Copenhagen and me

NORDITA NEWS 1997 / 5  October 1, 1997

NORDITA FELLOWSHIPS 1998/99
Information about NORDITA Fellowships for the academic year 1998-99 is attached. Completed application forms and letters of recommendation should arrive at NORDITA not later than November 15, 1997. NOTE THAT THE DEADLINE IS EARLIER THAN IN PREVIOUS YEARS. Please ensure that potential candidates, especially ones at institutes in other countries, receive this information.

OVERVIEW OF FUTURE NORDITA AND OTHER CONFERENCES

<table>
<thead>
<tr>
<th>Title / Date / Place</th>
<th>Contact Person</th>
<th>Fax / Email / www</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nordita's 40th Anniversary</td>
<td></td>
<td>+45 - 353 89157 (fax)</td>
</tr>
<tr>
<td>Nordita, Copenhagen. 3-4 November 1997.</td>
<td></td>
<td><a href="mailto:nordita@nordita.dk">nordita@nordita.dk</a></td>
</tr>
<tr>
<td>Cosmology: from COBE to Galaxy Formation.</td>
<td>A. Kashlinsky</td>
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</tr>
<tr>
<td>Nordita and Goddard Space Flight Center</td>
<td>A. Kashlinsky</td>
<td><a href="mailto:cosmology@nordita.dk">cosmology@nordita.dk</a></td>
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   - observational background, motivation

2. **Theory:** binary accretion
   - bright variable emission from binary

3. **Observations:** do we have to wait for GW detections?
   - SMBH binary candidates in quasar surveys
   - forecasts for LSST & LISA era

4. **Stellar-mass BH binaries:** mergers in AGN disks?
   - BH binaries form in or captured by nuclear gas disks
   - Bright EM emission outshining AGN
Multi-band Gravitational Waves

Lommen (2017)

(10^8-10^{10})M_☉ pulsar timing

(10^4-10^7)M_☉ LISA

(10-10^2)M_☉ LIGO
Multi-band Gravitational Waves

Lommen (2017)

\[(10^8 - 10^{10}) M_\odot\]

pulsar timing

\[(10^4 - 10^7) M_\odot\]

LISA

\[(10 - 10^2) M_\odot\]

LIGO

Stochastic background

IPTA

Supermassive binaries

LISA

Extreme mass ratio inspirals

Massive binaries

Type Ia supernovae

Compact binary inspirals

LIGO

Virgo

aLIGO
Massive BH binaries in galactic nuclei
Massive BH binaries in galactic nuclei

→ GW sources at / close to merger (LISA, PTA)
Massive BH binaries in galactic nuclei

→ GW sources at / close to merger (LISA, PTA)

→ EM sources earlier on (time-domain surveys e.g. LSST)
Massive BH binaries in galactic nuclei

→ GW sources at / close to merger (LISA, PTA)

→ EM sources earlier on (time-domain surveys e.g. LSST)

how do we find them?
Science from Multi-Messenger Astrophysics

Benefits of combining GWs and EM detections

(1) Astronomy and astrophysics
   — accretion physics: EM emission with known BH parameters
   — accretion physics: distortions to waveforms (Derdzinski + 2020, 2021)
   — quasar/galaxy (co)evolution: BH vs host galaxy relations

(2) Fundamental physics & cosmology
   — Hubble diagrams from standard sirens (Schutz 1986 + …)
   — $d_L(z)$ from GWs + photons: test of non-GR gravity (Deffayet & Menou 2007)
   — delay between arrival time of photons and gravitons: extra dimensions, graviton mass ($\gamma m_0 c^2 = hf$; Kocsis et al. 2008)

(3) EM counterparts can also help with GW detection
   — known EM source position helps break GW parameter degeneracies
   — EM counterpart can increase confidence of marginal GW detections

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Binary quasars

Gas cools and forms a compact (~ sub-pc) nuclear accretion disk.

inner disk: stable, geometrically thin, optically thick, $M_{\text{disk}} \ll M_{\text{bh}}$

