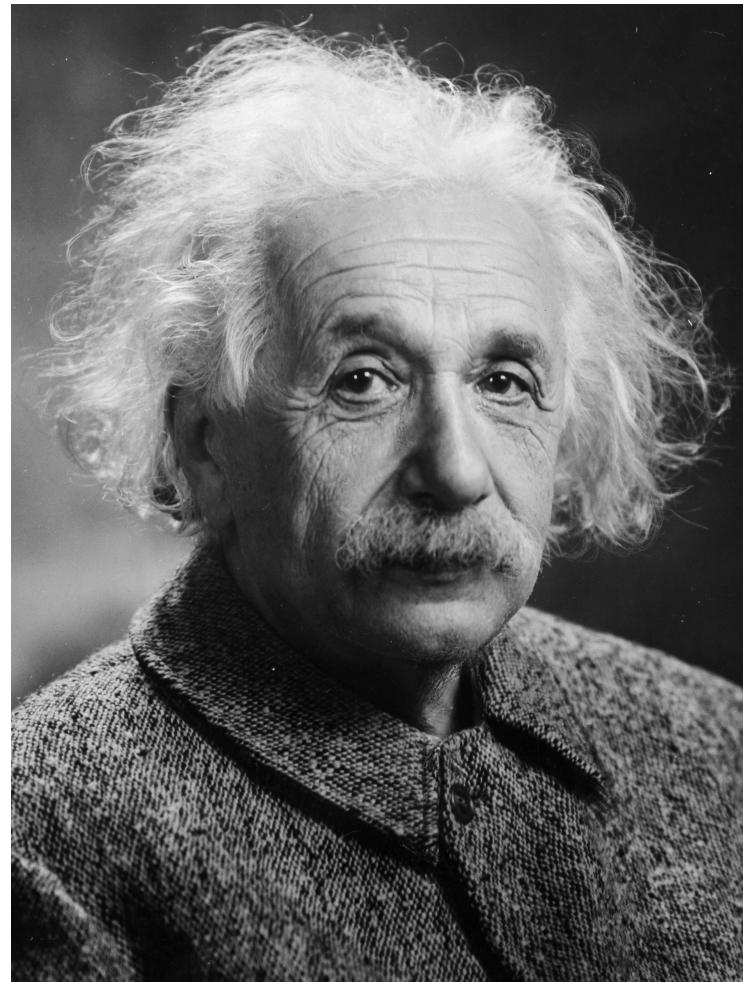


Gravitational Waves

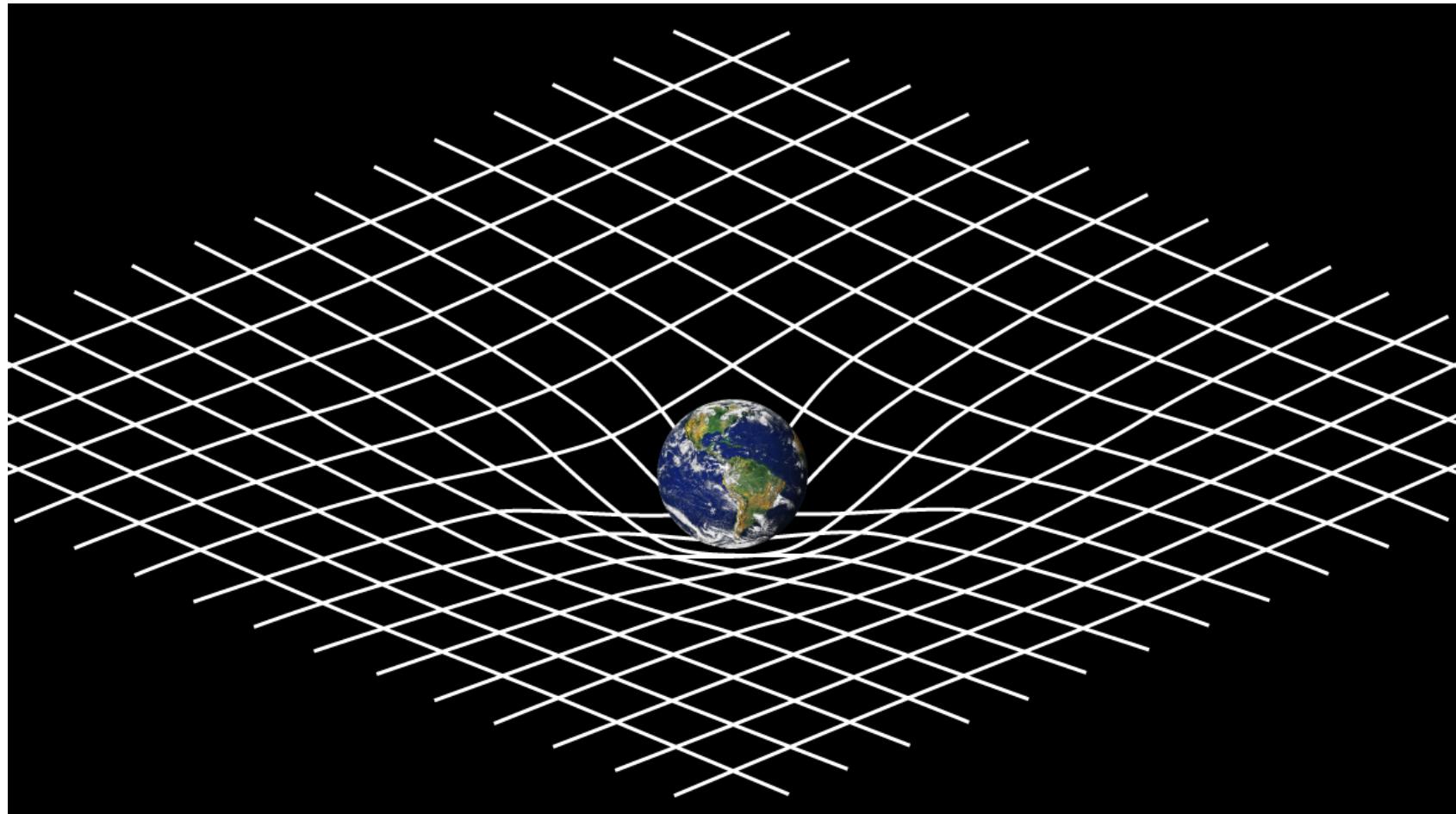
Jim Barrett

General Relativity

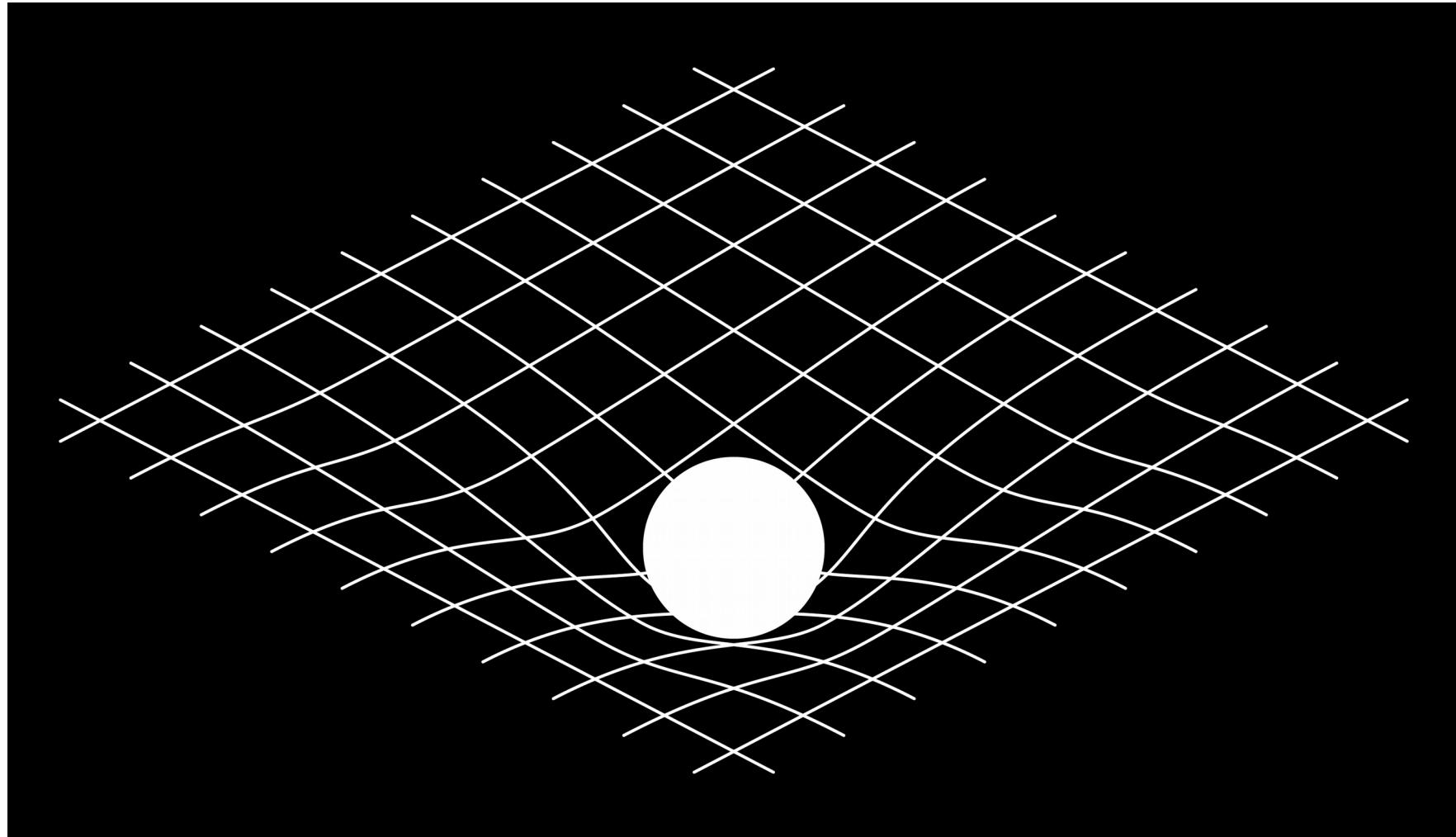
- Einstein published his papers on General Relativity in 1916
- Treats gravity as a geometric phenomenon
- I'll go/have gone into a bit more detail in my relativity lecture



