Gravitational Waves from Binary Black Hole Mergers
Gravitational waves and LIGO: short version

Binary black hole system

As detected by LIGO:

GW ripples are a space strain $h$, where $h = \frac{\Delta L}{L}$

Realistic sources: $h \sim 10^{-23}$

$\Rightarrow \Delta L \sim 10^{-19} \text{ m} \quad (\text{Yikes!})$
LIGO observatories: LHO and LLO

2 or more sites provides coincident detection - a crucial feature

R Frey June 24, 2016
Boom!

Hanford, Washington (H1)  Livingston, Louisiana (L1)

monitoring the non-GW environment – UO’s key contribution to first detection
Installing sensors

Terra and Vinny install accelerometers on PSL table
Is it really an astrophysical signal? Coincident environmental noise?

- GW waveform precludes known environmental disturbance.
- Would see a much larger environmental signal on nearby sensors than seen in GW detector.
- Saw nothing.

**Figure 2: Noise coupling example: determining magnetic field coupling for a location at LIGO-Hanford.**

The top panel shows the output of a magnetometer installed in the corner station (see Figure B1) during the injection of a series of single frequency oscillating magnetic fields at 6 Hz intervals (in red) and at a nominally quiet time (in blue). The middle panel shows $h(f)$ during this test (in red) and during the same nominally quiet time (in blue). The heights of the induced peaks in $h(f)$ can be used to determine the magnetic coupling (in m/T) at those frequencies, as shown in the bottom panel. The points in the bottom panel above 80 Hz were determined in a different test with a stronger magnetic field needed to produce discernible peaks in $h(f)$. The green points in the middle panel are an estimate of the contribution to $h(f)$ from the ambient magnetic noise during the nominally quiet time, calculated using the coupling function from the bottom panel. Injection tests also induced strong magnetic fields above 200 Hz. At higher frequencies, coupling was so low that the injected fields did not produce a response in $h(f)$, but were used to set upper limits on the coupling function. This figure only shows data for one (typical) location, but similar injections were repeated at all locations where magnetic coupling might be of concern.
GW150914 publications by LSC/Virgo

- **Discovery paper:** Phys. Rev. Lett. 116, 061102 (2016)
- Rate of BBH mergers: arXiv:1602.03842
- Parameter estimation: arXiv:1602.03840
- Data characterization: arXiv:1602.03844
- Detector status: arXiv:1602.03838
- Compact binary searches: arXiv:1602.03839
- Searches with minimal assumptions: arXiv:1602.03843
- Calibration: arXiv:1602.03845
- Implication for a stochastic GW background: arXiv:1602.03847
- High-energy neutrinos: arXiv:1602.05411
Is it really a merger of black holes?

• The chirp function tells us we have 2 objects each of mass about 30 solar masses ( $30M_\odot$ )

• At merger, they are orbiting each other 75 times per second and their separation is about 350 km… And they are still missing each other!

• They are indeed black holes.
Is General Relativity the correct description?

- Predicts gravitational waves… ✓
- Waveforms from GR fit the data beautifully… ✓

A unique and important test of GR

LIGO

### Main GW150914 parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$36^{+5}<em>{-4} , M</em>{\odot}$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$29^{+4}<em>{-4} , M</em>{\odot}$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$62^{+4}<em>{-4} , M</em>{\odot}$</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410^{+160}_{-180} , \text{Mpc}$</td>
</tr>
<tr>
<td>Source redshift, $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>