Gravitationally unstable region $Q(\text{Toomre}) < 1$

What if second black hole is present?
Residence time

GW-driven decay

Stellar Scattering driven decay

ZH, Kocsis, Menou (2009)
Residence time

Stellar Scattering driven decay

Gas disk Driven decay

[ sensitive to accretion disk model ]

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ZH, Kocsis, Menou (2009)
**Residence time**

- **GW-driven decay**
- **Stellar Scattering driven decay**
- **Gas disk Driven decay**
  - [sensitive to accretion disk model]

ZH, Kocsis, Menou (2009)
Periodic variability

Gravitational waves

Disappearing BH

GW dissipation ??

Mass-loss - shocks

Recoil - shocks

Accretion afterglow
Equal-mass, circular binary
Westernacher-Schneider et al. (2022)

**Sailfish**: GPU-enabled 2D hydro code, Cartesian coö’s mass ratio ($q$), eccentricity ($e$), temperature ($M$)
Key Features of Binary Accretion

Central cavity:
- Lack of stable orbits within ~twice the binary separation
- Density suppressed by factor of ~100

Lopsided cavity wall with lump:
- Circumbinary disk strongly lopsided (nonlinear instability)
- Dense lump appears at cavity wall, modulating accretion

Streamers:
- Enter cavity wall via strong shocks, extend into tidal region of BHs
- Fuel accretion is via gravity and shocks --- not viscosity/MRI!

Minidisks:
- Fueled by streamers -- net accretion rate matches that of single BH
- Strong shocks periodically appear and disappear
Signature I: binary quasars are periodic

Thermal emission; optical and IR

Circular

Eccentric

colder

warmer
Binary quasars are periodic.

**Circular**
- \( \alpha = 0.1 \) \( e = 0 \)
- \( \mathcal{M} = 21 \)

**Eccentric**
- \( \alpha = 0.1 \) \( e = 0.45 \)
- \( \mathcal{M} = 11 \)
- \( \mathcal{M} = 7 \)

- Optical
- Infrared

**Colder**
- Lump
- Beat between orbit & minidisk precession

**Warmer**
- No lump
- Orbit
Periodicity from Minidisks

Westernacher-Schneider et al. (2023, in prep)

With Sailfish; resolved lopsided minidisks with retrograde precession
Impact of mass ratio

0.3 < q < 1

Sawtooth/bursty variability, on **orbital time at cavity wall**

0.05 < q < 0.3

more sinusoidal variability, on **orbital timescale**

Accretion rate not suppressed – similar to bright quasar

⇒ periodic variability down to mass ratio of ~0.05
Periodicity from Doppler boost (EM “chirp”)

LISA binary

X-ray emission from quasars from few $R_g$

Minidisk $\rightarrow$ X-ray corona bound to single BH

Doppler effect modulates brightness at $O(v/c) \sim 0.1$

$\rightarrow$ dominates over hydro-variability for $q \lesssim 0.05$

Wide ($P \sim yr$) binary

optical: $\sim$ few 100 $R_g$

minidisk=quasar disk

$v/c \sim 0.01$

Tidal force from companion truncates minidisk

ZH (2017)

D’Orazio et al. (2016)

Duffell et al. (2020)
Periodic binary self-lensing

Interstellar (2014)

Event Horizon Telescope (EHT) 2017, 2022

M87* April 11, 2017

Sgr A* May 12, 2022
Binary self-lensing

D’Orazio & Di Stefano (2016)
Jordy Davelaar & ZH (2022a,b – PRL, PRD)

Illustration: APS, Carin Cain
Recurring Self-Lensing Spikes

Davelaar & ZH (2022a,b)

note: $\theta_e/\theta_{\text{bin}} = (2a_{\text{bin}}/R_s)^{-1/2}$

compact ($d=100 \: R_g$) edge-on binary $i=90^\circ$

- flares visible within $\pm 3-30^\circ$ of edge-on
- shadow visible if $\pm 1-10^\circ$ of edge-on
- week-long flares in periodic quasars
- 10x higher chance for LISA binaries (already compact)

