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Evolution of Black Hole Binary - From Birth to Final Coalescence

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ABSTRACT

This paper starts with the birth of Black Hole Binaries through major and minor mergers of galaxies accompanied with gravitational wave radiation. The formation of loss cone is described and if this loss cone is not replenished then the last parsec stalling of the merging BlackHole occurs. Spherical Symmetry, axi-symmetry and triaxial symmetry model of galaxies is described. Triaxiality ensures that loss cone is replenished and last parsec problem does not arise. Gravitational Wave Emission and their frequency range is described. Notable Black Hole Binaries are described. A century of Gravitational Wave Detection is described with the testing of Strong Equivalence Principle. Nano-Hz gravitational wave detection and their results are described.

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Introduction

Birth of Black Hole Binaries

Dynamical Friction is one of the most fundamental processes in astrophysics. S.Chandrasekhar introduced it in stellar dynamics [1-3]. Dynamical Friction is also known as Chanrashekhar Friction. The gravitational drag causes loss of momentum and Kinetic Energy of moving bodies through gravitational interaction with surrounding matter in space. Dynamical Friction plays a key role in the evolution of SMBH Binaries, galaxies, star clusters, binary star cores in the common envelope phase of evolution and in proto-planet migration. Dynamic Friction is the systematic deceleration effect of the fluctuating field of forces acting on a star in motion.

Hierarchical formation of Galaxies leads to merger of Galaxies and this leads to the formation of Supermassive Black Hole Binary. Galaxy evolution, Active Galactic Nuclei and Black Hole growth can be understood through the understanding of SMBH Binary.

Very few such binaries have been detected till date. Maybe they coalesced quickly or one component dissociated and escaped.

Major and Minor Mergers

There are two types of Galaxy merger: major and minor. When the two Galaxies are of comparable size with mass ratio $q < 3$ then we have major merger and when two galaxies have mass ratio $q > 5$ then we have minor merger.

Mergers must be Accompanied with Gravitational Wave Emission

Galaxy merger must be accompanied with gravitational waves emission because of SMBH binary - the two components on an elliptical path.Gravitational Waves Emission are expected from merging SMBH.

In September 2015, LIGO discovered GW 150911 and identified it as merging BH binary [4].

Mergers due to Dynamical Friction

There are different types of mergers:

- Merger due to dynamical friction between the SMBH positioned at respective centers of the host galaxies. These SMBHs sink to a common center of merged galaxies. The two SMBHs become a binary because
- The orbital decay is due to interaction between the stars, gas and dust of both the galaxies;
- When the SMBH become close enough the gravitational wave emission leads to inspiral, ring down, chirp signal and final coalescence;

  The last parsec problem:
- The required resolution has not been achieved to resolve the binary at the final stage;
- Hence BH coalescence has not been studied;

The fate of the merger at parsec scale depends upon the amount of surrounding stars and gas and their interaction with the SMBH Binary. In case of stellar background, due to Three Body scatter, formation of loss cones takes place. Whereas in case of gas rich merger, tidal forces inhibit the gas from falling into the binary hence creating a gap. This loss cone causes a decay period longer than the Hubble Time and hardening can be achieved for a triaxial stellar remnant with the loss cone being replenished and expected coalescence time ~ 10^8 y. For gas rich mergers the gap doesn't inhibit gas flow and a massive circumbinary disc around the SMBH binary promotes the decay leading to a time scale for equal mass binary ~$10^7 M_\odot$ that is less than the age of the Universe. For higher mass BH (~ $10^{8-9} M_\odot$) the time scale is larger. Khan et.al. have reported that for massive galaxies at high redshift (z>2) it takes a few million years for SMBH to coalesce once they have formed the binary [5]. Whereas at lower redshift z where nuclear density of the host is lower it takes a longer time of the order of Gy.

What is a Loss Cone?

In the context of SMBH binaries embedded in a stellar background, a loss cone is a region in phase space (specifically in angular momentum space) where stellar orbits are likely to bring stars close enough to the SMBH binary to interact strongly — typically resulting in:

- Slingshot ejection of the star (3-body scattering),
- Energy and angular momentum extraction from the binary,
- And thus hardening of the SMBH binary (i.e., shrinking the separation).

Why a Cone?

