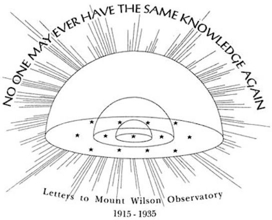

LIGO's black holes, the nature of gravitational waves, & gravitational waves in cosmology

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July 27, 2017

FULSum: a biased review of what we've heard

- Joe Lykken: Fermilab's mission is to study
  - The nature of the higgs particle & the strange neutrino mass
  - The nature of the dark matter & the strange cosmic acceleration
  - Explore the unknown
- Harrison Prosper, Marc Weinberg: the standard model of matter
  - *In reality there is nothing but atoms and the void*
- Anne Schukraft: the oddball neutrino
  - mass states are *not* flavor states! (say what?)
- Dan Hooper: physics & the standard model of cosmology
  - Dark matter! Matter that doesn't interact electromagnetically. All evidence for physics beyond the SM came from astrophysics.
- Brian Nord: astronomy & the standard model of cosmology
  - we see the light, gravity's role in the propogation of light

This talk will be about the void.

Atoms and the Void: particle physics

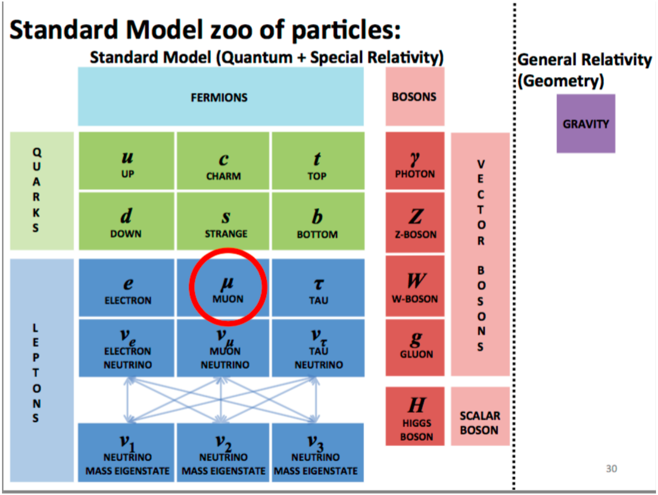


Figure 1 : The Standard Model of matter. One of the great successes of the 20th Century, quantum field theory says all fields are particles, but quantized gravity is so far unsuccessful.

Atoms and the Void: General Relativity

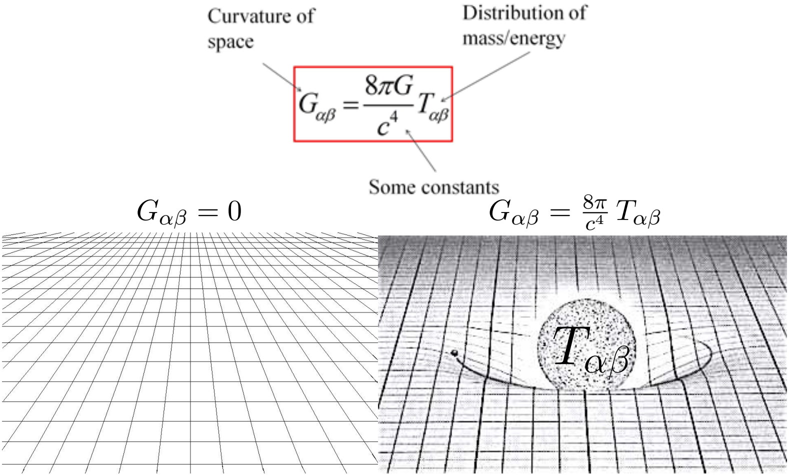


Figure 2 : Spacetime curvature. Gravity is the shape of spacetime near matter. Matter tells spacetime what shape to have and spacetime tells the matter how to free-fall.

Thanks, Brian!

Atoms and the Void: black holes

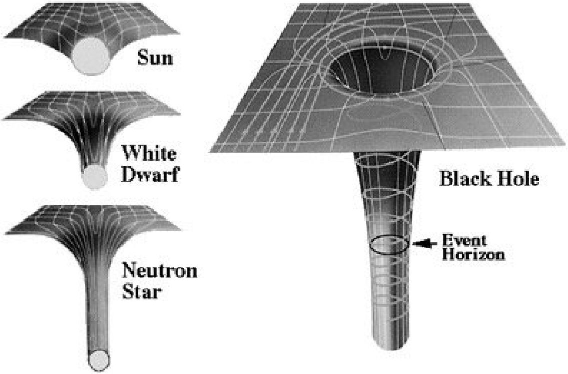


Figure 3 : When matter tells spacetime to curve to extremes, a black hole forms, leaving nothing behind but the curvature

Gravity: Black holes

Black holes are very simple, says the no hair conjecture. If one considers a BH at rest, eliminating position and velocity, then they are described only by:

mass, charge, & spin (angular momentum)

If BH have identical mass, charge, spin, and are otherwise isolated, then they are indistinguishable. Just as electrons.

electron at rest: mass, charge, spin
(quantized angular momentum)

If not isloated, things are different.

electron in an atom: m, q, (n, l, m, s)
BH in the center of a galaxy: quasars

The single most important feature of a BH is the event horizon, the radius at which even a radially propagating photon does not have escape velocity

What is a black hole: mental models

What is a black hole? A curved empty spacetime. . . a knot of slow time. . . the memory of matter. . . in any event, BH aren't made of matter.

We use various mental models:

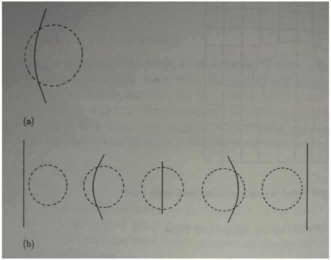
- optical astronomers: a 1 $M_\odot$ point source surrounded by a sphere of radius 3km, inside of which nothing can get out
- frozen star: seen from far away, things approach the event horizon but never reach it as gravitational redshift retards the light. The collapsing star is frozen into place
- membrane paradigm: the stuff near the event horizon acts as a 2-d viscous fluid which is charged and can conduct current but not heat, and has finite entropy and temperature.

