Black holes, gravitational waves and LISA

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The Laser Interferometer Space Antenna (LISA)

- Joint mission of NASA--ESA
- To observe the universe in gravitational waves
- Equilateral triangle orbits (5e6 km sides)
- Shielded free-floating proof-masses inside
- Interferometer measure changes in relative positions
- Yields gravitational wave strain \( h = \Delta L / L \sim 10^{-23} \)
- Awaiting full start pending favorable decadal review
- Technology verification now in LISA Pathﬁnder mission
- Launch in ~ten years?
LISA Pathfinder

- Technology development for LISA (Led by ESA)
- Like one arm of LISA packed onto a single spacecraft.
- Currently in integration and testing
- Launch in about two years.
Overview of expected LISA sources

- Galactic binaries:
  - \( \sim 10^7 \) binaries (\( \sim 10^4 \) resolvable), some known EM-sources
- BHBs:
  - \( 10^4 \) M\(_{\odot}\) -- \( 10^7+ \) M\(_{\odot}\)
  - \( M_1/M_2=q \): Comparable mass (\( q>0.1 \)) MBH-MBH / IMRI / EMRI (\( q<0.001 \))
- Extreme mass-ratio inspirals: BHB or BH-NS
- Other unknown/exotic possibilities
Science with binary BHB

- LISA
  - Physics and astrophysics of black holes
  - Merger history of galaxies and massive black holes to high-z
  - Observe strong gravitational dynamics - test General Relativity
  - Measure the accelerating expansion of the universe

Waveform predictions required!

Snapshots from a simulation of colliding galaxies each similar to the Milky Way, containing $10^5 M_{\odot}$ black holes, leaving a gas-poor galaxy with a $10^8 M_{\odot}$ BH — Di Matteo, et al. 2005
Observing MBH mergers with LISA….

- MBH binary with total mass $M=10^5 M_{\odot}$ at redshift $z = 15$
- Create “mock” LISA data: inject numerical waveform into simulated LISA data stream with instrumental noise and WD-WD stochastic background
- Michelson observable $X$ on system’s equatorial plane (min signal)
Observing MBH mergers...from space

- Non-spinning black holes
- Contours of SNR for detection using LISA sensitivity curve
LISA sees BHB differently

- Typical LISA SNR 10-100x larger than LIGO.
- Signals are much more precisely measured.
- Higher fidelity signal models will be required with LISA!
- Data analysis goals:
  - detection is easy
  - parameter precision (inversely prop. to SNR)
- Today’s needs:
  - What science can be done?
  - Key parameters are: sky position/distance

Event rates for mergers observable by LISA. Red/Blue are scenarios with small seeds (150 M_{\odot}).
Green/Black rely on heavy seeds (10^4-10^5 M_{\odot}). -- Volonteri 2006
Observing MBH mergers with LISA…

Need numerical simulations beyond “wiggle”
LISA BHB: The Importance of the merger

- LISA range at various SNR
- Plots: hybrid PN-NR info
  - q=1
  - q=1/20 waveforms are ‘extrapolated’ from NR results
- Merger dominates strongest signals
  - Always for M>10e6 M_{Sun}
  - For smaller systems too at high z
  - Less dominant for smaller q
- Does this mean higher-precision parameter measurements?
  - for given wf.: error σ ~ 1/SNR
  - but is there as much info. in the merger?

McWilliams, et al 2009 (in prep)
Understanding BHB signals: PN + NR

- Need numerical results
- Also need PN.
- \(\rightarrow\) Need to combine
- Must *understand* waveforms
- Also should *encode* the results
Numerical BHB simulations

Goddard Numerical Relativity Group
Joan Centralla, Sean McWilliams,
Bernard Kelly, Jim van Meter,
Darian Boggs, JB
Simulation for LISA waveforms

- **Run types**
  - Short simulations good for understanding final BH state
  - Waveform sims: $t>1000M$ needed for full PN matching

- **LISA needs now**
  - Understand simulations over full 7-D circular-inspiral MBH-MBH param space
  - Full phenomenological model for LISA science planning/design
    - moderate accuracy fine

- **LISA needs later**
  - high-fidelity waveforms
  - full model encoding of results over 7-D param space
    - probably also need eccentric, and IMRI
  - may need parameterized GR deviations.
Understanding waveforms: “Simplicity”

- Simple waveform appearance
- Simple underlying physics
- Amenable to analytic modeling
- Generalizes to large parameter space

Equal-mass non-spinning event horizon (Jena 2007)
GWs from unequal mass, nonspinning BHs...