- Energy radiated in GWs: $3.0^{+0.5}_{-0.5} \, M_{\odot} c^2$
- Peak GW power: $3.6^{+0.5}_{-0.4} \times 10^{56} \, \text{erg/s}$
GW150914 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EOBNR</th>
<th>IMRPhenom</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector-frame total mass $M/M_\odot$</td>
<td>$70.3^{+5.3}_{-4.8}$</td>
<td>$70.7^{+3.8}_{-4.0}$</td>
<td>$70.5^{+4.6}_{-4.5}$</td>
</tr>
<tr>
<td>Detector-frame chirp mass $\mathcal{M}/M_\odot$</td>
<td>$30.2^{+2.5}_{-1.9}$</td>
<td>$30.5^{+1.7}_{-1.8}$</td>
<td>$30.3^{+2.1}_{-1.9}$</td>
</tr>
<tr>
<td>Detector-frame primary mass $m_1/M_\odot$</td>
<td>$39.4^{+5.5}_{-4.9}$</td>
<td>$38.3^{+5.5}_{-3.5}$</td>
<td>$38.8^{+5.6}_{-4.1}$</td>
</tr>
<tr>
<td>Detector-frame secondary mass $m_2/M_\odot$</td>
<td>$30.9^{+4.8}_{-4.4}$</td>
<td>$32.2^{+3.6}_{-5.0}$</td>
<td>$31.6^{+4.2}_{-4.9}$</td>
</tr>
<tr>
<td>Detector-frame final mass $M_f/M_\odot$</td>
<td>$67.1^{+4.6}_{-4.4}$</td>
<td>$67.4^{+3.4}_{-4.0}$</td>
<td>$67.3^{+4.1}_{-4.0}$</td>
</tr>
<tr>
<td>Source-frame total mass $M_{source}/M_\odot$</td>
<td>$65.0^{+5.0}_{-4.4}$</td>
<td>$64.6^{+4.1}_{-3.5}$</td>
<td>$64.8^{+4.6}_{-3.9}$</td>
</tr>
<tr>
<td>Source-frame chirp mass $\mathcal{M}<em>{source}/M</em>\odot$</td>
<td>$27.9^{+2.3}_{-1.8}$</td>
<td>$27.9^{+1.8}_{-1.6}$</td>
<td>$27.9^{+2.1}_{-1.7}$</td>
</tr>
<tr>
<td>Source-frame primary mass $m_1_{source}/M_\odot$</td>
<td>$36.3^{+5.3}_{-4.5}$</td>
<td>$35.1^{+5.2}_{-3.3}$</td>
<td>$35.7^{+5.4}_{-3.8}$</td>
</tr>
<tr>
<td>Source-frame secondary mass $m_2_{source}/M_\odot$</td>
<td>$28.6^{+4.4}_{-4.2}$</td>
<td>$29.5^{+3.3}_{-4.5}$</td>
<td>$29.1^{+3.8}_{-4.4}$</td>
</tr>
<tr>
<td>Source-frame final mass $M_{source}/M_\odot$</td>
<td>$62.0^{+4.4}_{-4.0}$</td>
<td>$61.6^{+3.7}_{-3.1}$</td>
<td>$61.8^{+4.2}_{-3.5}$</td>
</tr>
<tr>
<td>Mass ratio $q$</td>
<td>$0.79^{+0.18}_{-0.19}$</td>
<td>$0.84^{+0.14}_{-0.21}$</td>
<td>$0.82^{+0.16}_{-0.21}$</td>
</tr>
<tr>
<td>Effective inspiral spin parameter $\chi_{\text{eff}}$</td>
<td>$-0.09^{+0.19}_{-0.17}$</td>
<td>$-0.03^{+0.14}_{-0.15}$</td>
<td>$-0.06^{+0.17}_{-0.18}$</td>
</tr>
<tr>
<td>Dimensionless primary spin magnitude $a_1$</td>
<td>$0.32^{+0.45}_{-0.28}$</td>
<td>$0.31^{+0.51}_{-0.27}$</td>
<td>$0.31^{+0.48}_{-0.28}$</td>
</tr>
<tr>
<td>Dimensionless secondary spin magnitude $a_2$</td>
<td>$0.57^{+0.40}_{-0.51}$</td>
<td>$0.39^{+0.50}_{-0.34}$</td>
<td>$0.46^{+0.48}_{-0.42}$</td>
</tr>
<tr>
<td>Final spin $a_f$</td>
<td>$0.67^{+0.06}_{-0.08}$</td>
<td>$0.67^{+0.05}_{-0.05}$</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance $D_L$/Mpc</td>
<td>$390^{+170}_{-180}$</td>
<td>$440^{+140}_{-180}$</td>
<td>$410^{+160}_{-180}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.083^{+0.033}_{-0.036}$</td>
<td>$0.093^{+0.028}_{-0.036}$</td>
<td>$0.088^{+0.031}_{-0.038}$</td>
</tr>
<tr>
<td>Upper bound on primary spin magnitude $a_1$</td>
<td>0.65</td>
<td>0.71</td>
<td>0.69 ± 0.05</td>
</tr>
<tr>
<td>Upper bound on secondary spin magnitude $a_2$</td>
<td>0.93</td>
<td>0.81</td>
<td>0.88 ± 0.10</td>
</tr>
<tr>
<td>Lower bound on mass ratio $q$</td>
<td>0.64</td>
<td>0.67</td>
<td>0.65 ± 0.03</td>
</tr>
<tr>
<td>Log Bayes factor $\ln B_{s/n}$</td>
<td>$288.7 ± 0.2$</td>
<td>$290.1 ± 0.2$</td>
<td>—</td>
</tr>
</tbody>
</table>
• GW150914 was the first observation of gravitational waves
• GW150914 was the first direct observation of a black hole
• Prior to GW150914, the astrophysical consensus was that there should not be \( \sim 30 M_\odot \) black holes – more on this later
Simulated (ideal) binary black hole system, $D \sim 100$ Mpc, $30 \, M_\odot + 30 \, M_\odot$
Robert Schofield leaves the site with one last test undone. The test would likely have taken the detector out of operation.

