Tidal Disruptions by Binary Black Holes in Dense Stellar Systems: Studying the Spin Magnitude and Direction of LIGO Sources

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Abstract

As the era of multi-messenger astronomy is well underway[1] there remain key mysteries as to the origin of the binary black hole (BBH) gravitational wave sources observed. The field has, in general, converged to two possible main formation channels: classical formation in the galactic field and dynamical assembly in dense stellar systems such as globular clusters (GCs). The search for a promising marker of the ancestry of LIGO BBHs (LBBHs) has narrowed down to a few key observables, one such being the spin of the individual BH constituents and their alignment[2]. We present a framework for how tidal disruption events (TDEs) by LBBHs in GCs can alter the expected values for the spin magnitude and direction of LBBHs. We present three unique TDE scenarios in which LBBH TDEs can take place and how the result of these interactions depend on each scenario.

Formation Channels

- **BBH formation channels can** be categorized as *Classic Field Formation* (CFF) or *Dynamical Assembly* (DA)
- **In the CFF channel**, stars are born in a binary and through stellar evolutionary processes become BHs then merge. CFF LBBHs are expected to have their individual BH spins aligned with the orbital angular momentum of the binary $\mathbf{J}_{\rm bin}$.
- **In the DA channel**, single BHs in GCs interact with binary and triple systems resulting in numerous few-body interactions and exchanges. Such chaotic interactions tend to keep the heaviest objects bound and this process continues until a LBBH is produced. The final LBBH product follows a random distribution of spin angles due to the isotropic nature of formation[3].
- **LIGO measures** spin through a parameter called $\chi_{\rm eff}$ which ranges from $[-1,1]$. A $\chi_{\rm eff}$ of 1 indicates that both spins are aligned with $\mathbf{J}_{\rm bin}$, -1 indicates that both spins are aligned opposite to $\mathbf{J}_{\rm bin}$. Let $\mathbf{J}_{\rm bin}$ point along the z-axis, then $\chi_{\rm eff}$ of 0 means that the z-component of the BH spins cancel. Therefore, it seems that CFF LBBHs have $\chi_{\rm eff}$ values greater than zero and DA LBBHs have a symmetric $\chi_{\rm eff}$ distribution centered about zero.
- **While the** preceding arguments define characteristic formation channel spin orientations of LBBHs, these are only valid assuming no further interactions with other systems occur before merger. We propose that LBBHs can be exposed to TDEs between formation and merger which can alter natal spin orientation and magnitude.

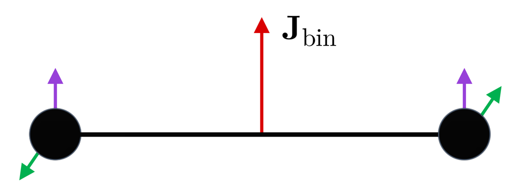

Figure 1: Current theoretical CFF and DA spin orientations

Tidal Disruption Events

- **TDEs** are physical phenomena which occur when a star comes within a critical distance defined as the tidal radius $R_\tau = q^{1/3}R_*$, where $q = M_{\rm bh}/M_*$.
- **TDEs are caused by** the differential gravitational field felt by the star as it approaches a BH. The gradient of the force of gravity becomes strong enough to rip the star apart when it crosses R_τ.
- **In dense globular cluster** cores, there is a high probability due to scattering events that a star will come within the R_τ of a BH leading to a TDE. The stellar material liberated during a TDE can subsequently be accreted by the BH and alter its spin.

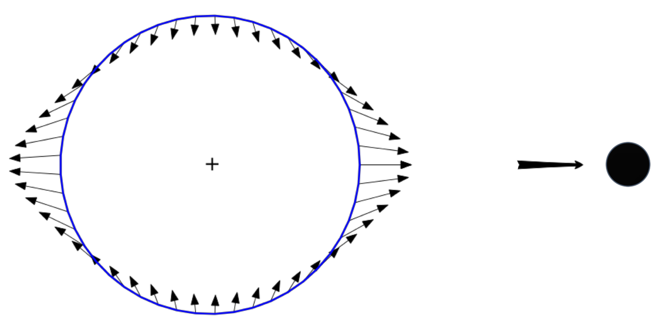

Figure 2: Gravitational tidal field (credit: WikimediaCommons)