The name comes from the analogy with stellar dynamics near a single black hole: stars on orbits with low enough angular momentum can plunge toward the center — "lost" to the system. These form a cone in velocity space, hence the term "loss cone."

The Challenge presented by "loss cone"

As the binary ejects stars, the supply of stars in these low-angular-momentum orbits is depleted. If the system is spherically symmetric, this depletion isn't replenished fast enough — the loss cone is "empty" and hardening stalls. This leads to the "final parsec problem" — the binary may stall at parsec scales with a decay timescale exceeding the Hubble time [6].

Gas Rich Mergers and Circumbinary Disks

In contrast, if the environment is gas-rich, the binary is embedded in a circumbinary disk. Here, different mechanisms operate:
The SMBH binary clears a central cavity (gap) due to tidal torques.

However, gas can still flow through streaming arms across the cavity and interact with the SMBHs, especially through mini-disks.

The interaction with the viscous gas (torques from density waves and accretion) continues to extract angular momentum, driving inspiral.

This process leads to efficient binary decay and circumvents the final parsec problem, especially for equal-mass binaries of $\sim 10^7$ M⨀, where coalescence can happen within a Gyr, well within the Hubble time.
"For higher mass BH (10^8–9 M⨀) the time scale is larger."

Higher mass SMBH binaries tend to:

- Open wider gaps in gas disks (harder to refill),
- Emit weaker gravitational wave (GW) radiation at large separations,
- Require more efficient gas inflow to sustain decay.

For stellar-dominated backgrounds, the dynamical friction and 3-body interactions are also less efficient due to fewer stars per unit mass at high mass scales.

Thus, for massive binaries (10^8–10^9 M⨀), both gas dynamical friction and stellar interactions become less effective, and coalescence time can be longer — potentially exceeding the Hubble time if no replenishing mechanism is active.

The key is whether efficient mechanisms (triaxiality, gas inflow, or resonant relaxation) are present to drive continued inspiral. The redshift dependence of SMBH binary coalescence timescales. The paper addresses the dynamical evolution of SMBH binaries and how environmental conditions, especially those evolving with cosmic time, affect their merger timescales [7]. In a static, spherical galaxy model, the binary stalls at final separation of parsec after ejecting all the stars in the loss cone. Centrophilic orbits in the triaxial galaxy model are key in refilling the loss cone at a high enough rate to prevent the Black Hole from stalling. The MERE axi-symmetry of the galaxy can solve the final parsec problem. Super Massive Black Hole binary evolution is independent of N (number of particles) for axis ratio of e/a = 0.8.

The SMBH and SMBH Binary separation reaches the gravitational radiation regime for e/a = 0.75. (axis ratio is the flattening ratio)

Difference between Spherical Symmetry and Axisymmetry in Galaxy Models Spherical Symmetry

A spherically symmetric galaxy is one in which the density and structure are the same in all directions from the center. This means:

- The galaxy has the same shape as a sphere.
- The gravitational potential is radially symmetric.
- Stellar orbits are generally isotropic (random in orientation).
- After a binary SMBH ejects stars within its loss cone, there's no efficient mechanism to repopulate it, leading to a final-parsec problem (stalling of orbital decay).

Axisymmetry

An axisymmetric galaxy is symmetric around one axis (usually the z-axis), meaning:

- It has a flattened or elongated shape, like an oblate or prolate spheroid (like a rugby ball or a disk).
- The gravitational potential depends on both radius and height from the equatorial plane.
- It allows centrophilic orbits — orbits that come very close to the center helping refill the loss cone.
- This replenishment enables further hardening of the SMBH binary, avoiding stalling.

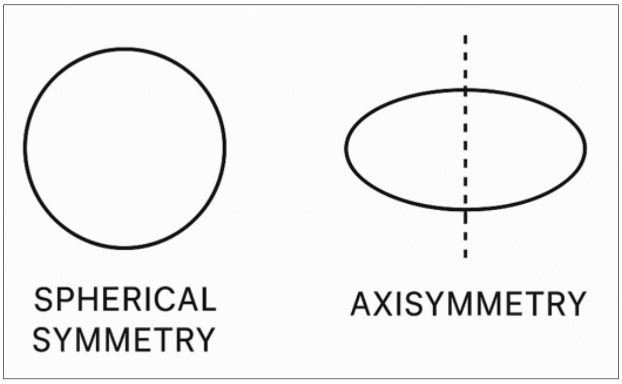


Figure 1: Spherically Symmetric and Axi-symmetric Galaxy

(Credit: ChatGPT Image June 1,2025, 12:46 AM.png)
In the context of the axis ratio e/a used to describe the shape of a galaxy, the terms typically refer to the following:

- a = the semi-major axis of the galaxy's ellipsoidal shape — the longest radius.
- e = the semi-minor axis along a direction perpendicular to a — the shorter radius.

