The Warped Side of the Universe:
From the Big Bang to Black Holes & Gravitational Waves

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Warped Side of the Universe

Phenomena and objects
Made from warped space and time
Black Hole
Black Hole

Hyperspace ("bulk")

Diameter >> Circumference

Diameter

Circumference

Singularity

Trampoline

Rock

Hyperspace

("bulk")

Black Hole
Black Hole

Horizon

Singularity
Black Hole

- Warping of space
- Warping of Time
- Time slows
- Horizon
- Whirl of space
- Singularity
• The Big Bang Singularity

• Our Universe as a Brane in a higher-dimensional bulk

• Cosmic String

\[ C/R = 2\pi(1-4G\mu/c^2) \]

• Singularity inside a black hole

• Naked Singularity

• Gravitational Waves
Probing the Warped Side: Tools

- What kinds of objects might exist?
  - General Relativity Theory
    - Progress has slowed…
  - Numerical Relativity
    - Exciting new era…
    - Part 1

- What kinds of objects do exist?
  - Electromagnetic observations
    - Limited information
  - Gravitational-Wave observations
    - Ideal tool for probing the Warped Side
    - Part 2
Part 1
Numerical Relativity
The “Holy Grail”: Collisions of Black Holes
- The most violent events in the Universe

~ 10 % of holes’ mass is converted into GWs [contrast with nuclear fusion: < 0.5 %]

GW Luminosity ~ 0.001 c²/G
~ 10^{24} L_{\text{sun}} ~ 10^4 L_{\text{EM universe}}

No Electromagnetic Waves emitted whatsoever
- only Gravitational Waves -
Collisions of Black Holes: The most violent events in the Universe

Details of the collision are encoded in the gravitational waves’ waveforms
Why are Black-Hole Collisions Interesting?

*Wild vibrations of warped spacetime*
Numerical Simulations of Black Hole Binaries

- Evolve the geometry of space and the warping of time.
  » Techniques under development since 1970s; only recently matured
  » Caltech/Cornell team: 2001 - spectral methods [vs finite difference] exponential convergence

- Example: Identical black holes, not spinning
  » Caltech/Cornell: Kidder, Lindblom, Pfeiffer, Scheel, Teukolsky
  » 10,000 cpu-hours on a 264 cpu cluster
“Rosetta Stone”

Numerical simulations and theory provide “rosetta stone” for interpreting observed Gravitational Waveforms
“Rosetta Stone”

- For generic binaries, waveforms are much more complex
  - Noncircular orbits; different sized holes, spinning, random orientations

- We are beginning to build a catalog of about 1000 waveforms for use in LIGO's searches for gravitational waves
  (new computer cluster … NSF/Fairchild funded; 50 million cpu-hours)

- We are also exploring the rich & complex dynamics of warped spacetime that produces these waveforms.
  Simple example:
What we are learning from Simulations

- Example: Holes spinning on their sides
Simulation:
  Manuela Campanelli
  Carlos Lousto
  Yosef Zlochower

Visualization:
  Hans-Peter Bischof

CCRG
RIT

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Analogous to 2 Vortices in a Fluid
Explanation of Bobbing and Kick
[Yanbei Chen, Kip, …]
Motion of Space *in Horizon* as seen in a reference frame that rotates with the merged hole
Singularity Inside a Black Hole

- Dynamics of spacetime near **singularity**
  - Approximate analytic calculations suggested (1971):

  - Chaotic pattern of stretch and squeeze has been confirmed by Numerical Relativity simulations [Garfinkle]

  - Future Challenge: How does singularity evolve as hole ages?

  Chaotic pattern of stretch and squeeze
Naked Singularities?

- Cosmic Censorship Conjecture [Penrose 1968]
  » All singularities (except the big bang) are hidden inside black holes.

Numerical Simulations
Matt Choptuik ~ 1994 - (U Texas -> UBC)

Imploding Waves
Naked Singularity
Part 2
Gravitational Wave Observations
Probe the Warped Side of Universe
Motivation

\[ \frac{\Delta L}{L} = h(t) \]
Laser Interferometer Gravitational-Wave Detector - “GW Interferometer”

\[
\Delta L = h L \lesssim 4 \times 10^{-16} \text{ cm}
\]

\[\lesssim 10^{-21} \quad 4 \text{ km}\]
How Small is $10^{-16}$ Centimeters?

