JETS AND WINDS FROM TIDAL DISRUPTION EVENTS

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JSI Winds Workshop, Oct 13. 2023

Thanks to the VLASS and the ZTF TDE teams, in particular Vikram Ravi, Dillon Dong, Erica Hammerstein, Gregg Hallinan, Wenbin Lu, and Yuhan Yao

WHAT IS A TIDAL DISRUPTION EVENT (TDE)?

- Star is scattered onto orbit with pericenter smaller than the tidal radius

$$R_T \approx 0.5\ \mathrm{AU}\ r_* m_*^{-\frac{1}{3}} M_6^{\frac{1}{3}}$$

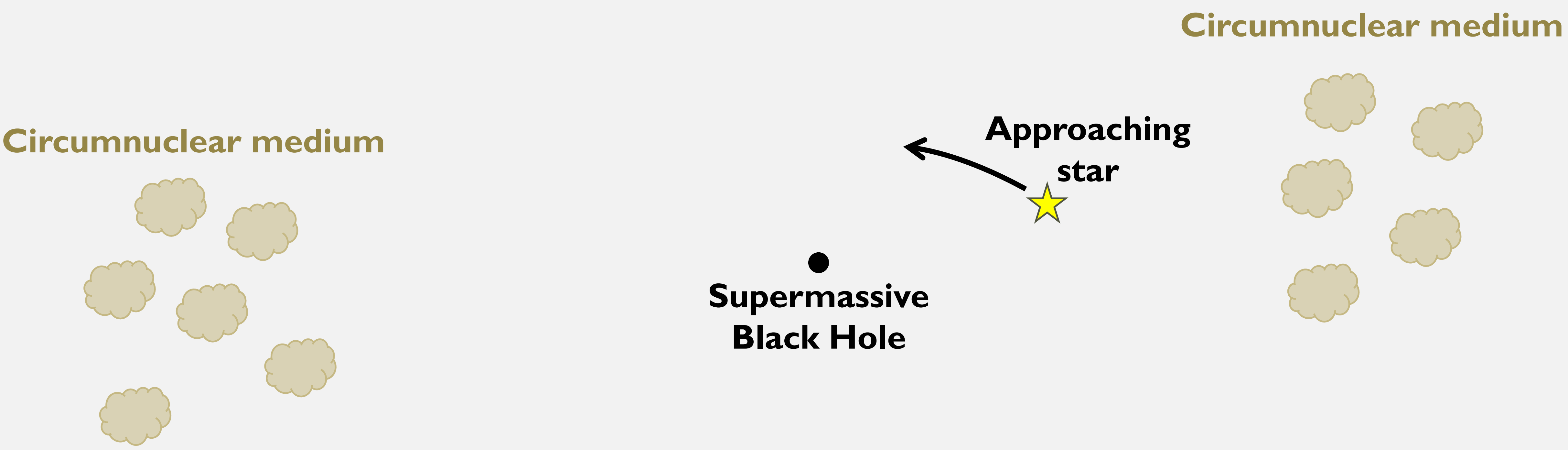
  $\longrightarrow$ star is shredded

- Temporarily turns on accretion
  $\longrightarrow$ illuminate quiescent massive black holes (MBHs)
- Only occur for $M_{BH} \lesssim 10^8\ M_\odot$

WHY DO WE STUDY TDES?

- Identify black holes in non-active, distant galaxies
- Measure black hole masses (hopefully?)
- Probes of accretion disk physics: one of the only ways to watch
  - ⟶ the real-time formation of accretion disks,
  - ⟶ the phases of supermassive BH accretion (super- to sub-Eddington)
- Study the circumnuclear medium in non-active, distant galaxies
- ***Study the launch of jets/winds from accretion disks***

EVOLUTION OF A TDE:
INITIAL DISRUPTION



Komossa & Bade 1999, Esquej+2007, Piran+2015, Miller+2015, Lu+2016, Krolik+2016, Lu & Bonnerot 2020

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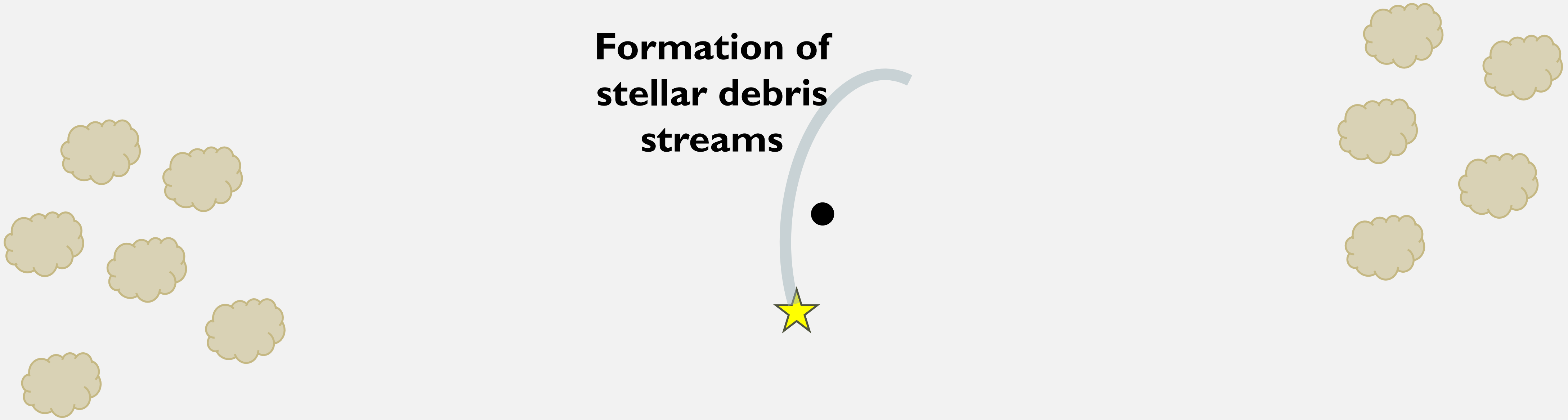

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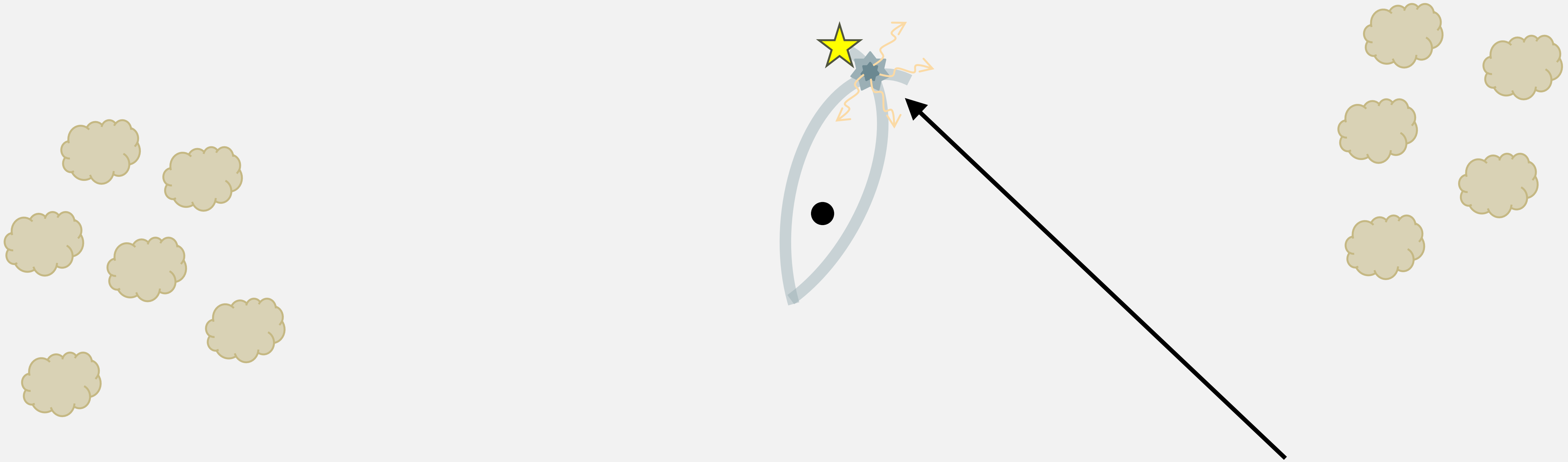
EVOLUTION OF A TDE:
DEBRIS STREAM SHOCKS

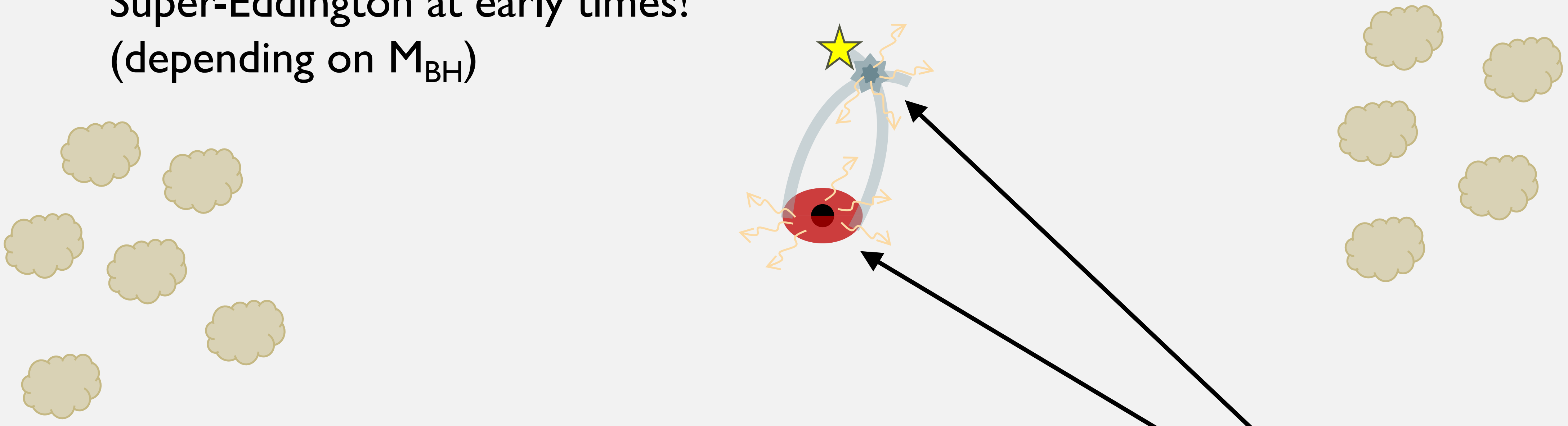


X-ray/EUV (+some optical?) – shocking stellar debris

Komossa & Bade 1999, Esquej+2007, Piran+2015, Miller+2015, Lu+2016, Krolik+2016, Lu & Bonnerot 2020

EVOLUTION OF A TDE: DISK FORMATION

Super-Eddington at early times!
(depending on M_{BH})