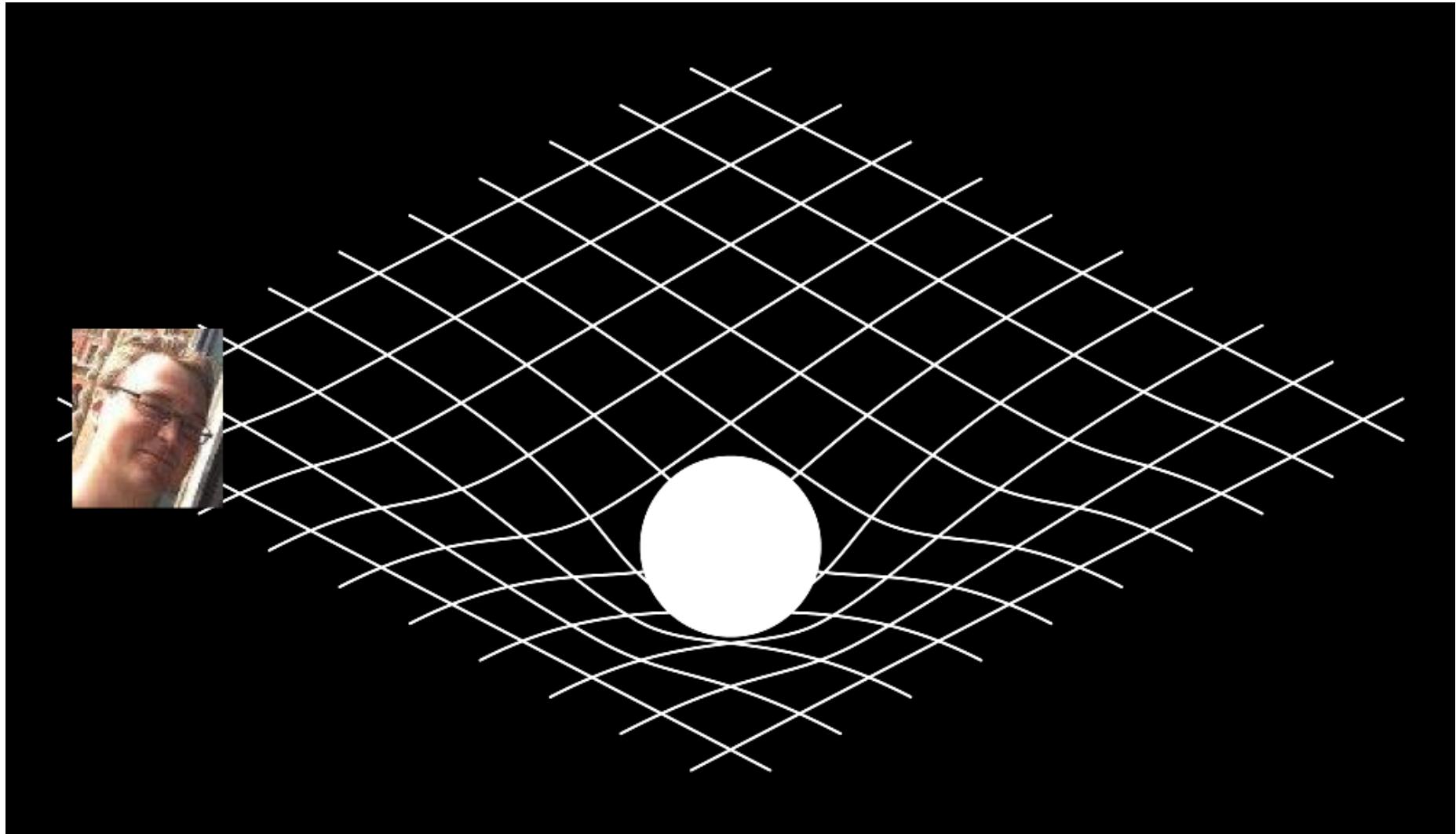
Spacetime Curvature



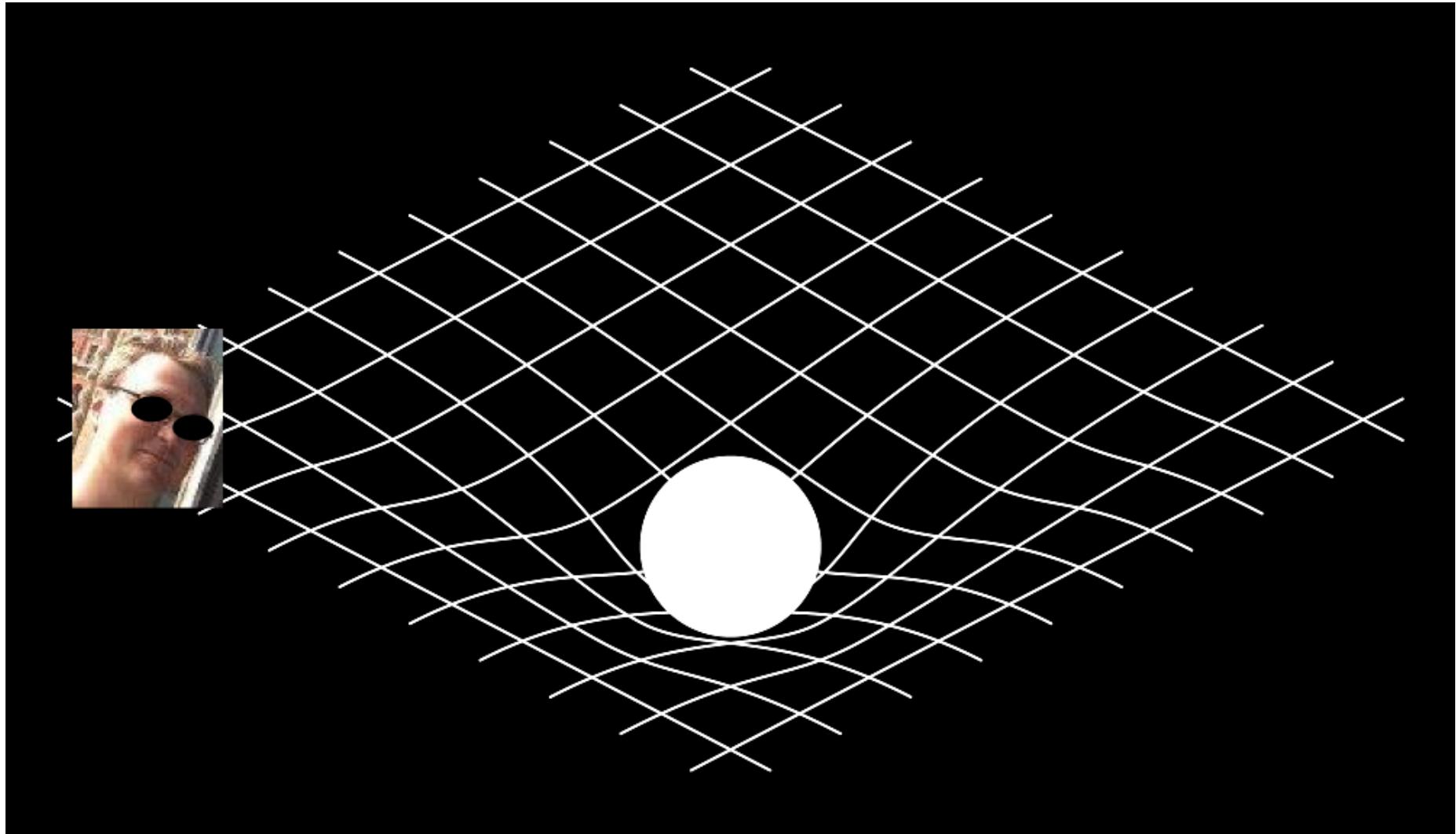
A Thought Experiment



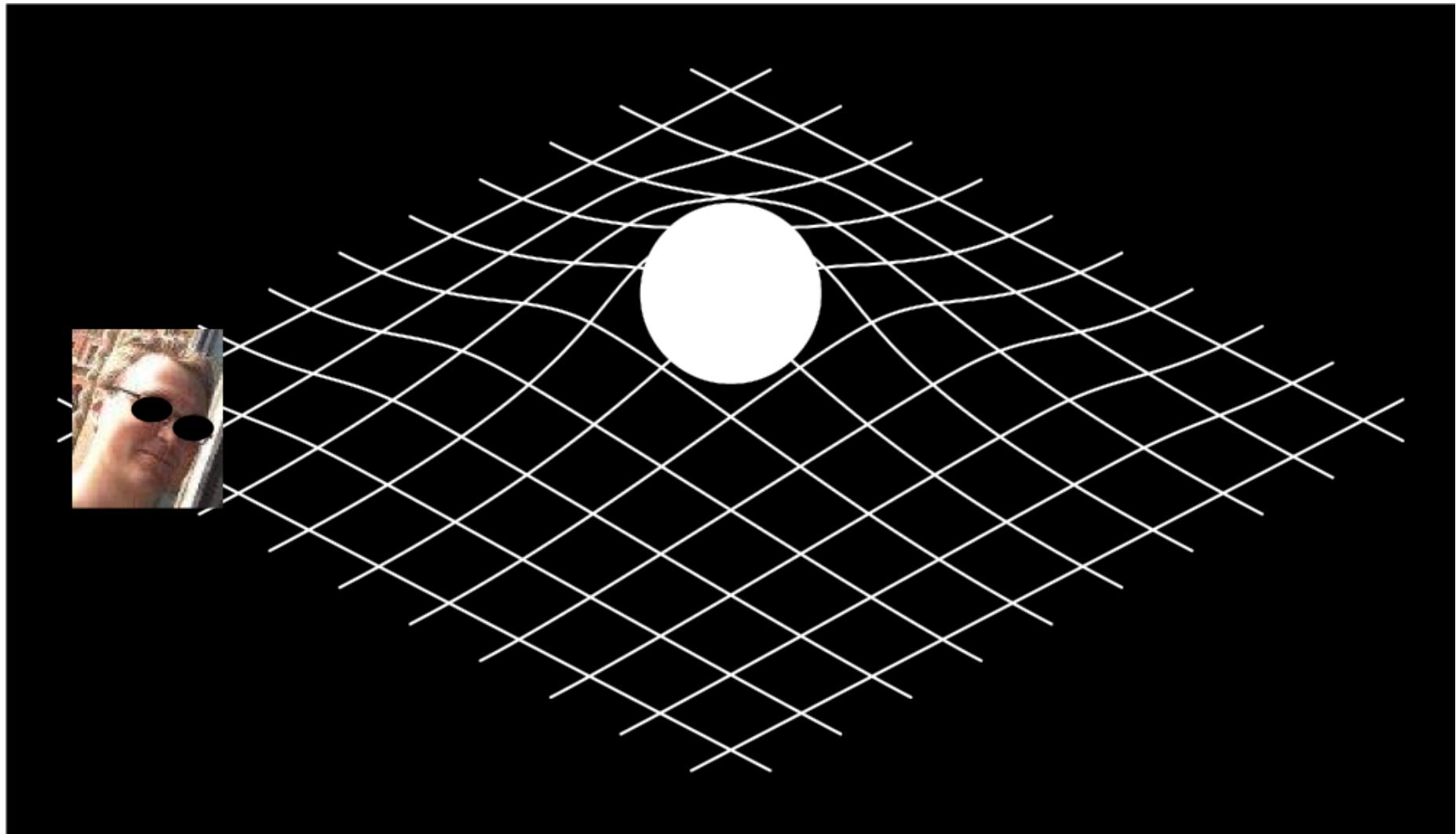
A Thought Experiment



A Thought Experiment



A Thought Experiment



A Thought Experiment

- I'm feeling a gravitational pull in a different direction
- I didn't see the ball move (electromagnetically), but I know it's moved
- The *information* that the ball moved had to reach me somehow...
- How did that information travel to me?