$\rightarrow$ 100s detectable by Vera Rubin Observatory (LSST, 2024+)
Signature II: Hard spectrum

Tang et al. (2017)

Thermal emission extends to hard X-rays from inner regions around each BH

\[ q = \frac{M_2}{M_1} = 1 \]
Signature III: Post-merger afterglow

Anisotropic GW emission causes BH to recoil and lose few % of its mass

Orbit crossings—spiral caustics
Lippai, Frei, ZH (2008)
Penoyre & ZH (2018)

Outward-propagating shocks
Corrales, ZH & MacFadyen (2010)
Rossi et al. (2009, 2010)
Megevand et al. (2010)
O’Neill et al. (2009)

→ afterglow on weeks/months timescale, unique evolution
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Searching for Periodic Quasars

inspiral time: \( t_{GW}(P \sim \text{yr}) \sim t_{\text{visc}} \sim 10^5 \text{ yr} \)

quasar lifetime: \( t_{QSO} \sim 10^8 \text{ yr} \)

expected periodic fraction: \( f_{\text{bin}} \sim t_{GW}/t_{QSO} \sim 10^{-3} \)

- Catalina Real-Time Transient Survey (CRTS)
  Graham et al. (2015)
  111 candidates with periods 1-5 years
  250,000 quasars to V~20, 9-year uniform baseline

- Palomar Transient Factory (PTF)
  Charisi et al. (2016)
  33 candidates with periods 60-400 days
  36,000 quasars R~22, 5 years non-uniform sampling

- Zwicky Transient Factory (PTF)
  Chen et al. (2022)
  127 candidates with periods 500-950 days
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how do we know they’re binaries?

Inspiral time: \( t_{GW}(P \sim \text{yr}) \sim t_{\text{visc}} \sim 10^5 \text{ yr} \)

Quasar lifetime: \( t_{QSO} \sim 10^8 \text{ yr} \)

Expected periodic fraction: \( f_{\text{bin}} \sim \frac{t_{GW}}{t_{QSO}} \sim 10^{-3} \)
Doppler-modulation is chromatic
PG1302-102  D’Orazio, ZH, Schiminovich (2015)

Bright z=0.3 quasar  \( M_{bh}=10^{8.3}-10^{9.4} M_\odot \)  \( a=0.01 \text{ pc (280 R}_S \)  
\( \pm 14\% \) variability with 5.16 \( \pm 0.2 \text{ yr period (in 250,000 quasars) } \)

*Incl. follow-up Swift data*  (Xin, Charisi, ZH et al. 2020)

**Optical**

**nUV**

Optical variability vs. UV variability consistent with Doppler boost

Chromaticity:
\( \Delta F_\nu/F_\nu = (3-\alpha) (v_\parallel/c) \)
\( \alpha=d\ln F_\nu/d\ln \nu \)
Search for Recurring Self-Lensing Spikes

KIC 11606854, a.k.a. “Spikey”  
Betty Hu, Dan D’Orazio, ZH et al. (2020)
Rare case of a quasar in the Kepler field (z=0.92), with symmetric spike

Well fit by eccentric SMBH binary:
\[ M_{\text{tot}} = 3 \times 10^7 M_\odot, \quad q = 0.2, \quad T = 418 \text{ d}, \quad e = 0.5, \quad \text{inclination} = 8^\circ \]
Binaries in LSST

Xin & ZH (2021)

LSST →

perfect for this search:

1. wide
2. deep
3. high cadence

1 year
1 day
How many do we expect in LSST?

