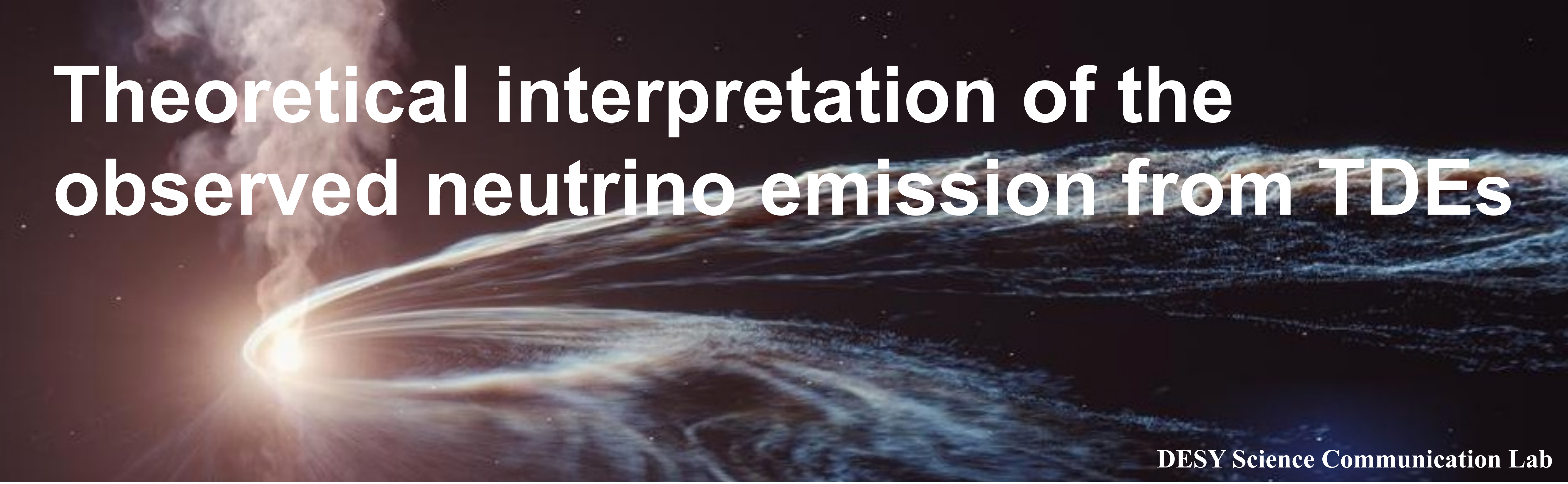
# Theoretical interpretation of the observed neutrino emission from TDEs



DESY Science Communication Lab

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ICRC 2021, originally planned for Berlin, featured by Zeuthen, #online
July 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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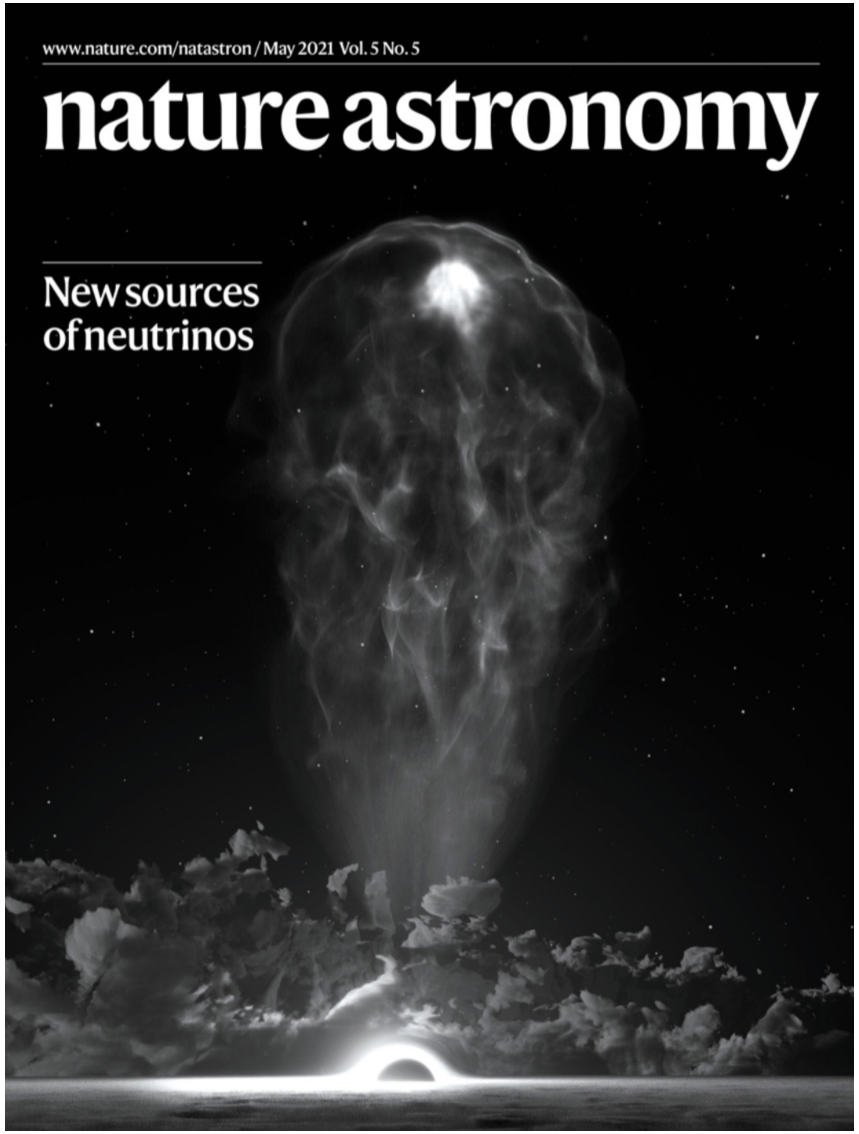
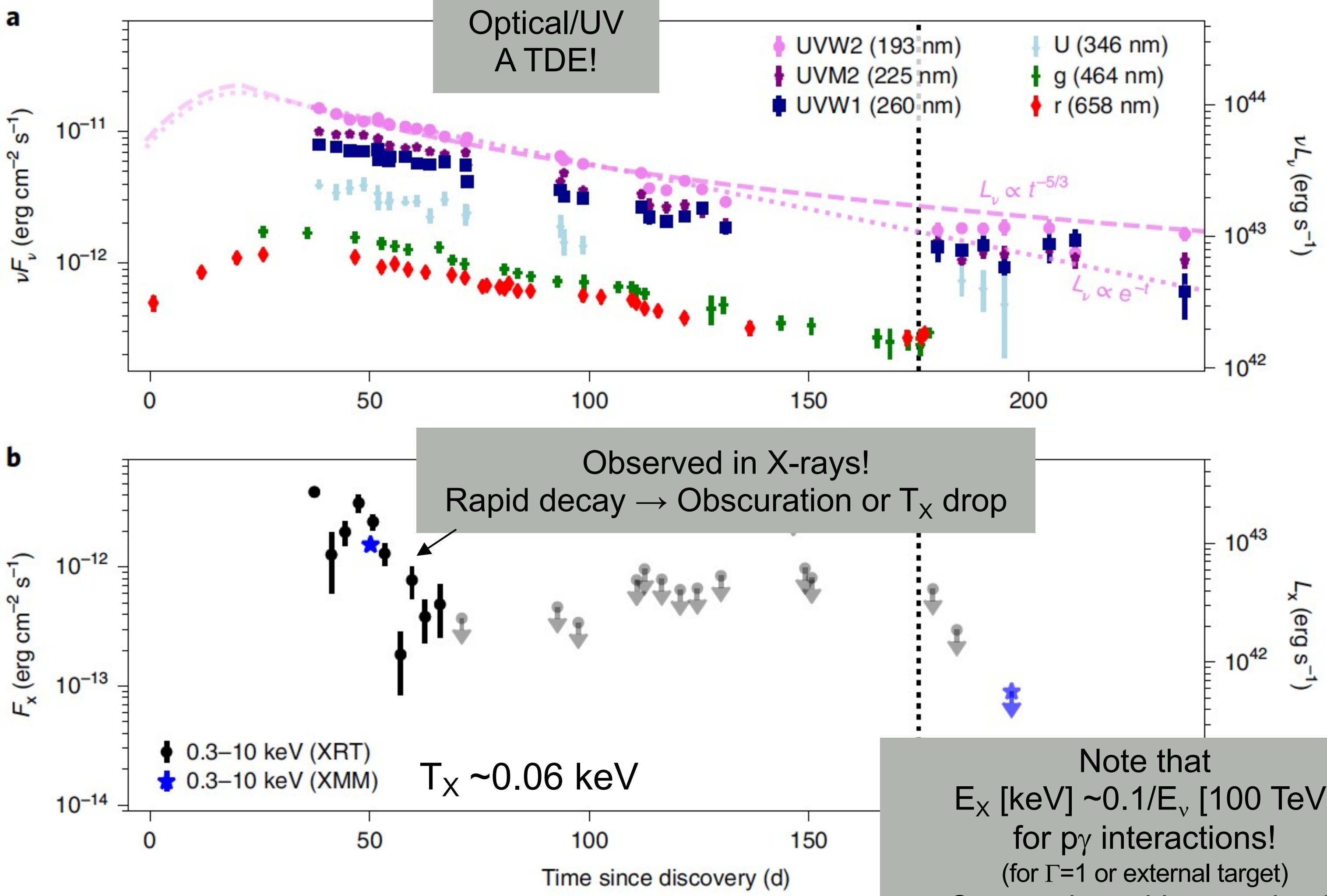



Watch our video –
it is less technical than the slides!
Do you find all gadgets?