So, e/a is the flattening ratio (also called axis ratio), indicating how elongated or flattened the galaxy is.

Interpretation:

- Spherical symmetry: e/a=1
  → All axes are equal → perfect sphere.
- Axisymmetry (oblate or prolate): e/a<1
  → Flattened along one direction; shape becomes like a disk or rugby ball.

- For e/a=0.8:
  The galaxy is moderately flattened — still axisymmetric, but the SMBH binary evolution becomes independent of particle number N due to efficient loss cone refilling.
- For e/a=0.75:
  The galaxy is even more flattened — helps drive the binary to separations small enough for gravitational wave emission to dominate.

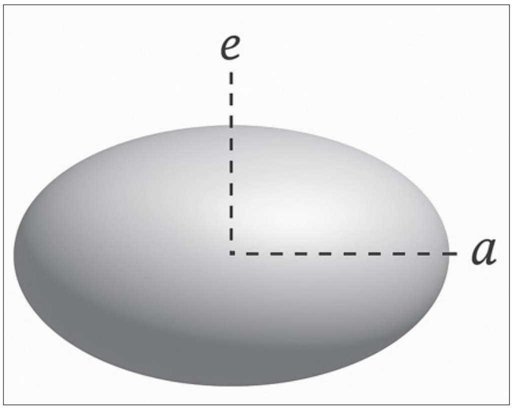


Figure 2: The axi-symmetric Galaxy-an ellipsoidal galaxy (Credit: ChatGPT Image June 1,2025, 12:46 AM.png)

We have spherical symmetry, axi-symmetric and we have tri-axial symmetry;
The term triaxial symmetry refers to a specific kind of symmetry in three-dimensional shapes—particularly in astrophysics and galaxy dynamics—where an object has three unequal principal axes of symmetry. Here's a breakdown of why and how it's used:

Definition of Triaxial Symmetry
An object has triaxial symmetry if it is symmetric with respect to three orthogonal axes, but the lengths of these axes are different. That is, the object is shaped like a triaxial ellipsoid, not a sphere or a rotational ellipsoid.

Mathematically, this means the spatial distribution follows:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \text{ where } a \neq b \neq c \text{ ;}$$

The spherical symmetry (where a=b=c) and axial symmetry (where, say, a=b≠c).

Why "Triaxial" in Galaxies?
In the context of galaxy morphology, particularly elliptical galaxies or the remnants of galaxy mergers, many systems exhibit non-spherical and non-axisymmetric structures. Observations and simulations show that:
- Spherical symmetry is idealized and rarely found in real galaxies.
- Axisymmetry (symmetry about a single axis) is more common but still limiting.
- Triaxial symmetry is general and realistic—it reflects that galaxies often look ellipsoidal with three unequal axes a, b, and c.

Thus, triaxiality is used to model galaxies more accurately, especially when studying:
- Stellar orbits
- Gravitational potential
- Dark matter halo shapes
- SMBH binary evolution and loss cone replenishment

Physical Implications of Triaxiality
Triaxial systems allow for special kinds of orbits not possible in spherical or axisymmetric potentials:
- Box orbits: Stars move in 3D boxes, reaching very close to the center.
- Centrophilic orbits: These helps funnel stars toward the galactic center, crucial in feeding SMBHs or refilling the loss cone for binary coalescence.

