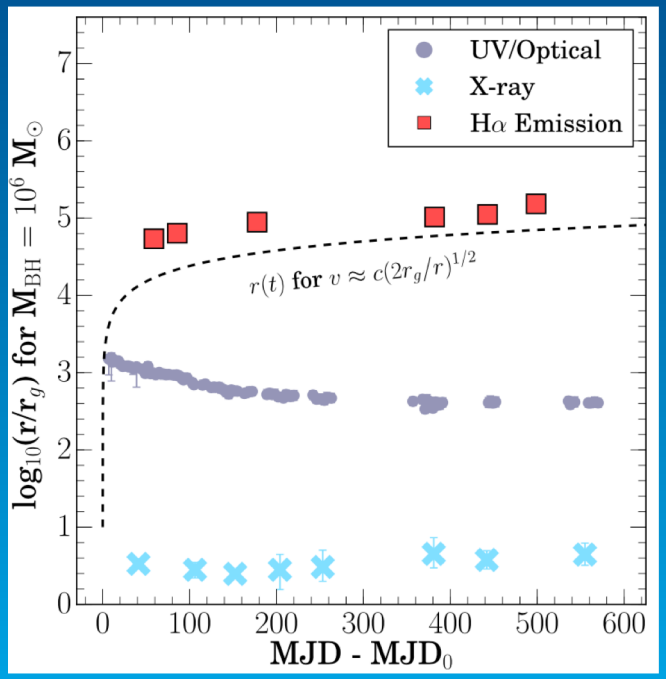
—> inclination effect (Dai LX et al. 2018)

—> absorption by optically thick wind

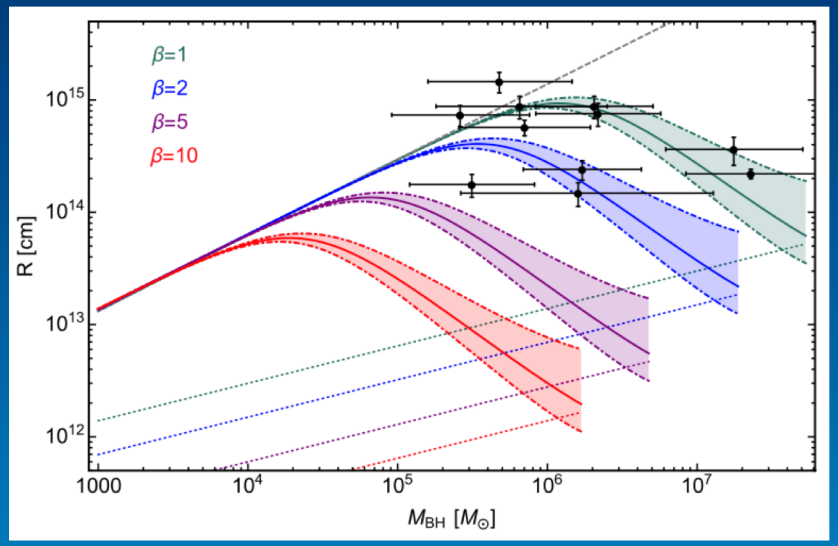
TOO BIG OPTICAL EMISSION REGION

$T_{opt\text{-}UV}$=(2-4) 10^4K;

$R_{opt\text{-}uv}$= $100r_t$!!!



ASASSAN-14li Brown et al. 2017



Wevers et al. 2017

Possibilities:

reprocessed emission (e.g., Loeb & Ulmer 1997 Metzger & Stone 2016)