Xin & ZH (2021)

Extrapolate quasar LF

Assume fraction $f_{\text{bin}}$ of quasars are binaries:

$$N_{\text{bin}} (P_{\text{orb}}) = \left[ \frac{t_{\text{res}} (P_{\text{orb}})}{t_{Q}} \right] f_{\text{bin}} N_{Q}$$

Side-steps modeling of cosmology/mergers
LISA “verification” binaries in LSST

Xin & Haiman (2021)

* O(100) binaries with $P \lesssim 1$ day: Redshift $z \sim 1-2$ Mass $\sim 10^5 - 10^6 \, M_\odot$
* Many more at longer periods but still well in GW inspiral regime
* Can identify them in archival data after LISA detection
EM signatures near merger

Luke Krauth et al. (2023)

Follow GW inspiral ($10^6 M_\odot$) for **last ~month** before merger (~400 orbits)

Follow post-merger disk including recoil and mass-loss of remnant

decoupling?  →  recoil/mass-loss?
EM chirp follows GW chirp
cf. earlier work by Tang et al. 2018
Pre-merger localization - ouch

Mangiagli et al. 2020
Disappearing black holes!

Binary suddenly vanishes in X-rays

But stays in optical UV and infrared

Can catch this with Athena (use LSST or its archival data)

No immediate effect of mass-loss or recoil
Disappearing minidisks and streams
Summary

1. Binaries quasars are periodic: hydro ($q \sim 1$) and Doppler ($q \lesssim 0.05$)
2. Some may have been already detected: chromatic periodicity
3. Additional recurring self-lensing flares present (esp. if Doppler)
   BH shadows detectable as further “dips” on top of lensing flares
4. $O(100)$ rare ultra-compact binaries in LSST $\rightarrow$ LISA sources
5. Binary disappears in X-ray but not opt/IR in last $\sim 20$ orbits ($\sim$day)
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Stellar remnant black hole mergers
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GW190521
85+66 M☉
eccentric?

$\chi_{\text{eff}} = 0.08 \quad \chi_p = 0.7$
Stellar remnant black hole mergers

GW190521
85+66 M☉
eccentric?

\[ x_{\text{eff}} = 0.08 \quad x_p = 0.7 \]

GW190412
30+8 M☉

\[ x_{\text{eff}} = 0.31 \quad x_p = 0.44 \]
Stellar remnant black hole mergers

GW190521
85+66 M☉
 eccentric?

GW190412
30+8 M☉

GW190814
23+2.6 M☉

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
isolated binary evolution

N-body dynamics in dense clusters

~ equal mass
~ aligned spin

~ equal mass
~ random birth spins
Stellar-mass BHs in quasar disks

Gas cools and forms a compact (~ sub-pc) nuclear accretion disk

inner disk: stable, geometrically thin, optically thick, \( M_{\text{disk}} \ll M_{\text{bh}} \)

Gravitationally unstable region \( Q(\text{Toomre}) < 1 \)

→ What if second black hole is present? ←
“1D” N-body simulation

SMBH, gas disk, stars+BHs in 3D cluster, in 2D disk

I. Binary formation
   (2-body, 3-body)

II. Binary disruption
    (binary-single scattering)

III. Binary evolution
     (circumbinary gas, GWs,
      binary-single scattering)

IV. Radial migration
    (Type I/II torque)

Tagawa, ZH, Kocsis (2020a)
Merger characteristics

* Most binaries in AGN form via dissipative gas capture

* Most LIGO events probably not from AGN disks, but properties of some recent events naturally expected:

1. Unequal mass ✓
   → different generations
2. High mass ✓
   → 2g+ (and some accretion)
3. High spin ✓
   → due to prior merger, correlates with mass
4. Misaligned spin \( \chi_{\text{eff}} \sim 0 \) but \( \chi_p > 0 \) ✓
   → scattering with 3\(^{rd}\) body
5. Eccentricity ✓
   → scattering with 3\(^{rd}\) body with GWs (if coplanar)
   → GW capture in inner region (if rapid migration to \(<10^{-3}\) pc)
Gas Capture Model