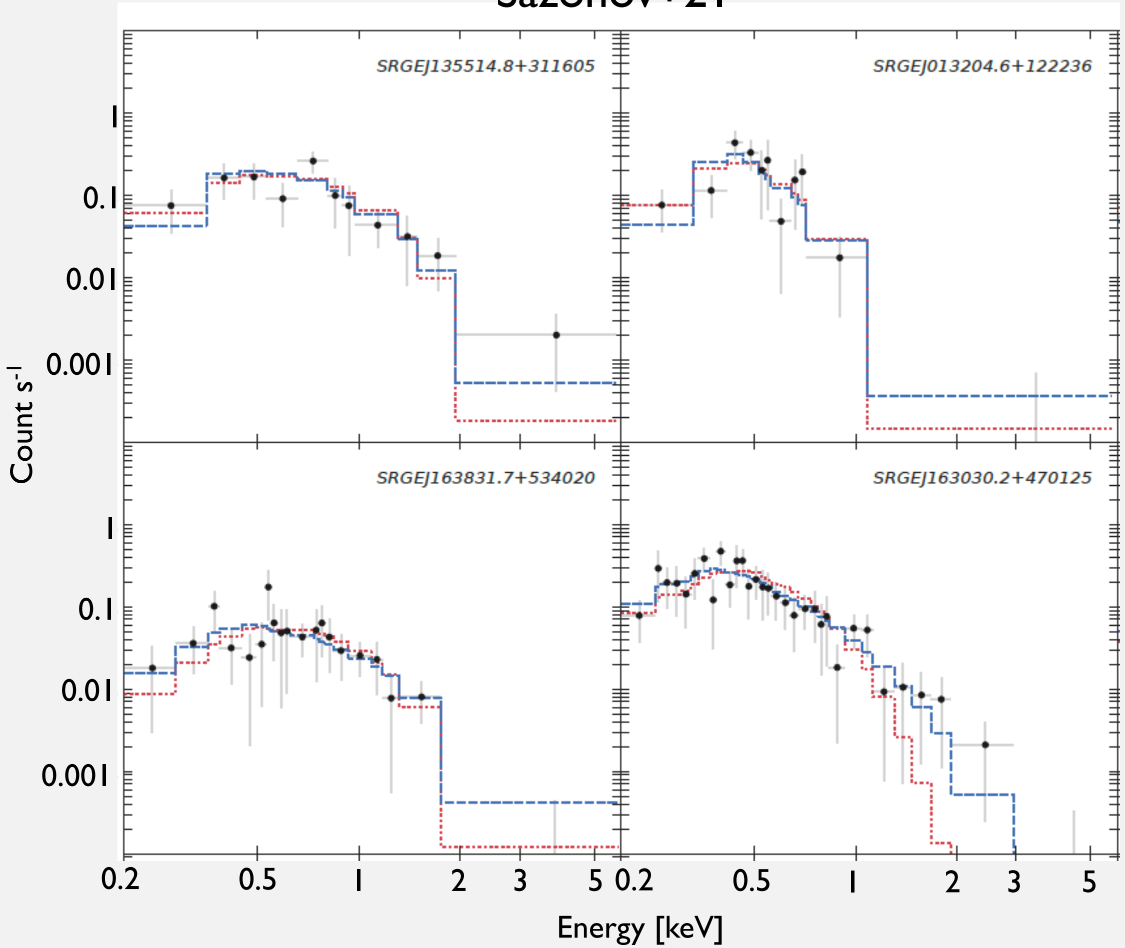


X-ray/EUV (+some optical?) – shocking stellar debris
+ accretion disk

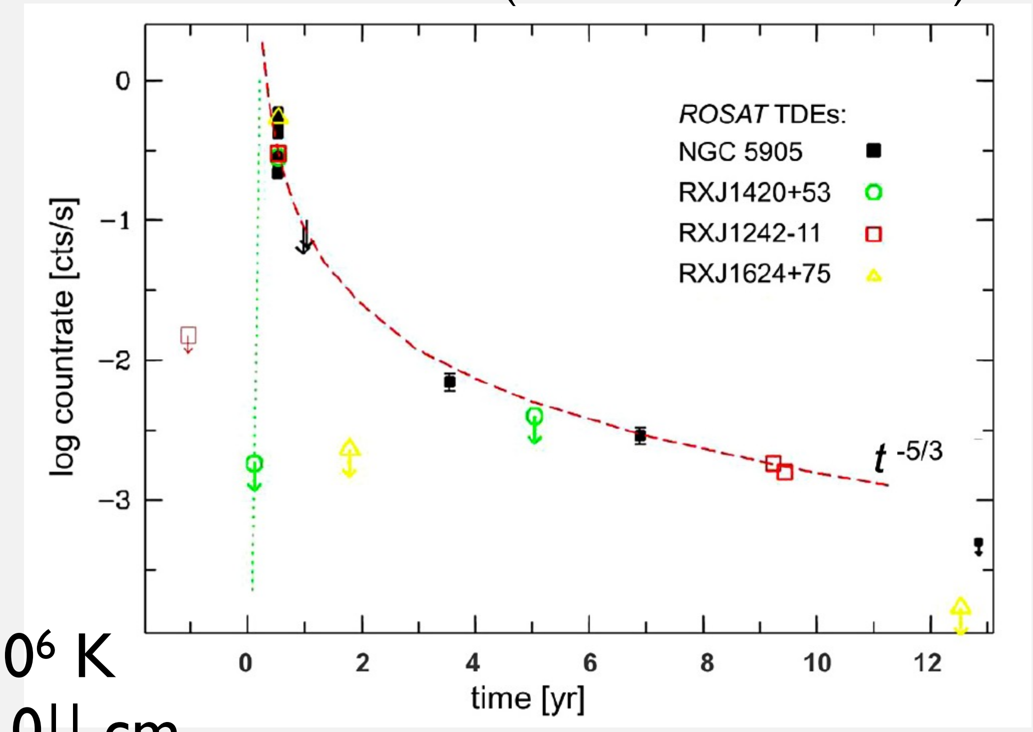
Komossa & Bade 1999, Esquej+2007, Piran+2015, Miller+2015, Lu+2016, Krolik+2016, Lu & Bonnerot 2020

EVOLUTION OF A TDE: DISK FORMATION

Sazonov+21



Saxton+22 (and references therein)



⟶ Tbb ~ 10^6 K

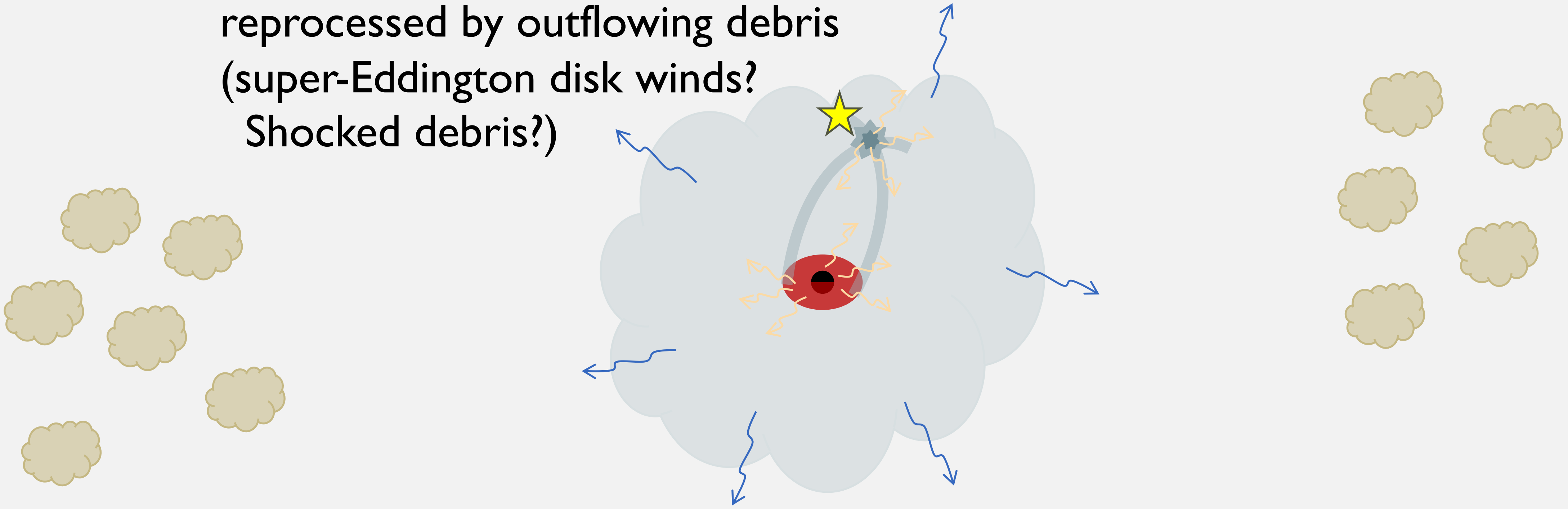
⟶ Rbb ~ 10^{11} cm

⟶ Wide range of properties (spectral transitions, variability, delayed turn on…)

Komossa & Bade 1999, Esquej+2007, Piran+2015, Miller+2015, Lu+2016, Krolik+2016, Lu & Bonnerot 2020

EVOLUTION OF A TDE: REPROCESSING ENVELOPE

Optical/UV – X-ray/EUV emission reprocessed by outflowing debris (super-Eddington disk winds? Shocked debris?)



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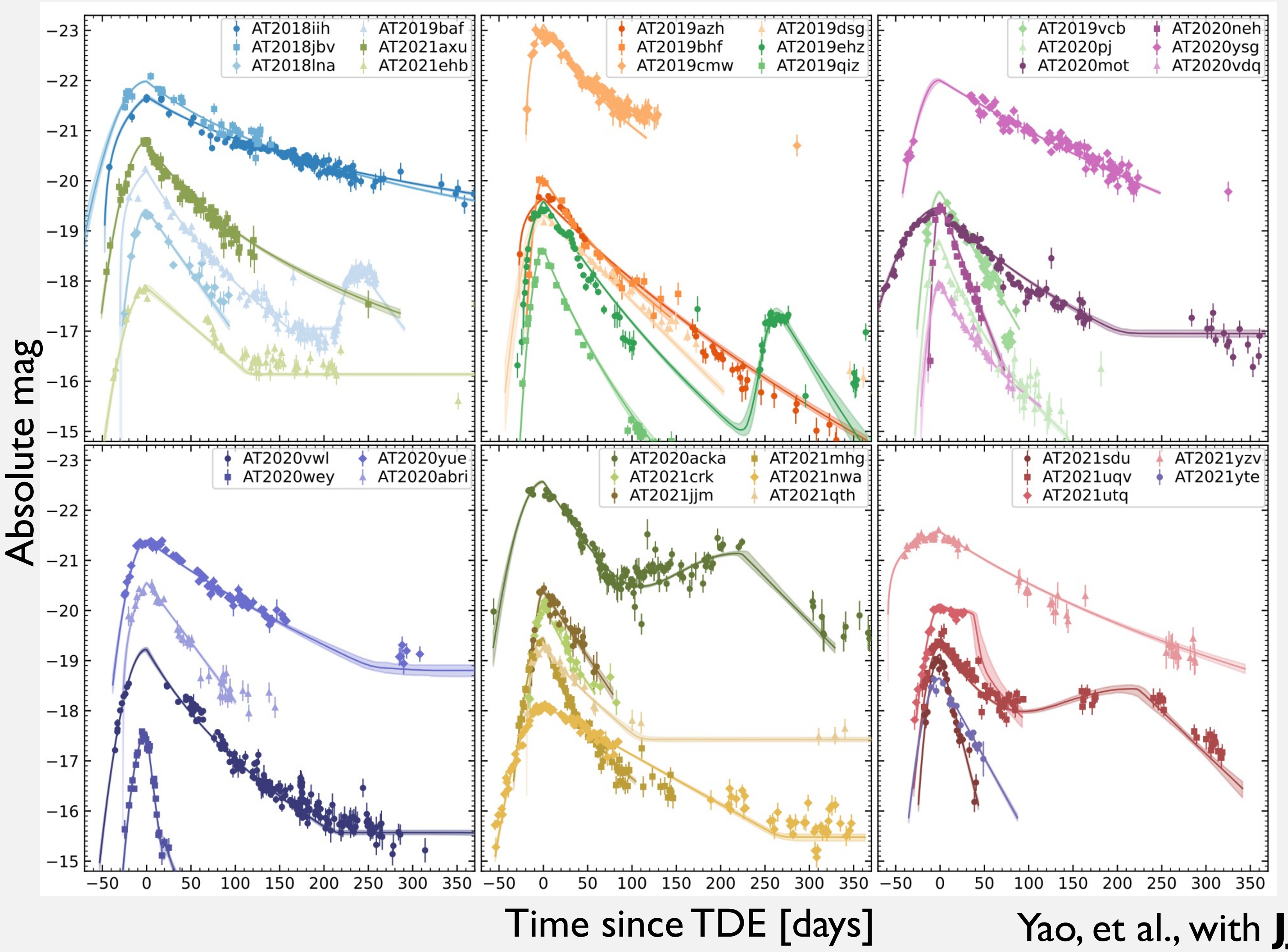
EVOLUTION OF A TDE: REPROCESSING ENVELOPE