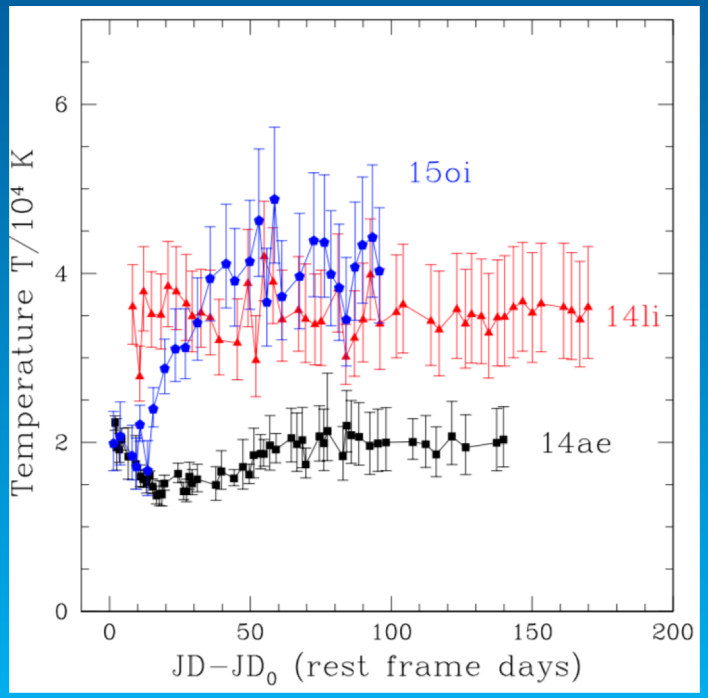
powered by collision of falling back debris (Piran 2015)

UNIQUE TEMPERATURE EVOLUTION

Constant color temperature (after initial rising or decreasing)

AGN颜色随光度升高变蓝

SN颜色随时间变红（例外：SN-IIP， Plateau4000-6000K之外）



Holoien et al. 2016

TOO LOW EVENT RATE?

theoretical predictions: 10^{-4} gal^{-1} yr^{-1} for $M_{BH}<10^{7.5}M_{sun}$ in relaxed galaxies: loss cone re-filling

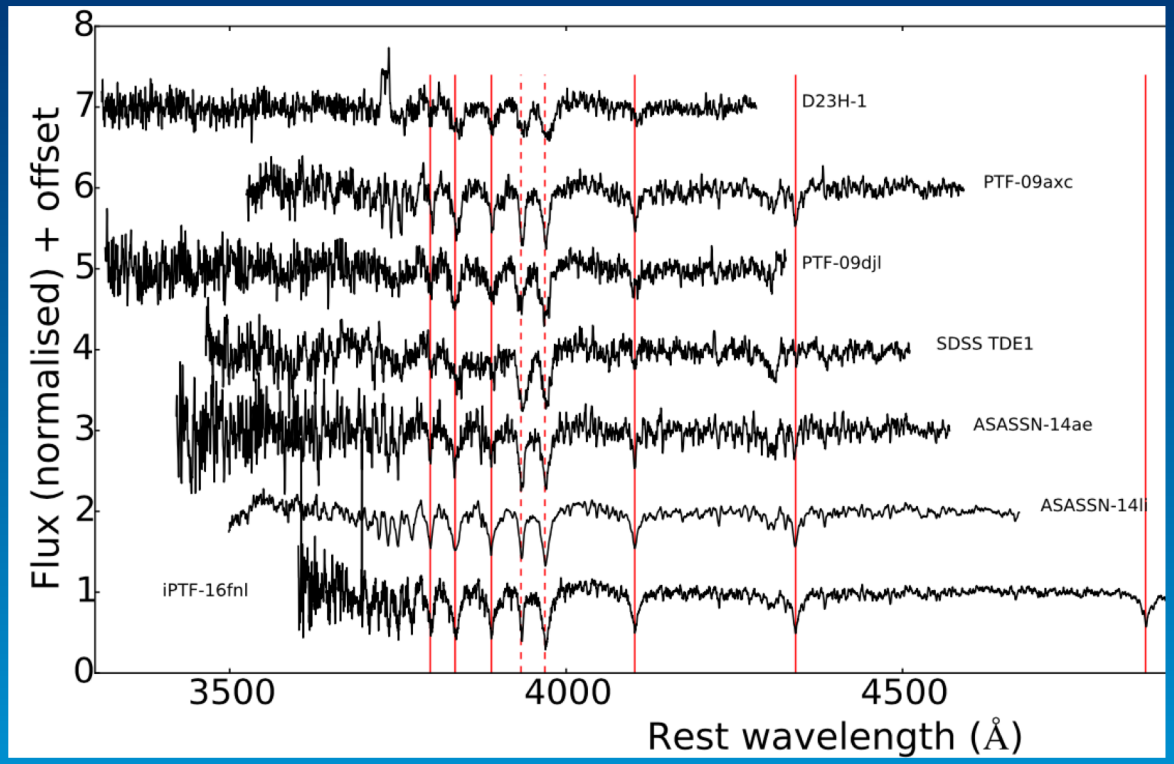
Merritt 13;Magorrian & Tremaine 99; Wang & Merritt 04; Merritt & Wang 05; Brockamp, Baumgardt & Kroupa 11; Vasiliev & Merritt 13; Kedsen 14 ;Stone & Metzger 16

