Neutrinos and Cosmic rays from Tidal Disruption Events (TDEs)

Cecilia Lunardini

Arizona State University

Structure of this talk

- TDEs as particle accelerators
    - TDE theory essentials
    - neutrino emission basics
- ν-TDE associations
    - Observations
    - Unified interpretation: scenarios
- Discussion and summary

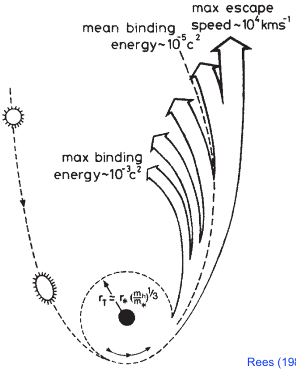
TDEs as particle accelerators

A tidal disruption event (TDE)

- a star is torn into pieces by the gravitational force of a SuperMassive Black Hole (SMBH)
- part of the debris are accreted, a flare is produced
  - important window into the physics of *in-active* galactic nuclei
- $\sim$ 100 candidate TDEs observed
  - most *thermal* (blackbody spectra)
  - 3 non-thermal; evidence of relativistic jets ("jetted" TDE)

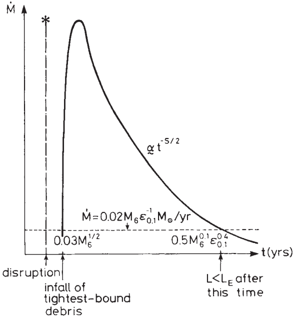
The physics

- masses:
  $m \sim (0.1 - 2)\ M_\odot$,
  $M \sim (10^4 - 10^8)\ M_\odot$
- $\sim m/2$ remains bound, falls back onto the SMBH
- mass accretion powers flare



Rees (1988)

- flare fades when mass accretion rate drops below Eddington Luminosity, $L_{\rm Edd} \simeq 1.3\ 10^{44}\ \frac{\rm erg}{\rm s} \left(\frac{M}{10^6 M_\odot}\right)$.
    - typical duration $\Delta T \sim \mathcal{O}(0.1-1)$ yr



Hills, *Nature* **254** (03, 1975) 295–298.
Rees, *Nature* **333** (1988) 523–528.
Lacy, C. H. Townes, and D. J. Hollenbach, *Astrophys. J.* **262** (Nov., 1982) 120–134.
Phinney, in *The Center of the Galaxy* (M. Morris, ed.), vol. 136 of *IAU Symposium*, p. 543, 1989.

Modern picture of a TDE (post-disruption)

SMBH + accretion disk (emitting in OptUV and X-rays)

- *possible* elements: jet, corona, stream-stream collision, outflow, dust torus
    - distances $\sim 10^{13} - 10^{17}$ cm
- dust echo:
    - absorbed X-ray/OptUV re-emitted in IR
    - Geometric time delay of IR flux

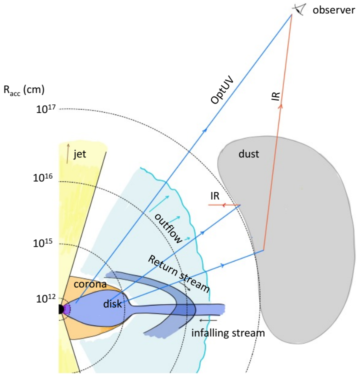


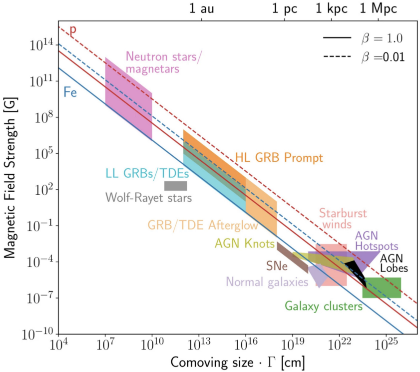
Fig from Winter and CL, arXiv:2205.11538, see also Hayasaki, Nat Astron (2021), arXiv:2102.11879

TDE as hadron accelerators

- meet the necessary condition for p acceleration:

$$\left(\frac{R}{10^{17}\ cm}\right)\left(\frac{B}{G}\right) \gtrsim 3\left(\frac{E_p}{10^{20}\ eV}\right)\Gamma^{-1}$$

- possible sites: jet, corona, accretion disk, colliding streams, ...