Methods

- **We simulate TDEs** of stars by LBBHs using modified versions of GADGET[4,5], a Smoothed Particle Hydrodynamics (SPH) code. All LBBHs have eccentricity $e = 0.5$ and initially zero spin.
- **LBBH TDEs** are categorized into three unique scenarios: *Single Scenario* (SS), *Circumbinary Scenario* (CS) and *Overflow Scenario* (OS).
- **The parameters which** determine the scenario are the binary separation d, R_τ, the semi-major axis of the orbit which contains 90% of bound debris a_{90}, and the Roche lobe radius R_L

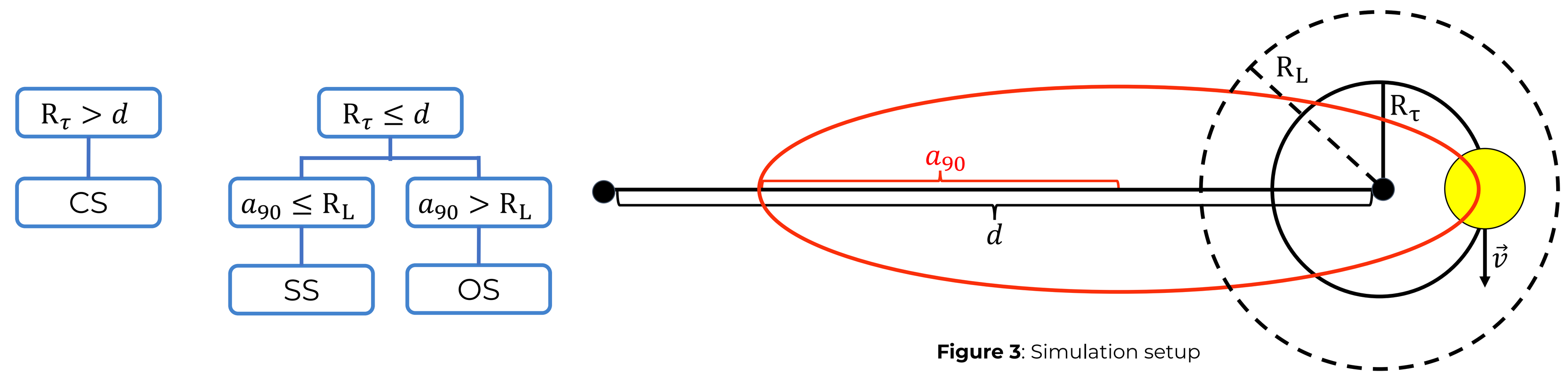

Figure 3: Simulation setup

Circumbinary Scenario

Circumbinary scenario (CS) occurs when d is larger than R_τ such that the accretion disk encompasses the binary.

Simulation Parameters:
- $M_* = 1\,M_\odot$, $R_* = 43\,R_\odot$
- $M_{\rm bh_1} = M_{\rm bh_2} = 15\,M_\odot$, $d = 0.2$ AU
- $R_\tau/d = 2.47$

Result: $\chi_{\rm eff,\,final} = -0.015$

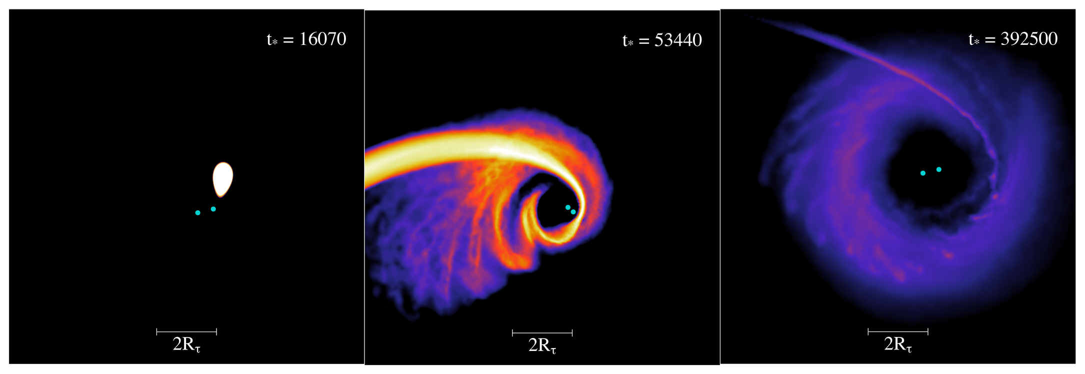

Figure 4: CS TDE using GADGET. R_τ and t_* are the tidal radius and dynamical time step of the star, respectively.