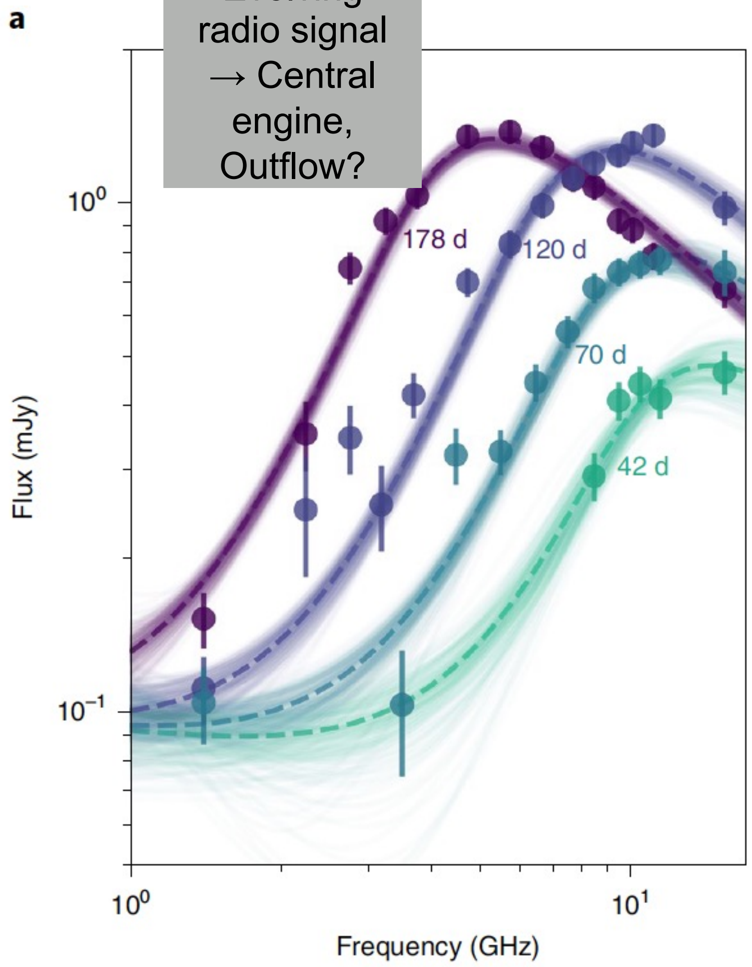
# Observation of a neutrino from AT2019dsg - recap




Optical/UV
A TDE!

Observed in X-rays!
Rapid decay → Obscuration or $T_X$ drop

$T_X$ ~0.06 keV




Evolving
radio signal
→ Central
engine,
Outflow?

Note that
$E_X$ [keV] ~0.1/$E_\nu$ [100 TeV]
for pγ interactions!
(for Γ=1 or external target)
→ Connection with ν production?

**Stein et al, Nature Astronomy 5 (2021) 510;**
**see also talk by Robert Stein**

# How to disrupt a star 101

- Force on a mass element in the star (by gravitation) ~ force exerted by the SMBH at distance

$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\,M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

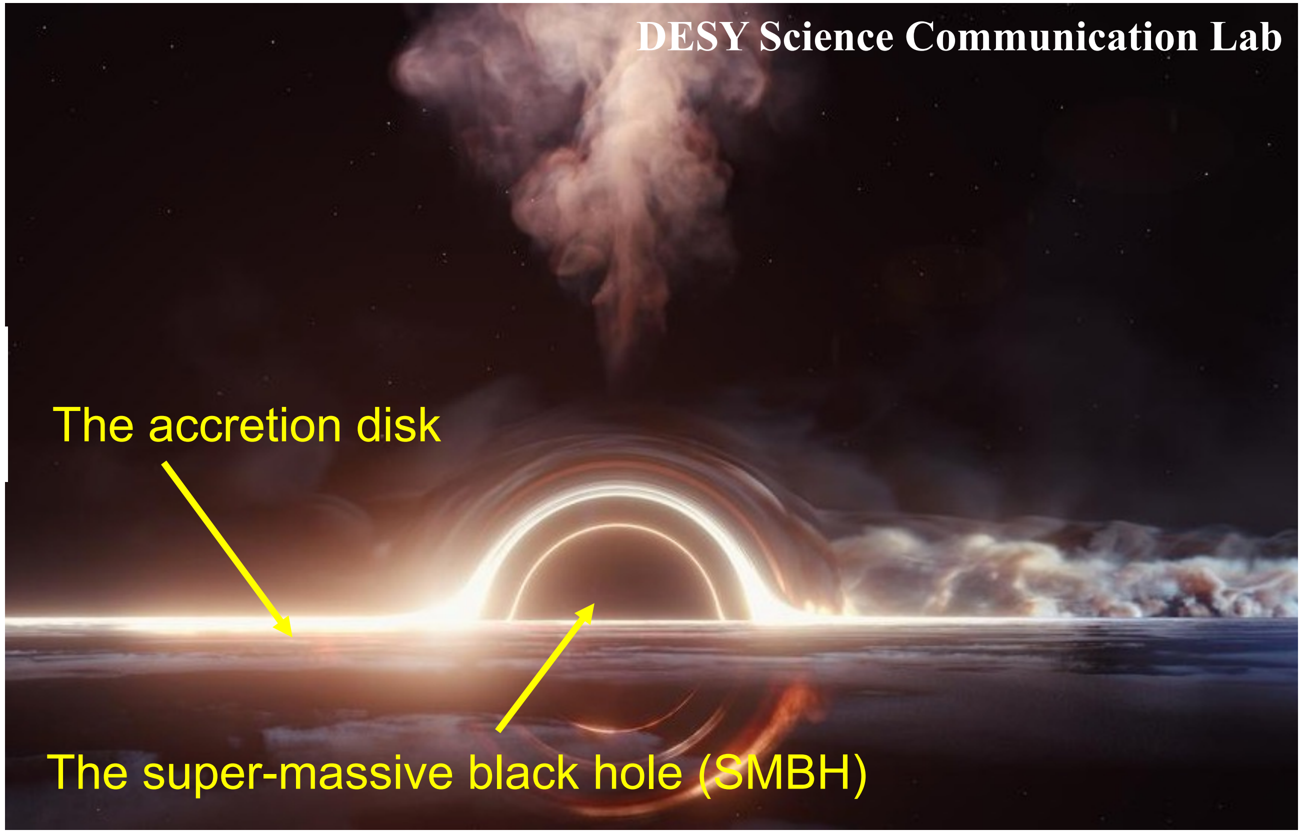
- Has to be beyond Schwarzschild radius

$$R_s = \frac{2MG}{c^2} \simeq 3 \times 10^{11}\,\mathrm{cm} \left(\frac{M}{10^6\,M_\odot}\right)$$

- From the comparison ($r_t > R_s$) and TDE demographics, one obtains M <~ 2 $10^7$ $M_\odot$
  Kochanek, 2016; van Velzen 2017
- Schwarzschild time indicator for time variability of an engine?

$$\tau_s \sim 2\pi R_s/c \simeq 63\,\mathrm{s} \left(\frac{M}{10^6\,M_\odot}\right)$$

→ Fastest time variability ~ 100s




- Measure for the luminosity which can be re-processed from accretion through the SMBH: Eddington luminosity

$$L_{\mathrm{Edd}} \simeq 1.3\ 10^{44}\ \mathrm{erg/s}\,(M/(10^6\ M_\odot))$$

(TDEs are often Super-Eddington at peak)

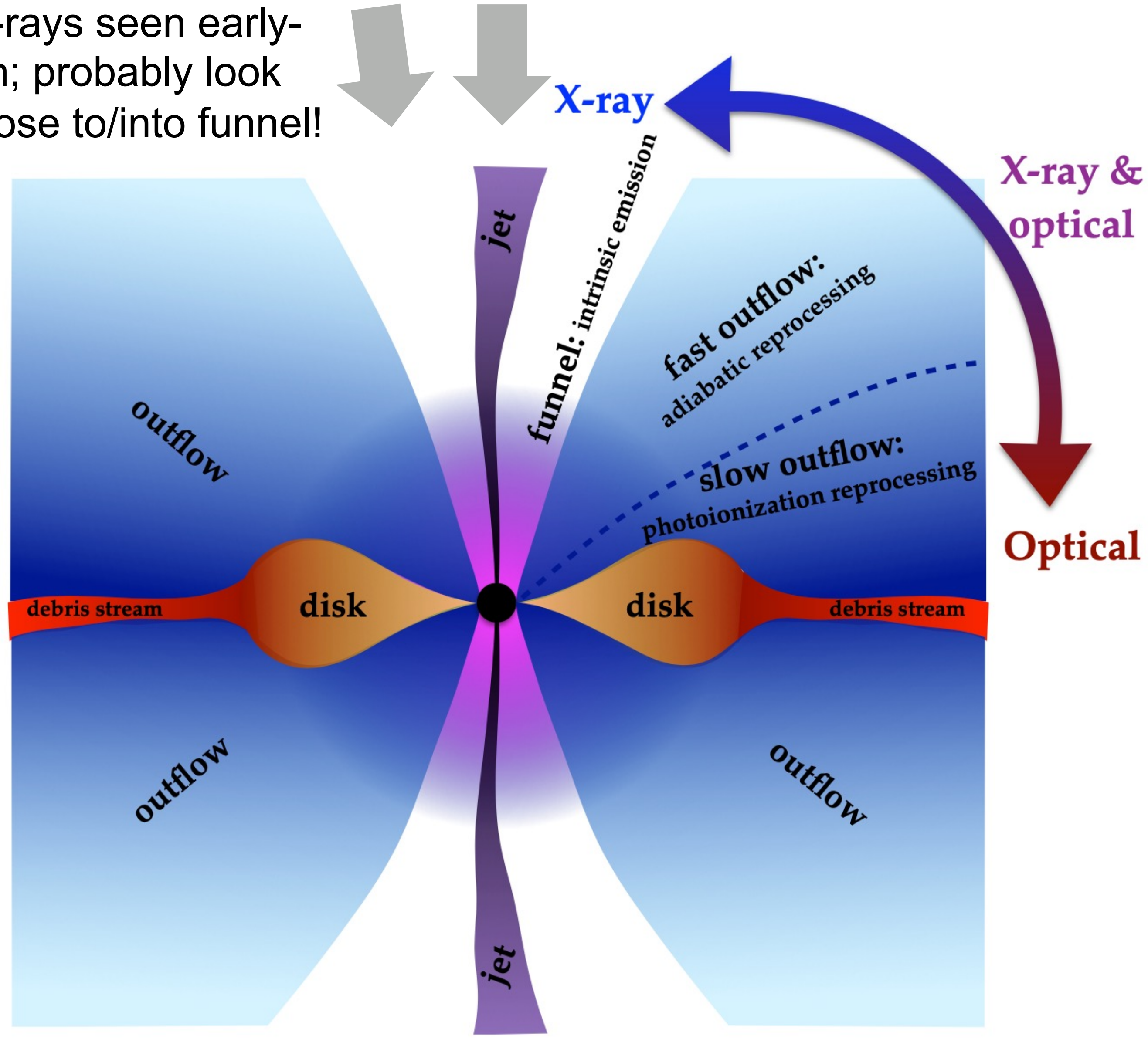
- Measure for the maximally available energy: $E_{max}$ ~ $10^{54}$ erg (half a solar mass)

# A TDE unified model

**... used to motivate a concordance model**

X-rays seen early-on; probably look close to/into funnel!

