1

Sources of Gravitational Waves

Joan Centrella

Laboratory for High Energy Astrophysics
NASA/GSFC

Gravitational Interaction of Compact Objects *KITP* *May 12-14, 2003*

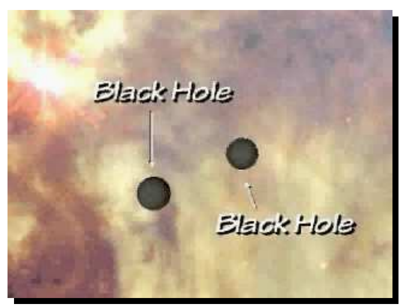
2

A Different Type of Astronomical Messenger
Gravitational Waves . . .

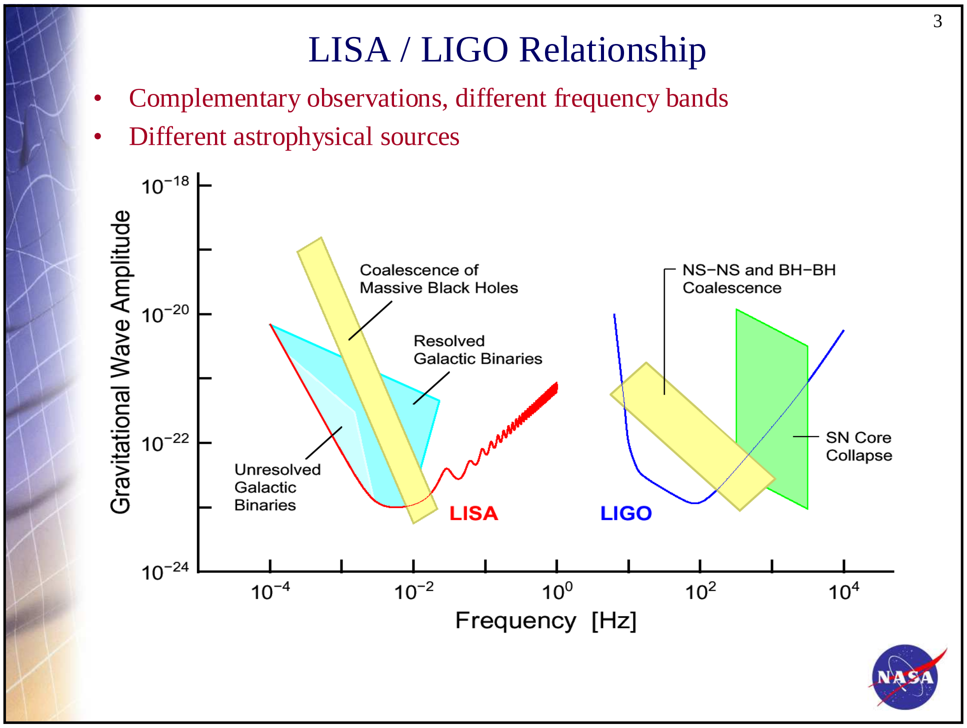
- **Characteristic amplitudes**

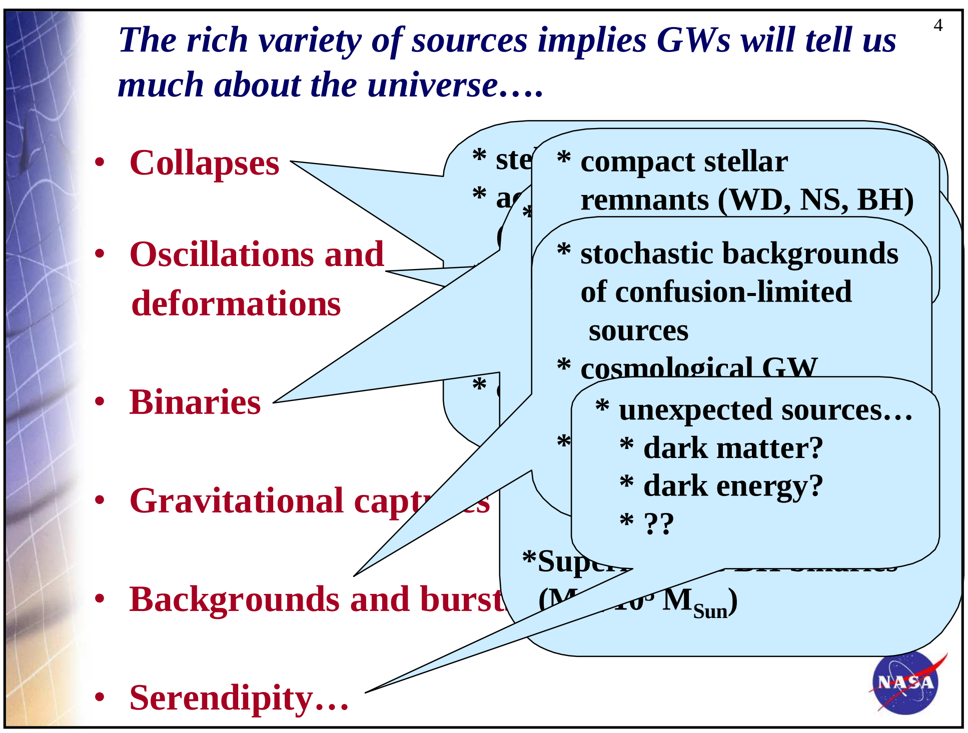
$$h \sim \frac{G}{c^4}\frac{\ddot{Q}}{r} \sim \frac{R_{Sch}}{r}\frac{v^2}{c^2}$$

