PROBING ULTRA-LIGHT BOSONS WITH STELLAR TIDAL DISRUPTIONS

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STELLAR TIDAL DISRUPTION EVENTS

Stars passing close to SMBH can be tidally disrupted by strong tidal forces

Credits: DESY, Science Communication Lab
Stellar TDE’s
Stellar TDE’s

\[ \vec{S} \]

Light bosons and black hole superradiance
Stellar TDE’s

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Light bosons and black hole superradiance
Stellar TDE’s

Light bosons and black hole superradiance
STELLAR TIDAL DISRUPTION EVENTS

- Stars passing close to SMBH’s in the center of galaxies can be disrupted by strong tidal forces

\[ r_t = \frac{R_\star}{\left(\frac{M_{\text{BH}}}{M_\star}\right)^{1/3}} \approx 10^{-6} \text{ pc} \]

- The disruption is followed by a bright flare due to subsequent accretion of the stellar gas into the black hole
THIS BEHAVIOR WAS PREDICTED
(Martin Rees, Nature 333 91988)

$L_{bb} = 10^{43}$ erg/s (peak)

Current status: ~50 optically/UV selected
BASICS OF EVENT SELECTION

• TDE colors are quite constant in time, differently from SN’s.

Zabludoff et. Al. 2021
BASICS OF EVENT SELECTION

- TDE light curves are smoothly falling, with power-like law behavior.
BASICS OF EVENT SELECTION

- TDE’s are ultra-bright transient events, with close to or sometimes super-eddington luminosity.
- TDE light curves must be smoothly falling, with power-like law behavior.
- The light-curve fall timescale is of the order of months.
- TDE’s are selected only in -quiescent galaxies-. No AGN’s in them, and no previous history of accretion.
- TDE colors are quite constant in time, differently from SN’s.
  - TDE’s are quite “blue”.
  - TDE’s spectra are black-body, differently from power-law AGN’s.
  - TDE’s are non-recurrent phenomena, differently from AGN flares.
  - TDE’s come with some specific atomic emission lines, which were actually predicted!
TDE RATES

Observed and predicted TDE rates:
\( \sim 10^{-4} / \text{galaxy/year} \)

Sharp cutoff at high masses

Van Velzen 1707.03458
(see Stone, Metzger 1410.7772 for details)
THE HILLS MASS: NON-SPINNING BH

• For heavy BH’s, the tidal radius falls within the BH horizon, and TDE’s become unobservable.

\[ r_t = R_\star \left( \frac{M_{BH}}{M_\star} \right)^{1/3} \]

\[ r_{SS} = 2GM_{BH} \]
For $r_t > r_{SS}$,

$$M_{BH} \lesssim 10^8 M_\odot \left( \frac{R_*}{R_\odot} \right)^{3/2} \left( \frac{M_*}{M_\odot} \right)^{-1/2} \equiv M_{Hills}$$
• The Hills mass depends on BH spin, which modifies the near-horizon geometry.

\[ M_{\text{Hills}}(a) < M_{\text{BH}} \]

Hills mass grows with BH spin

\[ M_{\text{Hills}}(a \to 1) \sim 10^9 M_\odot \]

Hills mass for a main-sequence star
THE HILLS MASS

• TDE rates for galaxies with BH’s above the Hills mass are strongly suppressed, with a spin-dependent cutoff

[Adapted from Kesden 1109.6329]

TDE rate -per galaxy-
Stellar TDE's

Light bosons and black hole superradiance
If ultra-light bosons exist, SMBH spins are affected by the *superradiant instability*

This would leave very unique imprints on the observed TDE rates
BLACK HOLE SUPERRADIANCE

\[ \frac{\mu}{m} \lesssim \Omega_{\text{BH}} \]

\[ \mu : \text{Boson mass} \]

\[ m = -l \ldots l \]

Zeldovich JETP Lett. 14 180, 1971
Arvanitaki et. Al. 0905.4720, 1004.3558
BLACK HOLE SUPERRADIANCE

\[ \frac{\mu}{m} \lesssim \Omega_{\text{BH}} \]

Gravitational coupling

\[ \alpha = G M_{\text{BH}} \mu \]
**BLACK HOLE SUPERRADIANCE**

\[ \frac{\mu}{m} \lesssim \Omega_{\text{BH}} \]

**Gravitational coupling**

\[ \alpha = G\mu M_{\text{BH}} \]

**Cloud radius**

\[ r_{\text{cloud}} \sim \frac{n^2}{\mu \alpha} \]
BLACK HOLE SUPERRADIANCE

For maximally spinning black holes

$$\frac{\alpha}{m} \leq 0.5$$
The SR rates are strongly suppressed at small $\alpha$

$$\tau_{SR} \sim 100 \text{ years} \left( \frac{\alpha}{0.1} \right)^{-6} \left[ \frac{M_{BH}}{10^8 M_\odot} \right]$$  

Vectors (dark photons)

$$\tau_{SR} \sim 10^6 \text{ years} \left( \frac{\alpha}{0.1} \right)^{-8} \left[ \frac{M_{BH}}{10^8 M_\odot} \right]$$  

Scalars (axions)

As a consequence, SR is most effective for $\alpha \sim 0.1 - 1$, or

$$\mu \sim \frac{1}{GM_{BH}} = \frac{1}{r_g} \sim 10^{-18} \text{ eV} \left[ \frac{10^8 M_\odot}{M_{BH}} \right]$$
SUPERRADIANT SPIN EXTRACTION

Spin-0 boson

Note: if your BH has a low spin to start with, SR is not an observable effect

$\mu = 10^{-18} \text{ eV}$
$\mu = 5 \cdot 10^{-19} \text{ eV}$
$\mu = 10^{-19} \text{ eV}$

small $\alpha$  \hspace{1cm} large $\alpha$
The effect of light bosons on TDE event rates
BOSONS DECREASE THE EFFECTIVE HILLS MASS

Ultra-light bosons decrease the “effective Hills mass”
THE EFFECTIVE HILLS MASS

$M_H(a = 0.998) < M_{BH}$

$M_{BH} [10^8 M_\odot]$ vs $\mu [10^{-19} \text{eV}]$

**Scalars**

$M_{BH} [10^8 M_\odot]$ vs $\mu [10^{-19} \text{eV}]$

**Vectors**
TDE RATES IN THE PRESENCE OF ULTRA-LIGHT BOSONS

Spin-0 boson

TDE rate -per galaxy-
Testing axions and dark photons with LSST measurements of TDE rates
TDE RATE ESTIMATES IN LSST

Scalars

(Our rate estimates in the absence of ultra-light bosons roughly agree with Bricman, Gomboc 1906.08235)
Include (arbitrary) 50% systematic on rate

**Scalars**

**Vectors**

**LIMIT PROJECTIONS**
SMEARING DUE TO MBH MEASUREMENT UNCERTAINTIES

Spin 1

Current

Optimistic? improvements

$N_{\text{TDE}}$ vs. $M_{\text{BH}}/M_\odot$ for different values of $\mu$.
CONCLUSIONS

• TDE’s rate measurements are a fascinating new probe of BSM physics.

• Ultra-light bosons leave unique imprints in the TDE rate distribution function, at high BH masses.

• In principle, this can be used to either discover or set limits on these BSM theories, but work is required to understand systematics.

• The prospects are encouraging: LSST will select somewhere between 10K-100K TDE’s.