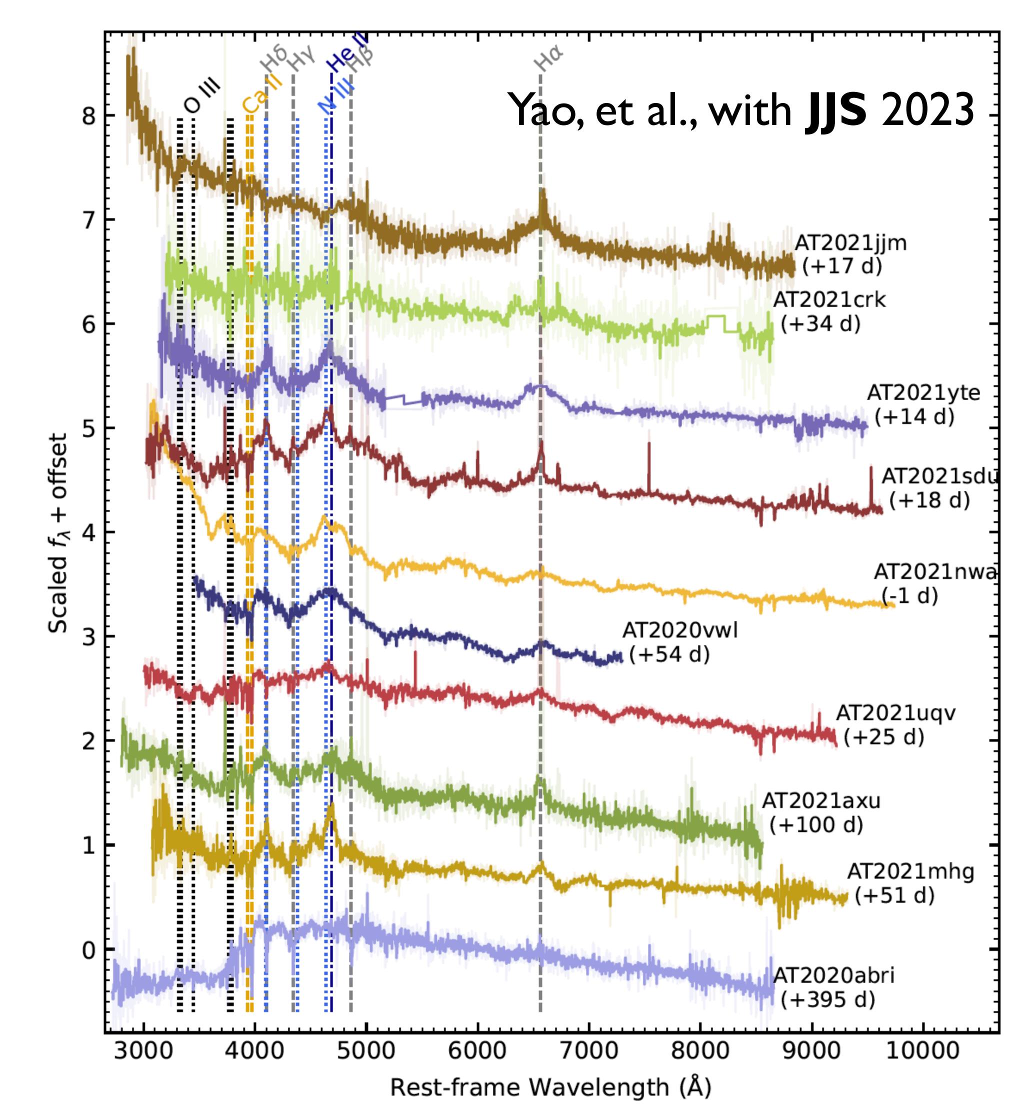
Yao, et al., with **JJS** 2023

→ T_{bb} ~ 10^4 K
→ R_{bb} ~ 10^{14} cm

~weeks rise and ~months decays

A range of late time behavior (plateau, rebrightening, fade)

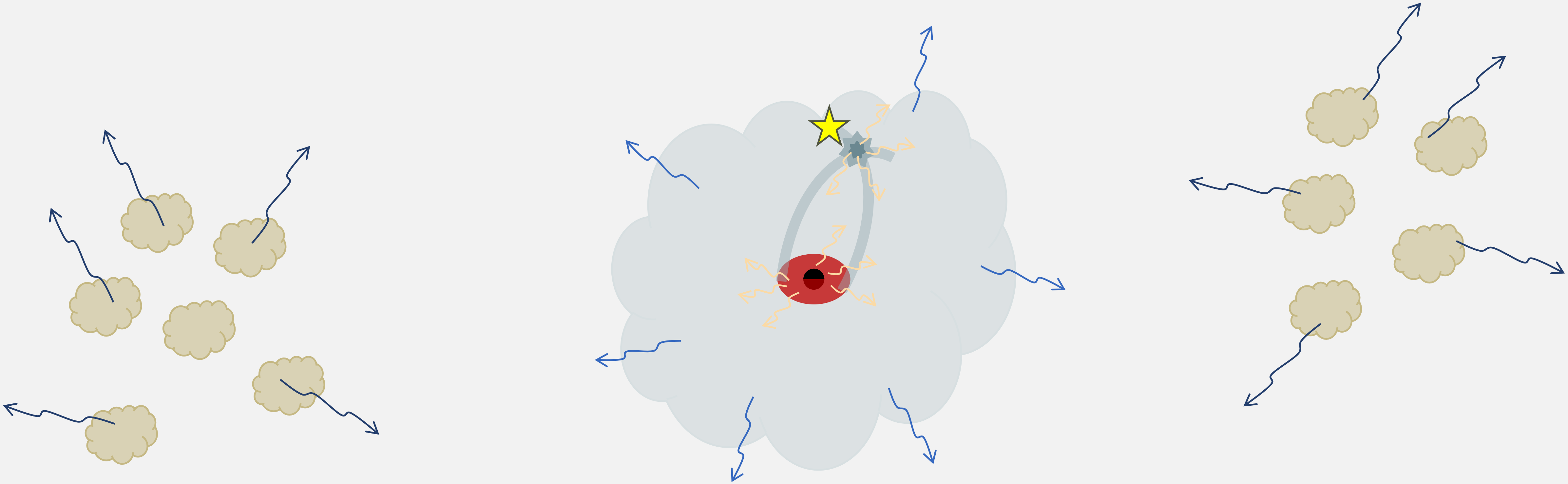
EVOLUTION OF A TDE: REPROCESSING ENVELOPE



⟶ Tbb ~ 10^4 K
⟶ Rbb ~ 10^{14} cm

Often associated with transient spectral lines
⟶ 10^4 km s^{-1} Balmer and He, fades within ~a year

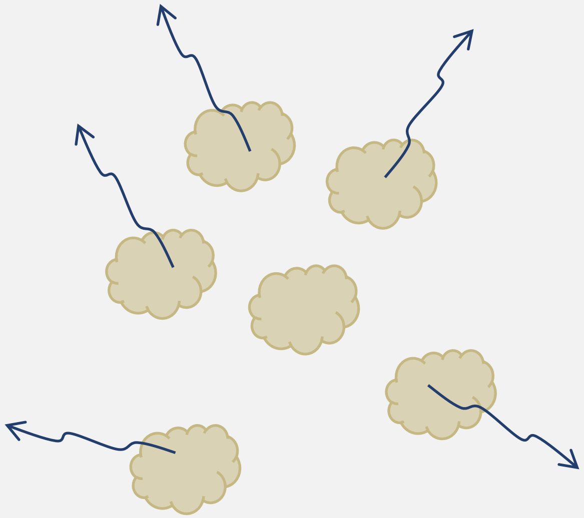
EVOLUTION OF A TDE: THE ROLE OF THE GALAXY



IR "dust echo"

Komossa & Bade 1999, Esquej+2007, Piran+2015, Lu+2016, Krolik+2016, Lu & Bonnerot 2020