  - ***r*** **= distance to source**
  - **R_{Sch} = 2GM/c^2**
  - ***Q*** **= (trace-free) quadrupole moment of source**
  - ***v*** **= characteristic nonspherical velocity in source**
- **generated by matter distributions with time-changing quadrupole moments → carry info about bulk motion of sources**
- **interact weakly with matter → carry information about deep, hidden regions in the universe**



- **Hulse-Taylor binary pulsar PSR 1913+16**
  - **Orbital period decay agrees with GR to within the observational errors of < 1%**
  - **Nobel Prize 1993**


3
LISA / LIGO Relationship
• Complementary observations, different frequency bands
• Different astrophysical sources
Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of Massive Black Holes
Resolved Galactic Binaries
Unresolved Galactic Binaries
LISA
NS–NS and BH–BH Coalescence
SN Core Collapse
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency [Hz]


4
The rich variety of sources implies GWs will tell us much about the universe….
• Collapses
• Oscillations and deformations
• Binaries
• Gravitational captures
• Backgrounds and bursts
• Serendipity…
* compact stellar remnants (WD, NS, BH)
* stochastic backgrounds of confusion-limited sources
* cosmological GW
* unexpected sources…
* dark matter?
* dark energy?
* ??
$(M \sim 10^{5} M_{Sun})$

5

Focus here on 3 sources involving black holes…

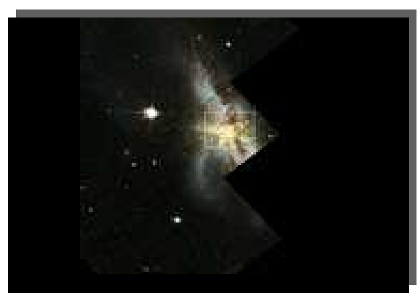
- **Final coalescence of BH/BH binaries…**
- **Collapse of a supermassive star to a SMBH…**
- **Capture of stellar remnants by SMBH at centers of galaxies…**

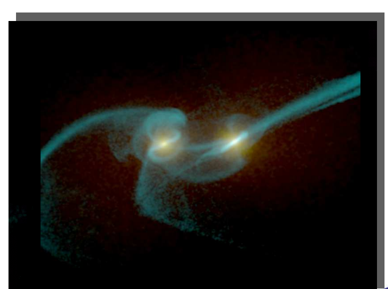
and what we can learn about astrophysics and the cosmos by observing the gravitational waves they emit….

6

Coalescing supermassive BH binaries….