Summary

Term	Symmetry Property	Example Shape
Spherical	a=b=c	Sphere
Axisymmetri c	a=b≠c	Oblate/prolate spheroid
Triaxial	a≠b≠c	Triaxial ellipsoid

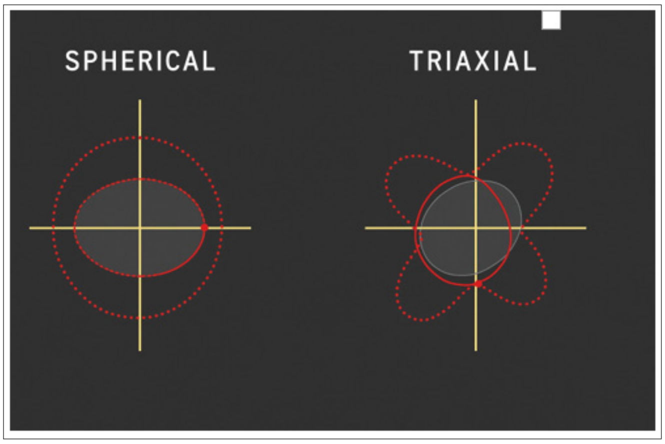


Figure 3: How stars orbit behave differently in Spherical Symmetric Galaxies and in Triaxially Symmetric Galaxies. (Credit: ChatGPT Image June 1,2025, 12:46 AM.png)

This is why Khan et al. and others emphasize triaxiality: it's a key to solving the final parsec problem in SMBH mergers [5]. Summary of Khan et al. Findings [5]:

Khan and collaborators conducted high-resolution direct N-body simulations of galaxy mergers containing SMBHs to examine how fast the SMBH binaries coalesce in different host galaxy environments.

Their key finding is:
At high redshift ($z > 2$), SMBH binaries merge rapidly — within a few million years after forming a bound binary. At lower redshifts ($z \sim 0$), the same process can take up to several gigayears.

Why is There a Redshift Dependence?
The difference in coalescence timescales comes down to host galaxy properties that evolve with redshift.
- **High Redshift Galaxies ($z > 2$)**
- **Gas-rich environments:** More abundant cold gas leads to strong dynamical friction and gas drag.
- **High nuclear densities:** Central stellar and gas densities are higher, providing a dense background for efficient angular

momentum extraction.
- **More compact galaxies:** The dynamical time is shorter; stars interact with the SMBH binary more frequently.
- **Efficient replenishment of the loss cone:** Due to triaxiality or ongoing gas inflows.

Result
Binary hardening and eventual coalescence occur quickly—typically <10 Myr after binary formation.

Low Redshift Galaxies (z ~ 0)
Gas-poor ("dry") mergers: Less cold gas, so gas drag is ineffective.
Lower central densities: Fewer stars interact with the binary; 3-body scattering slows down.
Spherical symmetry: Less efficient loss cone replenishment.
Longer dynamical times due to larger, more diffuse galaxies.

SMBH binaries can stall at parsec scales for up to ~1 Gyr or longer, especially if the environment is symmetric or lacks gas.

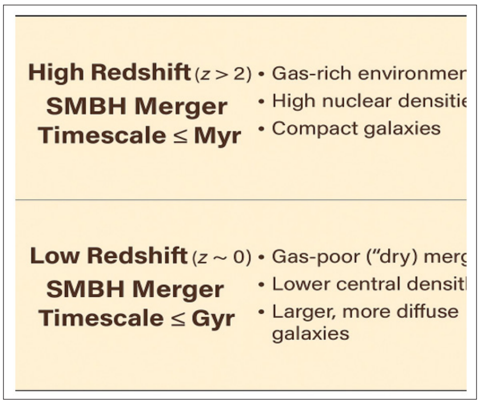
Supporting Mechanisms at High - z
Khan et al. (and others like Mayer et al.) argue that the following mechanisms help **overcome the "final parsec problem" at high z:**
Triaxiality of merger remnants: Keeps loss cone filled.
Gas inflows and clumps: Can torque the binary or drive inflows that refill the cavity.
Dynamical friction from dense nuclear star clusters and gas inflow channels.

Observational Implications
High-z SMBH mergers may contribute significantly to the population of high-frequency gravitational wave sources for future space-based observatories like LISA.

Low-z binaries may remain stalled, becoming ultra-long-period binaries, possibly detectable by PTA (pulsar timing arrays) as nanoHz GW sources — if they don't stall forever.

Conclusion
The environment at high redshift (z > 2) — being denser, more gas-rich, and more dynamically active — leads to rapid SMBH binary coalescence (within Myr).
At lower redshifts, the conditions are more passive and less efficient at extracting angular momentum, so binaries can take up to Gyr to merge — if at all.