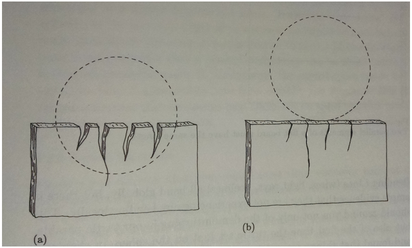
What is a black hole: curved space

We will need to gain some physical intuition of what curved space is. Imagine we have a beachball sized volume of curved space:

- You push a wire through it: the wire bends
- You push a board into it: the board splits
- You put it into a full bathtub: the water level goes down

This is not a "looks like", not a gravitational mirage.





What is a black hole: Metrics in curved space

How does one deal with curved space? Choose a coordinate system, get the unit vectors, decide how to combine them into a distance; that is, choose a metric.

Euclidean space:

cartesian coordinates: $ds^2 = dx^2 + dy^2 + dz^2$

spherical coordinates: $ds^2 = dr^2 + r^2(d\theta^2 + \sin^2\theta d\theta^2)$

$\equiv dr^2 + r^2 d\Omega$

Space in cosmology: $ds^2 = a(t)dr^2 + a(t)S_k^2\, r^2 d\Omega$

where

$$S_k^2 = \begin{cases} \frac{R_o^2}{r^2}\sin^2(r/R_o) & k = 1 \\ 1 & k = 0 \\ \frac{R_o^2}{r^2}\sinh^2(r/R_o) & k = -1 \end{cases} \quad (1)$$

and $a(t) = 1/(1+z)$ is the universe's size relative to today.

Space near a BH: $ds^2 = \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\Omega$

What is a black hole: Metrics in cosmological space

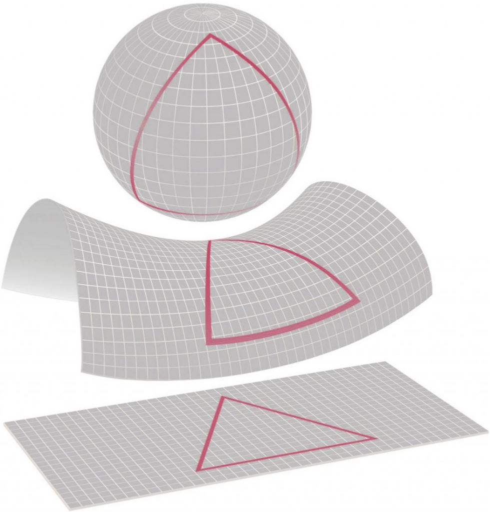


Figure 4 : The three cases in the last slide correspond to spherical (closed), hyperbolic (open), and flat global universes.

What is a black hole: 3+1 formalism

Spacetime includes time. The real Schwarzschild metric is:

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\Omega$$

Most numerical relativity, and the membrane paradigm in particular, use the 3+1 decompostion of spacetime into space and time. For an isolated BH, and far from it, there is a universal time t, whereas near the BH observers experience a redshifted time τ: $\frac{d\tau}{dt} \equiv \alpha = \left(1 - \frac{2M}{r}\right)^{1/2}$. The term α, bounded at $(0, 1]$, tells you how slowly τ ticks with universal time t. The mental model is that one works with the spatial metric and the redshifted time separately. Thus

$$d\tau = \alpha dt\,,\; ds^2 = dr^2/\alpha^2 + r^2 d\Omega$$

Of the two, most of the exotic physical effects of a BH are caused by the redshifted time τ, not the spatial curvature.

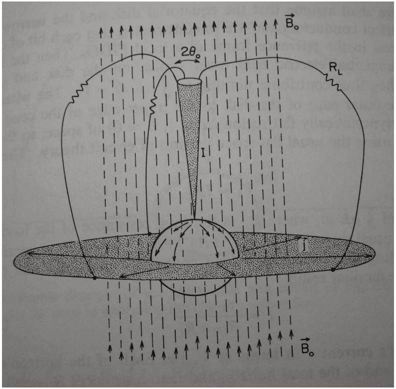
What is a black hole: the membrane

The membrane is a representation of the effect of the matter and fields deep in the redshifted time of the BH, but outside the event horizon. Examining Maxwell's equations at the membrane, one finds that effectively, the BH membrane has:

- surface charge
- electrically conductive
- has a surface resistivity of 377 Ohms
- charge is conserved on the surface

You will notice that it is easier to think about a BH if you think of them as matter.

What is a black hole: an engine for quasars



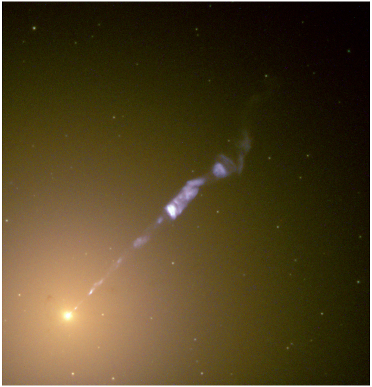


Figure 5 : The black hole acts as a resistor in a circuit, and when surrounded by magnetized material forms a motor. Out in the wild, astrophysical BHs often have accretion disks. The motor powers a jet- a tornado-like twistor of magnetic fields along which matter flows and is accelerated, and the BH becomes a engine of a quasar. M87 has a jet visible in the optical- it is $10^9 M_\odot$ BH starved of gas.

What does a BH look like: astronomy of gravitational lensing

Let's put an accretion around a BH, turn off the jet, and look. The spacetime is so curved so light from the back of the accretion disk is bent over the top and bottom of the BH.

The membrane also has a temperature:

$$T = \frac{\hbar c}{4\pi r_{BH}\, k_B}$$

where R_{BH} is the "radius" of the BH, $r_{BH} = 2M$. The derivation includes the redshift effect of α: this is T seen at distance.

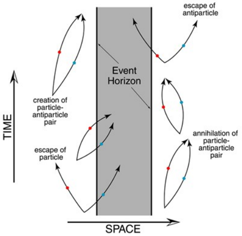


Figure 6 : The mechanism for the thermal atmosphere is a quantum field theory effect: virtual particles are created near the horizen, and some half pairs cross the horizon. This is called Hawking radiation.

Black holes and information: entropy and the holographic principle

Because the membrane has a temperature, it has an entropy:

$$S = \frac{k_B}{4\hbar} 4\pi r_{BH}$$

Notice that this depends on the area of the BH, $4\pi r_{BH}$. For a $1M_\odot$ BH, $S = 10^{77}$, whereas for the $1M_\odot$ Sun, $S = 10^{58}$.