- Sum over modes up to $l = 3$ at $\theta = 0$, $\varphi = 0$
- Scale by $\eta = (m_1 + m_2)/(m_1 + m_2)^2$


- Mass ratio 10:1
- $\Psi_{lm}(t)$ for $l = m$ modes
- Gonzales, Sperhake, & Bruegmann, (arXiv:0811:3952 [gr-qc])
Peak shape

- Focusing on flux near radiation peaks
  - Scaled by peak power
  - times shifted: $E_{22}$ peak at $t=0$

- Mass-ratio dependence
  - very similar peak shapes
  - difficult to notice differences in fall-off rate related to different final spins.

- Multipole dependence
  - $l=m>2$ modes most similar
  - N.B. relative peak times differ for strain/strain-rate/$\Psi_4$
Rotational Phase

- Waveform phase $\varphi$
  $\rightarrow$ rotational phase $\Phi$
  - $\Phi = (\Phi + C_{lm})/m$
  - Implicit source interpretation:
    $\Phi =$ Orientation of source multipole
    structural component

- Mass-ratio dependence:
  - scales with chirp-mass in inspirial
    (leading order PN)
  - Roughly similar in merger
    (up to several-to-1 mass ratio)
  - Clearer differences in ringdown.
    Effect of different spins.
**Multipolar phase comparison**

- **Result (4:1 case)**
  - Interpretation: rel. orientation of source moments
  - \( l=m \) modes
    - nearly phase-locked throughout
    - Requires approx m-scaling in ringdown freq.
  - (2,1) and (3,2)
    - more sensitive to extraction-radius
    - strong “shearing” in ringdown
Understanding aligned spins

- Generally similar picture holds for:
  - 1:1 (+0.8, +0.8) spin case (++)
  - 1:1 (-0.8, -0.8) spin case (--)  
- See also: Jena, AEI, RIT, Caltech-Cornell-CITA

![Graphs showing frequency evolution and amplitudes for ++ and -- spins.](image)
High accuracy: Spectral method results

- Caltech-Cornell collaboration
- Code:
  - Harmonic formulation
  - Pseudo-spectral numerical implementation
  - Excision
- q=1 Simulation
  - 15 orbits
  - ~1% radian numerical phase error
Comparing gravitational waveforms...2008

- Compare GWs from equal mass, nonspinning case
- 5 different, independently-written codes

Hannam, et al. (arXiv:0901.2437[gr-qc])
Measuring model differences

- Equal mass, quadrupole only:
  - Over time from 2000M before merger, small difference in model parameter, $\delta \lambda$,
    - induces a small time shift $\delta t$ and phase shift $\delta \Phi$
- In an observation
  - signal model becomes: $h(t-t_{\text{ref}},\Phi-\Phi_{\text{ref}})$
  - $t_{\text{ref}}, \Phi_{\text{ref}}$ are arbitrary/operationally defined
  - parameter coupling reduces ability to measure $\delta \lambda$
Measuring model differences

- A caution:
- Measuring model difference, $\delta \lambda$
  - requires significance in induced $\delta h$
  - must be discounted for parameter coupling to estimate measurability of $\delta \lambda$

Model wfs may be compared without shifting (raw), or by shifting in time and phase to optimize overlap (maquillaged).

$D_L$ where $\delta h$ would be measureable with SNR=1, as a fraction of $D_L$ where $h$ is measurable with SNR=1
An analytic phenomenological waveform model

• EOB-NR model
  – Effective-one-body EOB PN treatment
  – Reproduces high-order particle result in q->0 limit (allows extrapolation)
  – Buonanno/Damour/others
  – nonspinning to 3.5PN order
  – tunable extra parameters beyond 3.5 PN order
  – matching procedure for ringdown.