Table 1: SMBH Merger at high redshift and at low redshift



Gravitational Waves Emission from SMBH Binary
Different mass binaries produce different frequencies of gravitational waves. Orbiting WD/NS produce high frequency GW and SMBH binary produces low frequency GW. Strongest signals come from SMBH binaries because they most strongly wrap the space-time fabric. In 300My Hulse-Taylor Pair will finally coalesce.

A key feature of a black hole is its "event horizon" — the radius at which a beam of light would just fail to escape. Any event that takes place within this horizon can never be glimpsed from outside. For a non spinning, 10-solar-mass black hole, the event horizon spans approximately 37 miles (60 kilometers). Double the mass, and the diameter also doubles. A black hole spinning at the maximum possible rate has a diameter half that of a nonrotating one with the same mass.

Ronald Remillard of the Massachusetts Institute of Technology in Cambridge and Jeffrey McClintock of the Harvard Smithsonian Center for Astrophysics (also in Cambridge) have compiled the most up-to-date list of black holes in binary systems. Our galaxy contains 18; their locations and properties appear on page 49 [8].

Notable Black Holes and their Binary Systems
- **Cygnus X-1:** The Iconic Stellar-Mass Black Hole
- **Type:** Stellar-mass black hole in a high-mass X-ray binary (HMXB).
- **Companion:** A massive blue supergiant (HDE 226868).
- **Mass Estimate:** ~21 solar masses (as of latest studies).
- **Distance:** ~6,100 light-years.
- **Significance:** First strong black hole candidate; discovered via its X-ray emission in the 1960s.
- **Recent Milestone:** Confirmed via VLBI parallax and Doppler studies to be spinning rapidly (possibly near-maximal Kerr spin).

M15: Possible Intermediate-Mass Black Hole
- **System:** M15 (NGC 7078) – a dense globular cluster in Pegasus.
- **Candidate IMBH:** Some studies suggest a ~1,000 solar mass black hole at the core.
- **Debate:** The presence of an intermediate-mass black hole (IMBH) remains unconfirmed. Competing models involve a central concentration of neutron stars or stellar remnants.
- **Detection Methods:** Stellar velocity dispersion, dynamical modeling, and radio/X-ray constraints.
- **Relevance:** Finding an IMBH in a globular cluster bridges the gap between stellar-mass and supermassive black holes.

The Variety of Black Holes in the Milky Way

Type	Mass Range	Typical Diameter	Examples
Stellar-Mass	3–15 M⊙	~37 mi (60 km)	Cygnus X-1, V404 Cygni, etc.
Intermediate-Ma ss	100–100,000 M⊙	Up to ~60,000 km	M15? G1 (M31)? HLX-1 (outside MW)

Supermassive	~4 million M⊙ (in MW)	~24 million km	Sagittarius A* at galactic center

Note on Scale

- Stellar-mass black holes are roughly the size of a small city or the state of hode Island.
- Intermediate-mass black holes, if they exist, would span thousands of kilometers, akin to several Earth diameters.
- Supermassive black holes are solar system-scale objects by diameter.
- Milky Way Black Hole Inventory
- Confirmed Stellar-Mass BHs in X-ray binaries: ~18–20
- Candidate Intermediate-Mass BHs: Still under investigation (e.g. M15, Omega Centauri, 47 Tucanae).
- Supermassive BH: Sagittarius A* at the Galactic Center (~4 million M⊙).

Intermediate Mass Black Holes

If intermediate-mass black holes exist, they would extend a few Earth diameters. The central supermassive black hole spans 17 Suns. Astronomy: Roen Kelly companion star is a blue supergiant that tips the scales at approximately 19 solar masses. In fact, this luminous companion shines brightly enough that it appears in our sky as a 9th-magnitude star visible through amateur telescopes.

The black hole in Cygnus X-1 weighs close to 15 solar masses, which makes it the heaviest one known in a binary system. The two objects orbit each other once every 5.6 days at an average distance about half that between the Sun and Mercury. As matter in the accretion disk falls toward the black hole, magnetic fields channel some of it into a pair of high-speed jets that emerge perpendicular to the disk. Recent observations show that the black hole rotates at more than 90 percent of the theoretical maximum.

A Century of Gravitational Waves

Scott Ransom and his team at the National Radio Astronomy Observatory have been studying the unique triple star system PSR J0337+1715 to test the foundations of Einstein's theory of general relativity. This system, located approximately 4,200 light-years away in the constellation Taurus, comprises a millisecond pulsar and two white dwarf stars.