- **Supermassive BHs lurk at the centers of most, if not all, galaxies**
- **Masses $M \geq 10^5$ M_{Sun}**
- **Chandra X-ray observatory found the first known system of 2 SMBH starting to merge in the galaxy NGC 6240**
  - **distance ~ 120 Mpc → close!**
  - **BHs will merge in ~ few x 10^8 years**
- **Most galaxies are formed from the merger of 2 progenitor galaxies → merger of SMBHs**
- **LISA could observe roughly several per year, out to redshifts z > 10**





7

Coalescing intermediate mass or seed BH binaries…

- Black holes having masses M ~ few x 10^2 M_{Sun} – 10^4 M_{Sun}
- Predicted in hierarchical structure formation theories:
  - **galaxies form from successive mergers of protogalactic fragments**
  - **SMBHs at the centers of galaxies form from successive mergers of smaller "seed" BHs at the centers of these fragments**
- IMBH also can form
  - **from the collapse of massive Pop III stars that form BHs**
  - **in stellar clusters from successive mergers of lower mass BHs**
- LISA will be able to detect these systems out to redshifts z ~ 7 – 30

  → will give an unprecedented view of the merger history of galaxies
- Ground-based detectors will see the final coalescence of systems with masses ~ few x 10^2 M_{Sun}

8

Coalescing stellar black hole binaries…

- Black holes having masses M ~ few x 10 - 10^2 M_{Sun}
- Stellar BHs are formed as the end product of the core collapse of massive stars
  - **if mass of remnant core ~ 2 M_{Sun} or larger → BH will form**
  - **BH may also form from fallback of gas onto NS, causing collapse**
- Excellent source for ground-based interferometers….

Final Coalescence of BH binary….

9

- Dominant energy loss mechanism is GW emission
- Coalescence time for binary of total mass *M* and separation *a* (point masses, circular orbits):

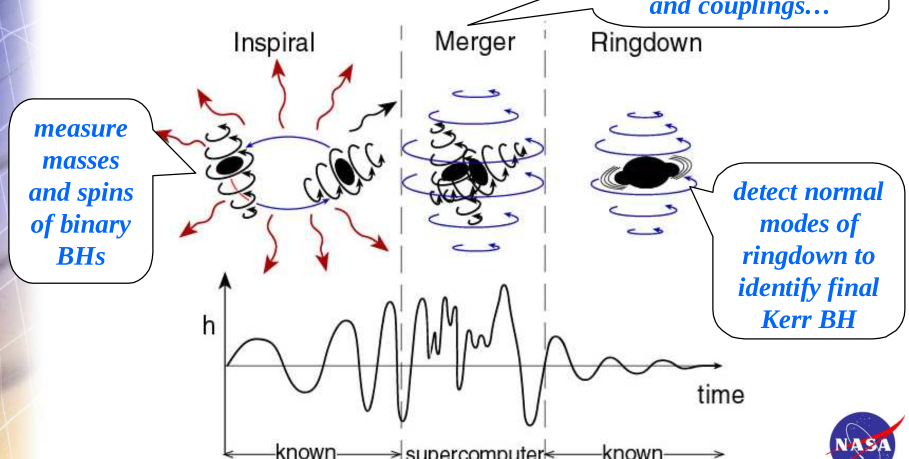
$$t_{\rm GR} = \frac{5}{64}\frac{c^5}{G^3}\frac{a}{M^3}$$

- For binary of total mass $M = 2 \times 10^6\ M_{\rm Sun}$ to coalesce within $t_H \sim 10^{10}$ years
  → separation $a < a_{max} \sim 2.53 \times 10^4\ M \sim 2.4 \times 10^{-3}$ pc
- GW detectors will observe the end stages of this coalescence, typically ~ 10^3 orbits
  – LISA: will observe massive BH binaries for ~ 1 year
  – Ground-based detectors: will observe stellar BH binaries for ~ 1 minute

Final coalescence proceeds in 3 stages . . .

10

- GW produced in all three phases of this evolution . . .
- Waveforms and dynamics scale with BH masses and spins
  → source modeling applicable to stellar BHs, IMBHs & SMBHs….



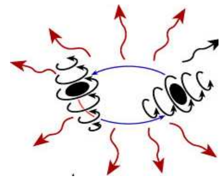
(graphic courtesy of Kip Thorne)

Inspiral stage…

11

- Slow, quasi-adiabatic inspiral driven by GW emission

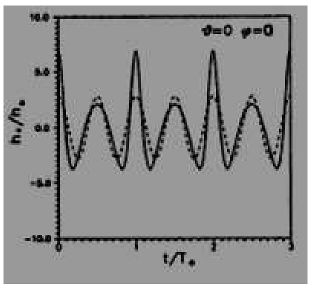
"chirp" waveform: sinusoid increasing in amplitude & frequency as the BHs get closer together