That for BH $S \propto$ area and not $S \propto$ volume led directly to the holographic principle: perhaps the information content of the universe is encoded on an 2 dimensional boundary and not in the 3 dimensional volume.

Fermilab's Holometer made a test of this idea.

Black holes and information: information loss?

Hawking started this line of thought in 1976, in a paper titled: "Breakdown of Predictability in Gravitational Collapse".

Information flows down into a BH with the matter; Hawking thermal radiation comes out; in time the BH evaporates. What happened to the information? The thermal bath can't carry it. Technically what breaks is unitarity: the sum of the probabilities of outcomes is 1.

Recently it has become the question of

"Is there a firewall at the horizon?".

The arguments intersect physics, quantum computing, and quantum information theory and are fascinating: my favorite worker is currently John Preskill- google "quantum information and spacetime".

What is a black hole: spin

One last insight into black holes:

If your mental model for spin of a BH is that of a spinning black ball, that is insufficient.

Imagine an unbreakable monofiliment of great length:

- use it to drop a spoon down to a neutron star surface- it will run into a neutron star mountain at high velocity.
- use it to drop a spoon down to the membrane of a non-rotating BH: time slows down at the spoon.
- use it to drop a spoon down to the membrane of a BH with spin: the spoon and filament starts orbiting the BH.

This is frame dragging: space is carried around the BH.

BH aren't a "thing", they are a feature in spacetime geometry.

LIGO: what did they hear?

Lets see a simulation of the first LIGO event.
`https://www.ligo.caltech.edu/video/ligo20160211v3`

LIGO: what is a gravity wave?

A gravity wave is a propagating curvature perturbation.

A perturbation in the metric. Recall that we can use a 3+1 metric, and out here in the low mass wilderness we can use the euclidean metric for the 3.

Metric in cartesian coordinates: $ds^2 = dx^2 + dy^2 + dz^2$

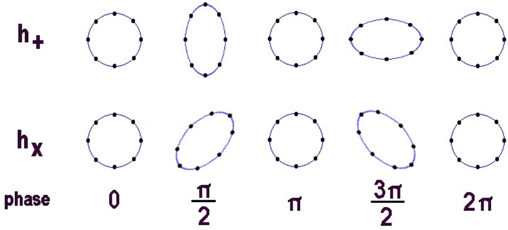


Figure 7 : Image 8 balls in freefall in a circular pattern as a gravity wave passes through.

LIGO: how do you measure a GW

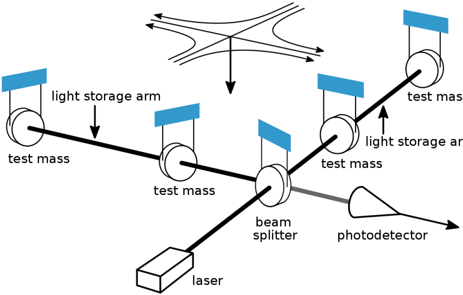
Get two rulers of the same length, say one made of steel and the other of a laser and a clock, then use the rigid one to measure the non-material one while it is in the curvature perturbation.

The LIGO solution was to use a pair of rulers at right angles over 4 km. As gravity waves are quadropoles, one arm could be unaffected.

The measurement is of strain: strain $= \Delta L/L$ and the signal of interest is strain$\approx 10^{-22}$.

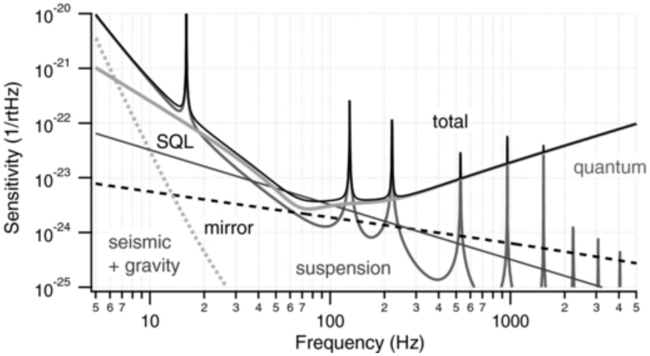
At LIGO's 4km length the change is still $\ll 1$ nm.

LIGO: the experimental layout



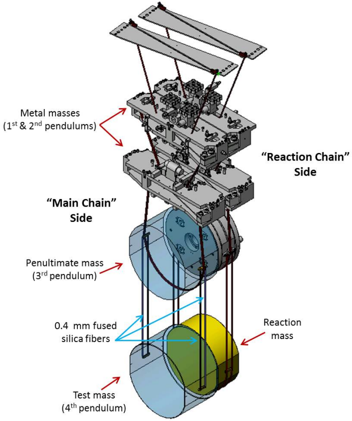
At heart, LIGO is just measuring the length of the two light storage arms, doing a difference of the two, and peering intently at the residuals.
They use a Michaelson interfermeter, which means they combine the lasers such that there is zero intensity when the length difference is zero.

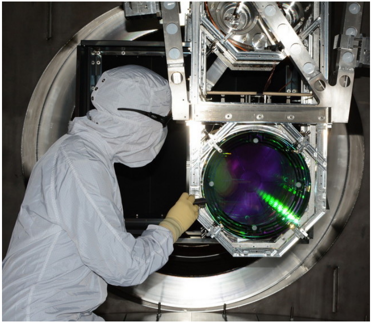
LIGO: noise



LIGO sensitivity is limited by jitter in the length of the light storage arms. Ground shake is dominant at low frequncy jitter. “Quantum” noise is just shot noise in the photons hitting the mirrors– buy a bigger laser or learn about squeezed light. “SQL” is suspension thermal noise and actuator noise- try better coatings. The mirror support is fantastic, see the next slide, but it rings.

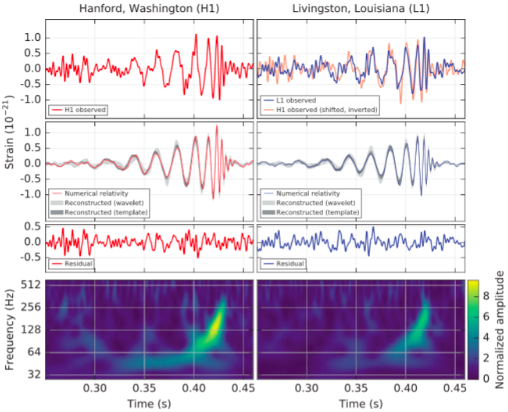
LIGO: the mirrors





The advanced LIGO test masses are suppored on 4 pendulum system. Earthquakes, wind, and trucks are still a problem. This they solve by two LIGO separated by 10ms of light travel and demanding both see the same signal.