Key Findings

Testing the Strong Equivalence Principle (SEP)

The team utilized the system to test the SEP, which posits that all objects, regardless of their mass or composition, fall at the same rate in a gravitational field. They observed that both the neutron star (pulsar) and its inner white dwarf companion fall toward the outer white dwarf at the same rate, with any difference in acceleration being less than three parts in a million. This result supports the SEP and places stringent constraints on alternative theories of gravity.

Precision Measurements

Through meticulous observations using the Green Bank Telescope, the Arecibo Observatory, and the Westerbork Synthesis Radio Telescope, the team achieved unprecedented precision in tracking the pulsar's pulses. They could account for every single pulse since observations began, determining the pulsar's location to within a few hundred meters.

Unique Laboratory for Gravitational Studies

The configuration of PSR J0337+1715, with its closely orbiting components, provides a natural laboratory for testing gravitational interactions in strong-field conditions. The system's dynamics allow for the examination of gravitational theories with a sensitivity several orders of magnitude greater than previous tests.

These findings not only reinforce the predictions of general relativity but also demonstrate the potential of using complex stellar systems to probe fundamental physics.

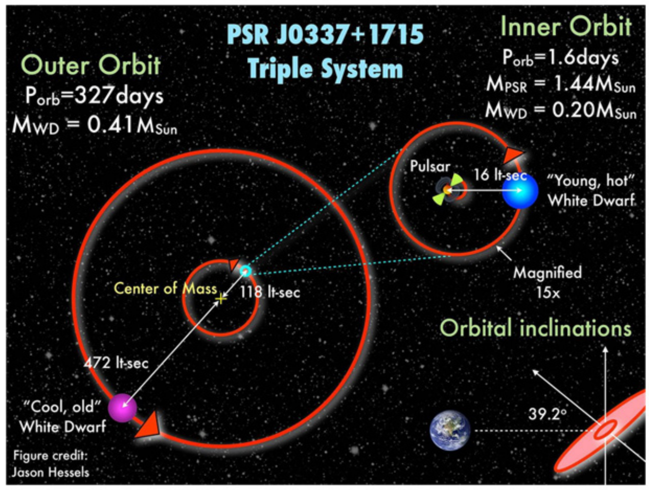


Figure 4: Architectural Layout of PSRJ0337+1715 Triple System (Credit:Jason Hessels)

NANOGrav is most likely to detect GW from merging Black holes which have reached orbital period of years. They would produce nanoHz Gravitational Waves.

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) has reported compelling evidence for the existence of nanohertz-frequency gravitational waves. arXiv+12Wikipedia+12astro.umd.edu+12

Key Findings from the NANOGrav 15-Year Data Set

- Detection of a Stochastic Gravitational-Wave Background (GWB): By analyzing 15 years of pulsar timing data from 68 millisecond pulsars, NANOGrav identified a common-spectrum stochastic process with spatial correlations consistent with the Hellings–Downs curve—a distinctive signature predicted by general relativity for a gravitational-wave background. Physical Review+8Wikipedia+8arXiv+8
- Likely Source – Supermassive Black Hole Binaries (SMBHBs): The spectral characteristics of the detected signal align with expectations for a population of inspiraling supermassive black hole binaries. These binaries, with masses ranging from approximately 100 million to 10 billion solar masses, are thought to form during galaxy mergers and emit gravitational waves as they orbit each other. NANOGrav
- Alternative Explanations Explored: While SMBHBs are the leading explanation, NANOGrav also considered other potential sources, such as cosmic strings or early-universe phase transitions. However, these alternatives currently lack the observational support that the SMBHB scenario has. arXiv+1NANOGrav+1

Current Status

Although the evidence is strong, the NANOGrav collaboration has refrained from declaring a definitive detection. This cautious approach stems from the need to rule out other noise sources and to confirm the signal's origin conclusively.