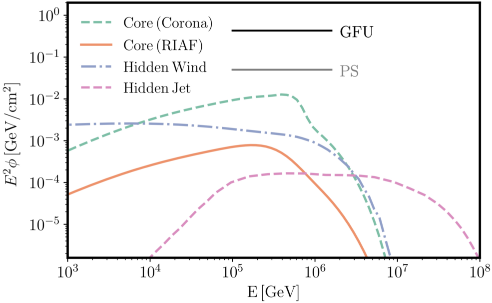


Farrar and Gruzinov, *Astrophys. J.* **693** (2009) 329–332.;

Hillas plot by F. Oikonomou, in Front.Astron.Space Sci. 6 (2019) 23

Neutrinos from TDEs

- TeV-PeV neutrinos from UHE proton cascades:
$p + \gamma \text{ (or } p) \rightarrow \pi^+ + anything, \quad \pi^+ \rightarrow \mu^+ + \nu_\mu,$
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Models reflect the several acceleration scenarios



X.-Y. Wang, et al., *Phys. Rev.* **D84** (2011) 081301;

Fig. from Murase, Kimura, Zhang, Oikonomou & Petropoulou, ApJ 902, 2020, 108

References

- Connection to Cosmic Rays
  Farrar and Gruzinov, *Astrophys. J.* **693** (2009) 329–332.
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  Pfeffer, Kovetz, and Kamionkowski, arXiv:1512.04959.
  Guepin, Kotera, Barausse, Fang, & Murase, 2018, Astron. Astrophys., 616
  Biehl, Boncioli, Lunardini, & Winter, 2018, Sci. Rep., 8, 10828

- Connection to HE neutrinos
  Murase 2008, AIP conference series; Murase & Takami 2009, ICRC conference proceedings
  X.-Y. Wang, et al., *Phys. Rev.* **D84** (2011) 081301.
  X.-Y. Wang and R.-Y. Liu, *Phys. Rev.* **D93** (2016), no. 8 083005.
  Dai and Fang, MNRAS 469 (2017) 2, 1354-1359
  Senno, Murase and Meszaros, ApJ 838 (2017) 1, 3
  Lunardini and Winter, PRD 95 (2017) 12, 123001
  Fang, Metzger, Vurm, Aydi & Chomiuk, arXiv:2007.15742
  Hayasaki & Yamazaki, ApJ, 886 114 (2019)
  Winter and Lunardini, arXiv:2005.06097
  Murase, Kimura, Zhang, Oikonomou & Petropoulou, ApJ 902, 2020, 108
  Liu, Xi and Wang, PRD 102, 2020
  Wu, Mou, Wang, Wang, & Li, 2021, arXiv:2112.01748

ν-TDE associations

New: from modeling to interpreting observations

- 3 TDE-neutrino associations have been observed
  - real-time IceCube alerts. Follow ups by: ZTF, Swift, eROSITA, neoWISE, and more
- *detailed* time-dependent multi-wavelength lightcurves and spectra
- attempts at *unified, multimessenger*, interpretation of all data
  - taking the observed γ fluxes as inputs, can we reproduce the neutrino observables?

References

On observed TDE-neutrino associations:

- Observational papers:

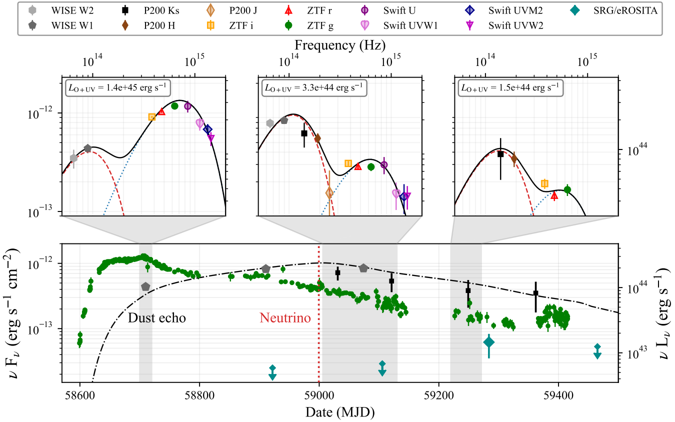
R. Stein et al., Nature Astron. 5 (2021) 5, 510-518 (see also talk at this conference)
S. Reusch et al., Phys.Rev.Lett. 128 (2022) 22, 221101