- Matches several aspects of AT2019dsg very well ($L_{bol}$, $R_{BB}$, X-rays/obscuration?)
- Supported by MHD sims; $M_{SMBH}$ = 5 $10^6$ $M_\odot$ used; we use **conservatively $M_{SMBH}$ = $10^6$ $M_\odot$**
- A jet is optional in that model, depending on the SMBH spin
- Observations from model:
  - Average mass accretion rate $\dot{M} \sim 10^2 L_{\rm Edd}$
  - ~ 20% of that into jet
  - ~ 3% into bolometric luminosity
  - ~ 20% into outflow
  - Outflow with v ~ 0.1 c (towards disk) to v ~ 0.5 c (towards jet)




Dai, McKinney, Roth, Ramirez-Ruiz, Coleman Miller, 2018

# Neutrino energetics

**... an upper model-independent limit**

- Upper limit for average neutrino luminosity ($4\pi$ solid angle emission, for pp similar):
  $L_\nu \sim 25\ L_{edd}$ x $f_{comp}$ x $\varepsilon_{acc}$ x $\tau_{p\gamma}$ x 1/8 **<< 0.1 $L_{edd}$**

  - $L_{edd}$: Average mass accretion rate
  - $f_{comp}$: Fraction in outflow, BB, jet, ... (0.03-0.2?)
  - $\varepsilon_{acc}$: Accelerated fraction into non-thermal PeV (!) energy protons (<< 0.2?)
  - $\tau_{p\gamma}$: Optical thickness <= 1, but typically << 1
  - 1/8: Per flavor

- Yields $E_\nu \sim 200$ days x $0.1\ L_{edd} \sim\ 2\ 10^{50}$ erg $(M_{SMBH}/10^6\ M_\odot)$
  $\rightarrow$ 0.2 events for $M_{SMBH} \sim 10^6\ M_\odot$ ⟶

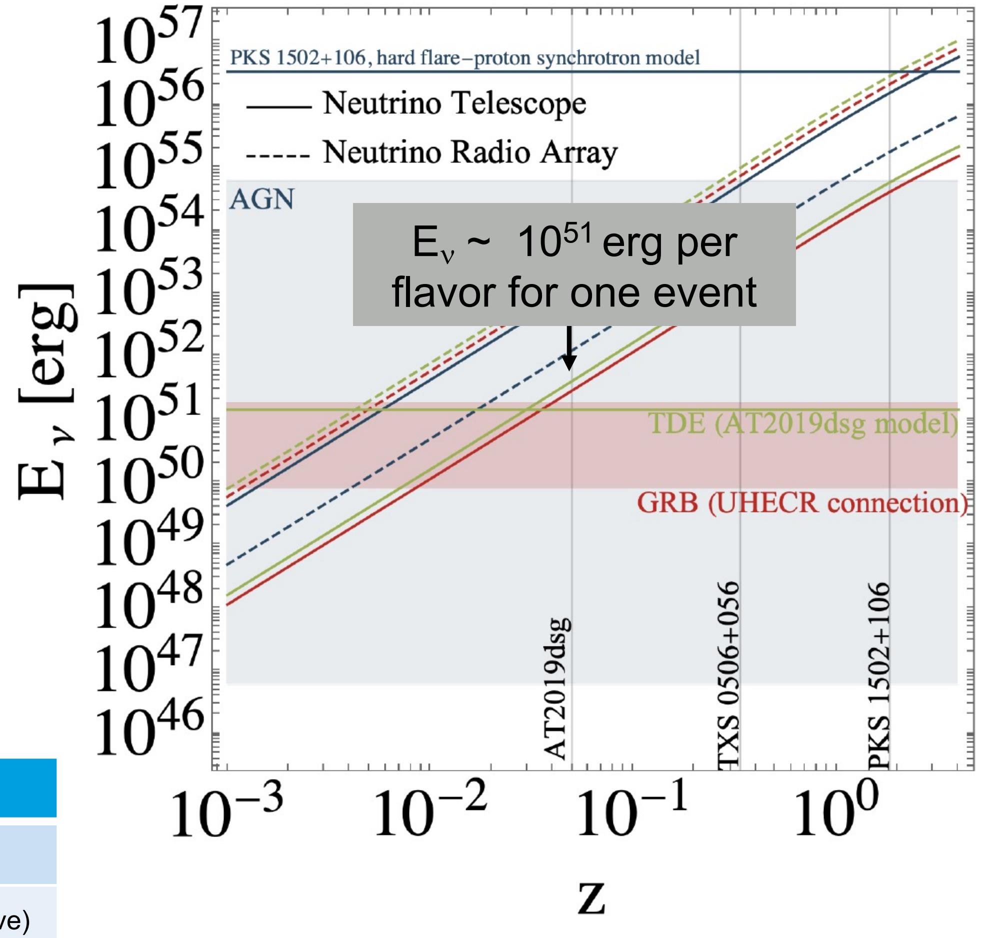
- **Conclusion:**
  <u>either</u> $M_{SMBH} > 10^7\ M_\odot$ <u>and</u> super-efficient energy conversion,
  <u>or</u> the outflow must be collimated with $\theta << 1$ such that $L_\nu \rightarrow L_\nu / \theta^2$

Estimates for SMBH mass

| $M_{SMBH}/M_\odot$ | Reference |
|---|---|
| ~ 2 $10^7$ | McConnel, Ma, 2012 |
| 3 $10^5$ ... $10^7$ | Wevers et al, 2019 (conservative) |
| 1.2-1.4 $10^6$ | Ryu, Krolik, Piran, 2020 |
| 2.2-8.6 $10^6$ | Cannizzaro et al, 2021 |

- For a relativistic jet: second option with $\theta \sim 1/\Gamma$

(figure for all flavors, typical spectral shapes)



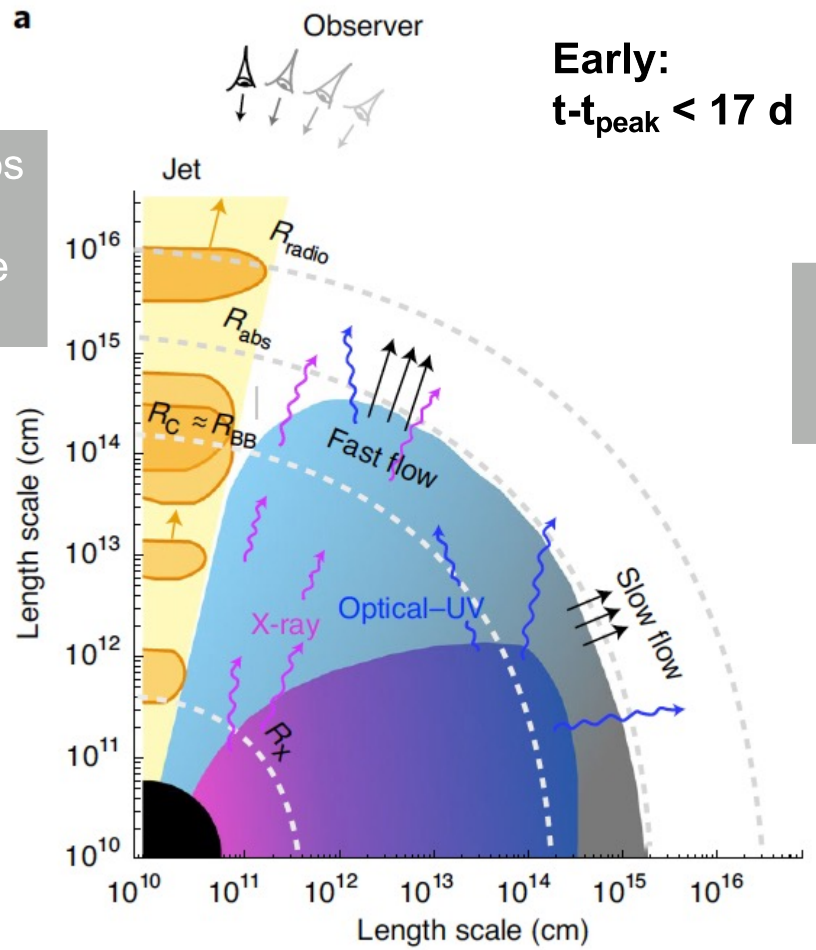

Fiorillo, van Vliet, Morisi, Winter, arXiv:2103.16577; see also talk Fiorillo (on neutrino spectra)

