

GW1—Introduction to Gravitational Waves

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1.1 — GWs in a nutshell



Gravitational waves are propagating ripples in spacetime, produced by the rapid accelerated motion of massive bodies.

GWs will open many new windows...





...on the most dramatic events in the Universe, the most luminous objects, the most extreme conditions.

Gravitational waves:

- are emitted by the bulk motion of accelerating masses
- have typical strength 10⁻²¹
- interact weakly with matter
- are phase coherent
- are measured by omnidirectional detectors
- do not form images



GWs are detected across the frequency spectrum as transverse oscillations in the distance of test masses.







[see this movie at https://youtu.be/QyDcTbR-kEA]

GW150914: the GW era is now

1.2 - sources







- black holes are pure vacuum (and hairless) GR solutions
- they are the endpoint of evolution for massive stars
- stellar-mass black holes are observed in x-ray binaries
- supermassive black holes are inferred at the centers of galaxies

[see this movie at https://youtu.be/l_88S8DWbcU]

- black-hole binary mergers are non-luminous (in EM!)
- they yield black-hole parameters to constrain population models
- they probe the dynamical, strong-field sector of gravitation
- they are the most luminous transient events in the Universe



- rapidly pulsating radio sources were identified with neutron stars
- decreasing orbital period of Hulse-Taylor binary pulsar provided indirect proof of GW emission
- binary pulsars allow precision tests of GR dynamics



See this movie at https://youtu.be/vw2sLcyV7Vc

- neutron-star binary mergers: well-modeled inspiral, hydro-influenced late-inspiral/merger
- possible engine for short gamma-ray bursts; coincident observations will confirm



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radio	isotropic, weak	months-years	low	wide-field LF higher-sensitivity HF
kilonovae	isotropic, weak	hours-days	high	transient factories, IR? > 6m spectroscopy

neutron stars are unique laboratories for nuclear physics: NS–NS and NS–BH GWs constrain their EOS

- NS maximum mass and radii are poorly known
- maximum mass: EOS stiffness at supernuclear densities
- radius: EOS at nuclear densities (esp. symmetry energy)
- NS–NS GWs: EOS influences tidal deformations in late inspiral, sudden/delayed collapse
- NS–BH GWs: EOS influences NS tidal disruption [MV 2000]



[Lattimer & Prakash 2007]

in the late NS–NS inspiral, companions raise quadrupolar tides; inspiral is faster for stiffer EOS





Lackey et al. 2011



 $Q_{ij} = -\lambda \mathcal{E}_{ij}$ $\lambda = \frac{2}{3} R^5 k_2$



Shibata group

in late NS/BH inspiral, larger NS are tidally disrupted, reducing the GW amplitude sharply before merger and suppressing ringdown



- NS radius can be extracted as well as 10% in aLIGO, a precision comparable to X-ray–burst measurements, but with very different physics
- significant modeling improvements are still needed

GW science in a nutshell: what's in a binary waveform?





1.3 — detection

Joseph Weber, 1919-2000







Gravitational wave

Gravitational-wave detector

Gravitational-wave detector



Universal: "it must get better before it gets worse"





Space-based interferometers









See this movie at https://youtu.be/tQ_telUb3tE

- ground-based interferometers use lasers to monitor differential length changes of km-size arms
- sensitive at 10s to 1000s Hz; extremely precise in measuring positions; limited by seismic, thermal, photon noise



Advanced LIGO & Advanced Virgo

1990

THE HISTORY OF LIGO

1970

Early work on gravitational-wave detection by laser interferometers begins with a 1972 MIT study describing a kilometer-scale interferometer and estimates of its noise sources.

1980

research and development.

National Science Foundation (NSF) funds

Caltech and MIT for laser interferometer

Site construction begins in Hanford, WA and Livingston, LA

200

During an engineering test a few days before the first official search begins. Advanced LIGO detects strong gravitational waves from collision of two black holes.

iLIGO runs

Construction of Advanced LIGO components begins.

LIGO CALTECH EDU # SOURCE



High-vacuum tubes and chambers





Multiple-stage active and passive seismic isolation





High-power laser, ultra-smooth high-Q test masses



Advanced LIGO sensitivity, September 2016



LIGO Hanford

LIGO Livingston

Operational Under Construction Planned

Gravitational Wave Observatories

GEO600

VIRGO

KAGRA

LIGOIndia

LIGO–Virgo science goals...