van Velzen et al., arXiv:2111.09391

- Theoretical interpretations:

Winter and Lunardini, arXiv:2005.06097
Hayasaki, Nat. Astron., News and Views, 2021
Winter and Lunardini, arXiv:2205.11538
Murase, Kimura, Zhang, Oikonomou & Petropoulou, ApJ 902, 2020, 108
Liu, Xi and Wang, PRD 102, 2020
Wu, Mou, Wang, Wang, & Li, 2021, arXiv:2112.01748

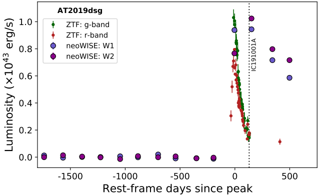
Example of detailed lightcurve: AT2019fdr



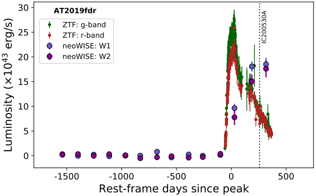
from S. Reusch et al., PRL 128 (2022) 22, 22110

TDE-neutrino associations

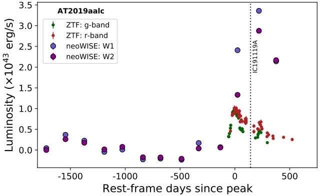
AT2019`dsg` :



AT2019`fdr` :



AT2019`aalc` :



Looking for **special** features:

- late neutrino arrival time
- unusually bright in X-rays
- unusually bright dust echo

figs: van Velzen et al., arXiv:2111.09391; small dots: OptUV; large dots: IR. Also observed in X-rays, Radio

Observations at a glance

	AT2019dsg	AT2019fdr	AT2019aalc
Overall parameters			
Redshift z	0.051	0.267	0.036
$t_{\rm peak}$ (MJD)	58603	58675	58658
SMBH mass M [$M_\odot$]	$5.0\,10^6$	$1.3\,10^7$	$1.6\,10^7$
Neutrino observations			
Name (includes t_ν)	IC191001A	IC200530A	IC191119A
$t_\nu - t_{\rm peak}$ [days]	154	324	148
E_ν [TeV]	217	82	176
N_ν (expected, GFU)	0.008–0.76	0.007–0.13	not available
Black body (OUV)			
$T_{\rm BB}$ [eV] at $t_{\rm peak}$	3.4	1.2	0.9
$L^{\rm bol}_{\rm BB}$ (min.) [$\frac{\rm erg}{\rm s}$] at $t_{\rm peak}$	$2.8\,10^{44}$	$1.4\,10^{45}$	$2.7\,10^{44}$
X-rays (X)			
$T_{\rm X}$ [eV]	72	56	172
$L^{\rm bol}_{\rm X}$ [$\frac{\rm erg}{\rm s}$] @ $t - t_{\rm peak}$	$6.2\,10^{43}$ @ 17 d	$6.4\,10^{43}$ @ 609 d	$1.6\,10^{42}$ @ 495 d
Dust echo (IR)			
$T_{\rm IR}$ [eV]	0.16	0.15	0.16
Time delay Δt [d]	239	155	78
$L^{\rm bol}_{\rm IR}$ [$\frac{\rm erg}{\rm s}$] @ $t - t_{\rm peak}$	$2.8\,10^{43}$ @ 431 d	$5.2\,10^{44}$ @ 277 d	$1.1\,10^{44}$ @ 123 d

$p = 2\ 10^{-4}$ (3.7 σ, see van Velzen, et al., arXiv:2001.01409; See also parallel talk by Jannis D. Necker.)