EVOLUTION OF A TDE: THE ROLE OF THE GALAXY



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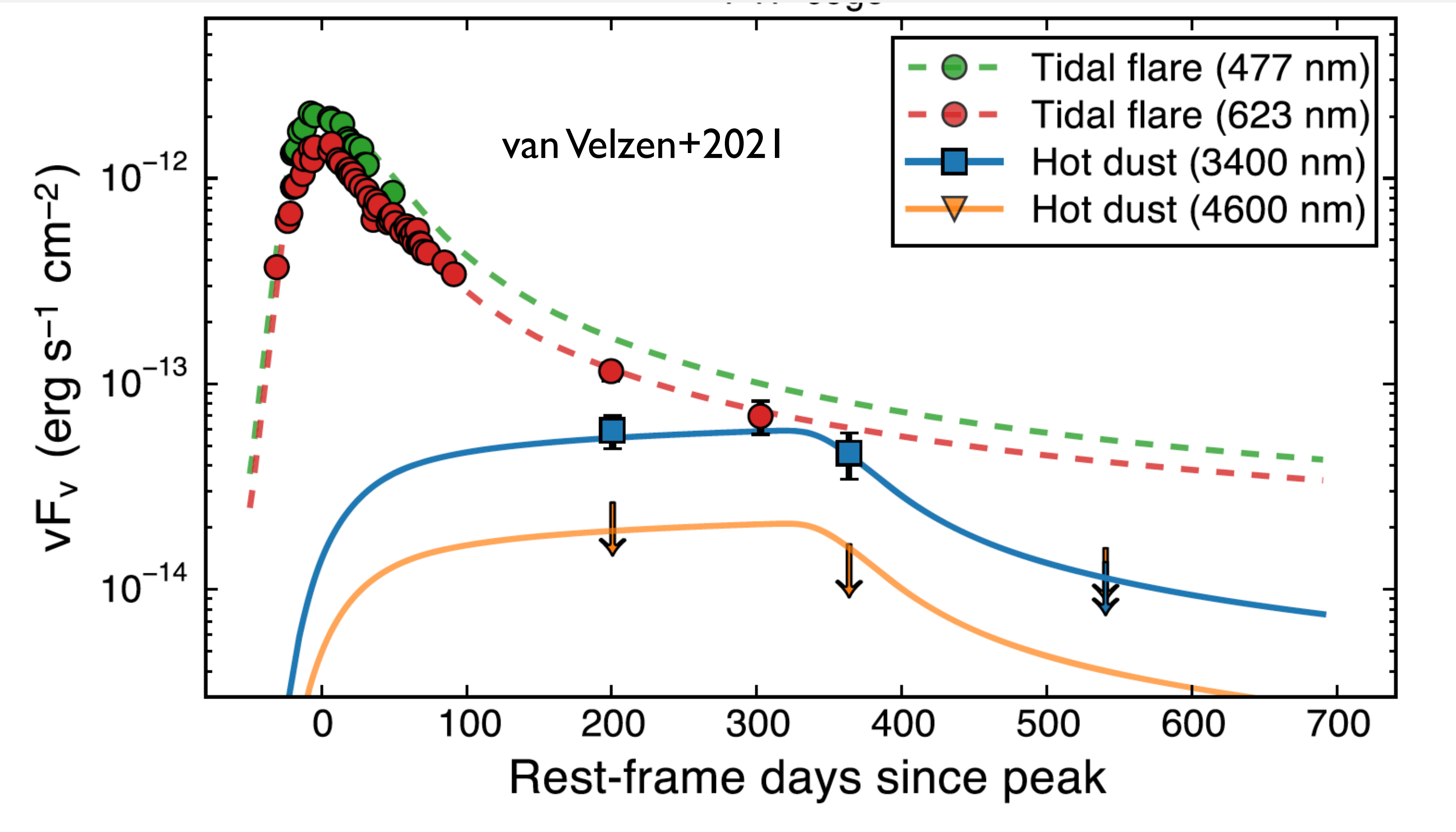

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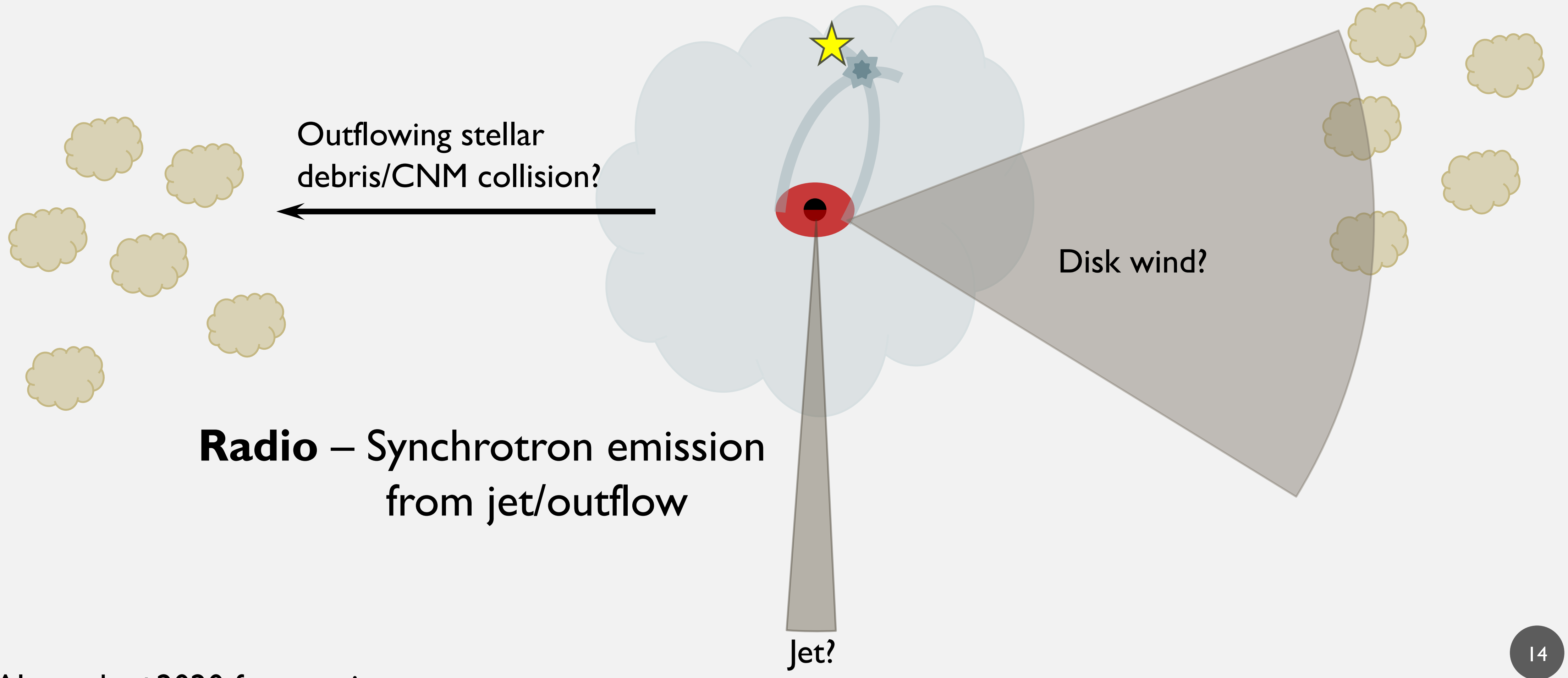
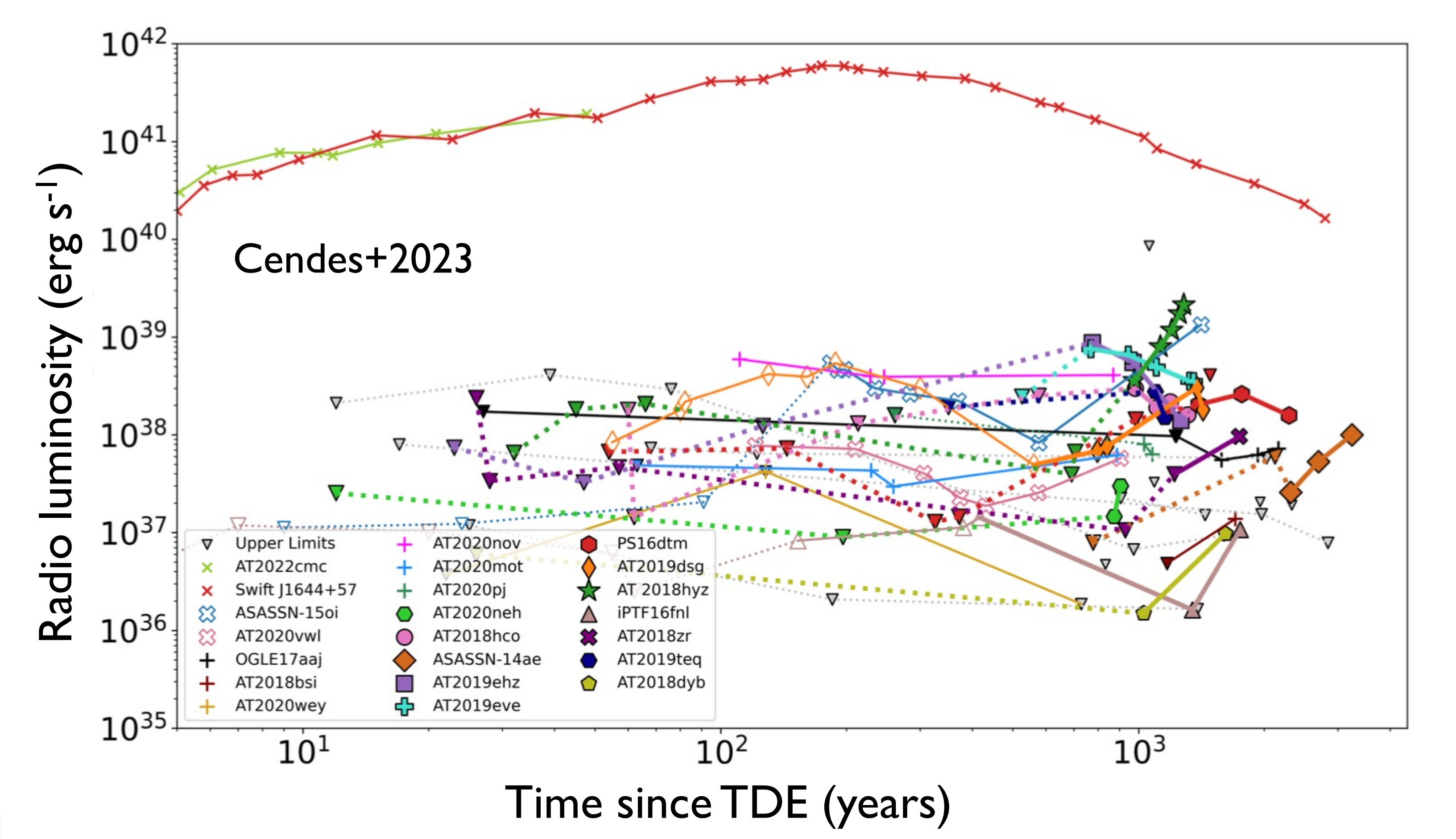
EVOLUTION OF A TDE: WINDS AND JETS



Radio – Synchrotron emission from jet/outflow

See Alexander+2020 for a review

EVOLUTION OF A TDE: WINDS AND JETS



No consensus on the origin of the emission!

See Alexander+2020 for a review

OPEN QUESTIONS

- Where does the optical/UV emission come from?

  $\longrightarrow$ disk winds? related to super-Eddington accretion

  Peter Kosec's talk

  $\longrightarrow$ outflows launched during shocks?

- What fraction of TDEs launch radio-emitting outflows?

  $\longrightarrow$ jets vs winds?

- How do TDEs launch radio-emitting jets? winds?