# A jetted concordance scenario

**... based on TDE unified model**

See BACKUP slides for more details

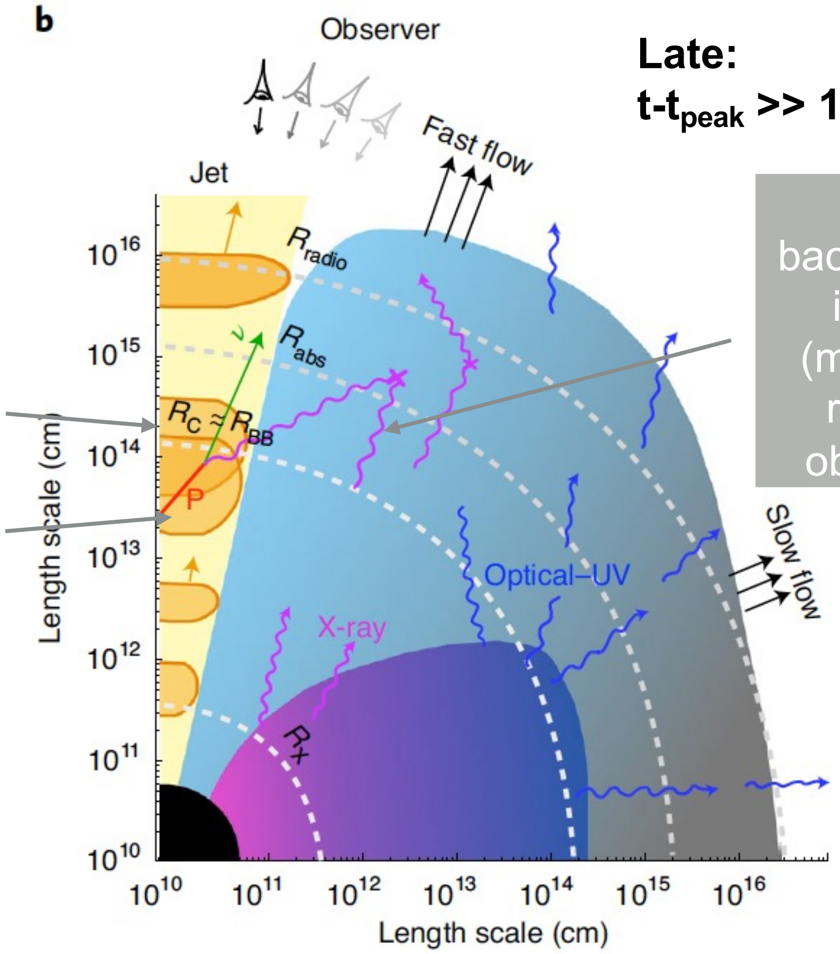
No neutrinos at $t_{peak}$ (no intense target)




**Early:**
**$t-t_{peak}$ < 17 d**

Production radius decreases with $R_{BB}$ (observed)

Particle acceleration in internal shocks




**Late:**
**$t-t_{peak}$ >> 17 d**

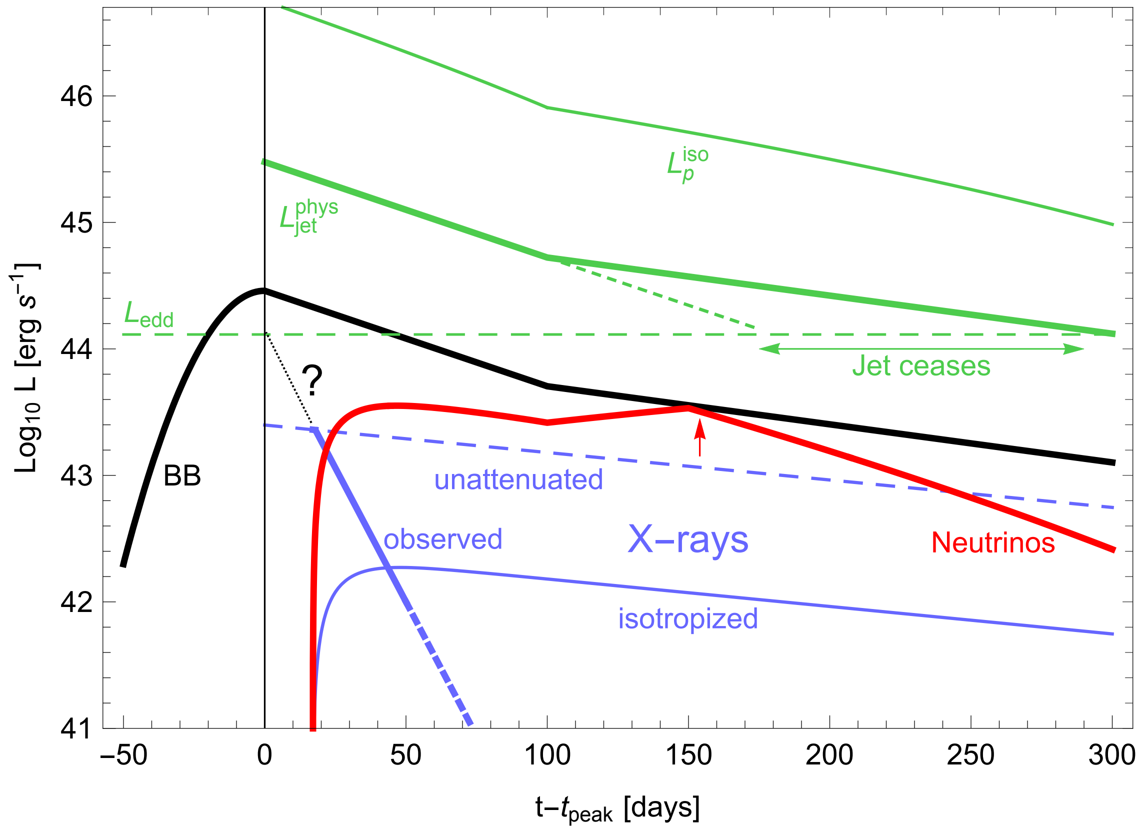
X-ray back-scattering in outflow (may also be reason for obscuration)

**Winter, Lunardini, Nature Astronomy 5 (2021) 472; see also Liu, Xi, Wang, 2020 for an off-axis jet**

# Results for neutrino luminosity lightcurve

- Neutrino production peaks at ~ 150 days (competition between decreasing production radius and proton luminosity)
- Jet ceases when jet luminosity drops below $L_{edd}$; no neutrino production at much later times
- The neutrino emission is connected to X-rays; it may be not a coincidence that AT 2019dsg was one of the few TDEs observed in X-rays?
- Prediction: no neutrinos at $t_{peak}$ yet (here connected with travel time of outflow, which is only mildly relativistic)
- Somewhat uncertain what happens with the X-rays for $t-t_{peak} < 17$ days (no data)

(black/thick purple: follow data; red curve: computational result; others: model ingredients)

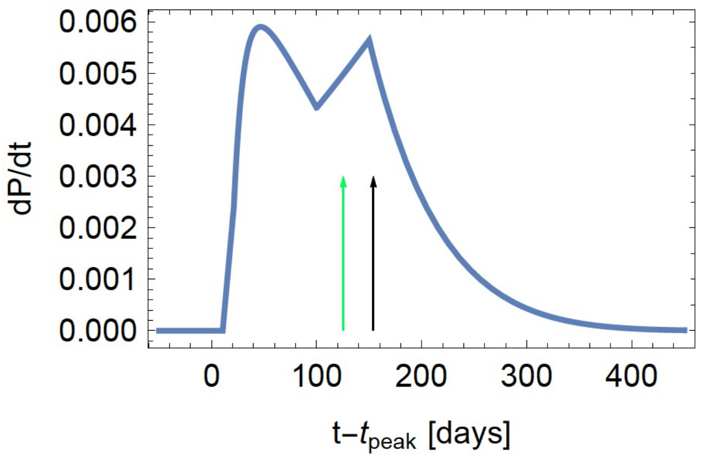


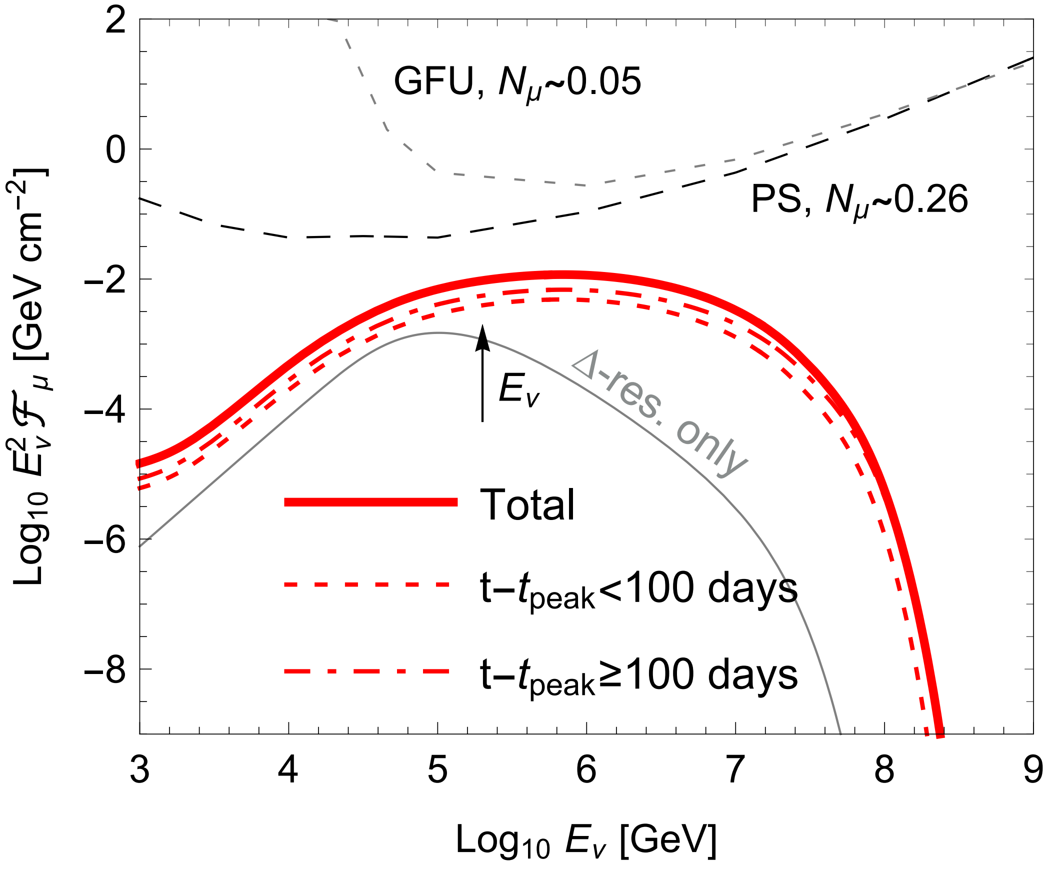

**Winter, Lunardini, Nature Astronomy 5 (2021) 472 (slightly modified figure)**

# Results for neutrino spectrum

- Expected neutrino energy between about 100 TeV and 10 PeV
- High target temperature; therefore multi-pion processes enhance and flatten pion production (cf, gray curve)
  Hümmer et al, 2010; see also Fiorillo, van Vliet, Morisi, Winter, arXiv:2103.16577, Fiorillo's talk
- Number of expected neutrino events:
  - 0.05 (gamma-ray follow-up - GFU)
  - 0.26 (point source analysis – PS)
- Green arrow: predicted average delay →