One centimeter ~ 1/2 inch

$\div 100$  [Image of a centimeter]

Human hair ~ 100 microns

$\div 100$  [Image of a hair

Wavelength of light ~ 1 micron

$\div 10,000$  [Image of a wave]

Atomic diameter $10^{-8}$ cm

$\div 100,000$  [Image of an atom]

Nuclear diameter $10^{-13}$ cm

$\div 1,000$  [Image of a LIGO symbol]

LIGO sensitivity $10^{-16}$ cm
Isn’t it OUTRAGEOUS to claim one can measure mirror displacements ~1000 times smaller than the nucleus of an atom?
Keys to Success

Thermal Noise:  
Average over space and time

Seismic Noise:  
Isolate from environment

Photon Shot Noise:  
Use lots of photons: $\sim 10^{20}$ in 0.01 second
**LIGO:** Laser Interferometer Gravitational Wave Observatory

Began as MIT/Caltech collaboration [Weiss; Drever, Kip]

Now: Collaboration of ~650 scientists at ~50 institutions in 8 nations  [J. Marx, Director; D. Rietze, Spokesman]

Hanford Washington
LIGO

USA, UK, Germany, Australia, India, Japan, Russia, Spain

Livingston, Louisiana
Earth-Based GW Interferometers

Network Required for:

» Detection Confidence
» Waveform Extraction
» Direction by Triangulation
LIGO Timeline

● 1971-94 R&D
● 1989: Construction proposal (to NSF). Two Stage Strategy:
  » Initial Interferometers: sensitivity where plausible to see GWs
  » Advanced: sensitivity where high probability to see many GWs
● 1995-2000: Construction
● 2001-2005: Initial Interferometers Installed & Commissioned
● 2005-2007: Initial GW Search
● 2008-2010: Advanced Interferometer components built; prepared for installation. Initial interferometers souped up (“Enhanced LIGO”), searching with them until October.
● 2010-2015: Advanced Interferometers Installed & Commissioned; GW searches begin.
Initial Interferometers! Noise (2005-07)

\[ x \sqrt{\Delta f} = h_{rms} \]

Livingston, LA  Hanford, WA

Design
Initial Interferometers! Noise (2005-07)

Livingston, LA  Hanford, WA

\[ \tilde{h} \]

Seismic noise

Thermal noise

Photon shot noise

Frequency, Hz

10
100
1000
10,000

Noise levels for Initial Interferometers, showing contributions from seismic noise, thermal noise, and photon shot noise.
Enhanced Interferometers! Noise (2009-10)

Hanford, WA

\(\tilde{h}\)

\(10^{-20}\)
\(10^{-21}\)
\(10^{-22}\)
\(10^{-23}\)

Frequency, Hz

Enhanced

Initial
2005-2007, 2009-10 GW Searches

Nothing seen yet

Interesting limits (later)
From Initial Interferometers to Advanced

ACTIVE VIBRATION ISOLATION
Seismic wall: 40 Hz → 10 Hz

Signal Recycling Mirror

- Steel wire 11 kg
- Fused silica 40 kg
- 40 kg

Initial Interferometers

Advanced Interferometers

~10kW
~1MW

Seismic Noise
Thermal Noise
Shot Noise
Advanced LIGO Interferometers
The Experimental Challenge

\[ \Delta L / L = h \]

- Monitor motions of 40 kg mirrors to:
  - \( \Delta L \sim 10^{-17} \text{ cm} \)
  - \( \sim 1/2 \text{ width of Schrödinger wave function of center of mass} \)

For the first time humans will see human-sized objects behave quantum mechanically!
Quantum Nondemolition (QND) Technology to deal with this
[Branch of Quantum Information Science]

Yanbei Chen’s talk to Lyncean Group, May 2009
2005-07 Initial LIGO Search: A few Results from ~1/2 Data