Single Scenario

Single scenario (SS) occurs when d is less than R_τ and a_{90} is *less than* R_L resulting in essentially a single BH TDE.

Simulation Parameters:
- $M_* = 1\,M_\odot$, $R_* = 1\,R_\odot$
- $M_{\rm bh_1} = M_{\rm bh_2} = 15\,M_\odot$, $d = 2$ AU
- $R_\tau/d = 0.01$, $a_{90}/R_L = 0.54$

Result: $\chi_{\rm eff,\,final} = -0.045$

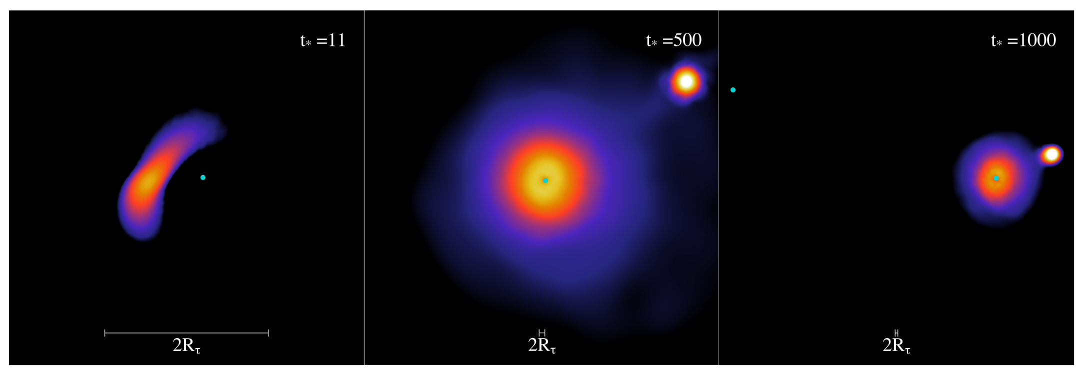

Figure 5: SS TDE using GADGET. R_τ and t_* are the tidal radius and dynamical time step of the star, respectively.

Overflow Scenario

Overflow scenario (OS) occurs when d is less than R_τ and a_{90} is *greater than* R_L resulting in accretion onto both BHs.

Simulation Parameters:
- $M_* = 1\,M_\odot$, $R_* = 1\,R_\odot$
- $M_{\rm bh_1} = M_{\rm bh_2} = 15\,M_\odot$, $d = 0.2$ AU
- $R_\tau/d = 0.06$, $a_{90}/R_L = 5.44$

Result: $\chi_{\rm eff,\,final} = 0.003$

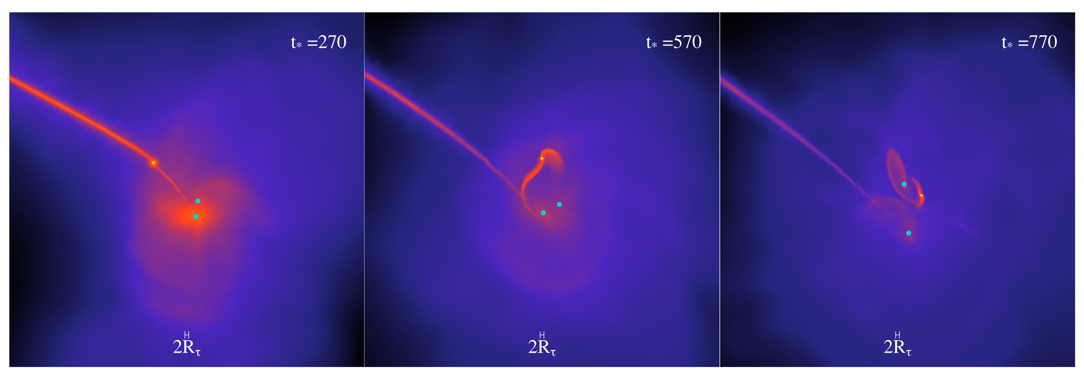

Figure 6: OS TDE using GADGET. R_τ and t_* are the tidal radius and dynamical time step of the star, respectively.