• Analytic/empirical description
  – Post-Newtonian approximation, tuned to match numerical results.
  – Provides efficient calculations for estimates of waveforms and final state

Gravitational waveform from merger if 4:1 mass-ratio non-spinning merger, showing good agreement of analytic model (EOB) with numerical (NR) results. Buonanno, et al 2007
BHB phenomenological model improvements

- Advances in EOB description
  - finer tuning by comparison with high-accuracy waveforms
  - Improved treatment of radiation
  - Include spin terms to 2.5PN order
  - Now calibrating with non-precessing, spinning binaries.
  - Comparisons shown for $q=1$, spins (0.4) anti-aligned with $L$
  - high-accuracy simulations from Caltech-Cornell-CITA Chu, et al arxiv:0909.1313
What about precession?

- Understanding emerging for 3-D non-precessing param sub-space
- Precession spans 4 more dims
- Precession is important inspiral param. est.
- Relatively few sims. so far

Trajectory difference

\[ \mathcal{I} = \mathbf{x}_1 - \mathbf{x}_2 \]

Campanelli, et al. (arXiv: 0808.0713 [gr-qc])

- \( m_1/m_2 \sim 0.8, a_1/m_1 \sim 0.6, a_2/m_2 \sim 0.4 \)
- Spins initially at arbitrary orientations
- Completes \( \sim 9 \) orbits before merger
LISA: Precision Measurements of BH Systems

High SNR waveforms carry precision information about the emitting systems

High-precision black hole properties from LISA measurements:

• Massive black hole mergers: Masses, spins to <0.1%,
distances to 3% or less, sky-position (arcmins-degrees);
  \(z=1\); an order of magnitude worse at \(z=20\)
• Extreme mass ratio inspirals: Spins to 0.01%, distances to
  1-2\% \((z<1)\)
• Masses, spins, and numbers as a function of redshift:
  How did black holes (BHs) initially form and what were their
  masses?  
  How do the masses/spins evolve over time?  
  What happened to BHs as the initial galaxies merged to make
  modern galaxies.
• Identify host:
  – red-shift/distance measurement  
  – complementary EM observations of galaxy
• Prompt EM signature:
  – understand matter-BH dynamics  
  – test 'speed of gravity' etc.
Measuring BHB parameters with LISA

- **Method:**
  - Apply non-spinning EOB-NR *complete* waveform model
  - Parameters estimated by Fisher-matrix approach
  - Monte Carlo over various BHB example
  - $1.3 \times 10^6 + 1.3 \times 10^6$ M$_{\odot}$ shown

- **Results:**
  - Merger adds significantly: error $\delta \sigma \equiv \delta\text{SNR}^{-1}$ except for $\sigma_M$
  - sky pos (mean $\sim$ ten arcmin), dist (mean $\sim 0.2\%$)

McWilliams, et al 2009: in prep
Measuring BHB sky position in real-time

- LISA can detect BHB before merger
- Opportunity for multi-messenger obs. (EM telescopes can search)
- Sky position (ecliptic latitude) parameter estimate as before,
- ... but now as function of time to merger:
  - \( M=1.3\times10^6 \): roughly \( \sigma_\beta-(t-t_c) \)
    for last day until minutes before merger
- Other masses/mass-ratio show slower improvement

McWilliams, et al 2009: in prep
Big Question Q5.

What are the Cosmological parameters, Dark energy?

Method for Q5.GW distance measures.

Indep of any astrophysical assumptions or phenomenology.

How it works: Massive Binary loses energy through GW. Causes orbit to shrink (fdot) at rate determined by \( \frac{dE}{dt} = \frac{d(GM_1M_2/2a)}{dt} = L_{gw} \sim f^2h^2D^2 \). Measure h, f, fdot. Solve for D. EM counterparts: EMRI: \( H_0 \) SMBH: \( D_L \) vs z to <1%.