LIGO: The first event



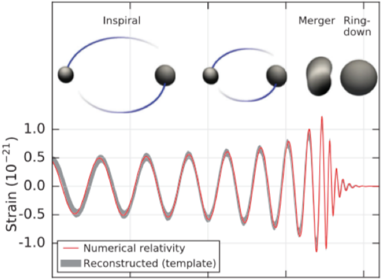
LIGO measures strain, $\frac{\Delta l}{l}$. The strain pattern from systems of merging compact objects is oscillatory. The strains from the two detectors were consistent with the time of flight.

LIGO parameter estimation: chirp mass, orbit period

For a face on merger, the two polarizations of GW strain are:

$$h_+(t) = 2\frac{\mathcal{M}}{D_c}\cos\theta_{gw}(t)$$

$$h_x(t) = -h_+(t)\frac{\sin\theta_{gw}(t)}{\cos\theta_{gw}(t)}$$



where $\theta_{gw}(t)$ is the time dependent phase of the wave (and is twice the orbital period^{-1}), z is the redshift, D_c is the cosmological comoving distance, and $\mathcal{M}$ is the chirp mass:

$$\mathcal{M} \equiv \left(\frac{m_1 m_2}{(m_1+m_z)^2}\right)^{3/5}(m_1+m_2) \;\propto f^{-11/5}\dot{f}^{3/5}$$

which is $\propto$ the strain frequency, f, and its time derivative, $\dot{f}$.

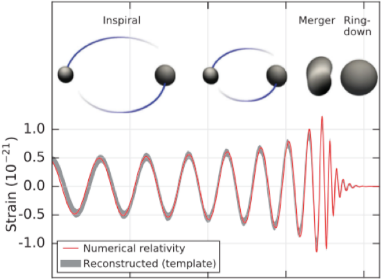
LIGO parameter estimation: distance

The chirp frequency and derivative gives you the chirp mass (though there is a $(1+z)$ affecting chirp mass), and then the chirp amplitude gives you the distance to the event.

$$h_+(t) = 2\frac{\mathcal{M}}{D_L}(1+z)\cos\theta_{gw}(t)$$

This distance is in luminosity distance, D_L, a construct related to comoving distance D_c by

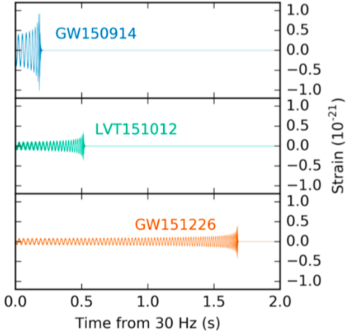
$$D_L \equiv (1+z)D_c = (1+z)\int_0^z \frac{c}{H(z)}$$



where $H(z)$ is the Hubble parameter giving the expansion history of the universe.

Note that the strain $\propto 1/d$. (!)

LIGO O1: events and parameters



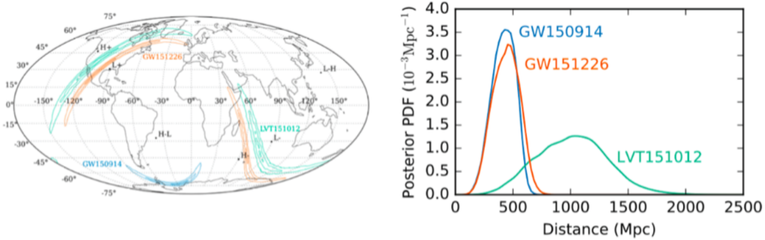
Time evolution of the waveforms after entering LIGO band-pass. From LSC et al. (2016).

LIGO astronomy: observing run 1

Event	**GW150914**	**LVT 151012**	**GW 151226**
signal to noise	23.7	9.7	13.0
significance	$> 5.3\sigma$	1.7σ	$> 5.3\sigma$
mass of primary ($M_\odot$)	$36.2^{+5.2}_{-3.8}$	23^{+18}_{-6}	$14.2^{+8.3}_{-3.7}$
mass of secondary ($M_\odot$)	$29.1^{+3.7}_{-4.4}$	13^{+4}_{-5}	$7.5^{+2.3}_{-2.3}$
chirp mass ($M_\odot$)	$28.1^{+1.8}_{-1.5}$	$15.1^{+1.4}_{-1.1}$	$8.9^{+0.3}_{-0.3}$
final mass ($M_\odot$)	$62.3^{+3.7}_{-3.1}$	35^{+14}_{-4}	$20.8^{+6.1}_{-1.7}$
mass radiated as gw ($M_\odot$)	$3.0^{+0.5}_{-0.4}$	$1.5^{+0.3}_{-0.4}$	$1.0^{+0.1}_{-0.2}$
luminosity distance (Mpc)	420^{+150}_{-180}	1000^{+500}_{-500}	440^{+180}_{-190}
sky localization (deg^2)	230	1600	850
other observatories notified	yes	no	yes

Details of the three most significant events. Reported are median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. The sky localization is the area containing 90% of the spatial probability. From LSC et al. (2016)

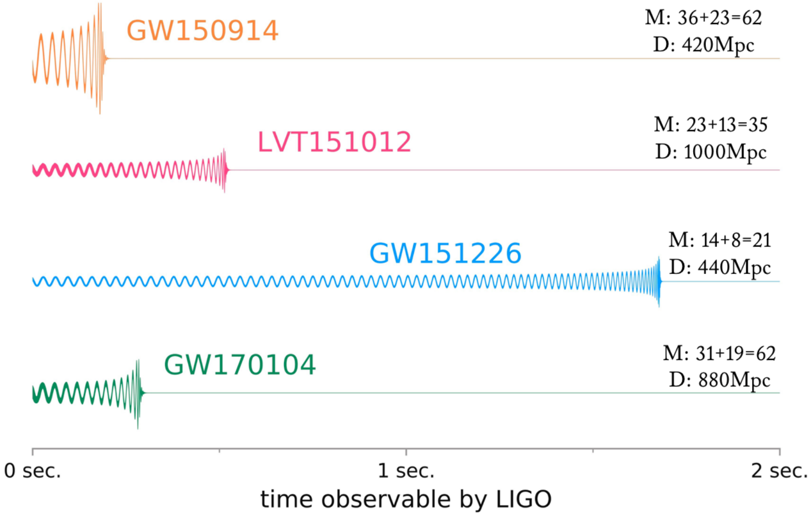
LIGO parameter estimation: spatial and distance