Massive Overflow Scenario

Low $\chi_{\rm eff,\,final}$ values from the previous simulations can be expected since the final spin depends heavily on q. Therefore we simulate a massive overflow scenario (MOS) which has $q = 0.5$.

Simulation Parameters:
- $M_* = 5\,M_\odot$, $R_* = 6\,R_\odot$
- $M_{\rm bh_1} = M_{\rm bh_2} = 10\,M_\odot$, $d = 0.1$ AU
- $R_\tau/d = 0.35$, $a_{90}/R_L = 16.14$

Result: $\chi_{\rm eff,final} = -0.019$, this result is a bit deceptive because both BH spin magnitudes increased significantly but were anti-aligned.

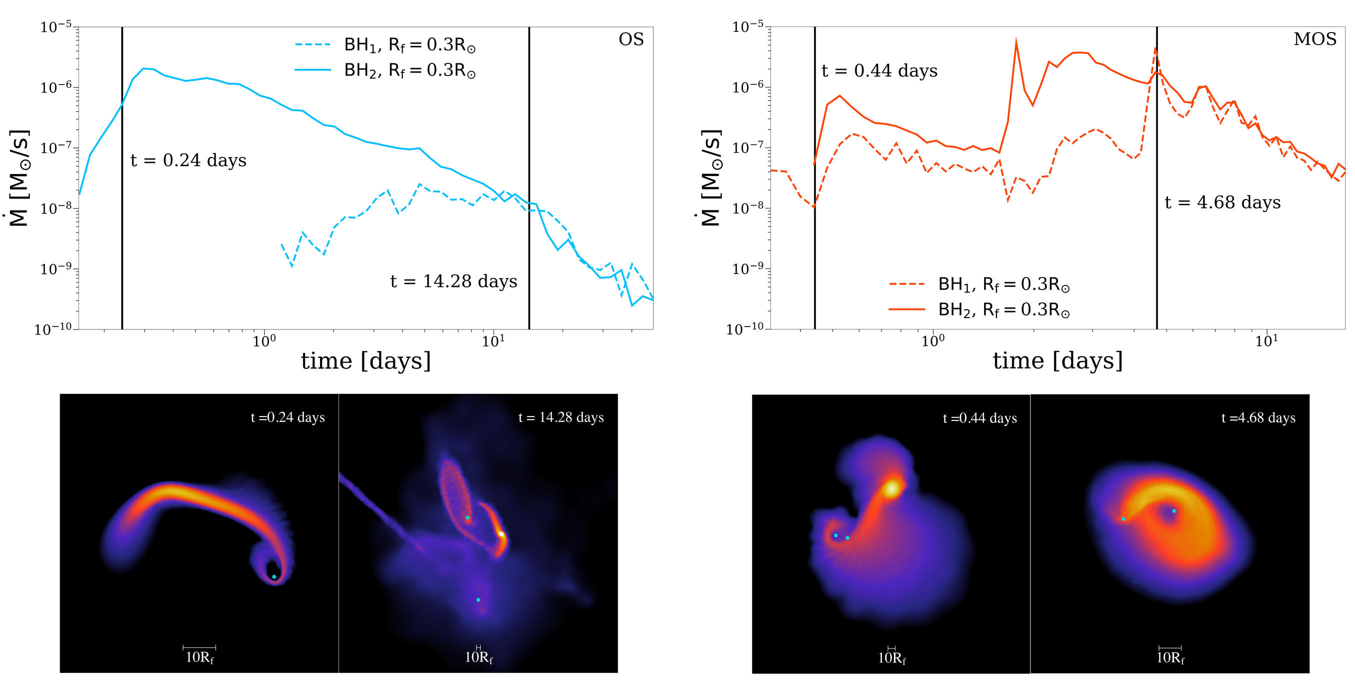

Figure 7: OS and MOS $\dot{M}$ curves with simulation frames corresponding to vertical lines. R_f is the accretion radius.