A Thought Experiment

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Gravitational Waves

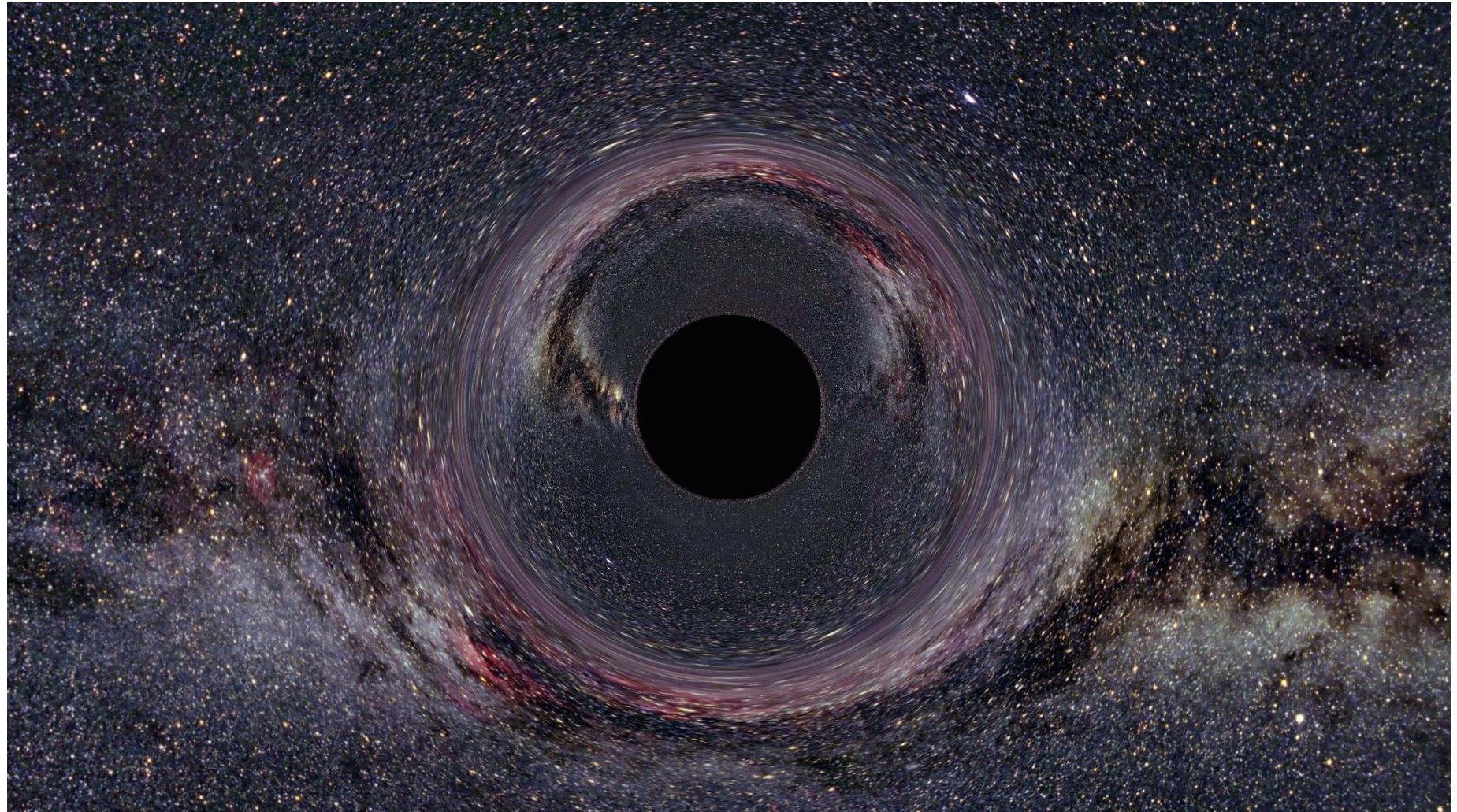
Gravitational Waves

- Come from *changing* Gravitational fields
- Propagate at the speed of light
- Incredibly tiny!
- Energy emitted in gravitational waves from the orbit of the sun around the earth is around 200W
- This is about the same as a human walking briskly...
- We need much more extreme gravitational events