Building a ν interpretation: basics

Winter and CL, arXiv:2205.11538

- Assume that AT2019`dsg`, AT2019`fdr`, and AT2019`aalc`:
  - are TDEs
  - are the sources of the associated neutrinos
- Assume that the neutrino production mechanism:
  - is the *same* for the three TDEs
  - is dominated by $p + \gamma$ ($p + p$ included, not discussed here)

- Compute neutrino fluxes for three scenarios:
  - each with different *dominant* photon target: X-ray, Opt-UV, IR.
  - check if results reproduce observed ν energy and arrival time

p and γ from TDEs: minimal assumptions

Photon luminosities (at emission radius):

- $L_{IR}(t)$ from dust echo (data+in-house model)
- $L_X(t)$ assumed constant or slowly decaying
  - justified by theory
  - observations explained by propagation effects
- L_{BB} (OptUV luminosity) normalization inferred from dust echo

Protons:

- (quasi)-isotropic emission (non-jetted)
- luminosity: $L_p(t) \propto L_{BB}(t)$
  - $L_p \sim 20\ L_{Edd}$ at peak, justified by theory (Dai et al., ApJ 859, L20 (2018))
- spectrum: $dN_p/dE \propto E^{-2}$, with cutoff $E_{p,max} \gtrsim 1$ PeV

$p + \gamma$: key ideas

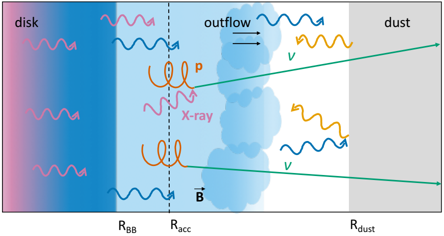
- dominated by resonance: $p + \gamma \rightarrow \Delta \rightarrow \pi^+ + \ldots$
  - $E_\gamma E_p \sim m_\Delta^2 \rightarrow$ lower T_γ requires higher E_p (higher $E_{p,max}$)
- $E_\nu \sim 10^{-2} E_p$ (parent proton energy)
  - $\rightarrow$ lower T_γ implies hotter ν spectrum:

$$T_\gamma \simeq 80\,\mathrm{eV} \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-1}$$

- interaction rate must be more efficient than escape
  - escape: free streaming or diffusion

$$\frac{\partial N_i(E,t)}{\partial t} = \underbrace{\tilde{Q}_i\,(E,t)}_{\text{Injection}} + \underbrace{\frac{\partial}{\partial E}\left(\frac{E}{t_{\rm cool}(E,t)}\, N_i\,(E,t) \right)}_{\text{Cooling}} - \underbrace{\frac{N_i\,(E,t)}{t_{\rm esc}\,(E,t)}}_{\text{Escape}}$$

Scenario 1: X-ray are dominant targets (M-X)

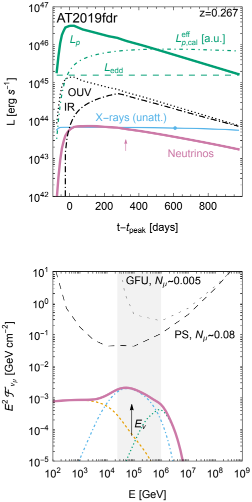


- $R \sim 5\ 10^{15}$ cm (radiation zone radius)
- $T_X \sim 60 - 200$ eV $\rightarrow E_{p,max} \sim 5$ PeV
- system is thin to $p + \gamma$, but *calorimetric* ($\mathbf{B} = 1$ G)
  - protons gyrate and stay confined; in-source p density builds-up over $\mathcal{O}(10^2)$ days

(see also hidden wind model in Murase, Kimura, Zhang, Oikonomou, Petropoulou, ApJ 902, 2020, 108)