Observed: optical discovered TDE, 10^{-5} gal^{-1} yr^{-1}

Donley et al. 2002; Gezari et al. 2008; van Velzen & Farrar 2014 Holoien et al. 2016 ; c.f., Hung et al. 2017

possibilities: obscured TDEs, optical TDE sample are strongly biased, slowed TDE, weak reprocessor

PREFERENCE OF E+A



by a factor of 30-100 Arcavi et al. 2016,French et al. 2017

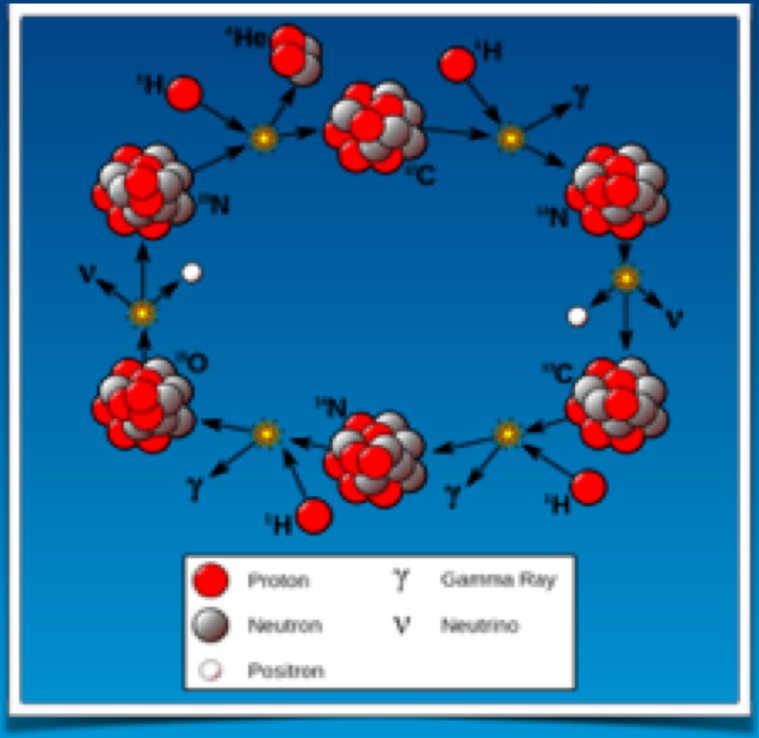
High stellar density; anisotropic velocity field; massive perturber; binary black holes in merged systems;

