The flaring X-ray sky: high-E counterparts to GW sources

- intro
- extreme mass-ratio inspiral: „tidal flares“
  puzzles & predictions
- binary SMBHs:
  „(pre/post) coalescence flares“
- kicks & superkicks:
  „recoil flares“, @ recoil and long after

S. Komossa
TUM/ ExCU/ IPP
Garching
e.m. counterparts to GW sources

• NS-NS mergers: short GRBs

• extreme mass-ratio inspirals (EMRIs):
  star – MBH pairs "tidal flares"
  WD – IMBH pairs
  stellar-mass BH – MBH none ?

• SMBH – SMBH mergers: "pre/post-coalescence flares",
  "recoil flares"
synergies between e.m. and GW astrophysics

**GW**
- approx. location
- masses
- spins
- luminosity distances
- merger rates
  - low-M, high z
  - high-M, low z (PTAs)

**e.m.**
- precise sky coo
- luminosities
- spectra
- $z$
- merger rates

- ctrpart, $t_{\text{stalling},...}$
- $L/L_{\text{edd}}$
- accretion phys
- cosmology
- merger history

proof of existence of
- GWs, SMBHs coalescences

high-precision measurements
of BH properties; various tests
of strong-field gravity

physics of *matter* under strong
gravity; feeding, growth,
feedback, cosmic evolution

approx. measurements of BH
para
extreme mass-ratio „pairs“: tidal capture & disruption of stars by massive BHs

„destructive“ tidal forces on single stars in the immediate vicinity of a black hole; independent way of BH detection, in non-active galaxies; & new probe of strong gravity [e.g., Rees 88, Komossa & Bade 99]
tidal disruption of stars by SMBHs

- disruption @ \( r = r_{\text{tidal}} \), with tidal radius \( r_{\text{tidal}} = R_*(M_{\text{BH}}/m_*)^{1/3} = 7 \times 10^{12} M_{\text{BH},6}^{1/3} (R_*/R_{\text{sun}}) (m_*/m_{\text{sun}})^{-1/3} \) cm

- high initial gas supply rate \( \rightarrow L_{\text{peak}} = L_{\text{edd}} \)

- bbdy temperature at \( r_t \) approx \( 10^{5-6} \) K

- return rate \( \frac{dm}{dt} \sim t^{-5/3} \)

- > 90% of the stellar debris is unbound

- event rate \( 10^{-4-.5} /\text{yr} /\text{galaxy} \)

[e.g., Hills 75, Carter & Luminet 82, Rees 88 + 90, Evans & Kochanek 89, Cannizzo+ 90, Loeb+Ulmer 97, Wang & Merritt 04, Li+ 00, Ayal+ 00, Lodato+09, Rossi+ 10.....]
tidal flares

first X-ray events in RASS

- \( L_x \) huge: up to sever. \( 10^{44} \) erg/s
- very steep X-ray spectra
- from optically \textit{inactive} galaxies
- factor up to 6000 decline
- follow \( t^{-5/3} \) decline law

most recent „SWIFT flare“

- peculiar lightcurve, rapid variability (\( \Delta t \sim 100s \)), \( L_{x,\text{isotropic}} = 10^{44} - 4 \times 10^{48} \text{ erg/s} \), \( z_{\text{host}} = 0.35 \)
- rapid onset of jet formation, perhaps following tidal disruption ?

[e.g., Komossa & Bade 99, Komossa & Greiner 99, Grupe+00, Greiner+00, Komossa+04]

[eg., Barres de Almeida & De Angelis 11, Bloom+11, Burrows+11, Krolik+11, Cannizzo+11, Zauderer+11]
tidal flares

- ultra-soft X-ray spectra, initially
- then spectral hardening, first seen with ROSAT & XMM (NGC 5905, RXJ1242-1119)
tidal flares – results from recent searches

• ongoing X-ray searches:
  ~4 more with *XMM*
  ~2 with *Chandra* in clusters of galaxies

• UV detections:
  ~few with *GALEX*, 1 on phot. plates

• optical continuum variability
  ~2 from SDSS, 1 from PTF

• a few emission-line „light echoes“, based on SDSS spectroscopy

[eg., Esquej+ 07,08, Capellutti+ 09, Gezari+ 07,08,
Luo+ 08, Komossa+ 08,09, Maksym+10, Meusinger+10, Cenko+ 11, Drake+ 11, van Velden+ 11, Lin+ 11,
Saxton+ 11– this conf. ]

• super-strong Fe lines
• fade dramatically, in yrs
• very unusual Balmer profile
• but faint X-rays, ~$10^{41}$ erg/s, few yrs after high-state

• observed rate $10^{-5}$/yr /galaxy
(partial) disruption of WDs by IMBHs

- solar-type stars: GWs only detectable from GC
- stellar-mass BHs: only GWs (?)
- WDs: (partially) tidally disrupted for $M_{\text{BH}} < 10^5 \ M_{\odot}$ → em & GW signal
- *LISA* rates: approx 0.1 – 100 /yr

WD tidal disruption by an IMBH in a globular cluster in the Fornax-elliptical NGC 1399?