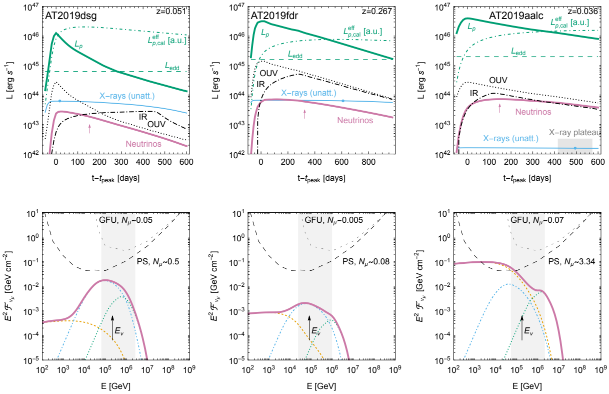
Results: X-ray based scenario, AT2019fdr

- ν time delay OK!
  due to p accumulation time scale and near-constant L_X
- observed E_ν OK!
  due to “just right” T_X
- predicted event number at IceCube is low

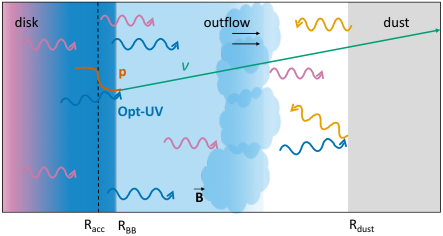


Results: X-ray based scenario,

AT2019dsg, AT2019fdr, AT2019aalc



scenario 2: Opt-UV are dominant targets (M-OU)



- $R \sim R_{BB} \sim (5-10)\ 10^{15}$ cm (Opt-UV photosphere radius)
- $T_{BB} \sim 1-3$ eV $\rightarrow E_{p,max} \sim 10^2$ PeV
- system is thick to $p+\gamma$ for OptUV

(See also Stein et al., Nature Astron. 5 (2021) 5, 510-518)

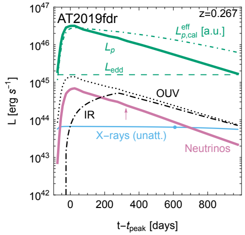
Results: Opt-UV based scenario, AT2019fdr

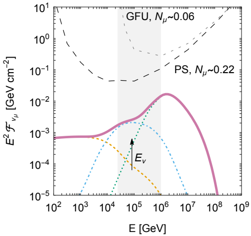
- ν time delay: tension

  little p buildup, $L_\nu(t)$ follows L_{BB}
- observed E_ν tension

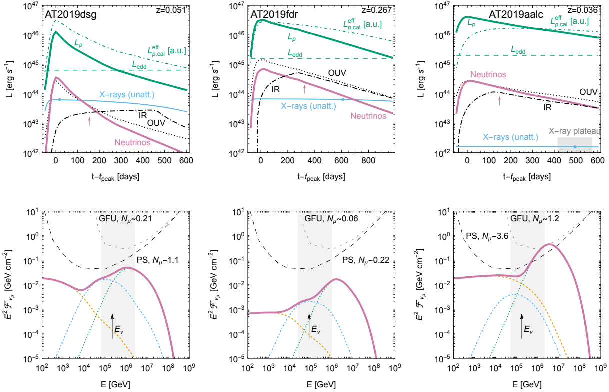
  Due to $T_{BB} \ll T_X$
- predicted event number at IceCube is higher

  because $L_{BB} \gg L_X$

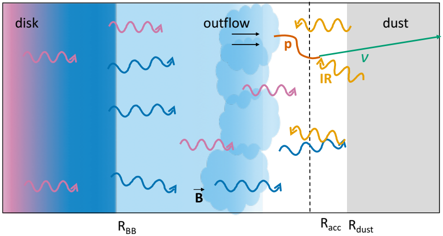




Results: OptUV-based scenario, AT2019dsg, AT2019fdr, AT2019aalc



scenario 3: IR are dominant targets (M-IR)



- $R \sim R_{dust} \sim (5 - 10)\ 10^{16}$ cm (dust torus radius)
- $T_{IR} \sim 0.15$ eV $\rightarrow E_{p,max} \sim 5\ 10^3$ PeV
- system is barely thick for IR, moderately calorimetric ($\mathbf{B} = 0.1$ G)

Results: IR-based scenario, AT2019fdr

- ν time delay: OK!

