Hunting Intermediate-Mass Black Holes with Gravitational Waves and Neutrinos

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Intermediate-Mass black holes

There are 3 classes of BHs:

1. Stellar black holes (SBHs)
2. IMBHs, $10^2 - 10^5 \ M_\odot$
3. Supermassive black holes (SMBHs), $10^5 - 10^9 \ M_\odot$

There is strong evidence for the existence of SBHs and SMBHs.

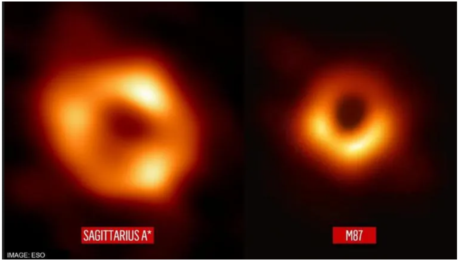

Figure: Images of the surroundings of two SMBHs.

Intermediate-Mass black holes

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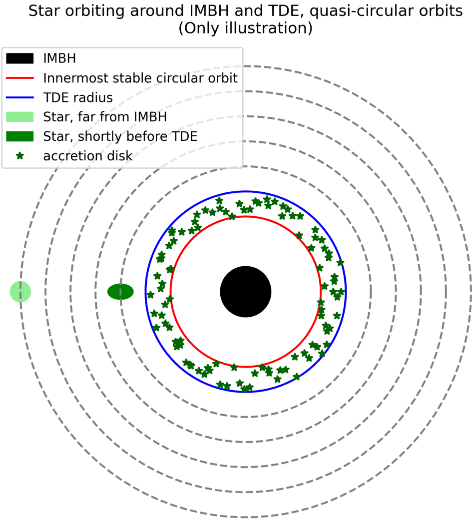
There is strong evidence for the existence of SBHs and SMBHs.

However, specific candidates for IMBHs have not yet been found.

Expected to be at the center of dwarf galaxies and globular clusters.

Tidal Disruptions Events

TDE = a star is tidally disrupted by a compact object



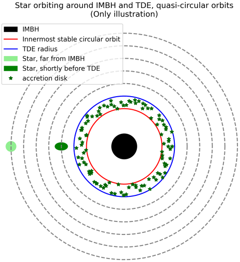
Tidal Disruptions Events

TDE = a star is tidally disrupted by a compact object

If it happens in outside the innermost circular orbit it will produce an accretion disk where particles can be accelerated and escape.

Two observables:

1. **GW emission** (from quasi-circular orbits)
2. **Neurino emission** (after the formation of the accretion disk)



Rates of TDEs

Models of dwarf galaxies predict a disruption of a star every 1000 years if they have an IMBH. 1% of the tidally disrupted stars are white dwarfs.

N-body simulations of globular clusters predict one TDE every 10^9 years, so we will neglect them.

Density of dwarf galaxies observed around us is approximately 10^8 Gpc^{-3}.

$$\text{Rate of TDEs} = 300 f_D \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

Kate Maguire, Michael Eracleous, Peter G. Jonker, Morgan MacLeod, and Stephan Rosswog. Tidal disruptions of white dwarfs: Theoretical models and observational prospects. Space Science Reviews, 216(3), mar 2020

Gravitational Waves detection

The quasi-circular spiral phase of the star orbiting IMBH will be within the observable window of the planned LISA detector (expected launch 2037).

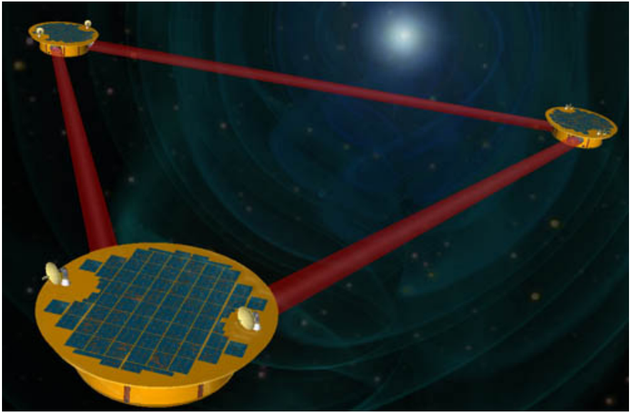
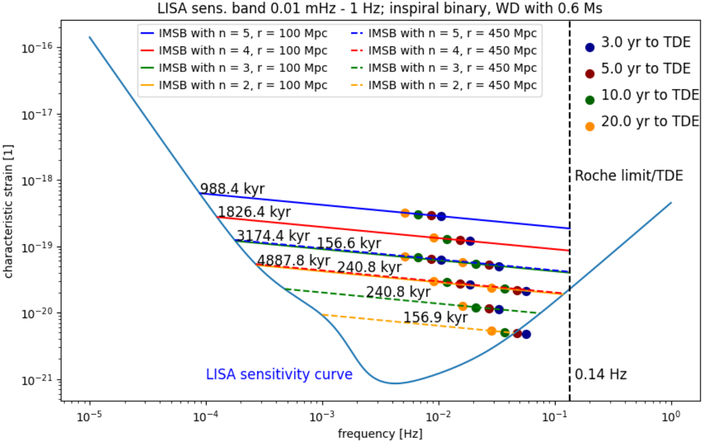


Figure: Cartoon depiction of LISA

Gravitational Waves detection



For frequency of 10^{-2} Hz LISA can give you an angular resolution of $\sim 10^{-3}$ rad for a SNR $= 10$, see[1]. The resolution goes $\propto \frac{1}{\mathrm{SNR}}$.