De Laurentiis, Epstein-Martin & ZH 2023

3-body problem with gas dynamical friction, REBOUND

\[ F_{DF} = -\frac{4\pi G^2 M^2 \rho}{v_M^3} f\left(\frac{v_M}{c_s}\right) v_M \]

\[ f(x) = \begin{cases} 
0.5 \ln\left(\frac{1+x}{1-x}\right) - x & 0 < x < 1 \\
0.5 \ln(x^2 - 1) + \ln(\lambda_c) & x > 1.
\end{cases} \]

(Ostriker 1999)
Selected Examples of Encounters

De Laurentiis, Epstein-Martin & ZH 2023

→ impact parameter →

dynamical friction: OFF

dynamical friction: ON

dynamical friction: ON → OFF

binary bound between Hill radius & pericenter
Fate vs Impact parameter

wide and smooth bands of capture with effective cross section $b \sim O(R_{\text{Hill}})$

cf. fractal structure of frictionless “Jacobi capture”; Boekholt+2022
Gas Capture – 3d simulations

Rowan, Boekholt, Kocsis & ZH (2023)

SPH (Phantom), 3D, global disk annulus

Parameters:

\[ M_{\text{SMBH}} = 4 \times 10^6 M_\odot \]
\[ \dot{M}_{\text{inflow}} = 0.1 \dot{M}_{\text{edd}} \]
\[ H/R = 0.005 \ (\alpha=0.1) \]

\[ m_1 = m_2 = 25 M_\odot \]
\[ R_{1,2} \sim 0.01\text{pc} \ (P_{\text{orb}} \sim 30 \text{yr}) \]
\[ \Delta R_{\text{sim}} = 20 \ r_{\text{Hill}} \]
\[ \Delta \theta = 20^\circ \]

\[ N = 2.5 \times 10^7 \text{particles} \]
\[ r_{\text{sink}} = 0.01 \ r_{\text{Hill}} \]
\[ r_{\text{soft}} = 0.01 \ r_{\text{sink}} \]

3 disk mass \((23, 110, 570 \ M_\odot)\) × 5 impact para (2.5-3.5 r_{\text{Hill}}) = 15 sims
Gas Capture – Summary of Fiducial Sims

Rowan, Boekholt, Kocsis & ZH (2023)

- Initial condition
- Minidisk formation
- Minidisk collision
- Accretion + outflow
- Captured binary w/CBD
Optical counterpart to GW190521 (?)

Claim of coincident flare in ZTF

Graham et al. 2020

<table>
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<th>Value</th>
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<td>$t_{\text{duration}}$</td>
<td>$\sim 28$ days</td>
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<td>$t_{\text{delay}}$</td>
<td>$\sim 18$ days</td>
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<tr>
<td>$L_{\text{opt}}$</td>
<td>$\sim 10^{45}$ erg/s</td>
</tr>
<tr>
<td>$z$</td>
<td>0.438 ($\sim 2-3$ Gpc)</td>
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<tr>
<td>$M_{\text{SMBH}}$</td>
<td>$(1-10) \times 10^8$ M$_{\odot}$</td>
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<tr>
<td>$L_{\text{bol}}/L_{\text{Edd}}$</td>
<td>$0.02 - 0.23$</td>
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AGN:
- $z = 0.438$ ($\sim 2-3$ Gpc)
- $M_{\text{SMBH}} = (1-10) \times 10^8$ M$_{\odot}$
- $L_{\text{bol}}/L_{\text{Edd}} = 0.02 - 0.23$

Flare:
- $t_{\text{duration}} \sim 28$ days
- $t_{\text{delay}} \sim 18$ days
- $L_{\text{opt}} \sim 10^{45}$ erg/s
- $g, r$ band: $\sim 480, 650$ nm

$\sim 10^5 L_{\text{Edd}}$ for $\sim 100$ M$_{\odot}$ BH
Gamma-ray counterpart to GW150914 (??)