  Black arrow: observed neutrino

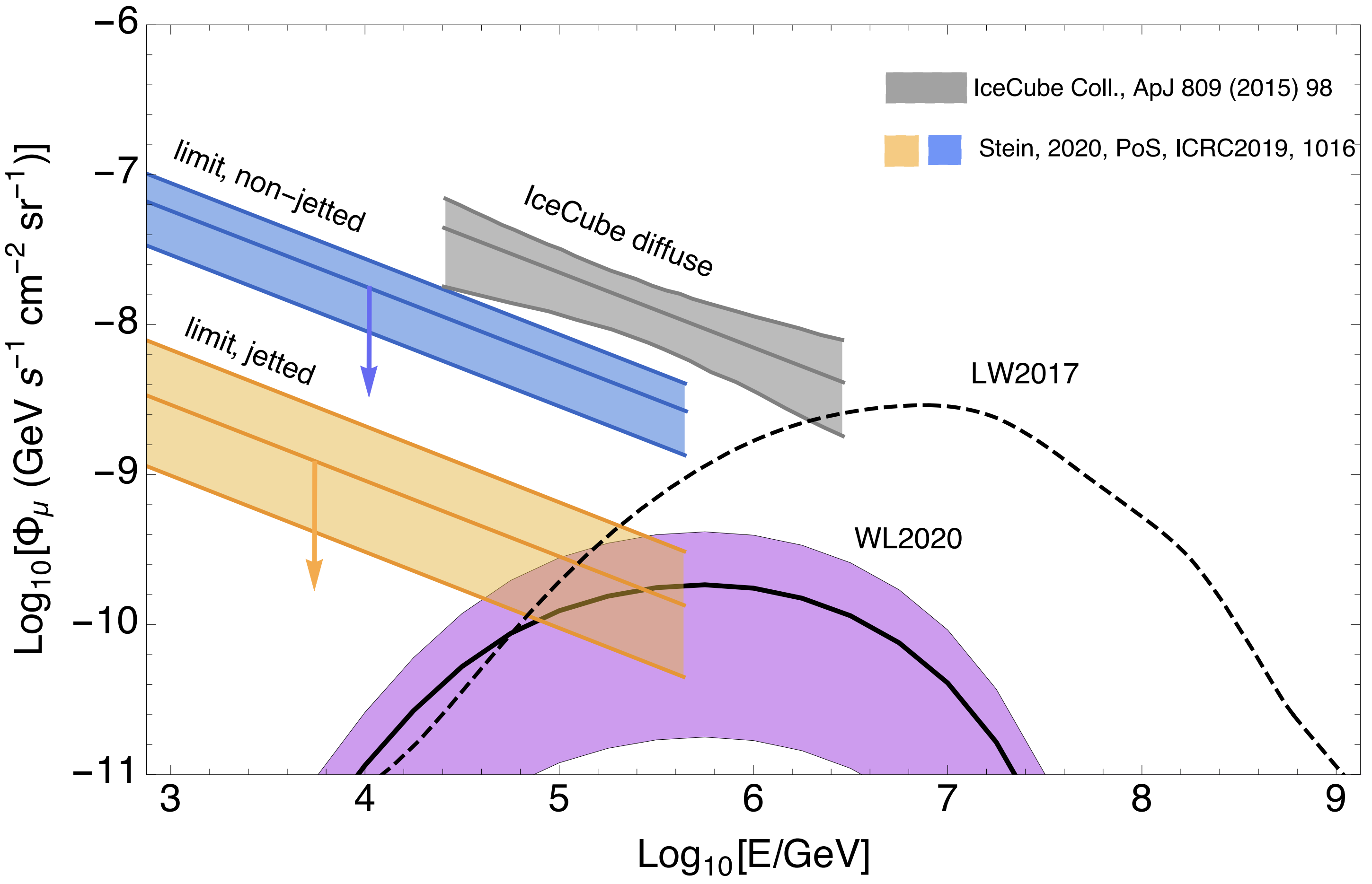


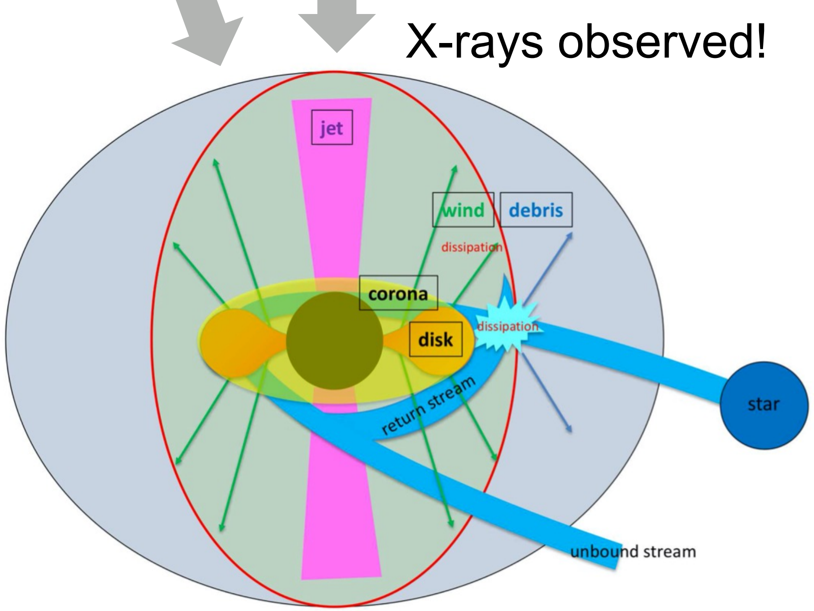

Winter, Lunardini, Nature Astronomy 5 (2021) 472 (slightly modified figure); see also Fiorllo's talk for shape of neutrino spectra

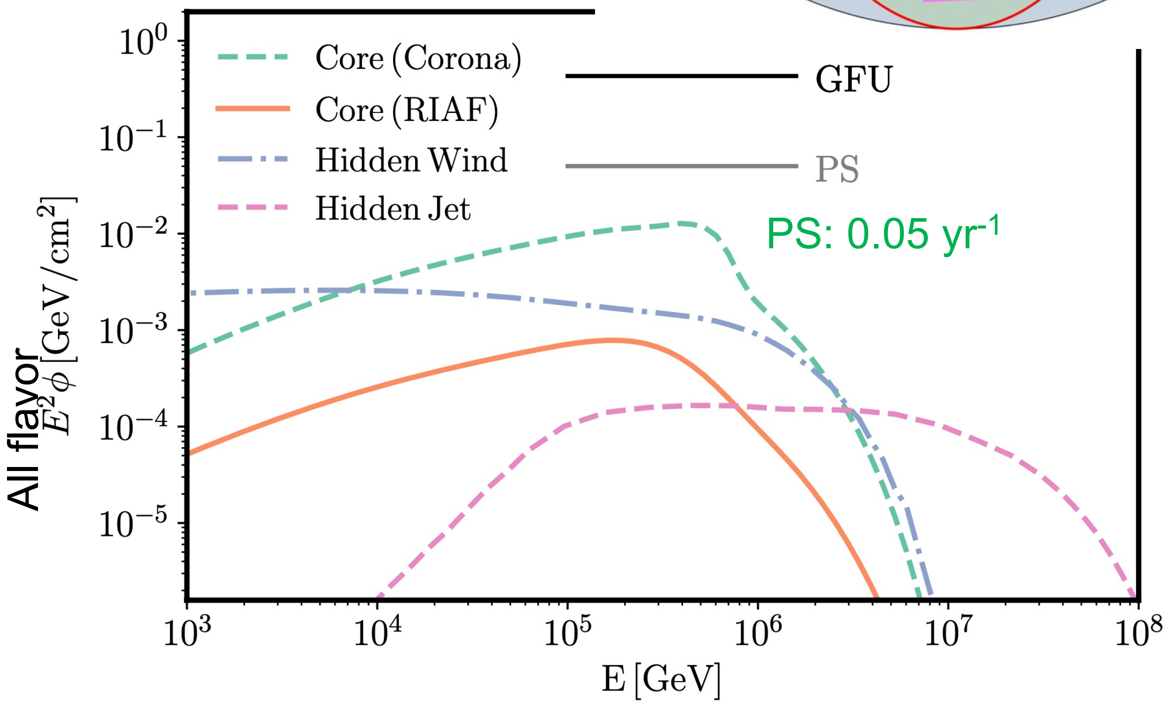
# A population of neutrino TDEs?

- Diffuse flux from a population of such TDE consistent with current bounds
- Expected contribution to the IceCube diffuse neutrino flux at few percent level (compare to **Bartos et al, 2105.03792:** 8%-62% at the 90% CL)
- The typical neutrino TDE is probably less luminous than SwJ1644+47 →
  **(used in Lunardini, Winter, Phys. Rev. D 95 (2017) 12, 123001 as prototype)**
- Could neutrino-emitting TDE also power the UHECR flux?
  **Biehl, Boncioli, Lunardini, Winter, Sci. Rep. 8 (2018) 1; see also Zhang et al., 2017, Guepin et al, 2018**
  Note especially recent indications for under-estimated white dwarf TDE rate by factor of 50! (was most critical factor?)
  **Tanikawa, Giersz, Sedda, 2021**



# Challenges and comparison to alternatives




Murase et al, arXiv:2005.08937; see also Hayasaki, Yamazaki, 2019

Jetted models

- Choked jet: probably too low luminosity
- **Jet breakout model: where are other non-thermal signatures?** (see backup)

Core models

- Corona model: parameters guesstimated from AGNs (where large assumed B for efficient stochastic acceleration is potentially in conflict with radio data ... Inoue, Khangulyan, Doi, arXiv:2105.08948)
- RIAF phase:
  typically many years after peak

Hidden wind model:

- Large uncertainties from geometry

Alternatives to jetted models have in common:

- Lower neutrino event rate
- No late-arrival prediction for neutrino
- Require large SMBH mass > $10^7$ $M_\odot$ (→ energetics problem on page 6)
- Do not explain why X-rays seen