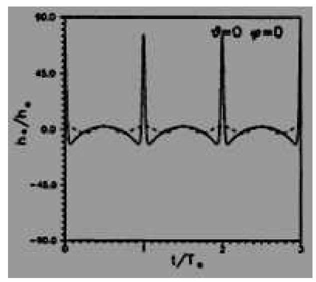


$$f_{\text{binary}} = \frac{2 f_{\text{orbital}}}{(1+z)} = \frac{1}{\pi}\frac{1}{(1+z)}\left(\frac{GM}{a^3}\right)^{1/2}$$

– **Eccentricity can alter waveform shape significantly (Pierro, et al.)**

e = 0.274 (PSR 1534+12) **e = 0.617 (PSR 1913+16)**

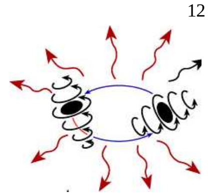




– **Also, precession effects due to BH spin (Vecchio, Kalogera…)**

Inspiral stage:

12

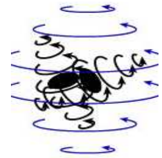


- MBH observable by LISA for ~ months to years
- Use waveforms as templates for data analysis by matched filtering
- If observe a sufficient number of cycles of inspiral waveform (for LISA, ~ few months or longer) within the detector's frequency band, can measure redshifted masses (1+z)M:
  – Chirp mass $\mathcal{M}_c = (M_1 M_2)^{3/5}/[M_1 + M_2]^{1/5}$
  – Reduced mass (less accurately) $\mu = M_1 M_2/[M_1 + M_2]$
  – Also some information on spins…
- If know cosmology to ~ 10%, invert luminosity distance relation D_L (z) to get redshift z → M_{tot} (Hughes 2002)
- Typically, get $(1+z)\mathcal{M}_c$ to ~ 0.1% or better

  → $\mathcal{M}_c$ to ~ 15 – 30%

13

Merger stage…



- Inspiral lasts until separation $a \sim 3R_{\mathbf{Schw}} = 6M$

$$\rightarrow \quad f_{\text{inspiral}} \leq 4 \text{ x } 10^{-3} \text{ Hz} \left(\frac{10^6 \, M_{\text{Sun}}}{(1+z)\, M} \right)$$

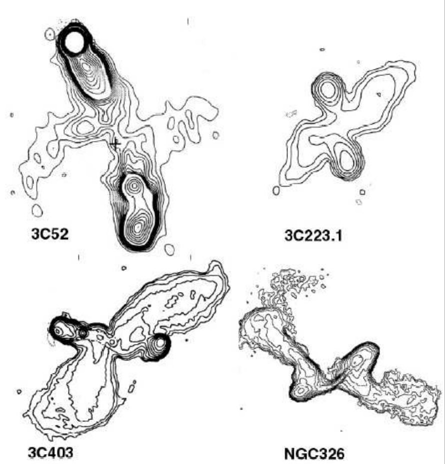
- BHs leave quasi-static orbits and plunge together
- Expect ~ several cycles of gravitational radiation
  - **→ "burst" waveform, observable by LISA for ~ minutes – hours**
  - **→ knowledge of merger waveform important to enhance detectability in ground-based GW observatories…**
- Strong, highly nonlinear, dynamical gravitational fields
- Requires numerical solution of the full 3D Einstein equations…
- Merger can be phenomenologically rich
  - **test of General Relativity in the dynamical, nonlinear regime**
  - **possible ejection of final BH for $M_1 \neq M_2$**
  - **effects of spin: spin-spin and spin-orbit couplings, spin flips…**

14

SMBH mergers and radio lobe morphology...

- **Jets emanating from centers of active galaxies**
  - **believed to result from accretion onto central SMBH**
  - **jet directed along spin axis**
- **Mergers of spinning BHs can change orientation of BH spin axis**

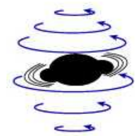
  → sudden flip in direction of associated jet
- **Can identify the winged or X-type radio sources with galaxies in which a merger has occurred**



(Merritt & Ekers, Science, 2002)

15

Ringdown…



- **Merger → rotating, highly distorted BH**
- **"Rings down" to a quiescent Kerr BH by emitting GW**
- **Ringdown waveforms are *exponentially damped sinusoids*, dominated by the strongest l = m = 2 quasinormal mode**

$$f_{\rm ring} = \frac{f_{\rm QNR}}{(1+z)} \cong \left[1 - 0.63(1-\hat{a})^{3/10}\right]\left[\frac{10^6 M_{\rm SUN}}{M}\right]\left(\frac{3.2\text{x}10^{-3}\,\text{Hz}}{(1+z)}\right),\ 0 \le \hat{a} \le 1$$