[Irwin +10; see Maccarone & Warner 10 for alternative]

$Lx \sim 10^{39}$ erg/s

H-lines absent

[Amaro-Seoane 07, Rosswog+ 08, Sesana+ 08, Menou+ 08, Amaro-Seoane + Preto 11]
(2) (Super)massive Binary Black Holes

evolution

1. dynamical friction regime
2. binary hardening
e.g., by stellar slingshot effects
(loss-cone refilling), interact. with
gas, to prevent stalling @ ~0.1 pc *)
3. emission of GWs

*) [e.g., Saslaw & al. 74, Quinlan & Hernquist 97, Gould & Rix 00, Merritt 01,03, Milosavljevic &
Merritt 01,03, Zier & Bierrmann 01, Ivanov+ 99,04, Yu 02, Blaes et al. 02, Poon & Merritt 02,
Haehnelt & Kauffmann 02, Hemsendorf+ 02, Armitage & Natarajan 02,05, Escala+ 03,05,
Makino & Funato 04, Berczik+ 05,06, Haardt+ 06, Dotti+ 06, Merritt 06,07, Matsui & al. 06, Zier
07, Alexander 07, Mayer+ 07, Perets &
Alexander 08, Sesana & 08, Berentzen & 08,
Mayer+ 09, ....................]

[1] [2] [3]

Begelman, Blandford, Rees 1980
supermassive binary BHs

- **galaxy mergers** are the sites of major BH growth
- **coalescing BBHs** are powerful emitters of grav. waves;
  - **GWs**: test GR predictions, precisely measure BH mass & spin, merger rate
  - **e.m.**: identify ctrpart, host galaxy, $z$
  - structure of host galaxy, $t_{\text{stalling}}$
  - iron lines, accretion physics around BHs with known masses & spins
- **GW recoil**: BHs oscillate about gal. cores, or even escape → wealth of potential astrophysical applications
- **central to our understanding of assembly history & demography of BHs, & galaxy-BH (co-)evolution**
observations of SMBH pairs in single and interacting galaxies, in an early phase of evolution, in X-rays:

no further one in ~30 LIRGs, observed with Chandra (but could still be there & obscured)

[e.g., Komossa+ 03, Guainazzi+ 05, Piconcelli+ 10, Green+ 10, Iwasawa+ 11]
coalescence flares

pre-coalescence:

- high tidal disruption rate
  (dramatically enhanced temporarily)
- t-dependent accretion signatures ($\Delta t \sim$ weeks – yr)

right after coalescence:

- „viscous flares“
  when inner disk reforms
- „perturbed-disk flares“, after
  GW-induced mass loss, or
  recoil

[e.g. Milosavljevic & Phinney 05, Armitage & Natarajan 02, Liu+ 03, Dotti+ 06, Kocsis+ 08, Liu & Chen 07, Tao+ 07, Hayasaki+ 08,11, Shields & Bonning 08, Lippai + 08, Schnittman+ 08, Haiman+ 08, 09, Loeb 09, Cuadra+ 09, Palenzuela+ 09,10, van Meter+ 09, Megevand+ 09, Bogdanovic+ 10, Krolik 10, Chen+ 09, 11, Liu+ 09, Mösta+ 10, Zanotti+ 10, Schnittman 10, Tanaka+ 10, Centrella+ 10, Roedig+ 11, ....]
coalescence flares: viscous flares

after BBH coalescence: evolving, brightening X-ray spectrum, when disk spreads viscously inward

\[ t_v \sim 10(1+z) \left( \frac{M}{10^6 M_{\text{sun}}} \right)^{1.3} \text{ yr} \]

\(~ 10\) sources with \( \frac{\text{d} \ln L_x}{\text{d}t} > 30\% / \text{yr} \) for several years, in an all-sky survey with sensitivity \( f_x < 3 \times 10^{-14} \) (like LWFT), with systematic hardening of X-ray spectrum

Number of afterglow sources as function of their 0.1-3.5 keV flux, \( 1 < z < 3 \).

[Milosavljevic+Phinney 05, Tanaka+ 10]
after coalescence: recoiling supermassive black holes, „recoil flares“
recoiling supermassive black holes: kicks & superkicks

- anisotropic emission of GWs from coalescing BBHs leads to recoil of the newly formed single BH
- NR simulations predict BH “kicks“ with velocities up to 3800 km/s; (10,000 km/s)
  - highest for $m_1=m_2$, $a_1=-a_2$=max & in orb. plane
- recoiling BHs oscillate about host galaxy core, or may even be ejected — various astrophysical implications for galaxy assembly at the epoch of structure formation; BH growth; detection of GW signals; unified AGN models

[e.g., Peres 62, Bekenstein 73, Redmount & Rees 89, ... / Baker+ 06,07,08, Brügmann+ 08, Campanelli+ 06, 07a,b, 08, Dain+08, Gonzales+ 06, 07a,b, Healy+ 09, Herrman+ 07a,b, Koppitz+ 07, Lousto & Zlochower 08, Lousto+ 09, Pretorius 05, 07, Pollney+07, Schnittman+ 07, 08, Sperhake+ 10, Tichy & Marronetti 07, vanMeter+ 10 ... review: Centrella+ 10]
right after coalescence: disk flares
long after coalescence: **tidal flares:**

- stars will remain bound to the BH within
  \[ r_k < \frac{GM_{BH}}{v_k^2} \sim 0.4 \left( \frac{M_{BH}}{10^8 \, M_{\odot}} \right) \left( \frac{v_k}{10^3 \, \text{km/s}} \right)^{-2} \, \text{pc} \]
- → stellar tidal disruption X-ray **flares**, of **quasar-typical luminosity** – off-nuclear or even **intergalactic**

- from bound and unbound stellar pop., at high „early“ rate, and „late“ rate comparable to „non-recoil rate“

- + accretion from stellar mass loss → reservoir of NL gas at \( v_{\text{kick}} \)
- + intergal. SNe & peculiar WD detonations, no-host GW signals, ....

[Komossa & Merritt 08]
recent predictions of transient events accompanying mergers/coalescences; motivated in part by breakthroughs in NR
- tidal flares (esp. from WDs accreting on IMBHs)
- various types of coalescence flares
- recoil flares

→ search for these in ongoing & future e.m. surveys

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