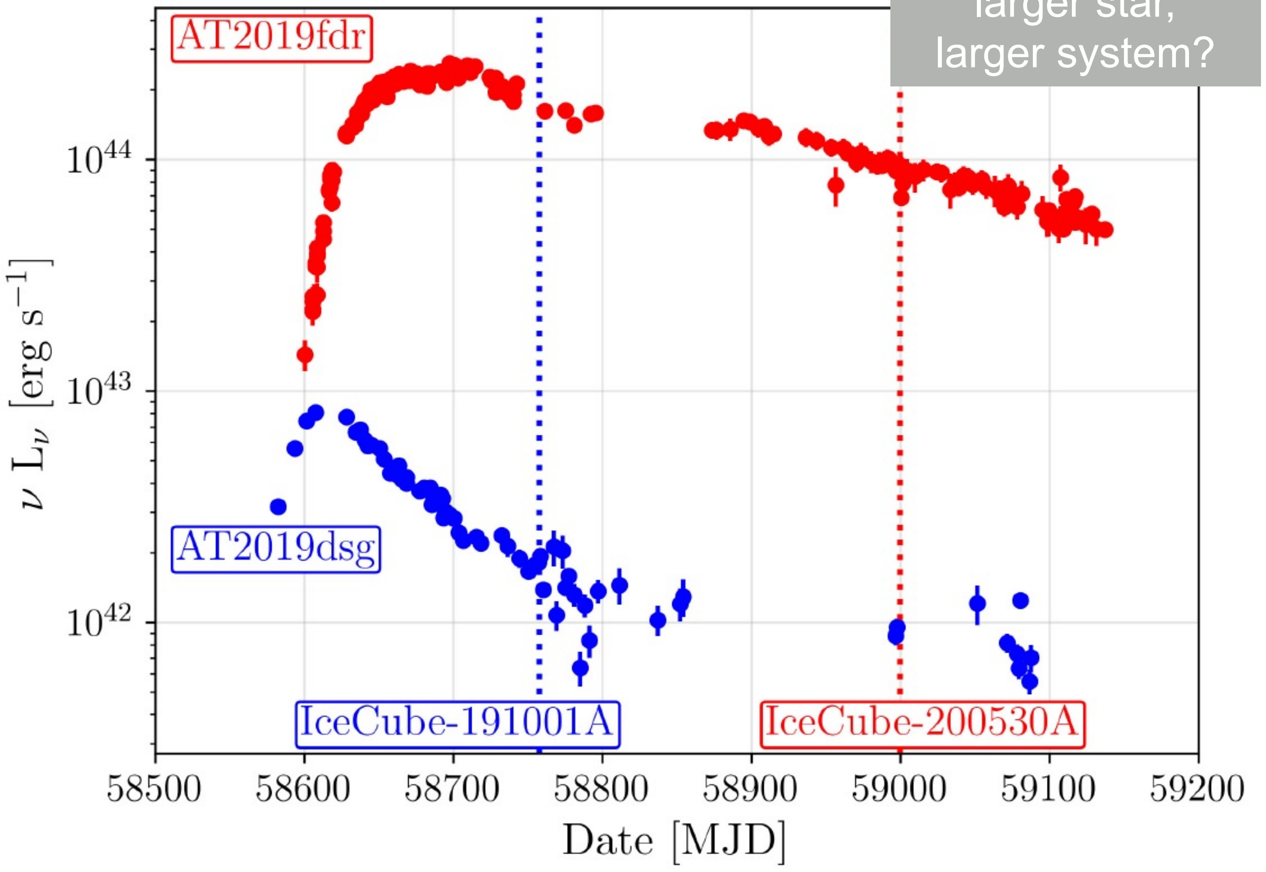
# Outlook/expectations

- There has been another neutrino association with a potential TDE (AT2019fdr)
- The neutrino also came late after the peak (in this case, about a year later)
- Nevertheless the parameters/environment must have been very different

Expectations/extrapolations from the jetted concordance scenario (qualitatively):

- There should be X-ray target photons (although the parameters, such as $T_X$, could be different, or the X-rays may be obscured by dust)
- The neutrino delay scales with the time it takes to travel to the scattering region (or the time the target builds up), i.e., the size of the system
- If the properties scale with $M_{SMBH}$ (to first order), the black hole mass of AT2019dsg must have been much smaller than that of AT2019fdr

More luminous, longer duration → larger $M_{SMBH}$, larger star, larger system?




**From: Robert Stein & Simeon Reusch @ Cosmic Rays and Neutrinos in the Multi-Messenger Era, Paris, Dec. 7-11, 2020; Reusch et al, in preparation**

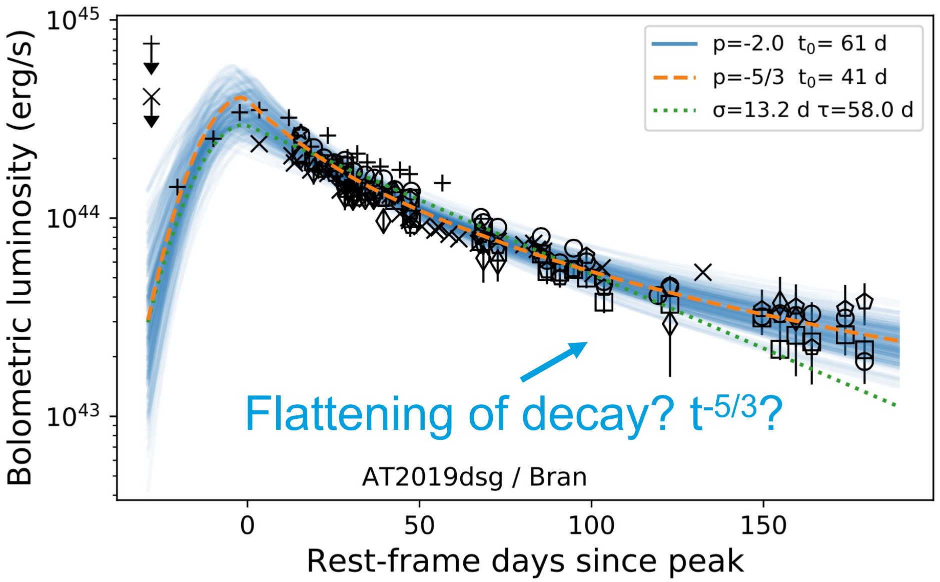
# Summary and conclusions

- From **energetics** for AT2019:
  Option 1) very large SMBH mass and super-efficient energy conversion into neutrinos
  Option 2) a collimated (anisotropic) emission
- We followed the **jet** hypothesis in this talk, where the presence of a jet has, however, not unambiguously been established. On the other hand, a jet is a known efficient particle acceleration site expected to appear for a high enough black hole spin
- AT 2019dsg is one of very few TDEs observed in **X-rays**
  → viewed in/close to "funnel"?
  → also points towards anisotropic neutrino emission model
  → relevant for neutrino production, as right energy range for $p\gamma$ interactions
- **Delayed** neutrino emission wrt peak luminosity may be related with timescale the X-rays build up as target; here timescale from a mildy relativistic outflow exceeding the production region
- Neutrino TDEs may substantially contribute to the **diffuse** neutrino flux; could potentially also power UHECR if C-O (or O-Ne) white dwarf disruptions are abundant enough
- We expect that the model can be applied to **AT2019fdr** as well; there are however substantial differences in that event
- **Alternative neutrino production sites** could be an AGN-like corona, the disk, or the outflow/debris stream; these alternatives typically fall into energetics option 2) above

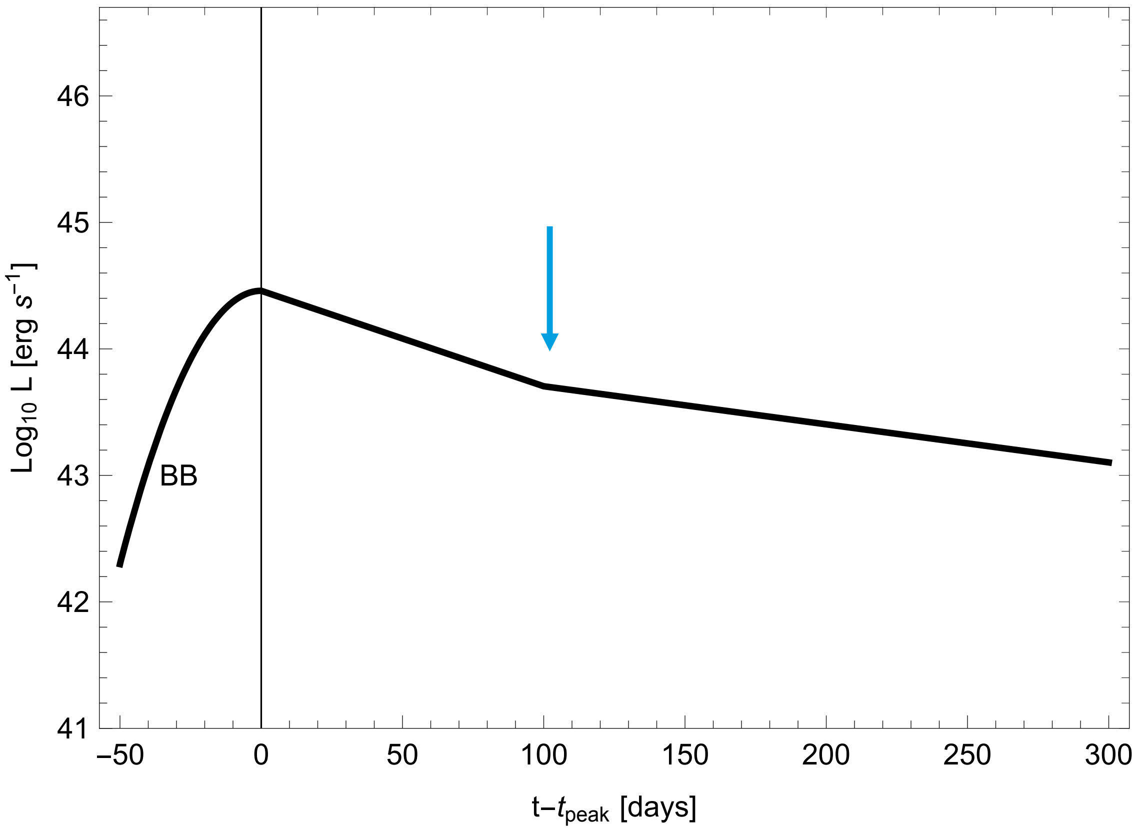
# BACKUP

# TDE observations: Black Body radiation

- BB radius drops over a timescale of ~ 150 days, then remains roughly constant **van Velzen et al (ZTF), 2020**
- Assume: neutrino production radius scales with BB radius (boosts late-term emission!)