- **Black Hole Binaries:** <1/860 yrs in Milky Way type galaxy

- **Crab Pulsar:** <7% of spindown energy goes to GWs

- **GWs from big bang:**
  GW energy in LIGO band < 1/100,000 of energy to close the universe
Advanced LIGO Science [2015…]

- Will see 15 times farther into the universe than Initial LIGO
  - $15 \times 15 \times 15 = 3000$ more sources
- Black-hole binaries: see to 3 billion light years (1/5 of way to edge of observable universe)
  - Predicted rate: ~ 1/month to 1/day
- Other sources we expect to see:
  - Supernova explosions (births of neutron stars)
  - Pulsars (spinning neutron stars)
  - Black holes tearing neutron stars apart
  - Neutron-star binaries … inspiral, collision, merger
  - Central engines for “gamma ray bursts”
  - …
Third-Generation GW Interferometers

- Design study underway in Europe for Einstein Telescope
  - To operate in 2020s
  - Tentative goal: reduce noise below Advanced LIGO by factor 10 to 30
  - See all merging black hole binaries in our entire universe with masses below about 300 suns.
    and many many other phenomena on warped side
- LIGO's third generation should be similar
Laser Interferometer Space Antenna

GW wavelengths
10,000 longer than LIGO

Supermassive holes, $\sim 10^5 - 10^7$ Msun throughout universe. S/N $\sim 10$ to 10,000
LISA: Joint ESA/NASA Mission

- Technology test flight: 2012
- Launch: 2018 or later
Mapping a Quiescent Black Hole

Full Map is encoded in the waves
Some Numbers for LISA

5 million km = 20 light sec

Final Year:
100,000 orbits with Circumference < 4 x (Horizon circumference)

3 billion light yrs

10 Msun

1 million Msun

$h \sim 10^{-20}$

$L = 5$ million km

$\Delta L = 10^{-8}$ cm
What if the Map is Not that of a Black Hole?

May have discovered a new type of “inhabitant” of dark side of the universe. Two long-shot possibilities:

- Dense objects made from cold, dark matter
  - (Dark ``Stars!!)
  - e.g. boson stars

- Naked Singularities
Over the Next 40 Years

**Probe the Initial Second of Universe’s Life**

1. Waves (vacuum fluctuations?) from singularity amplified by Inflation.

**Rich Violence in First Second -- Four Examples**
Planck Era

**Planck Satellite**

**Inflation**  
**Gravitational Waves**  
**CMB Polarization**

*Will indirectly study GWs with wavelengths ~ (0.01 to 1) x the size of our observed universe*

*And through them: explore the birth of the universe and its inflation*
BBO: Big Bang Observer
Launch ~2030 or later

Will study birth of the universe & inflation with wavelengths ~ earth-moon distance

also explore many other objects on warped side of universe
2. Cosmic Strings

- *Inflation* enlarges some superstrings to cosmic size
- Kinks, cusps and waves on cosmic strings produce gravitational waves
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- **Inflation** enlarges some superstrings to cosmic size
- Kinks, cusps and waves on cosmic strings produce gravitational waves

*We are searching for these waves NOW, with LIGO*

*Ken Olum - Tufts*
3. Birth of Fundamental Forces

- At age $\sim 10^{-12}$ seconds [$kT \sim 1$ TeV ... LHC energy]:
  - Phase transition: Electroweak force $\rightarrow$ EM + Weak

Waves are in LISA’s domain

Phase transition at age $\sim 10^{-22}$ sec
[$kT \sim 10^5$ TeV]
Is in LIGO’s domain
4. Our 3-D Universe as a “Brane” in Higher Dimensional Bulk

- May have formed wrinkled
- As universe expanded, adjacent regions discovered the wrinkle between them
- Wrinkle began vibrating -- producing gravitational waves - brane smoothed out

Example of the kind of surprise gravitational-waves may bring us
Conclusions

Numerical Relativity and Gravitational Wave Observations are on the threshold of producing a revolution in our knowledge of the Warped Side of our Universe

Gravitational-wave technology is bringing quantum physics into realm of human-sized objects