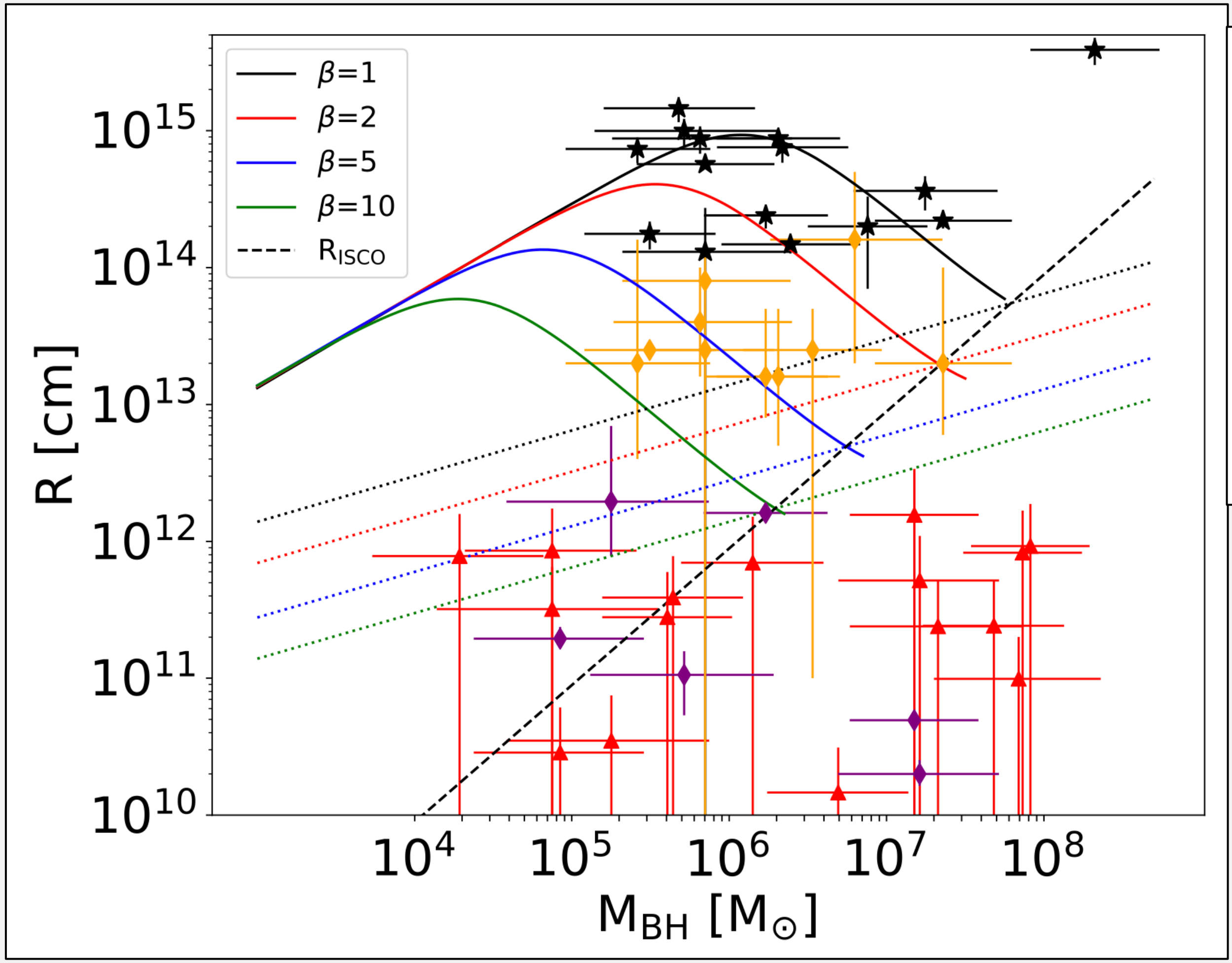
  $\longrightarrow$ Is there an X-ray binary like disk-jet connection?

Small scales ($\lesssim 10^{16}$ cm)

Large scales ($\gtrsim 10^{16}$ cm)

(and, of course, many others unrelated to winds!)

WINDS AND JETS FROM TDES:
EVIDENCE FROM OPTICAL BROADBAND EMISSION



Black – optical TDE observations
Orange – UV observations
Red/purple – X-ray

Solid lines – self intersection radius
Dashed line – ISCO radius

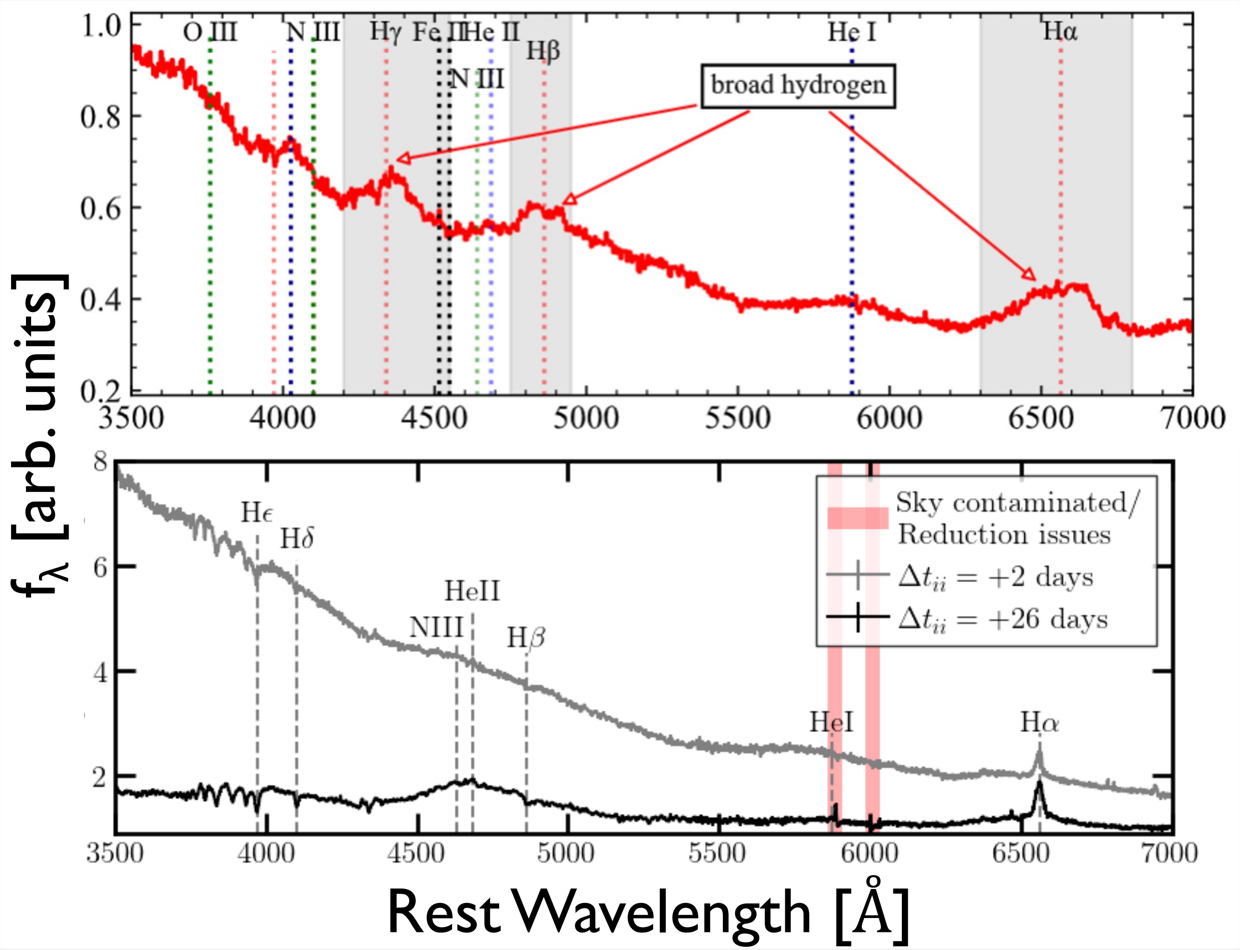
Optical emission cannot be disk

$\longrightarrow$ too cool

$\longrightarrow$ radii too big

Wevers+2022

WINDS AND JETS FROM TDES:
EVIDENCE FROM OPTICAL SPECTRA



$\sim 10^4$ km s^{-1} emission lines

$\longrightarrow$ asymmetric profiles

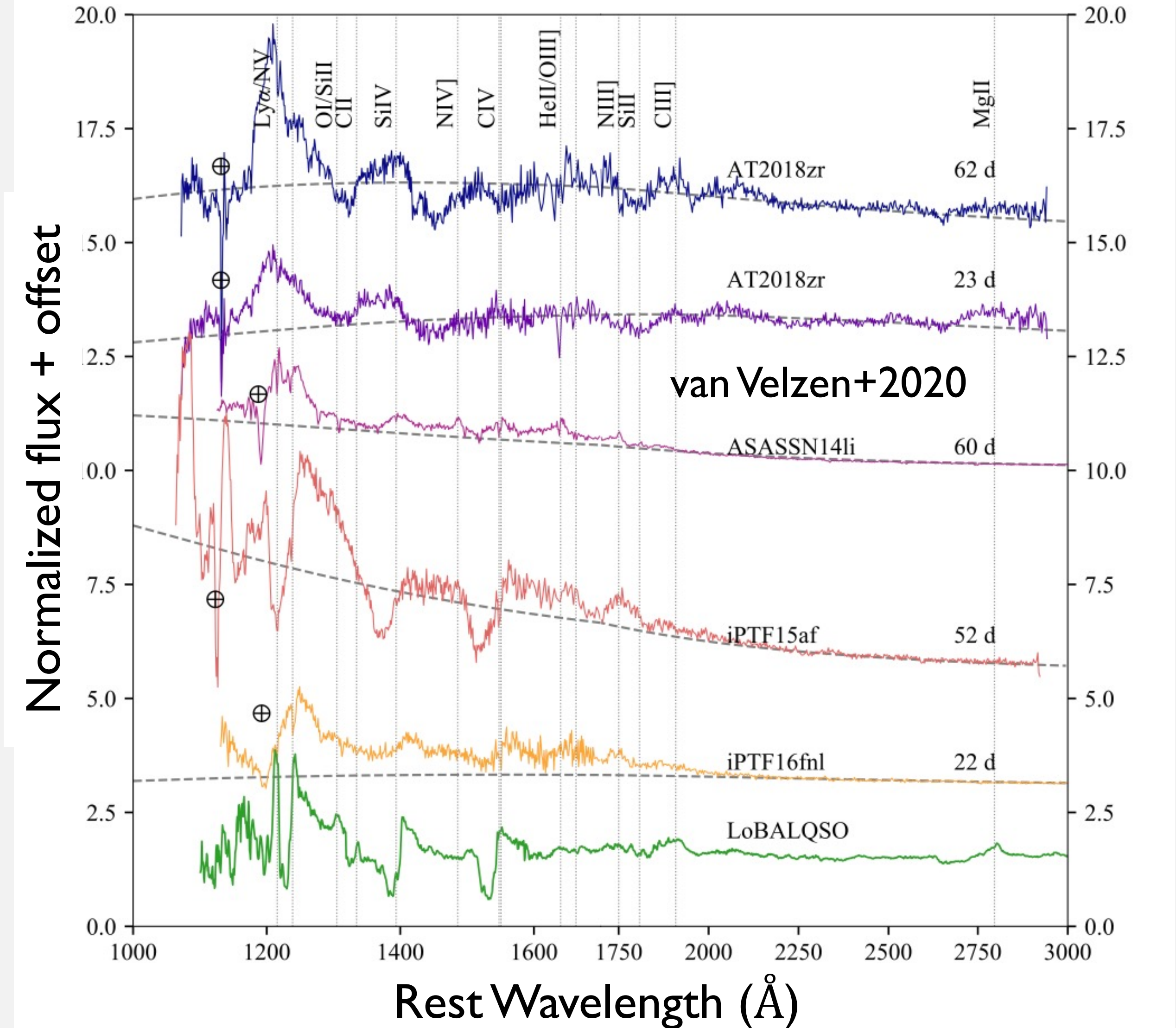
Late time (yrs) $\sim 10^3$ km s^{-1} emission