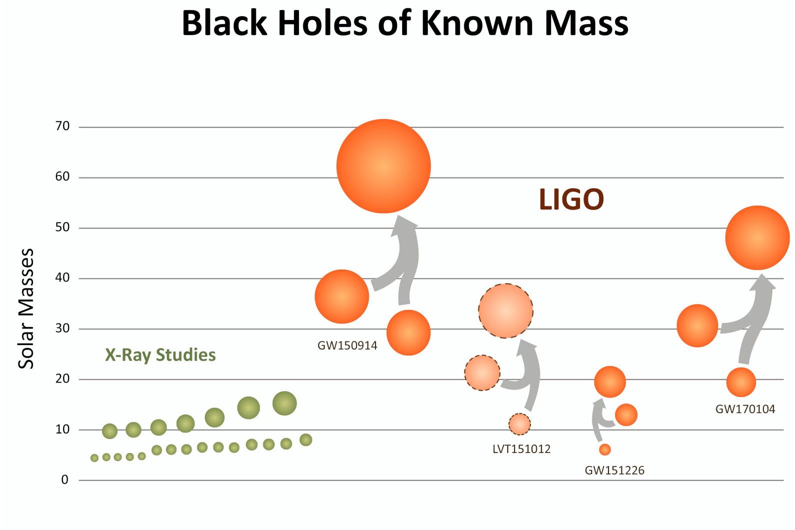
Posterior probability distributions of the sky locations of GW150914, LVT151012 and GW151226 on a Mollweide projection on the left, and of the luminosity distances to the three events on the right. From LSC et al. (2016).

In my mind, these are remarkably poor spatial localizations and remarkably good distance localizations.

LIGO O1 & O2: all the signals

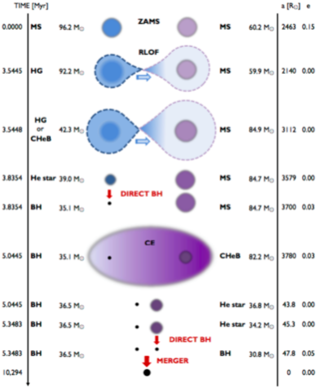


Astrophysics and Cosmology: LIGO black holes



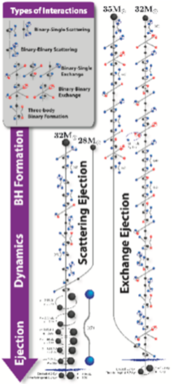
Astrophysical models

Common envelope evolution



Courtesy of Wojciech Gladysz

Globular cluster dynamics

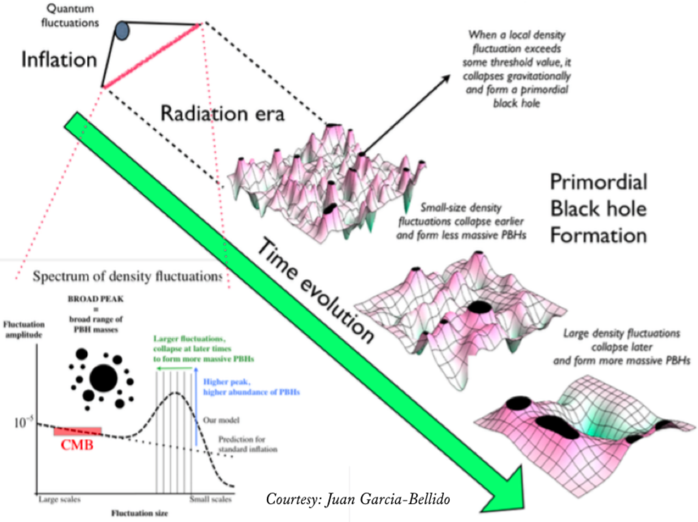


Rodriguez, Haster, Chatterjee et al

Quasar accretion disk dynamics

Courtesy of Zoltan Haiman

Cosmological models



LIGO black holes could be the dark matter, if formed prior to nucleosynthesis

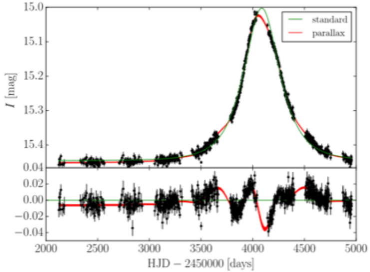


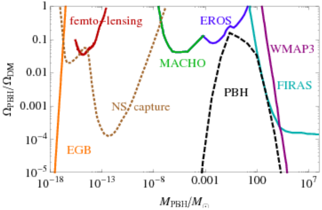
Figure 7. Light curve and standard (green) and parallax (red) microlensing models and their residuals for the event OGLE3-ULENS-PAR-02. The solution shown ($u_0 < 0$) has a 99.8 per cent probability of a dark lens of 8.7 $M_\odot$ lens at 1.8 kpc.

$A = \frac{2+u^2}{u\sqrt{4+u^2}}$ $u = \frac{r}{r_E}$ amplification

$\overline{\Delta t} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$ average $\frac{1}{2}$ crossing

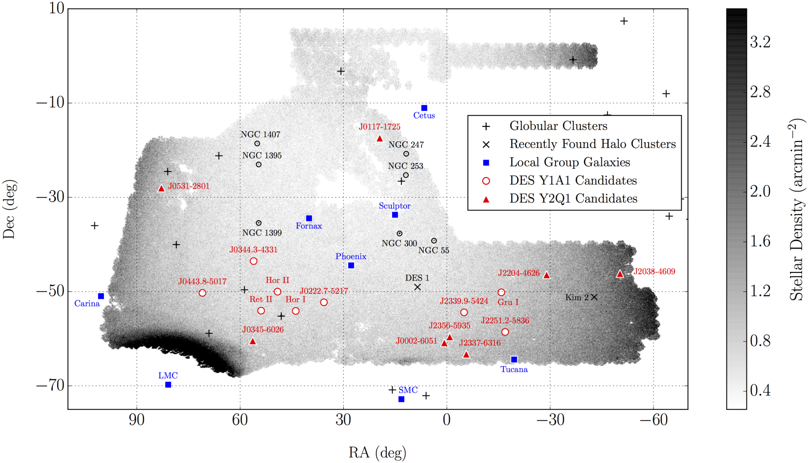
$M_D = 10\ M_\odot \Rightarrow \overline{\Delta t} = 1.23$ years