In summary, NANOGrav's findings mark a significant milestone in gravitational wave astronomy, providing the first strong evidence for a low-frequency gravitational-wave background, likely originating from a population of supermassive black hole binaries.arXiv+6arXiv+6arXiv+6

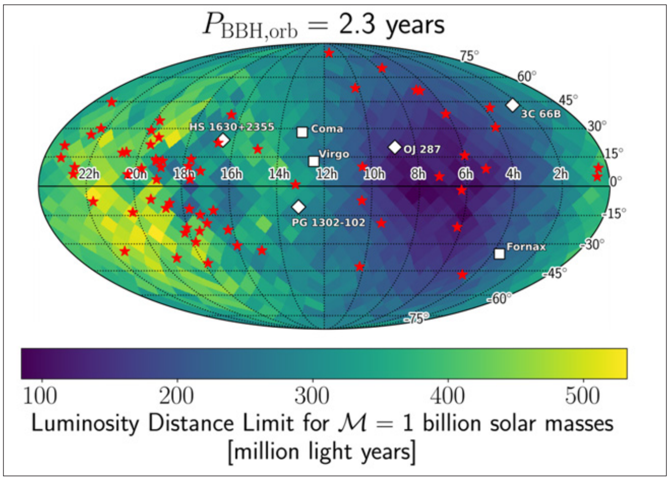


Figure 5: Correlation Map in the sky for nano-Hertz Gravitational Waves Signals

[Credit: The NANOGrav15yrData Set: Constraints on Supermassive Black Hole Binaries from the Gravitational Wave Background arXiv:2306.16220v2 [astro-ph.HE] 18 Jul 2023 Gabriella Agazie ,1 Akash Anumarlapudi ,1 Anne M. Archibald ,2 Paul T. Baker ,3 Bence B´ ecsy ,4 Laura Blech]

Marked sources are Super Massive Black Hole Binaries contributing the nano Hz gravitational waves. These sources are HS1630+2355, PG1302-102,3C668 and OJ287.

Discussion

According to Einstein SPACE may be thought of not as an enormous empty expanse but as a boundless rubber sheet. Such a sheet can be manipulated in a lot of ways-it can be stretched,or squeezed or it can be straightened or bent. It can even be indented, indented in spots. As long as heavenly bodies exist, the indentations it creates on the mat will be part of the permanent landscape of the COSMOS.

If a star collapses in a smooth and symmetrical way then all GW are lost in destructive interference.If explosion is uneven and lumpy then a GW signal stretching mile after mile from peak to peak will be sent out.

Hulse Taylor pair semi-major axis has shortened by 136m in 40 years and in 300My final merger will take place.

Conclusions

Colliding Galaxies and the formation of Black Hole Binary has opened a new window in gravitational Wave Astronomy. This will profoundly shape our understanding of Galaxies formation,evolution and Galaxy mergers.

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Conflict of Interest

There is no conflict of interest financial or otherwise with anybody

Declaration of generative AI and AI assisted technologies in the writing process

During the preparation of this work the Author used ChatGPT and deepseek in order to reason. After using this service the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

"Ethics, Consent to Participate and Consent to Publish Declaration" not applicable Author's Contribution

Author collected data regarding LOD (Length of Earth Day) from popular science books by Isaac Asimov, George Gamow and Carl Sagan (COSMOS). After receiving the Press Release of NASA on Silver Jubilee Anniversary of Man's landing on Moon on 20th July 1994 that Moon has receded by 1m in last 25 years, author redid the Earth-Moon analysis and presented at 82nd Session of Indian Science Congress at Jadavpur University,Kolkata,in 1995. The Author further elaborated the analysis of the E-M system and presented the Kinematic Model of the E-M System at World Science Congress,Houston, in 2002. In 2004, at the 35th Scientific assembly of COSPAR, Author presented the New Perspective on Birth and Evolution of our Solar System and exo-planetary systems. In 2012, at the 39th Scientific Assembly at Mysore,India, paper B03- 0011-12, "Iapetus sub-satellite revisited and it reveals the celestial body formation in Primary Centric Framework. In 2017,at CELMEC VII, Rome, the Advanced Kinematic Model of Earth-Moon System was presented and finally published in Journal Of Geography And Natural Disasters where the perfect match between the Observed LOD curve and Theoretical LOD curve was achieved. A sequential paper on the Past, Present and Future of Earth-Moon Globe Orbit Dynamics and its habitability was published in JMTCM. The present paper is a paper in the same series where the author is trying to study different binary systems in Primary-Centric Framework. In this paper Black Hole binaries are studied in the Primary-Centric Framework.

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Clinical Trial Number not applicable.

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