Inspiral/merger/ringdown GWs from NS and BH binaries

- determine rate of mergers and parameter distributions
- establish GRB link to NS–NS mergers
- probe NS equation of state
- test strong-field GR and alternative theories



Modeled and unmodeled bursts

- observe core collapse of massive stars; determine blow-up mechanism (neutrino, MHD, acoustic)
- discover IMBHs (mergers, ringdowns, eccentric encounters)
- look for cosmic (super-)string cusps
- search in coincidence with EM and neutrino events (GRBs, SGRs, pulsar glitches, supernovae), compare energetics

...LIGO-Virgo science goals



Continuous waves from rapidly rotating NSs

- detect elastic or magnetic deformations; unstable mode oscillations; free precession
- understand properties of solid and fluid NS phases (inertia tensor, magnetic field, viscosity, internal structure)
- discover accretion-powered GW emission in LMXBs



Cosmological and astrophysical stochastic backgrounds

- constrain inflationary, superstring, pre-Big Bang models
- look for cosmic strings
- constrain source populations in the Galactic neighborhood

See this movie at https://youtu.be/aTPkoZxyovo

• LISA: a 2030s ESA mission with NASA participation, will use laser interferometer to monitor picometer fluctuations in the Mkm distance between freely-falling test masses protected by the spacecraft To remove clock (laser-frequency) noise 160 dB louder than GWs we combine one-way measurements in the interferometers synthesized with Time Delay Interferometry

(D. Shaddock)





Unequal arms





LISA science goals (classic)



LISA science goals (new)



Proving data analysis: the Mock LISA Data Challenges



Testing technology: LISA Pathfinder/ST7

Test mass

Laner Interlering

Optional Isanoch

Disturbance Reduction System (DRS)

This NAGA explised instrument will use micronewton thrusters & advanced software to control the space-outly ensuring the test-messes have a disturbance-free environment.

Brag Free and Attitude Control System (OFACS)

The diag-free control system consists of an mental sensor, a proportional micro-propulsion system and a control loop. To achieve the mission objective - sensying that a test mass can be kept in gravitational heated and/oard the speciesraft - the position and rolation of the test mass is constantly montored.

10⁻⁶

and millionth of a newton, is the minimum fonce the microthrusters can apply to shift the spececraft so that the test masses stay pertrect. Their typical force of 30 micronewtons would be just sufficient to stop a movifiele failing to the ground.

LISA Technology Package (LTP)

The LTP is a miniature variable of one app of the future is LTM interfacements. The distance between the two test masses is socied down from one mittion kitometres to around its centimetres. The two identical kit mm cube test masses are housed in individual recourt enclosures.

Getting there

LIGA Pathfinder's destination is an arbit around the first lium Earth Lagrangian point L1, a region of thermal and gheritational statistic, Constantly Eurinated by the Euriand in good communication distance from Earth, it will blow the Earth on its path eround the sur.

ience module

Propulsion module

Testing technology: LISA Pathfinder/ST7

→ LISA PATHFINDER EXCEEDS EXPECTATIONS







www.ena.int

The rotation of the spacesoalt required to keep the solar array pointed at the Sun and the antenna, pointed towards Santh, coupled with the nesse at the startischers produces a naisy controllopal large on the test masses. This mean term fact been rodificanted, and the secure of the model noise after substantian is still being investigated.



Spectrus R. ELECTE methology Anter ISACEU. Autobasie Collaboration

The name term becallers analler

with time, as more gas maincales

are central to space

The sensing noise of the optical methology system used its member the people and anertation of the test masses, at a level of 25 lies (xHp), tas already surpressed the level of precision wasken observations by a factor of more than 200.

European Space Agamey



- Pulsar-Timing Arrays: using pulsars as fundamental clocks for GW measurement
- Pulsars have rapid, **regular** rotation (ms to s)
- Radio emission along magnetic field axis; misalignment of rotation and magnetic field axes creates "lighthouse" behavior



Pulsars: Nature's precision clocks

[Manchester 2015]



Deterministic effects in timing residuals *f* = 300 Hz [Manchester 2015]

$$\sigma_{\text{TOA}} = \frac{W}{\text{SNR}\sqrt{N_{\phi}}}$$

$$TOA$$
Pulse profile averaging

B0950 (P = 253 ms), 100 top pulses in 5-min integration [Stairs 2003]



See this movie at http://www.astron.nl/pulsars/animations/

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The NANOGrav pulsars

[McLaughlin 2013]

The NANOGrav 9-year dataset [NANOGrav 2015]





isotropic SMBH background 9-year analysis

[NANOGrav 2015]



detection probability given the PPTA limit

[Taylor, Vallisneri, et al. 2015]



... to follow, on this screen...

- 2: GW theory
- 3: GW150914 (colloquium)
- 4: data analysis
- 5: cosmology and testing GR