$M_D = 1\ M_\odot \Rightarrow \overline{\Delta t} = 5$ months



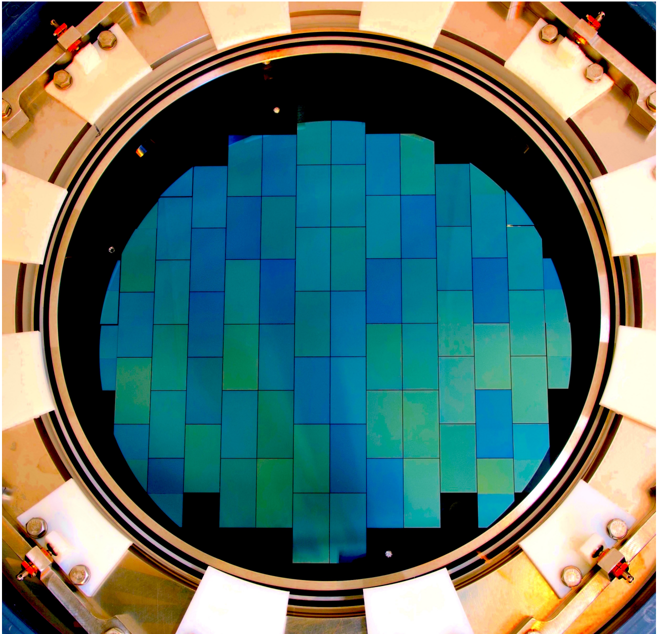
This idea can be tested with gravitational microlensing of background stars. Summer scientists Celeste Keith, Marika McGhee, Mishelle Mironov are pursing PBH in the DES data.

Astrophysics: microlensing on DES stars

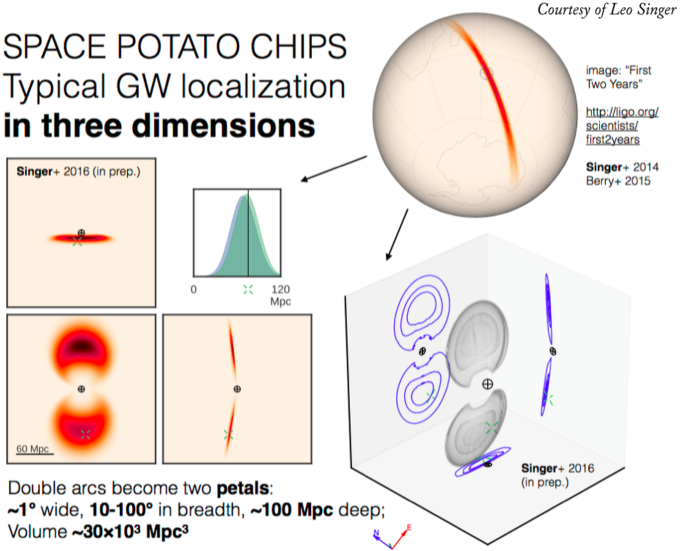


There are plenty of stars to work with.

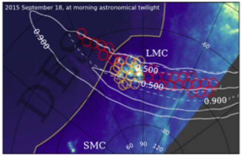
Astrophysics: we use DECam



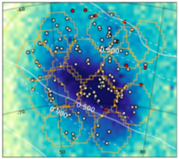
Astrophysics: DECam followup of LIGO sources



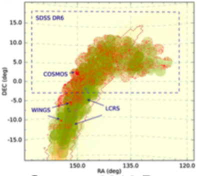
Astrophysics: DECam followup of LIGO sources



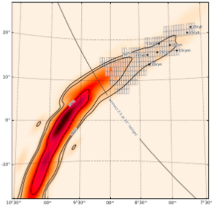
Soares-Santos+ 2016 Deep, wide-field follow-up with DECam to *i*=22.5



Annis+ 2016 DECam search for missing supergiants in LMC

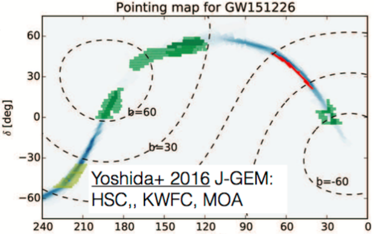


Smartt+ 2016 Pan-STARRS



Kasliwal, Cenko, Singer+ 2016

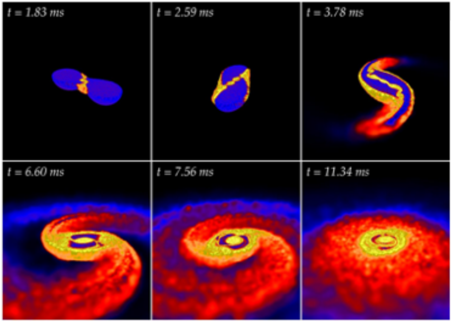
iPTF OT search, Keck spectra <1 hour after discovery, + a serendipitous superluminous supernova

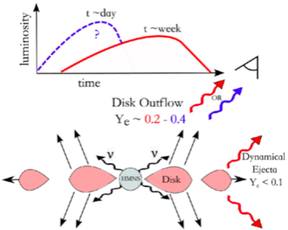


Yoshida+ 2016 J-GEM: HSC,, KWFC, MOA

Our DESgw project is designed to find merging neutron stars, not black hole mergers.