$\longrightarrow$ asymmetric profiles

$\longrightarrow$ some redshifted centroids

JJS+2023ab (arXiv: 2310.03795, 2310.03782), Hammerstein, et al., with **JJS** 2023 (arXiv:2203.01461)

WINDS AND JETS FROM TDES:
EVIDENCE FROM UV SPECTRA



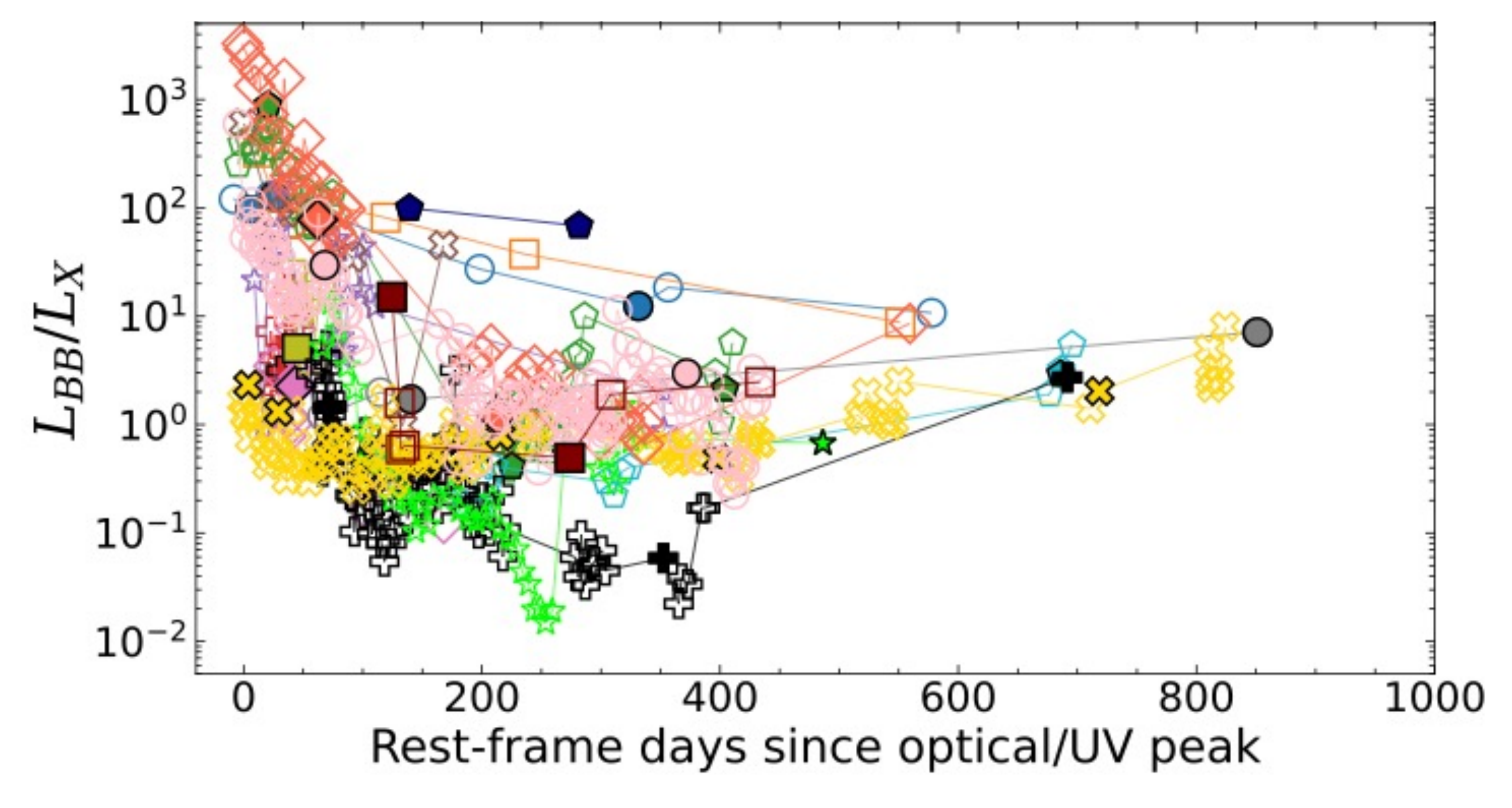
Broad absorption lines (BALs) and broad emission lines (BELs)

⟶ analogous to BAL quasars

⟶ different line ratios

Parkinson+2022, Brown+2018, Blagorodnova+2019, Hung+2020

WINDS AND JETS FROM TDES:
EVIDENCE FROM X-RAY EMISSION



Guolo+2023,

X-ray emission tends to decrease near optical peak

⟶ obscuration by outflow?

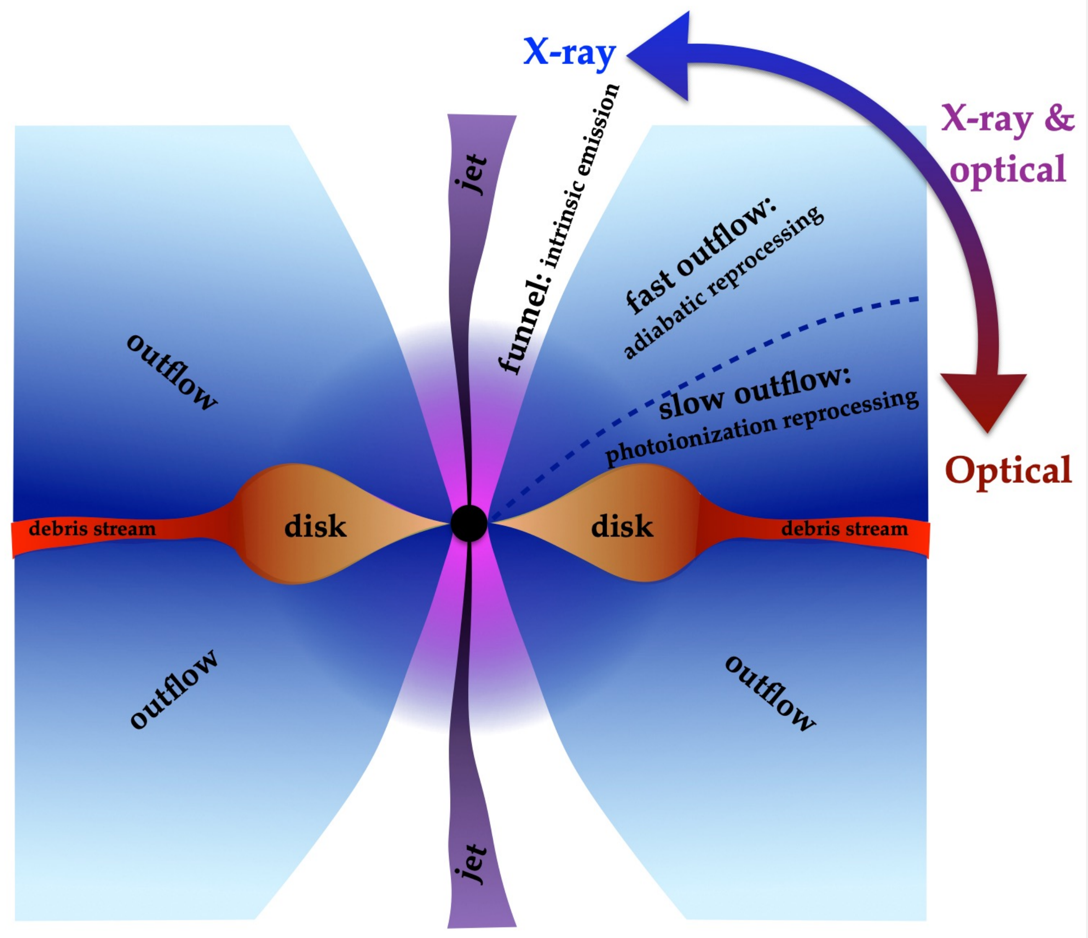
Evidence for winds from spectral features

⟶ see Peter Kosec's talk

WINDS AND JETS FROM TDES: MODELS FOR UV/OPTICAL/X-RAY

Broadband emission from:

shocking debris streams	accretion disk surrounded by outflow
⟶ delayed disk formation? ⟶ may not happen for low M_{BH}	⟶ viewing angle effects ⟶ outflow from super-Eddington disk? debris stream shocks? both?



Broad lines produced in outflow:

⟶ viewing angle matters
⟶ sensitive to outflow properties and/or electron scattering optical depth

Lu & Bonnerot 2019, Dai+2018, Steinberg & Stone 2022, Metzger 2022

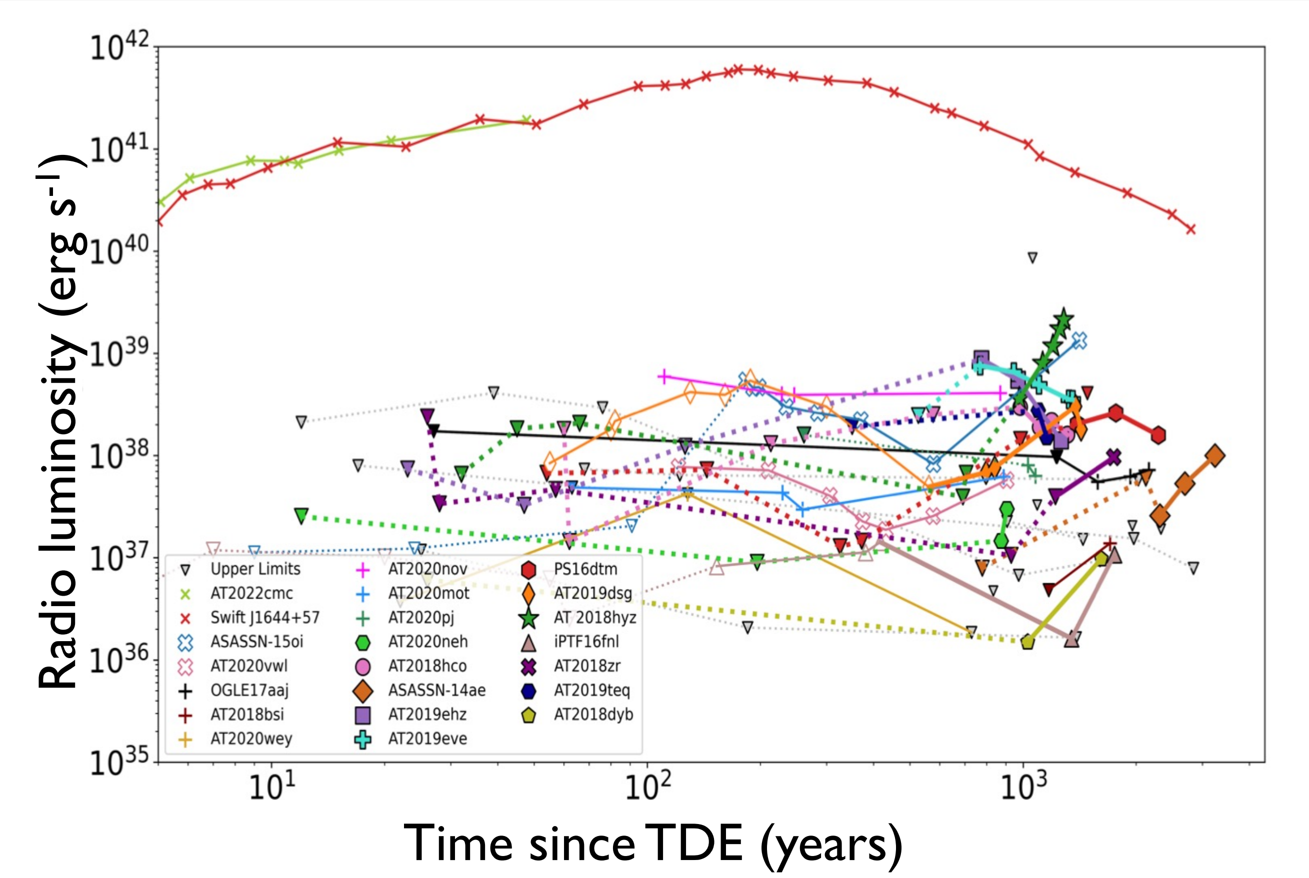
WINDS AND JETS FROM TDES:
EVIDENCE FROM RADIO (FOLLOW-UP)