Claim of coincident flare in Fermi GBM:

- GW150914 (1st event, $M_{\text{rem}} \sim 62 M_\odot$)
- $L_{\text{max}} \sim 2 \times 10^{49}$ erg/s (10 keV-10 MeV)
- $t_{\text{duration}} \sim 1$ s
- $t_{\text{delay}} \sim 0.4$ s from GW150914
- $E \sim 2 \times 10^{49}$ erg
- $d_L \sim 410$ Mpc
- association significance: $2.9 \sigma$
  (prob. of high S/N event within 30 s)

Controversy:

Criticism: background value, detectors (Greiner+16)

Rebuttal: binning, sky location, complex geometry, used detectors (Connaughton+18)
Jets and cocoons from BHs in AGN disks

\[ \dot{M}_{\text{BHL}} \gg \dot{M}_{\text{edd}} \rightarrow \text{spinning BH} \rightarrow \text{jet (cf. GRB)} \rightarrow L \gg L_{\text{edd}} \]

Tagawa, Kimura, ZH, Perna Tanaka, Bartos (2022)
Episodic accretion / jet activity

Time-averaged accretion rate is reduced by a factor $\gtrsim 10$
**EM emission**

Disk parameters \((H_{\text{AGN}}, \rho_{\text{AGN}})\) as a function of distance from SMBH follow from \(M_{\text{SMBH}}, \dot{M}_{\text{SMBH}}, \alpha_{\text{eff}}\) \((\text{Thompson+05})\)

BH accretion: \(\dot{m}_{\text{BHL}} \rightarrow\) jet power: \(L_{\text{jet}} \sim a_{\text{BH}}^2 \dot{m}_{\text{BHL}} c^2\)

\[ t_{\text{delay}} \sim \frac{H_{\text{AGN}}}{v_{\text{sh}}} \]

\[ \Delta t_{\text{BO}} = t_{\text{diff}} \quad \text{at} \quad t_{\text{diff}} = t_{\text{dyn}} \]

\[ = \frac{c}{(\rho_{\text{AGN}} v_{\text{sh}}^2 \kappa)} \]

\[ T_{\text{BO}} \sim (18 \rho_{\text{AGN}} v_{\text{sh}}^2 / 7a)^{1/4} \]

\[ L_{\text{BO}} \sim L_{\text{jet}} \]

\[ L_{\text{NT}} \sim \varepsilon_e L_{\text{BO}} \quad (N_e \gamma \sim \gamma^{-p}) \]

1. thermal shock-breakout emission
2. non-thermal emission from shocks: synchrotron, inverse Compton
3. high-energy emission from internal shocks
Post-merger EM emission from binary BHs

Tagawa, Kimura, ZH, Perna Bartos (2023)
Examples: LIGO EM counterpart claims

Tagawa et al. 2023

Match luminosity, color, delay time, and duration

Parameters:

- The distance to SMBH, $R = 3$ pc
- Merger remnant BH mass, $m = 150$ $M_{\text{sun}}$
- Conversion efficiency $\eta_j = 0.5$
- Enhancement factor of accretion due to shocks $f_{\text{acc}} = 15$
- SMBH mass, $M_{\text{SMBH}} = 10^8$ $M_{\text{sun}}$
- Accretion rate onto the SMBH, $\dot{M} = 2$ $L_{\text{Edd}}c^2$
- Energy fraction of electrons in shocks, $\varepsilon_e = 0.3$
- Energy fraction of magnetic fields in shocks, $\varepsilon_B = 0.1$

- $R = 10^{-4}$ pc
- $m = 60$ $M_{\text{sun}}$
- $\eta_j = 0.5$
- $f_{\text{acc}} = 1$
- $M_{\text{SMBH}} = 10^6$ $M_{\text{sun}}$
- $\dot{M} = 0.2$ $L_{\text{Edd}}c^2$
EM emission – full spectrum
Summary

1. **Some LIGO events’ properties naturally produced in AGN disks:**
   - large mass & mass ratio, nonzero eccentricity, unusual spins
2. Also natural environment for **EM emission related to jets**
   - hot shocked cocoon: thermal + non-thermal emission
3. **Optical/IR and gamma-ray** flares like those claimed for LIGO
4. **Internal shocks** → high-energy ν’s, cosmic rays, MeV γ-rays
The End