GW150914 arrives 18 minutes later.

Robert Schofield, UO Research Professor
GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott et al.*

(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$, and the final black hole mass is $20.8^{+6.4}_{-1.7} M_\odot$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of $440^{+180}_{-190}$ Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.
### Source parameters for GW151226

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$14.2^{+8.3}<em>{-3.7}$ M$</em>\odot$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$7.5^{+2.3}<em>{-2.3}$ M$</em>\odot$</td>
</tr>
<tr>
<td>Chirp mass</td>
<td>$8.9^{+0.3}<em>{-0.3}$ M$</em>\odot$</td>
</tr>
<tr>
<td>Total black hole mass</td>
<td>$21.8^{+5.9}<em>{-1.7}$ M$</em>\odot$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$20.8^{+6.1}<em>{-1.7}$ M$</em>\odot$</td>
</tr>
<tr>
<td>Radiated gravitational-wave energy</td>
<td>$1.0^{+0.1}<em>{-0.2}$ M$</em>\odot$c$^2$</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.74^{+0.06}_{-0.06}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$440^{+180}_{-190}$ Mpc</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>
• About 30 cycles of GW waveform observed
• Precision test of General Relativity
Actually, three BBHs Observed in First Run!

GW150914
LVT151012
GW151226

FIG. 3. Search results from the two analyses. The upper left hand plot shows the PyCBC result for signals with chirp mass $\sim 10^8 M_\odot$. The upper right hand plot shows the GstLAL result. In both analyses, GW150914 is identified as the most significant event remaining in the data. GW151226 is more significant than the remaining background in the PyCBC analysis, with a significance greater than 5.

A detailed discussion of GW150914 is given in [16, 38, 43]. GW150914 was observed on September 14, 2015 at 09:50:45 UTC with a matched filter SNR of 23.7. Actually, three BBHs Observed in First Run.

GW151226

GW150914

GW150914

GW151226

GW150914

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GW151226

GW150914
Some properties of the 3 BBH events

FIG. 4. Posterior probability densities of the masses, spins and distance to the three events GW150914, LVT151012 and GW151226. For the two dimensional distributions, the contours show 50% and 90% credible regions.

Top left: component masses $m_{\text{source}}^1$ and $m_{\text{source}}^2$ for the three events. We use the convention that $m_{\text{source}}^1 > m_{\text{source}}^2$, which produces the sharp cut in the two-dimensional distribution. For GW151226 and LVT151012, the contours follow lines of constant chirp mass ($M_{\text{source}} = 8.9 + 0.3 M_{\odot}$ and $M_{\text{source}} = 15.1 + 1.4 M_{\odot}$ respectively). In all three cases, both masses are consistent with being black holes.