Black Holes

- When sufficiently massive stars die, they leave behind incredibly dense region of space time
- These regions are so dense, that even light can't escape their gravity
- These regions are called Black Holes
- A typical black hole might be around 10 times heavier than the sun, whilst only being a few 10s of kilometers across.

Black Holes



Question

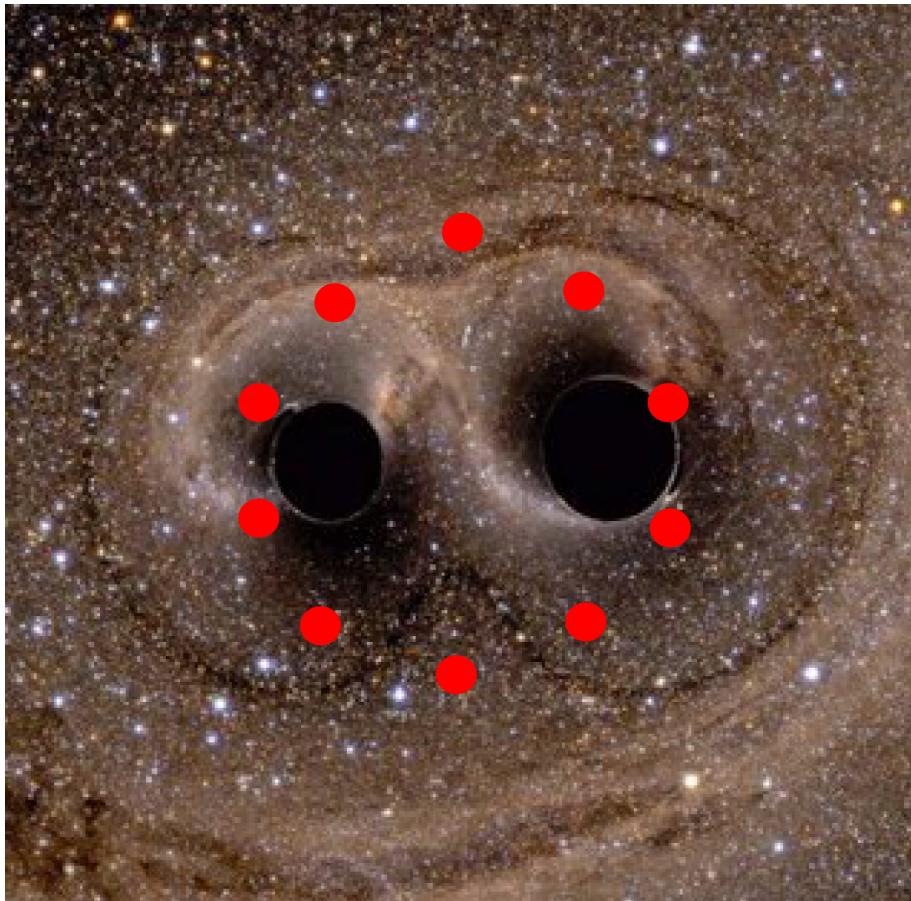
What's more gravitationally extreme than a black hole?