Spin Orientations

- The orientation of accretion following a LBBH TDE will determine the direction of BH spin up and the final $\chi_{\rm eff}$
- Below are a few of the accretion disks that formed during our simulations.

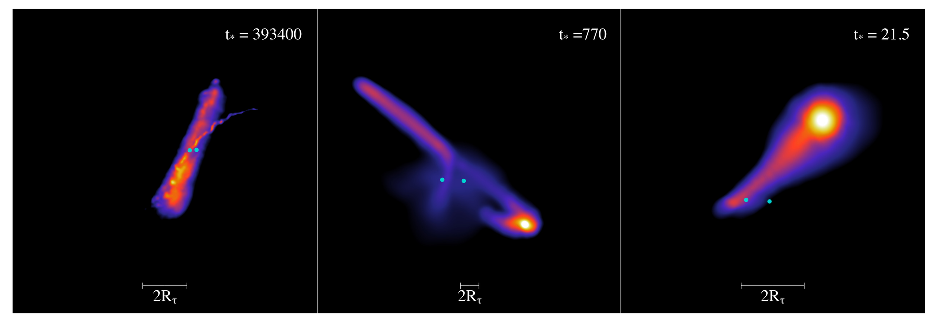

Figure 8: Side view of accretion disks for the CS (left), OS (middle), and MOS (right). t_* is the dynamical time step of the star

- In general, we can infer characteristic spin orientations based on which scenario a LBBH TDE falls under.
- All scenario orientations depend on whether the stellar orbit is clockwise or counter-clockwise with respect to $\mathbf{J}_{\rm bin}$.
- SS and CS orientations are straightforward where only the CS has the potential to align both BH spins.
- The OS can result in aligned or anti-aligned spins. The non-disrupting BH has its spin aligned with $\mathbf{J}_{\rm bin}$ as a result of accreting material as it plunges into the accretion disk of the disrupting BH.

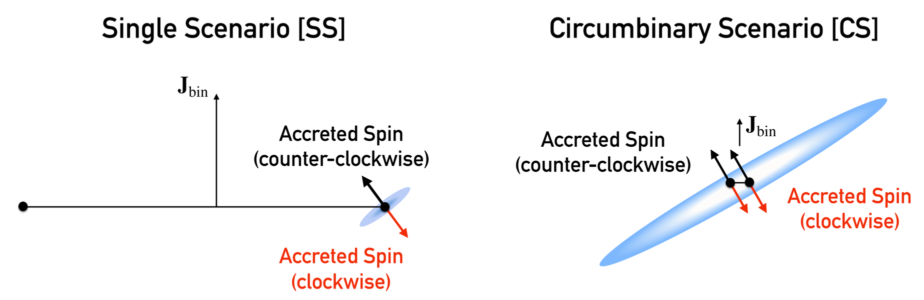

Figure 9: General final spin orientations for the SS and CS. Clockwise and counter-clockwise refer to the direction of the stellar orbit relative to $\mathbf{J}_{\rm bin}$.