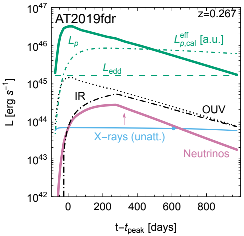
  $L_\nu(t)$ follows $L_{IR}(t)$

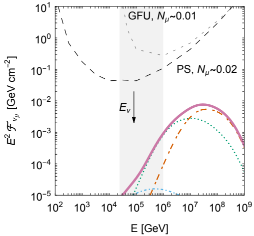
- observed E_ν tension

  Due to $T_{IR} \ll T_X$

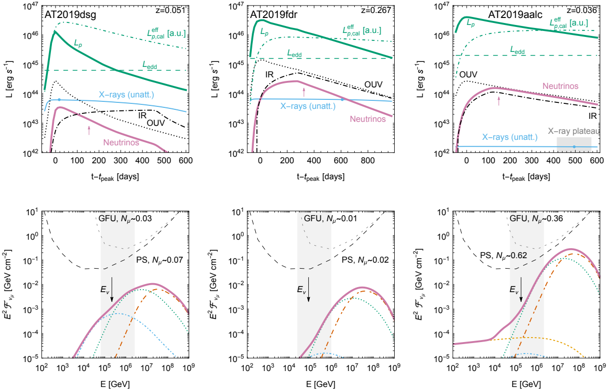
- predicted event number at IceCube is low

  larger R, scatterer density is diluted





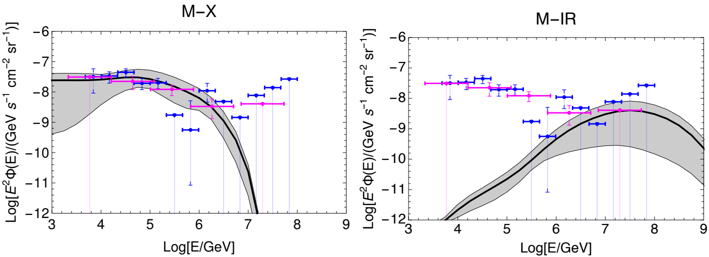
Results: IR-based scenario, AT2019dsg, AT2019fdr, AT2019aalc



Scenario comparison

Model criterion	**M-X**	**M-OUV**	**M-IR**
Probable accel. region	$10^{15} - 10^{16}$ cm	~BB photosph. $\sim 10^{15}$ cm	10^{16} to 10^{17} cm
Main targets	X-rays, protons	Optical-UV blackbody	IR photons from dust echo
Observational correlation	X-ray signals	High $L_{\rm BB}$	Dust echoes
Origin of ν time delay	Diffusion (high B)	Unrelated to size of system	Dust echo travel times
Description ν time delay	Intermediate	Poor	**Good**
ν event rate	Low	**Intermediate-High**	Low
Required $E_{p,\rm max}$	**Moderate**	Intermediate	High
ν energy	**Matches**	Somewhat high	Very high
ν spectral time evolution	**Matches**	Right direction	Wrong direction
Diff. flux spectrum	**Matches**	High E only	Highest E only
Diff. flux contribution	0.8% – 20%	$\gtrsim$ 4% (high E only)	$\gtrsim$ 38% (highest E only)

Could TDEs explain the diffuse flux at IceCube?



(fraction of contributing TDEs : $\lesssim 0.3$; assuming that AT2019dsg, AT2019fdr and AT2019aalc are representative of the population. Smaller (larger) error bars: cascade (track) events at IceCube)

- X-ray based scenario: yes, for most for the spectrum (and optimistic parameters)
- Opt-UV and IR-based models: higher energy portion only

see also IceCube, R. Stein, PoS ICRC2019, 1016, 2020.

Discussion and summary

Summary: star-destroying supermassive BH

- 3 likely ν-TDE associations substantiate the (formerly exotic) idea of TDEs as neutrino sources
- TDEs could account for tens of per cent of the diffuse ν flux at IceCube
- candidate ν-emitting TDEs have several *special* features
- which special feature reveals the ν production mechanisms? Not clear...
    - several scenarios allowed by the data

Questions for future study

- are the three associations real? are AT2019fdr and AT2019aalc really TDEs?
  - Long term observations; statistics studies desirable
- is the ν production mechanisms linked to dust echo? X-ray emission? proton confinement?
  - The next observed association may give the answer!
- if IceCube is observing TDEs, what can neutrinos teach us about them?
  - supermassive BH population? spins? surrounding stellar population?