**van Velzen et al (ZTF), 2020**




**Winter, Lunardini, Nature Astronomy 5 (2021) 472**

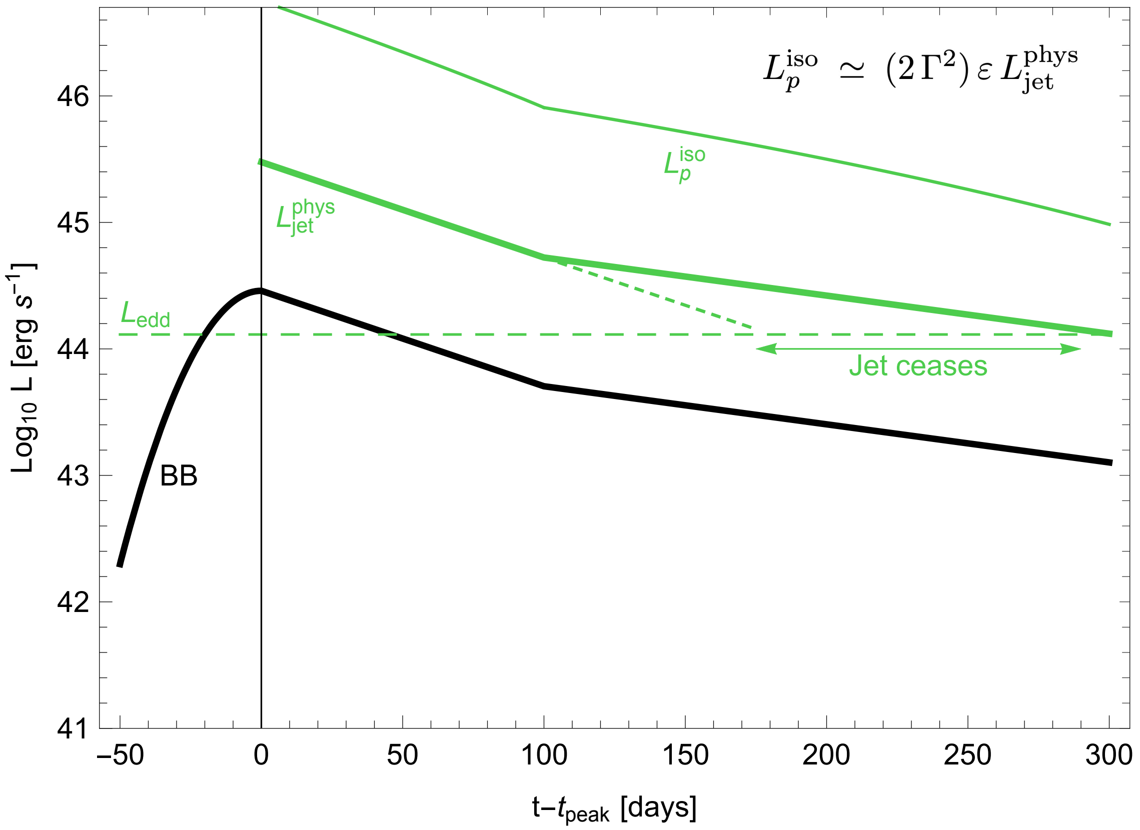
# Proton acceleration in internal shocks of a jet?

**Motivation for a jet:**

- Some evidence for a relativistic jet from optical polarimetry Lee et al, 2020
- A jet is consistent with expectations from the concordance model; located in "funnel"
- A jet provides a "natural" environment for proton acceleration, e.g. in internal shocks
- X-rays provide a target for neutrino production

**Assumptions:**

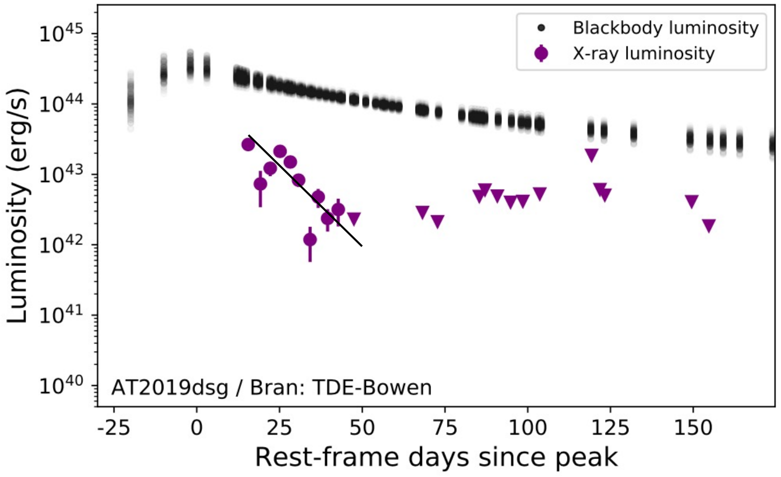
- Energetics from concordance scenario, starts at 20 $L_{edd}$
- Jet ceases when jet luminosity drops below $L_{edd}$
- $\Gamma$=7, D=14 (on-axis view, perhaps less aligned ...) $\rightarrow R_c \sim 2\,\Gamma^2\,t_v \sim R_{BB}$
- Efficiency: $\varepsilon$=20% of jet kinetic energy radiated into non-thermal protons (with expectation for GRB models)



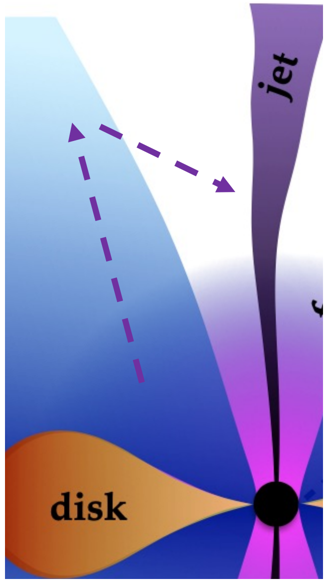

Winter, Lunardini, Nature Astronomy 5 (2021) 472

# X-rays as externals targets (T ~ 0.06 keV)

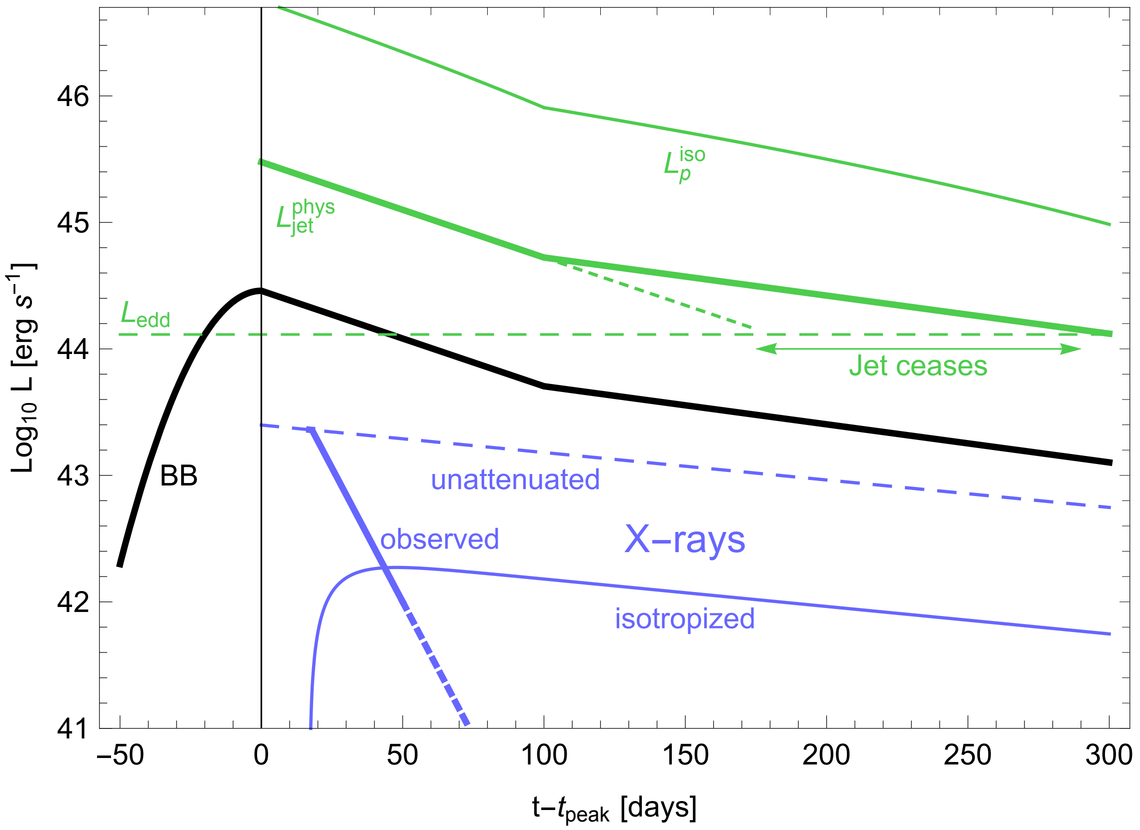
- Expansion of outflow obscures X-rays on timescale of 10 days (from observation). Alternative: accretion disk cooling Cannizaro et al, 2020
- Same effect causes back-scattering of isotropized X-rays as **external radiation** into jet (10% assumed)
- Roughly consistent with attenuation length obtained from Dai et al, 2018 → effect expected even if accretion disk cooling causes decay
- Unattenuated X-rays from slim disk model Wen et al, 2020




van Velzen et al (ZTF), 2020




Dai et al, 2018




Winter, Lunardini, Nature Astronomy 5 (2021) 472

# Comments on possible signatures of a jet

- **Efficient energy dissipation?**
  Dissipation efficiency problem (kinetic power into non-thermal radiation) known in GRBs.
  Efficient energy dissipation would solve several issues (less jet power required, reduced afterglow)
- **Afterglow actually observed?**
  Can the radio observations be also described by the afterglow of a relativistic jet beyond "vanilla" assumptions, e.g., entering a steep density profile?
  Cannizzaro et al. 2020; see also Generozov et al, 2016; Cendes et al, 2021; Alexander, van Velzen, Horesh, Zauderer, 2020
- **X-ray emission from jet observed?**