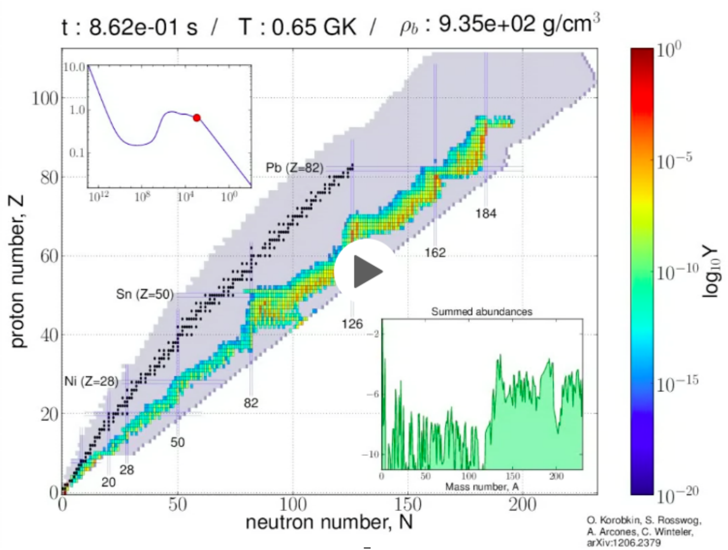
Astrophysics: kilonova





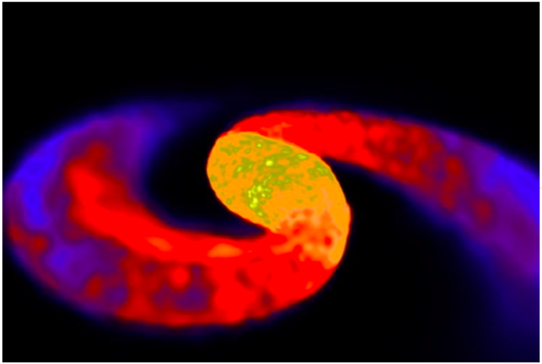
We really are looking for neutron star mergers, which have a rich and fascinating matter physics. They blow up and are visible in the optical via r-process element decay energy.

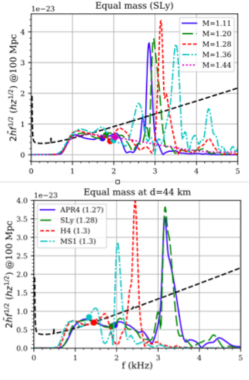
Astrophysics: r-process element creation and fission



O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

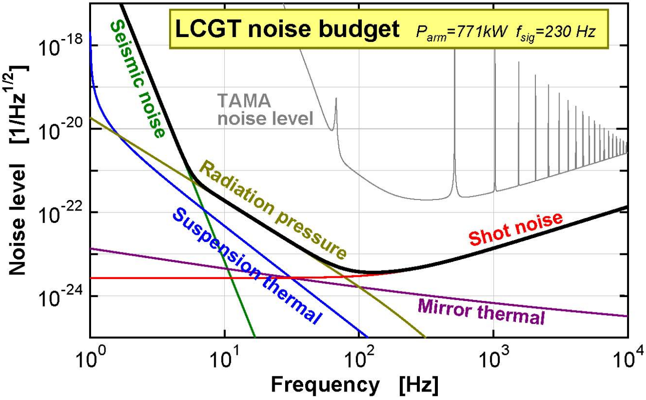
Astrophysics: kilonova in gravity waves





Spectral analysis of gravitational waves from binary neutron star merger remnants, Maione et al 2017. LIGO isn't sensitive enough to do this.

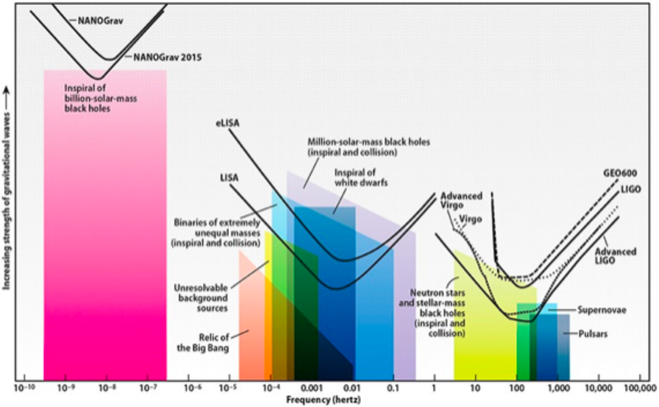
Astrophysics: what limits GW detection?



We're going to need a bigger laser to pursue NS spectral analysis at a rate of 1/year. Or learn about the entanglement properties of squeezed light. In fact, the noise sources tell you what you have to do to work there.

Astrophysics and Cosmology: GW Spectrum

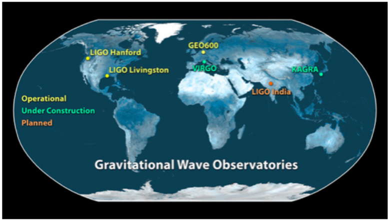
Astronomy: Roen Kelly, after C. Moore, R. Cole, and C. Berry (Institute of Astronomy, Univ. of Cambridge)

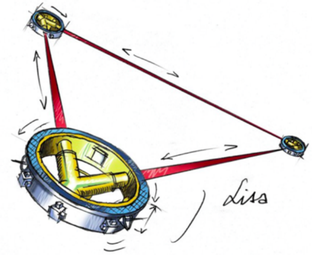


10^6 Hz: Holometer (Fermilab, the fixed target beamline)
10^2 Hz: LIGO
1 Hz: dropped atom interferometry (Fermilab soon, at NuMI)
10^{-3} Hz: lasers in space, LISA.
10^{-9} Hz: clocks in space = pulsar timing networks
10^{-16} Hz: ... no direct detection, instead CMB polarization

Astrophysics and Cosmology: LIGO A+ and LISA

In the next decade there will be ground based laser interferometer network of 5 machines. We plan on using this system to pursue cosmology via redshift-distance relation.