Radio follow-up of optically-selected TDEs

(Cendes+2023):

- >40% of optical TDEs emit in radio
- delayed by 100-1000s of days
- Typically, non-jetted

  (although see Sfaradi+2023)



Cendes+2023

Observations of on-axis, jetted TDEs

- <0.003% of TDEs are jetted
- Non-thermal emission in radio/X-ray/gamma-ray

Andreoni+2023, Yao+2023, Pasham+2023

WINDS AND JETS FROM TDES: EVIDENCE FROM RADIO (SURVEYS)

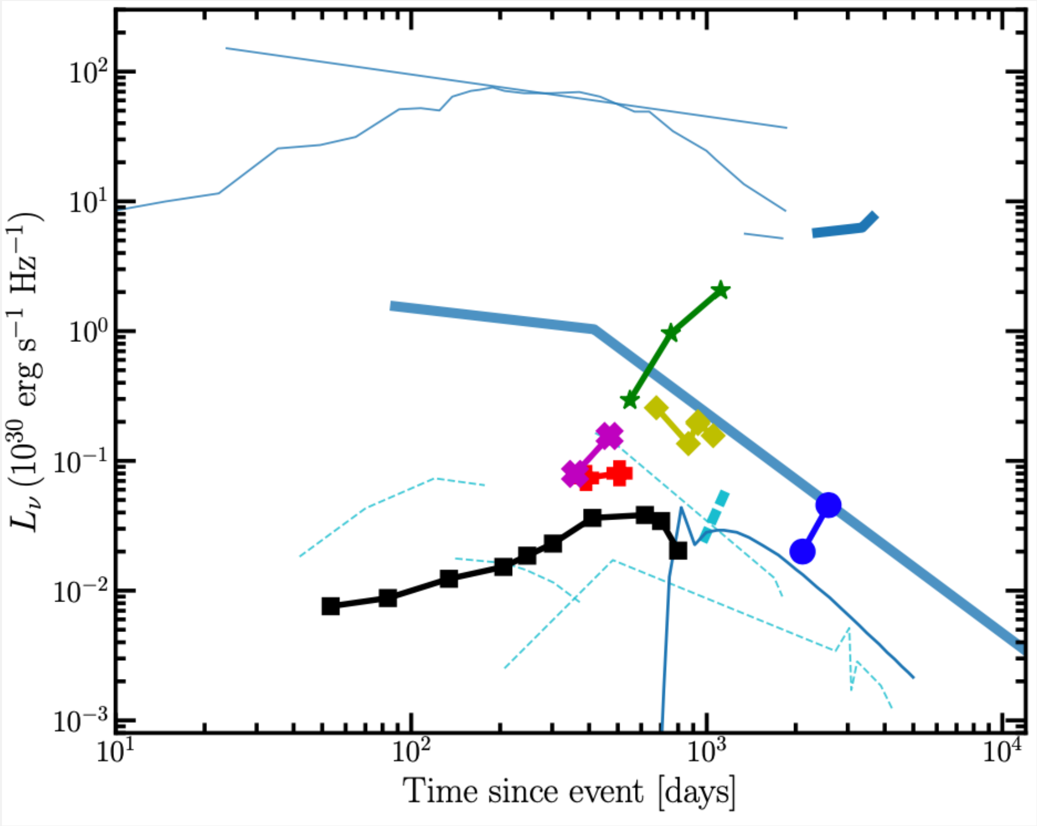
Untriggered radio TDE searches may probe new populations

- Currently VLA Sky Survey (3GHz), ASKAP/VAST (1.4GHz)
- Eventually DSA 2000 (1.4GHz), ngVLA, etc

TDEs can be identified as

- Radio transients
- in galactic nuclei with no AGN
- easier with a multiwavelength counterpart, but not necessary

⟶ has been done in the VLA Sky Survey with ~3yr time baseline

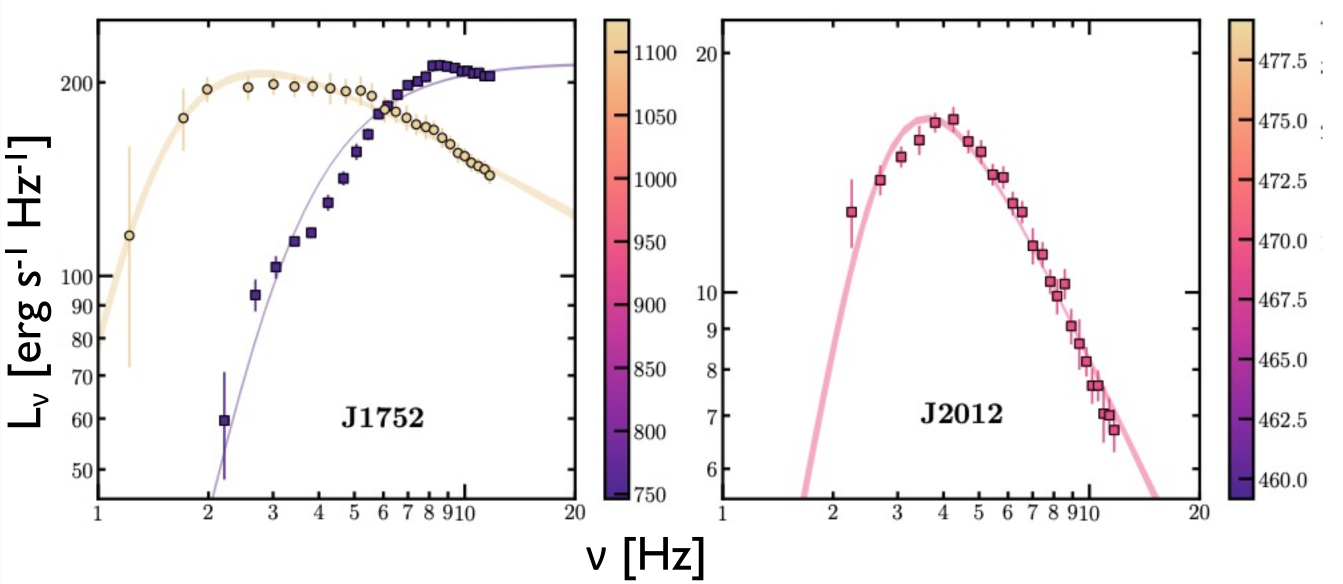


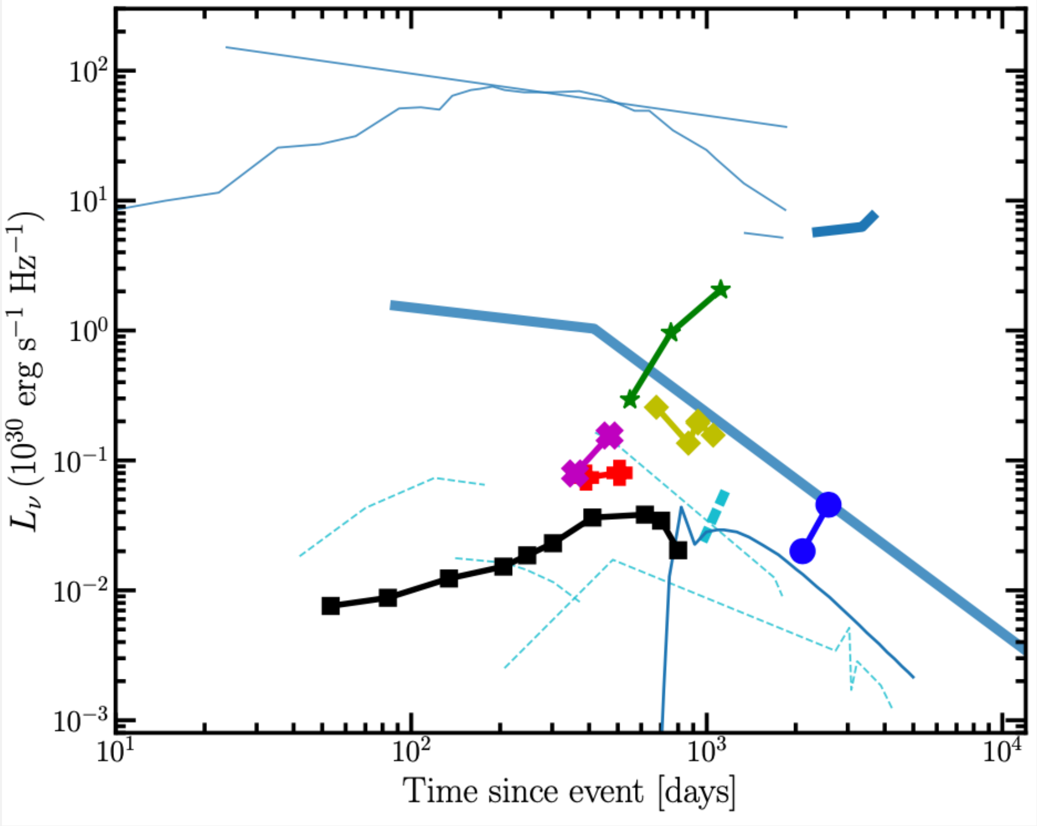
JJS+2022 (arXiv:2108.12431), **JJS**+2023c (arXiv:2310.03791)

WINDS AND JETS FROM TDES:
EVIDENCE FROM RADIO (SURVEYS)

Radio-selected, optically-detected TDEs are

- >10% of optical TDE rate
- Prefer lower mass MBHs
- Associated with cool/faint optical flares
- Mix of possible jets/winds





JJS+2023c (arXiv:2310.03791)

WINDS AND JETS FROM TDES: EVIDENCE FROM RADIO (SURVEYS)