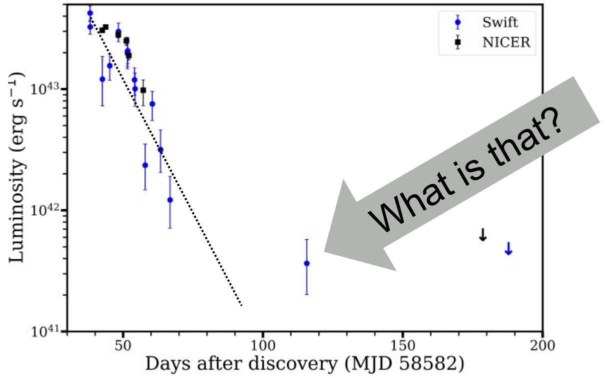
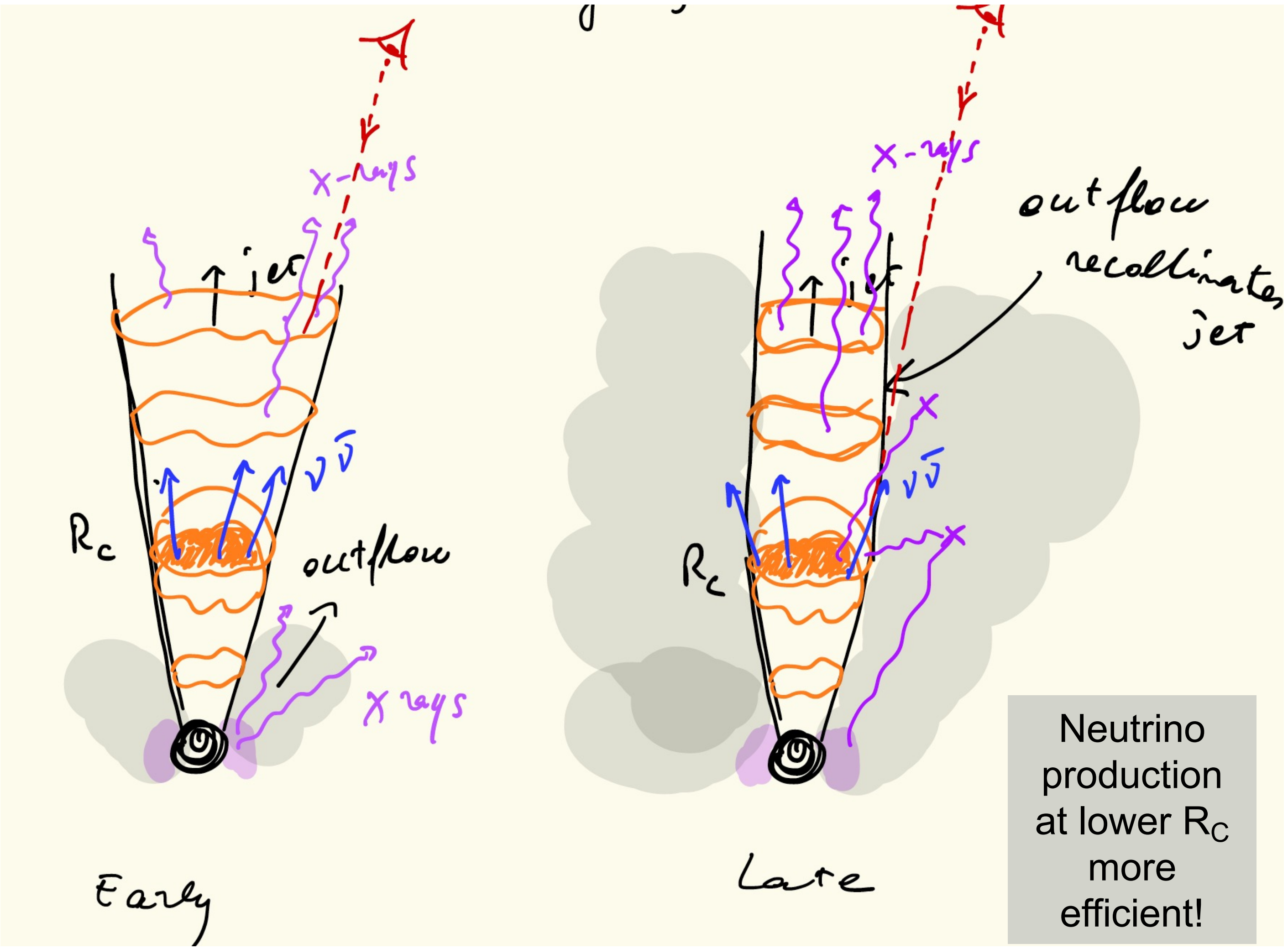



Fig. from: Cannizzaro et al, arXiv:2012.10195

- **Recollimated jet or special jet geometry? Precession?**

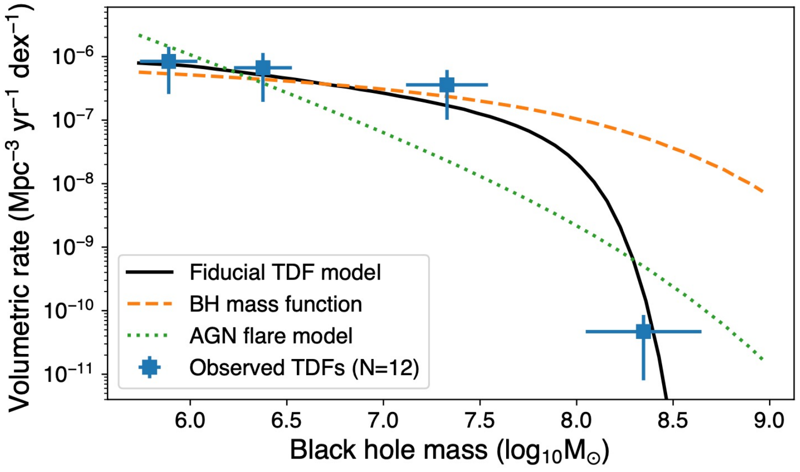



Artwork by Lunardini; see also Bustamante et al, Nat. Commun. 6, 6783 (2015)

# Notes on TDE demographics

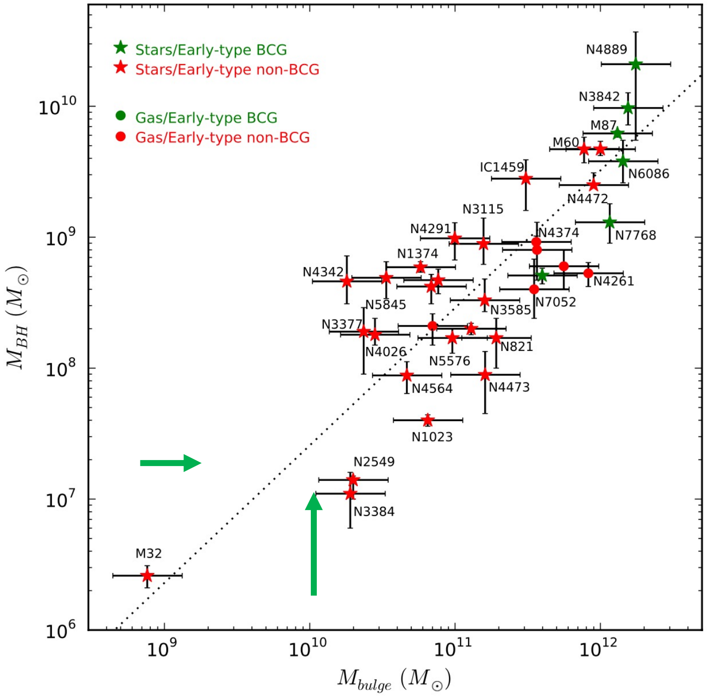
**$M_{bulge}$ ~ 50% x 10^10.5 $M_\odot$ (host galaxy mass) ~ 10^10 $M_\odot$**

- TDE rate



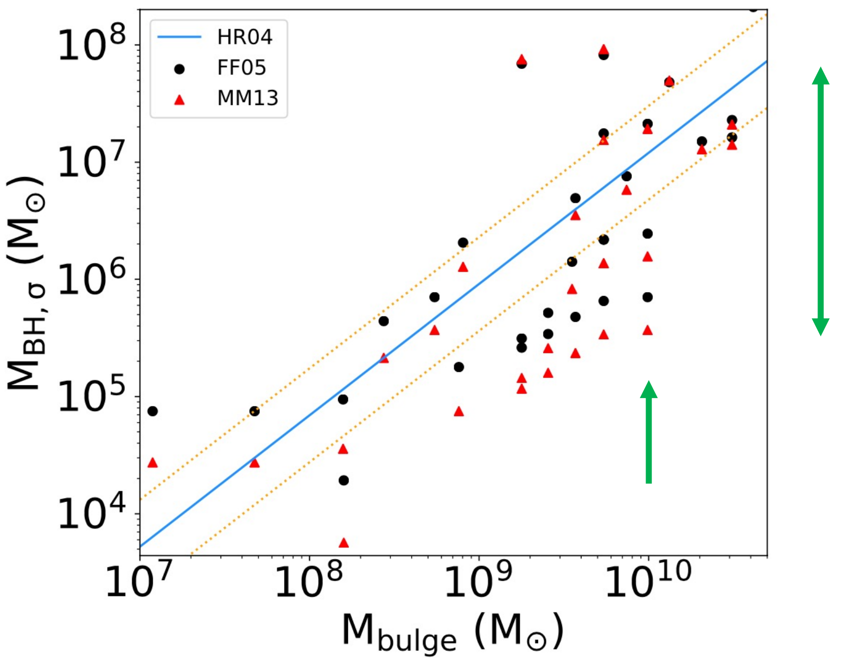

Van Velzen, 1707.03458

- $M_{bulge}$-$M_{BH}$ correlations




McConnel, Ma, 1211.2816

- TDE-specific $M_{bulge}$-$M_{BH}$




Wevers et al, 1902.04077