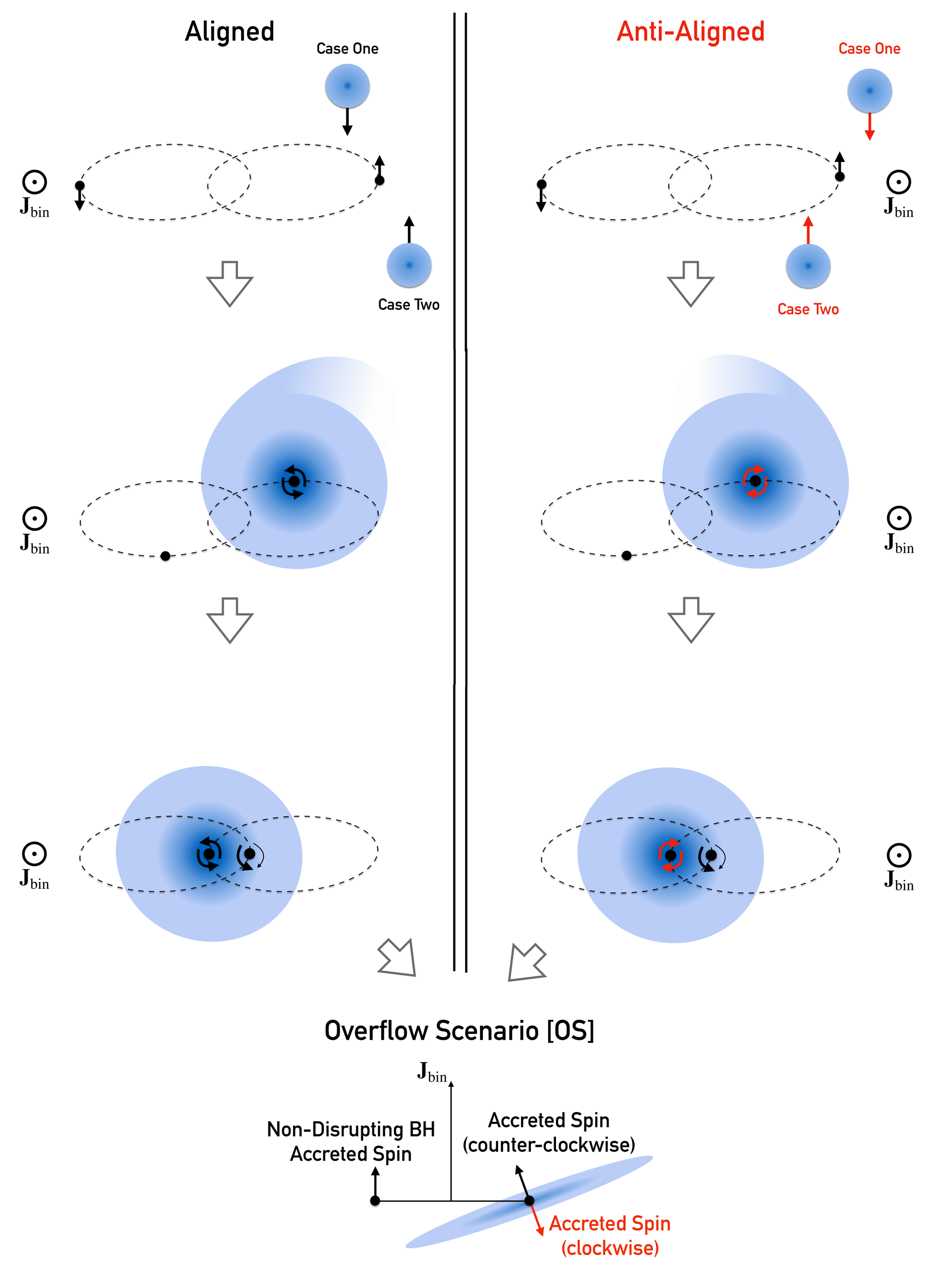

Figure 10: General final spin orientations for the OS. Clockwise and counter-clockwise refer to the direction of the stellar orbit relative to $\mathbf{J}_{\rm bin}$.

Conclusion

We have shown that TDEs by LBBHs can change the individual birth spin magnitude and direction. For further discussion of the implications of our results and possible observables please see our paper **arXiv: 1812.01118**.

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References:
[1] Abbott, B. P. et al. 2016, Physical Review Letters, 116, 061102, 1602.03837; **[2]** Farr, W. M., Stevenson, S., Miller, M. C., Mandel, I., Farr, B., & Vecchio, A. 2017, Nature, 548, 426, 1706.01385; **[3]** C. L. Rodriguez, M. Zevin, C. Pankow, V. Kalogera, and F. A. Rasio, Astrophys. J. 832, L2 (2016); **[4]** Springel, V. 2005, MNRAS, 364, 1105; **[5]** Pakmor, R., Edelmann, P., Röpke, F. K., & Hillebrandt, W. 2012, MNRAS, 424, 2222, 1205.5806;