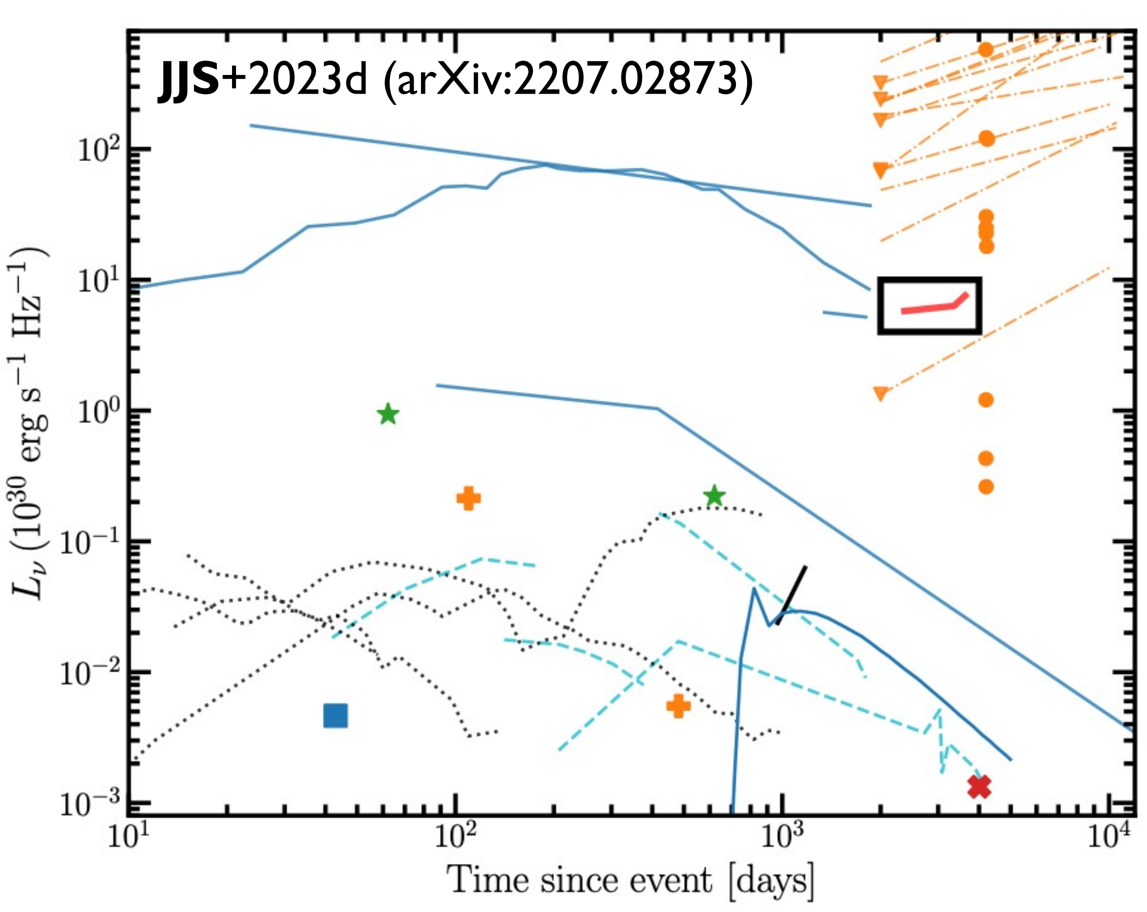
Longer timescale emission present (~decade transients)

$\longrightarrow$ jets with energy injection

Compact symmetric objects:

- A subset of jetted AGN with O(100 pc) symmetric jets
- Kiehlmann+2023a,b Readhead+2023a, including **JJS**
  $\longrightarrow$ CSOs are not young jetted AGN

CSOs could be produced by TDEs of massive and/or evolved stars!



Ravi+2022; Dong, **JJS**, et al. in prep; **JJS**+2023d (arXiv:2207.02873)

WINDS AND JETS FROM TDES:
MODELS FOR RADIO EMISSION

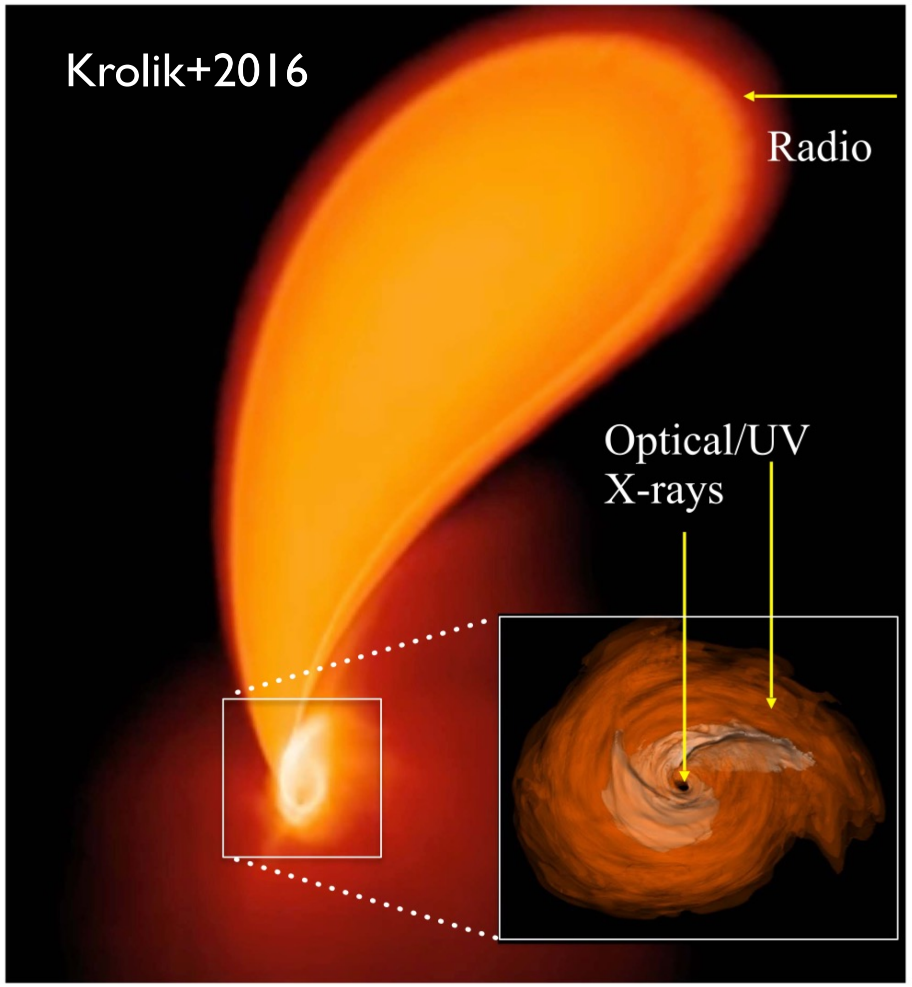
I. $10^{-(1\text{-}2)}$ c outflows from stream-stream collisions
   - ⟶ launched promptly
   - ⟶ expected for higher M_{BH}
   - ⟶ relatively faint

   plausible for early-time radio TDEs

II. Unbound debris colliding with CNM
   - ⟶ velocity ~$10^{3\text{-}4}$
   - ⟶ small amount of fastest mass dominates

   some argue detected for ASASSN-14li

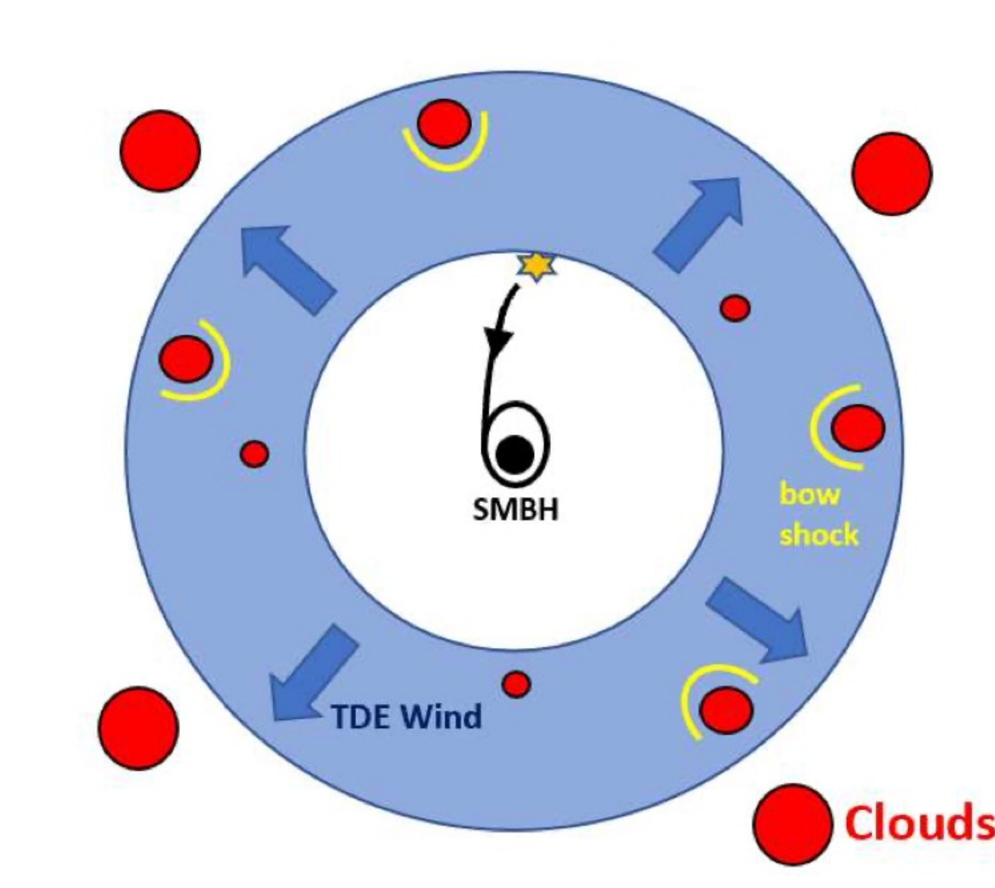
Yalinewich+2019, Lu & Bonnerot 2019, Goodwin+2023, Krolik+2016



WINDS AND JETS FROM TDES: MODELS FOR RADIO EMISSION

III. Super-Eddington accretion induced winds
   ⟶ may be delayed
   ⟶ lower MBH ($M_{BH} \lesssim 10^7\ M_\odot$)
      Possible for some radio-selected TDEs

IV. Jets: how do you launch a jet from a young disk?
   ⟶ seed magnetic field from fossil disk
   ⟶ magnetic field seeded by star
      Possible for some radio-selected TDEs, on-axis jetted TDEs



Tchekhovskoy+2014, Curd+2022, Bu+2023, de Colle 2020

CONCLUSIONS

Winds and jets play a critical role in TDE emission and evolution!

- evidence from X-ray, optical, and UV that super-Eddington disk winds occur
- possible evidence from radio for larger scale super-Eddington disk winds
- evidence from radio that jets can be launched (but the mechanism is not understood)

⟶ *no consensus? Super-Eddington disk winds probably happen, but may not be enough*

Much remains to be understood. We need:

- Systematic radio follow-up of well-motivated TDE sample
- Prompt, deep radio follow-up
- Systematic follow-up of blindly-selected radio TDEs
- Characterization of pre-peak and early time optical/UV emission
- Long term optical spectral series