Top right: The mass and dimensionless spin magnitude of the final black holes.

Bottom left: The effective spin and mass ratios of the binary components.

Bottom right: The luminosity distance to the three events.

a greater impact upon the inspiral. We find that smaller spins are favoured, and place 90% credible bounds on the primary spin $a_1 \leq 0.7$ for GW150914, $a_1 \leq 0.7$ for LVT151012, and $a_1 \leq 0.8$ for GW151226. In the case of GW151226, we infer that at least one of the components has a spin of $0.2$ at the 99% credible level.

While the individual component spins are poorly constrained, there are combinations that can be better inferred. The effective spin $c_{\text{eff}}$, as defined in Equation 6, is a mass-weighted combination of the spins parallel to the orbital angular momentum [71–73]. It is $+1$ when both the spins are maximal and parallel to the angular momentum, $-1$ when both spins are maximal and antiparallel to the angular momentum, and 0 when there is no net mass-weighted aligned spin. Systems with positive $c_{\text{eff}}$ complete more cycles when inspiralling from a given orbital separation than those with negative $c_{\text{eff}}$ [70, 110]. While $c_{\text{eff}}$ has a measurable effect on the inspiral, this is degenerate with that of the mass ratio as illustrated for the lower mass inspiral-dominated signals in Fig. 4.

Observations for all three events are consistent with small values of the effective spin: $|c_{\text{eff}}| \leq 0.17, 0.28$ and $0.35$ at 90% probability for GW150914, LVT151012 and GW151226 respectively. This indicates that large parallel spins aligned or antialigned with the orbital angular momentum are disfavored. It may be possible to place tighter constraints on each component's spin by using waveforms that include the full effects of precession [39]. This will be investigated in future analyses.

All three events have final black holes with spins of $\approx 0.7$, as expected for mergers of similar-mass black holes [111, 112]. The final spin is dominated by the orbital angular momentum of the binary at merger. Consequently, it is more precisely constrained than the component spins and is broadly similar across the three events. The masses and spins of the final black holes are plotted in Fig. 4.
~30 $M_\odot$ BHs ??

- Implies low metallicity and weak winds; Pop III stars?
- Rate ~consistent with isolated binary formation; may require dynamical formation

$LIGO$


Weak wind

Strong wind

Isolated binaries

Merger Rate Density [$yr^{-1} Gpc^{-3}$]

$0.12Z_\odot$  $0.25Z_\odot$  $0.5Z_\odot$  $0.75Z_\odot$  $Z_\odot$  $1.5Z_\odot$

$t = 13.6$ Gy

$1.2$ Gy

$1.5$ Gy

$10^{-1}$

$10^0$  $10^1$  $10^2$

$10^{-1}$

$10^0$  $10^1$  $10^2$

$10^{-1}$

$10^0$  $10^1$  $10^2$

$10^{-1}$

$10^0$  $10^1$  $10^2$

$10^{-1}$

$10^0$  $10^1$  $10^2$
Sky location of the 3 events
and as seen from earth
ABSTRACT

With an instantaneous view of 70% of the sky, the Fermi Gamma-ray Burst Monitor (GBM) is an excellent partner in the search for electromagnetic counterparts to gravitational wave (GW) events. GBM observations at the time of the Laser Interferometer Gravitational-wave Observatory (LIGO) event GW150914 reveal the presence of a weak transient source above 50 keV, 0.4 s after the GW event was detected, with a false alarm probability of 0.0022. This weak transient lasting 1 s does not appear connected with other previously known astrophysical, solar, terrestrial, or magnetospheric activity. Its localization is ill-constrained but consistent with the direction of GW150914. The duration and spectrum of the transient event suggest it is a weak short Gamma-Ray Burst arriving at a large angle to the direction in which Fermi was pointing, where the GBM
Can we expect more LIGO BBH events?