Limited only by weak lensing variations in \( D_L \) (Holtz)

Standard sirens for dark energy -similar to SNae, but indep, better?
Multi-messenger observations...?

• Does the merger produce an EM signal?
  – Merging MBHs could be surrounded by gas, accretion disk, magnetic fields…
  – Will there be any effects of the merger that produce EM radiation?
  – Effects of ejected or dislodged central MBHs?
• Many possibilities…active area of research:
  – Inspiraling binary may cause “pulses” in the disk
  – ~4% of mass emitted in GWs → disk may react to this change in the gravitational potential
  – Gas flows and accretion onto the merging BHs themselves….
Modeling flows around BH mergers…

- Model the behavior of gas and magnetic fields in the *dynamical* spacetime around the merging BHs

- First step: map flow of test particles as BHs merger
  - Set up initial distrib. of particles around BH binary
  - Evolve the BH binary using numerical relativity
  - Trace the motion of the particles along the geodesics as the binary evolves
  - (Van Meter et al 2009)

- Estimate energetics of the flow from “collisions”
  - For each particle, look at nearest 8 neighbors and calculate min distance between these two particles
  - If this minimum distance is < $r_{\text{crit}} = 0.1M$ → “collision”
  - Collision energies insensitive to the chosen value of $r_{\text{crit}}$ in the range $0.01M < r_{\text{crit}} < 1M$
Particle velocity distributions….

- **“Orbital”**
  - Disk-like case
  - $V_c(r) = \text{tangential velocity for circular orbit in a Schwarzschild spacetime, at each radius } r$
  - Initial velocities are randomly distributed around $V_c$ to give a scale height of $5M$

- **“Isotropic”**
  - Extreme case
  - Particles have only random velocities
  - Each velocity component is sampled from a Gaussian with standard deviation $V_c/\sqrt{3}$
Merger of $m_1 = m_2$ Schwarzschild BHs…

Particle disk with \textit{orbital} velocities

“Collisions” are color-coded from red ($\gamma = 1$) to yellow ($\gamma = 5$)

- Some initial infall
- Binary evacuates central region
- Particles remain orbiting in ‘disk’
“Orbital” Particle Disk… max γ merger
Merger of $m_1 = m_2$, Schwarzschild BHs…

Particle disk with isotropic velocities

2 orbits to merger

“Collisions” are color-coded from red ($\gamma = 1$) to yellow ($\gamma = 5$)

Particles continue infalling to center throughout merger
“Isotronic” Particle Disk... max γ merger

- Isolated, Nonrotating
- Nonrotating, 5 orbits to merger
- Rotating, 5 orbits to merger

Maximum Lorentz Factor vs Time [M]
High-velocity outflow

Equal-mass, Schwarzschild binary, $t = 0.000$
BHB as a particle accelerator?
Summary I

• GW for LISA (now)
  – Goal: understand science possibilities
  – Good results for non-spinning and some for non-precessing
    • already OK for wet-merger sub population (3D/7D)
  – Need to much more to understand/model spin-precession in merger

• GW for LISA: Future goals (~10 yrs)
  – High-accuracy
  – NR contributions to broader parameter range
    • $0.001 < q < 0.1$ “IMRI”
    • non-circular inspirals (7D --> 9D)
  – NR-on-demand? (if modeling is unfaithful for very-high SNRs)
    • Subtlety: Can NR-PN spin-directions be compared?

• Better understanding of possible EM effects:
  – role of hydrodynamics
  – role of EM field
  – and astrophysically: what density of gas is plausible
Summary II

• Toward a more perfect simulation
  – continue improvements:
    • wave-extraction
    • differencing
    • toward near-extremal spins
  – simple simulations for simple physics:
    • Too much happens in our simulations!
    • eliminate numerical sub-luminal advection
    • defeat CFL
• Was Einstein right?
  – LISA aims to test GR
  – Null test requires a parameterized non-GR model
  – May be done with EOB-type models
  – Eventually may need to simulate non-GR theories.