THANK YOU!

Backup

Tidal radius, etc.

- masses: $m \sim (0.1 - 2)\ M_\odot$, $M \sim (10^4 - 10^8)\ M_\odot$
- Tidal radius: where SMBH gravity $\simeq$ star's self gravity

$$r_t = \left(\frac{2M}{m}\right)^{1/3} R$$

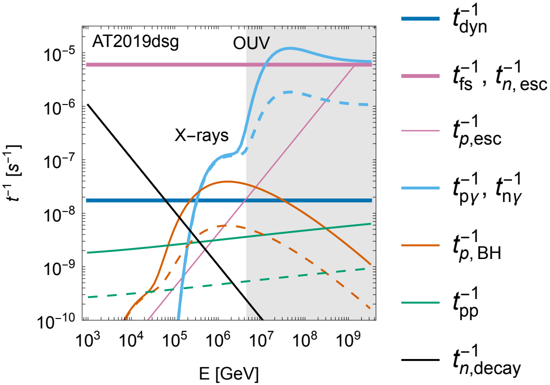
$$\simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

- Schwarzschild radius

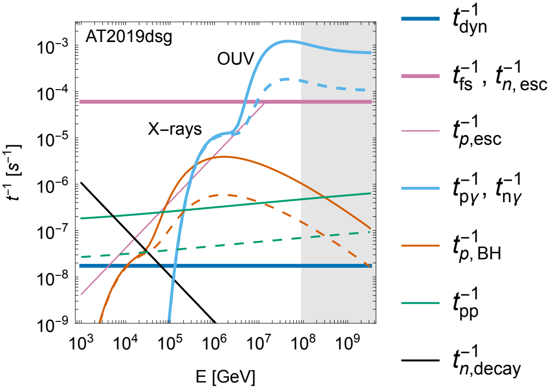
$$R_s = \frac{2MG}{c^2} \simeq 3 \times 10^{11}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)$$

  - Condition for TDE: $r_t \gtrsim R_s \rightarrow M \lesssim M_{\rm max} \simeq 10^{7.2}\ \ M_\odot$

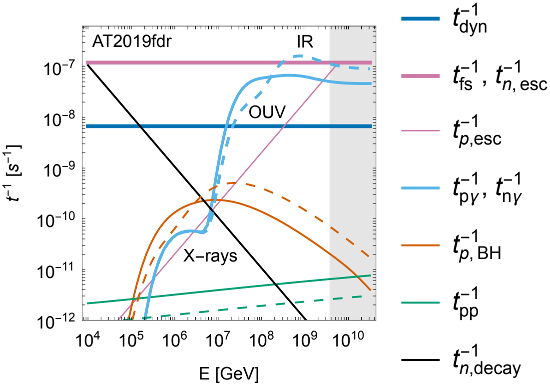
Interaction rates: M-X



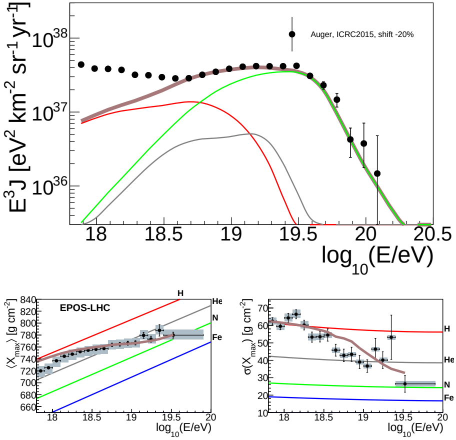
Interaction rates: M-OU



Interaction rates: M-IR



UHECR from TDEs



tidal disruption of white drwarfs

fig. from Biehl, Boncioli, Lunardini and Winter, Sci. Rep. 8, 2018, 10828