- Short Answer: “Yes”
- Longer Answer:
  - The ~3 months of run O1 yielded 3 BBH events.
  - For O1, LIGO was at ~30% of its design sensitivity
  - Expect improved sensitivity for O2, O3, … until 100% reached 2019-ish
    - O2 scheduled to start late summer 2016
  - At design: 1 event/month $\rightarrow$ 1 event/day
# Compact binary coalescence: predicted rates ~2010

For O1, sensitivity 3x lower. Expectation <1 NS-NS event

---

TABLE V: Detection rates for compact binary coalescence sources.

<table>
<thead>
<tr>
<th>IFO</th>
<th>Source$^a$</th>
<th>$\dot{N}_{\text{low}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{re}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{high}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{max}}$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>NS-NS</td>
<td>$2 \times 10^{-4}$</td>
<td>0.02</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Initial</td>
<td>NS-BH</td>
<td>$7 \times 10^{-5}$</td>
<td>0.004</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>BH-BH</td>
<td>$2 \times 10^{-4}$</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>IMRI into IMBH</td>
<td></td>
<td></td>
<td>$&lt; 0.001$ b</td>
<td>0.01 c</td>
</tr>
<tr>
<td>Initial</td>
<td>IMBH-IMBH</td>
<td></td>
<td></td>
<td>$10^{-4}$ d</td>
<td>$10^{-3}$ e</td>
</tr>
<tr>
<td>Advanced</td>
<td>NS-NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
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<tr>
<td>Advanced</td>
<td>NS-BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
<td></td>
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<tr>
<td>Advanced</td>
<td>BH-BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>IMRI into IMBH</td>
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<td></td>
<td>$10^b$</td>
<td>$300^c$</td>
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<tr>
<td>Advanced</td>
<td>IMBH-IMBH</td>
<td></td>
<td></td>
<td>$0.1^d$</td>
<td>$1^e$</td>
</tr>
</tbody>
</table>
Our expectations on September 12, 2015

- Advanced LIGO had just turned on with sensitivity about 30% of the eventual (2019-ish) goal.

- Expectation was that we would have about a 10%-ish chance for observing a faint binary neutron-star merger.

- Speculation was rife for other kinds of signals, such as supernovae, black-hole mergers, gamma-ray bursts, … But all very uncertain.

- Expect other types of astrophysical sources!
The 2\textsuperscript{nd} generation GW detector network

- **Advanced LIGO, 2015**
- **Virgo, 2016**
- **GEO, 2014**
- **Kagra, ~2019**
- **LIGO-India, ~2022**

3 or more detectors: localization from ~100 square degrees to ~10 sq degrees
take home…

• Gravitational Waves discovered.
  ▪ UO rocks!

• General Relativity (still) looks good.

• A lot of science from a few events

• The (really) exciting part:
  A new window on the Universe…
  The fun is just beginning!
A few extra slides with some math…
Gravitational Waves (GWs) in General Relativity (GR)

In special relativity:

\[ ds^2 = (c\, dt)^2 - (dx^2 + dy^2 + dz^2) = \sum \eta_{\mu\nu} dx_\mu dx_\nu \]

Einstein, 1905

\[ \eta_{\mu\nu} = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & 0 & -1
\end{pmatrix} \]

GR:

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \quad G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \]

Einstein, 1915

\[ \eta_{\mu\nu} \rightarrow g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

\[ \left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = -16\pi T_{\mu\nu} \]

Einstein, 1916
Black holes? The inspiral waveform (lowest order)

- The phase evolution implies $\mathcal{M} \approx 30 M_\odot$
- $\Rightarrow M_{\text{tot}} \geq 70 M_\odot$
- at merger, orbit freq is $\sim 75$ Hz. Separation is $\sim 350$ km $\sim 3R_s$
- $R_s = 2GM/c^2$

\[
h_+ = h_o \frac{1 + \cos^2 \iota}{2} \cos 2\Phi(t)
\]
\[
h_\times = -h_o \cos \iota \sin 2\Phi(t)
\]

\[
\Phi(t) = \Phi_c - \left[ \frac{t_c - t}{5(1 + z)\mathcal{M}} \right]^{5/8}
\]

\[
\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}
\]

\[
h_o = \frac{(1 + z)\mathcal{M}}{D} \left[ 8\pi f(1 + z)\mathcal{M} \right]^{2/3}
\]