(Echeverria; Leaver)

- **Quality factor** $Q \cong 2(1-\hat{a})^{-9/20} = \pi\tau_{\rm damp} f_{\rm QNR}$
- **Ringdowns are "burst" waveforms**

For *M* = 2 x 10^6 M_{Sun}, if $\hat{a} = 0.5$, $f_{\rm ring} \approx \frac{7.8\text{x}10^{-3}\,\text{Hz}}{(1+z)}$, $\tau_{\rm damp} \approx 6M \approx 1\text{hr}$

For $\hat{a} = 0.98$, $\tau_{\rm damp} \approx 29M \approx 4.8\text{hr}$

- **Note: we observe redshifted damping timescale** $(1+z)\tau_{\rm damp}$
- **identify mass and spin of final Kerr BH**

16

Collapse of supermassive stars to form supermassive BHs….

(Shapiro, Shibata, Baumgarte, New….)

- Collapse of uniformly rotating supermassive star of mass ***M*** simulated in axisymmetry using full general relativity
- N=3 polytrope; initial SMS rotates at mass-shedding limit and is marginally unstable to radial collapse

→ forms a BH with mass ~ 0.9***M*** and spin parameter J/M^2 ~ 0.75, which is surrounded by a rotating disk of mass ~ 0.1 ***M***

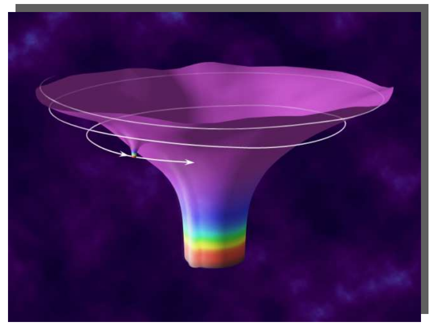
- In some cases, a nonaxisymmetric instability such as a bar mode can develop → additional GW emission possible

Still to come: calculate gravitational waveforms of supermassive star collapse → may enable detection by LISA and shed light on mechanism by which supermassive BHs form….

17

Gravitational capture from nuclear star clusters…

- Compact stellar remnants orbit the massive object in the center of a galaxy
- GW emitted as remnant spirals in
- Expect LISA can detect ~ 10^5 orbits of remnant around central SMBH in last year of inspiral
  → high precision map
- These inspiral waves carry the signatures of the multipole moments of the central object
  → map its spacetime geometry
  → determine if central object is indeed a BH by measuring 3 multipole moments



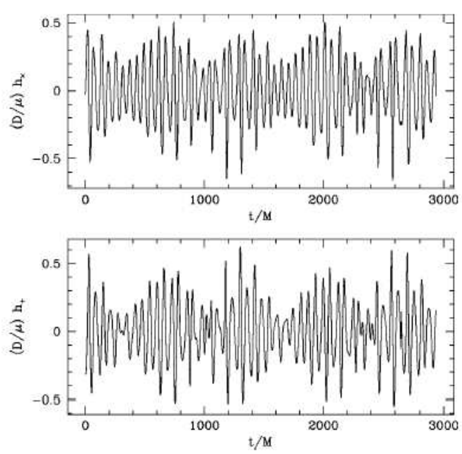
➢ Expect LISA can detect ~ several events per year, perhaps many more, out to distances of ~ few Gpc for ~10 M_{Sun} BH remnants

18

Inspiral of stellar compact objects into massive BHs….

(Hughes, Creighton, Glampedakis, Thorne, Finn, Ryan….)

- *Challenging!*
- Waveforms are influenced by many harmonics of orbital frequencies…
- Signals will be relatively week (they set the noise floor for LISA)
- Relatively large numbers of parameters…



Non-equatorial circular orbit at r = 7M i=62.43°, about BH with a = 0.95M, observed in equatorial plane of BH (Hughes 2000)

19

Gravitational Waves . . .

a new kind of cosmic messenger

"Every time you build new tools to see the universe, new universes are discovered. Through the ages, we see the power of penetrating into space."

-- David H. DeVorkin (paraphrasing Sir William Herschel)