HOW TO DISTINGUISH AGN VARIABILITY FROM TDE

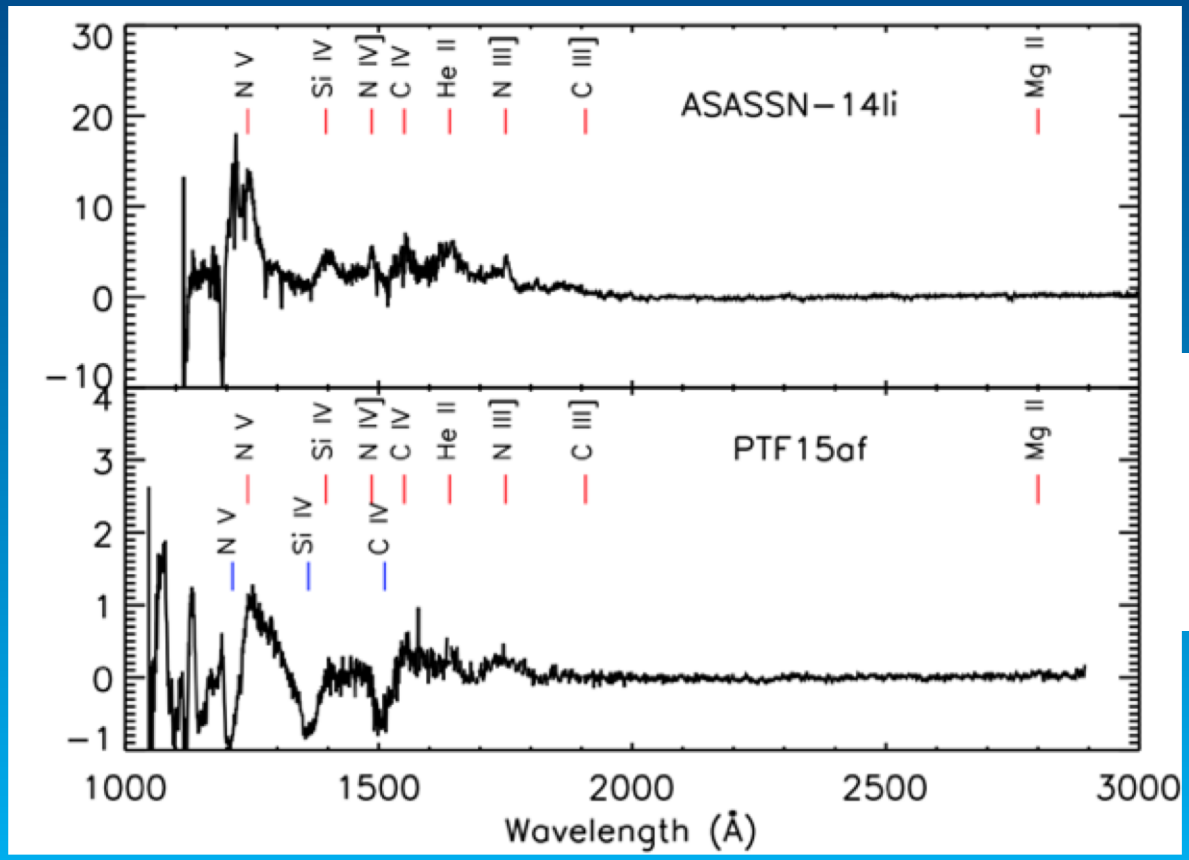
- Light curve / time scale?

  yes / no

- Chemical signature 【N/C]