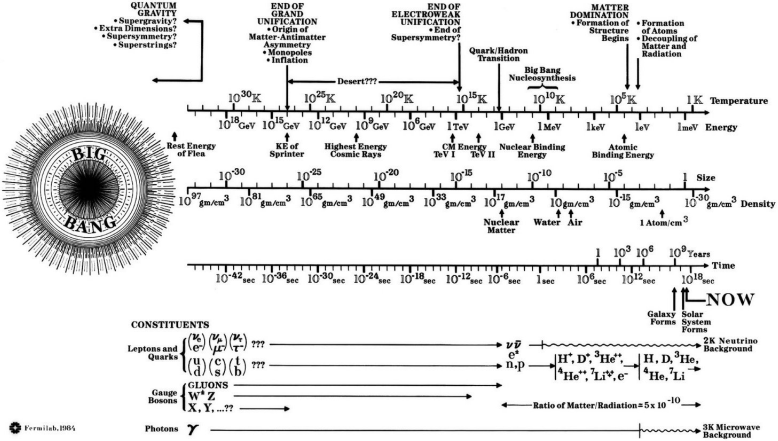




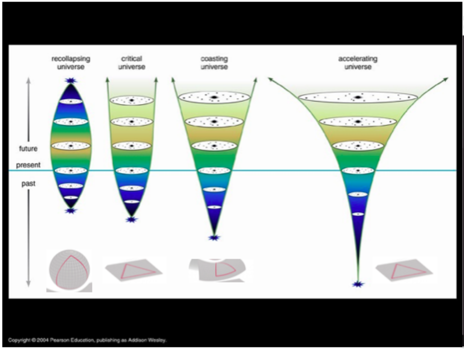
Courtesy: Ira Thorpe, GSFC/NASA

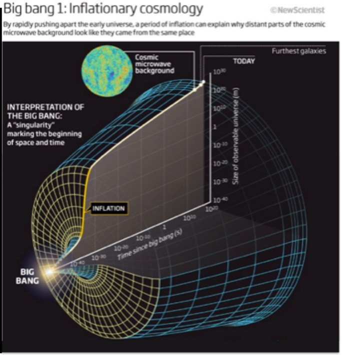
In 15-20 years, the space-borne LISA machine could be flying. LISA could detect gravitational wave signals from the electroweak phase transition.

As the universe cools below 10^{15}K, around 10^{-12} seconds after the big bang, a phase transition from electroweak to broken symmetry occurs, likely in some places before others. LISA machine could detect the sound of the phase transition bubbles in the early universe coalescing.



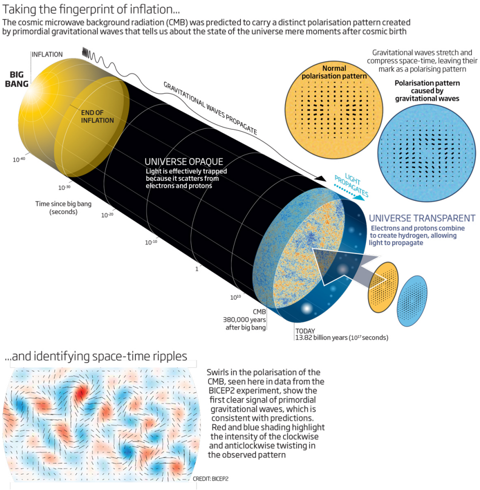
Cosmology: GW on the largest scales





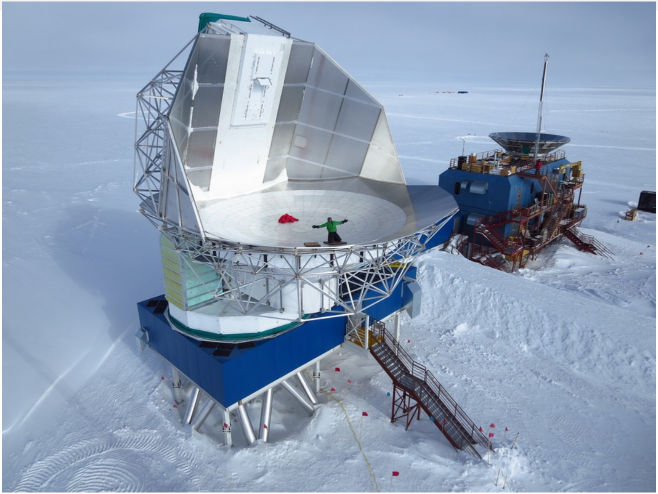
The metric of space in cosmology: $ds^2 = a(t)dr^2 + a(t), r^2 d\Omega$, where we've taken $S_k^2 = 1$ as we've measured the universe to be globally flat. That $a(t)$ is very interesting: there is late time acceleration, the dark energy, and an early time inflation which pushed quantum fluctutions up to cosmological sizes. Early time is 10^{-32} seconds: most of what you think of as the big bang is the reheating as inflation ends.

Cosmology: inflation GW seen in the CMB



The polarization of the CMB is a reflection of the effect of gravitational waves on the dense matter at the time photons became free.

Cosmology: The South Pole Telescope

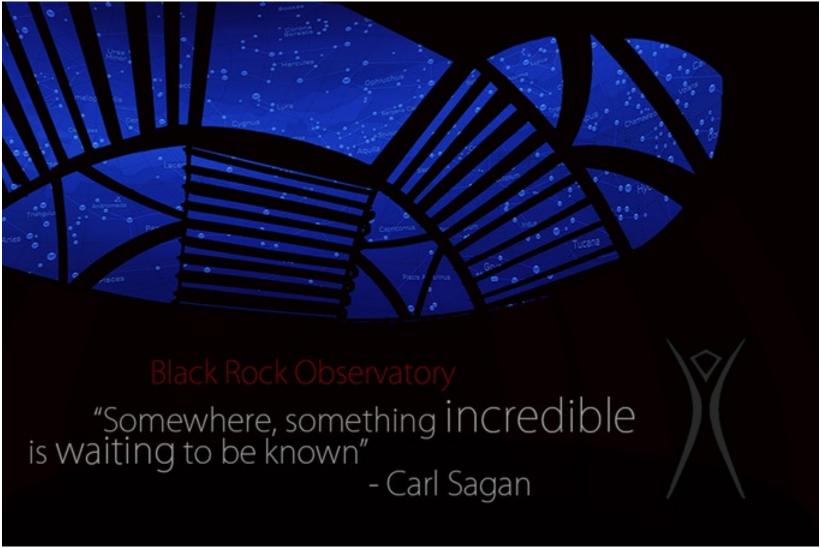


The South Pole Telescope is operating now. In the next decade the next generation of ground based CMB telescopes will be being built at the South Pole.

Summary

- LIGO opened the window of gravitational wave astronomy of black hole mergers
- Black holes are not matter but a feature in the spacetime geometry
- Most of the exotica of black holes are associated with the gravitational time delay near the horizon, and the existence of the horizon
- LIGO measures moving curvature perturbations (gravity waves) using a pair of laser interferometers.
- Gravitational wave astronomy and cosmology is just beginning.

Ending


Black Rock Observatory
"Somewhere, something incredible is waiting to be known"
- Carl Sagan

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