[1]https://doi.org/10.1103%2Fphysrevd.57.7089

Neutrino emission

The energy spectrum at which these TDEs emit is poorly known, see for example [2]. We take the model M-X as an order of magnitude estimate.

We then obtain the diffuse flux due these events as:

$$\Phi_{tot} = \int dV n_s \epsilon(M, z)$$

$$\epsilon = \frac{1}{4\pi} \Phi(M) R \frac{1}{4\pi\chi^2(z)(1+z)}$$

Note the dependence of the fluence on the mass of the black hole.

[2] Walter Winter and Cecilia Lunardini. Interpretation of the observed neutrino emission from three tidal disruption events. The Astrophysical Journal, 948(1):42, may 2023.

Neutrino emission

Comparing then with Icecube data we can expect 4-21% of 100 TeV neutrinos to come from this kind of TDEs

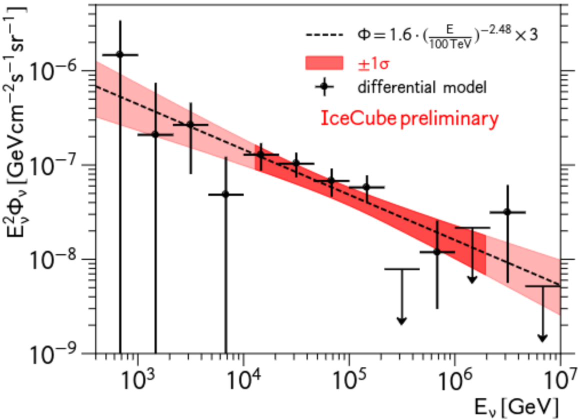
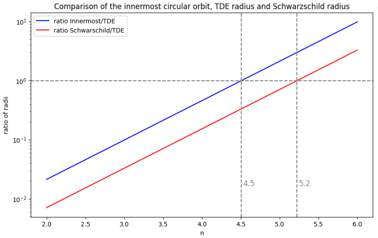


Figure: The icecube neutrino observatory - contributions to icrc 2017 part ii: Properties of the atmospheric and astrophysical neutrino flux, 2017.

Impossibility of Coincidence Studies - White Dwarf Case

Only TDE of a White dwarf in an IMBH that can produce both Gravitational Waves and Neutrinos in a single event



[3] Establishing accretion flares from massive black holes as a major source of high-energy neutrinos, 2021.

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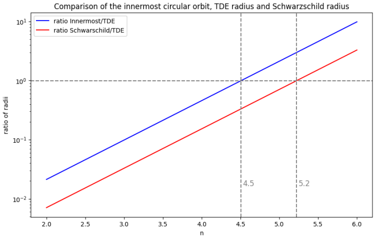

Problem: The expected delay between Gravitational Waves and Neutrinos is ~ 30 years (highly dependent on the parameters of the TDE) [3]

$$t_{delay} \sim 0.57\beta^{-3}\frac{0.1}{\eta}\left(\frac{10^7 M_\odot}{M_{BH}}\right)^{7/6}\left(\frac{M_*}{M_\odot}\right)^{8/25} yr \propto \frac{1}{M_{BH}^{7/6}}$$

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Future Work: Angular Cross-Correlation in Harmonic Space

If the GWs and some of the high energy neutrinos come from the same kind of events, they should be tracing the same underlying angular distribution $\rightarrow$ Study their **angular cross-correlation in harmonic space**.

Consider two independent maps, one of GWs and one of neutrinos, then expand as:

$$a_{lm} = \int d\Omega Y_{lm}(\mathbf{n}) M_b(\mathbf{n})$$

Calculate the cross correlation as:

$$\langle a^{\nu}_{lm} a^{*GW}_{lm} \rangle_{m=0...2l+1} = C_l^{\nu GW}$$

The shot noise needs to be taken into account:

$$C_l^{\nu GW} = S_l^{\nu GW} + N_l^{\nu GW} \quad ; \quad N_l^{\nu GW} = \frac{\bar{N}_{\Omega,\nu\wedge GW}}{\bar{N}_{\Omega,\nu} \bar{N}_{\Omega,GW}}$$

Thank you for your attention!

Any questions?