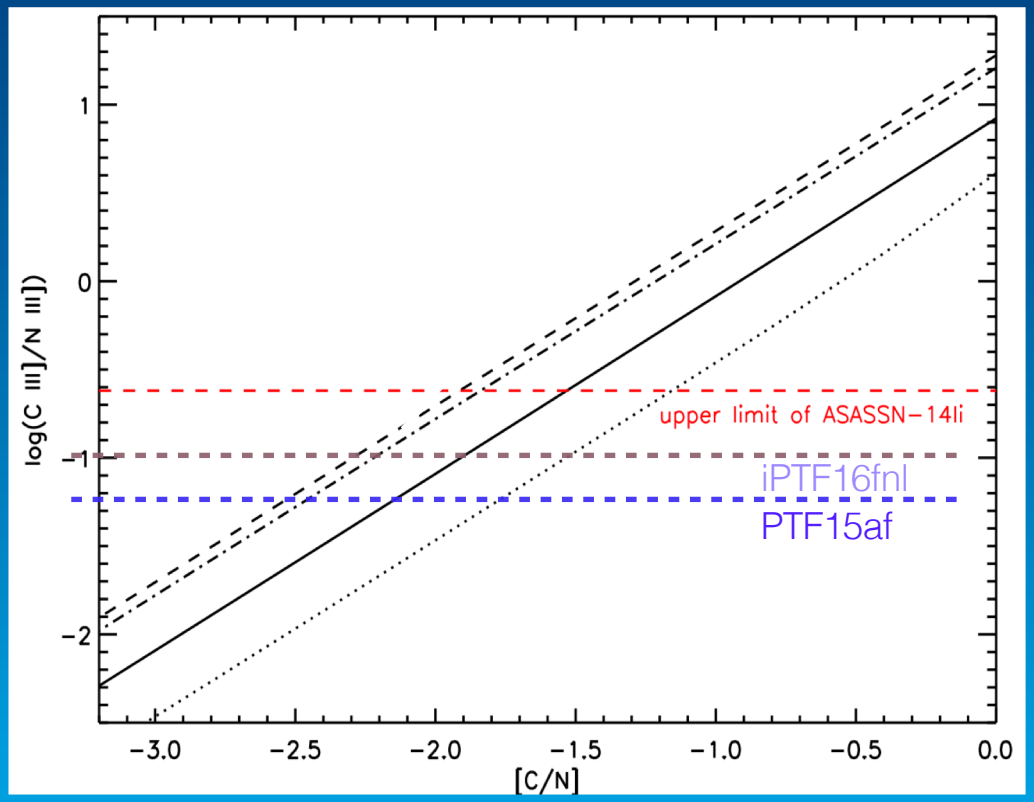
NIII] AND NV ENHANCEMENT



Cenko et al 2016
Yang ***WTG***, et al 2017

object	log(N iii]/C iii])
ASASSN-14li	>0.62
PTF15af	>1.21
iPTF16fnl	>0.97

NIII]/CIII] AS DIAGNOSTIC OF N/C



N/C is 30-100 times of the solar value, qualitatively support disruption of star

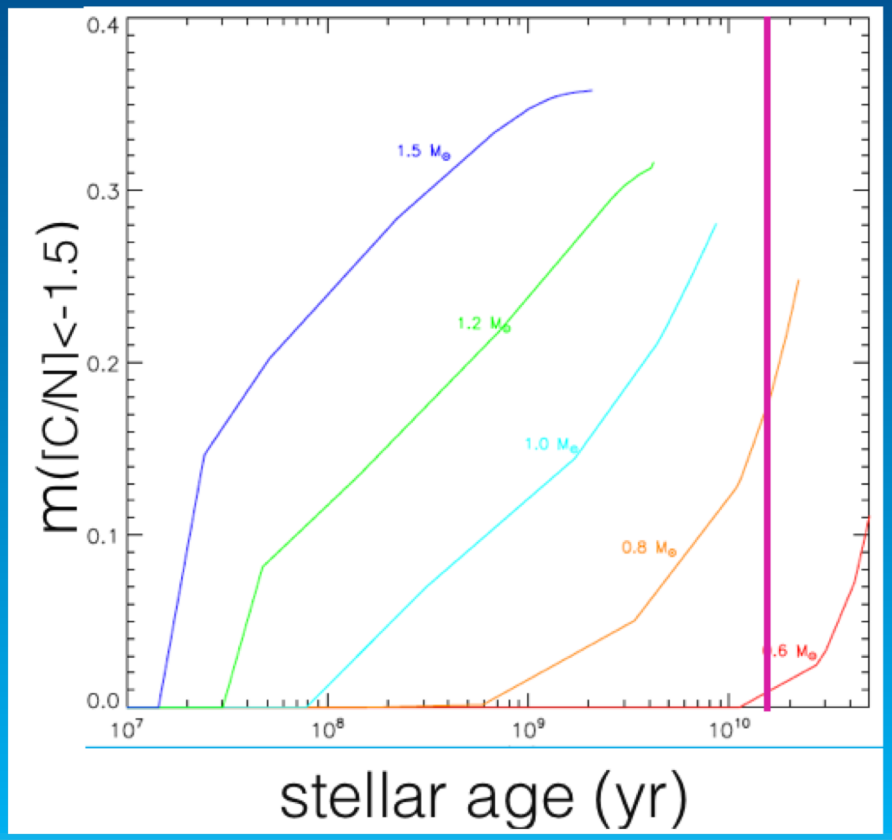
Yang et al. 2017

CONSTRAINTS ON DISRUPTED STAR AND ORIGIN OF BLR

ASSAN-14li

age of universe

Yang et al. 2017



- For ASASSN 14-Li, disrupted star must have a mass >0.6 Msun
- Lower limits on other two TDEs should be even higher
- Theoretical prediction: most probable 0.3Msun Kochanek et al 2016
- BLR is made of debris of stellar core fall-back at late time