Question

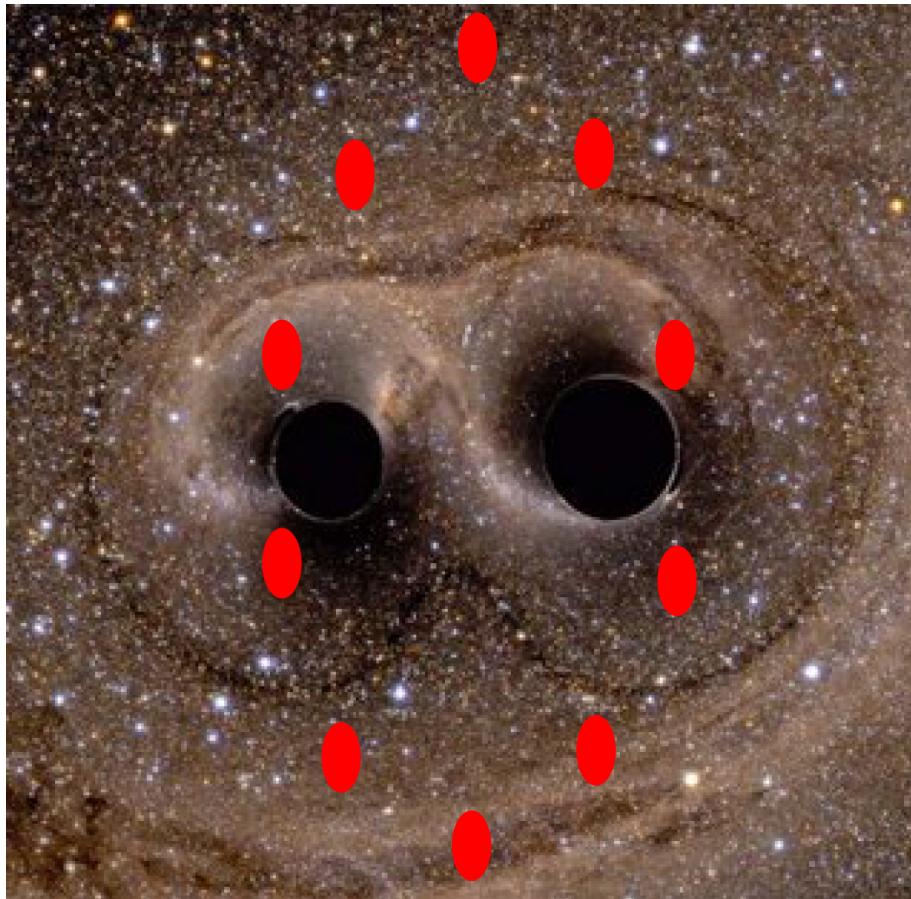
Two Black Holes!



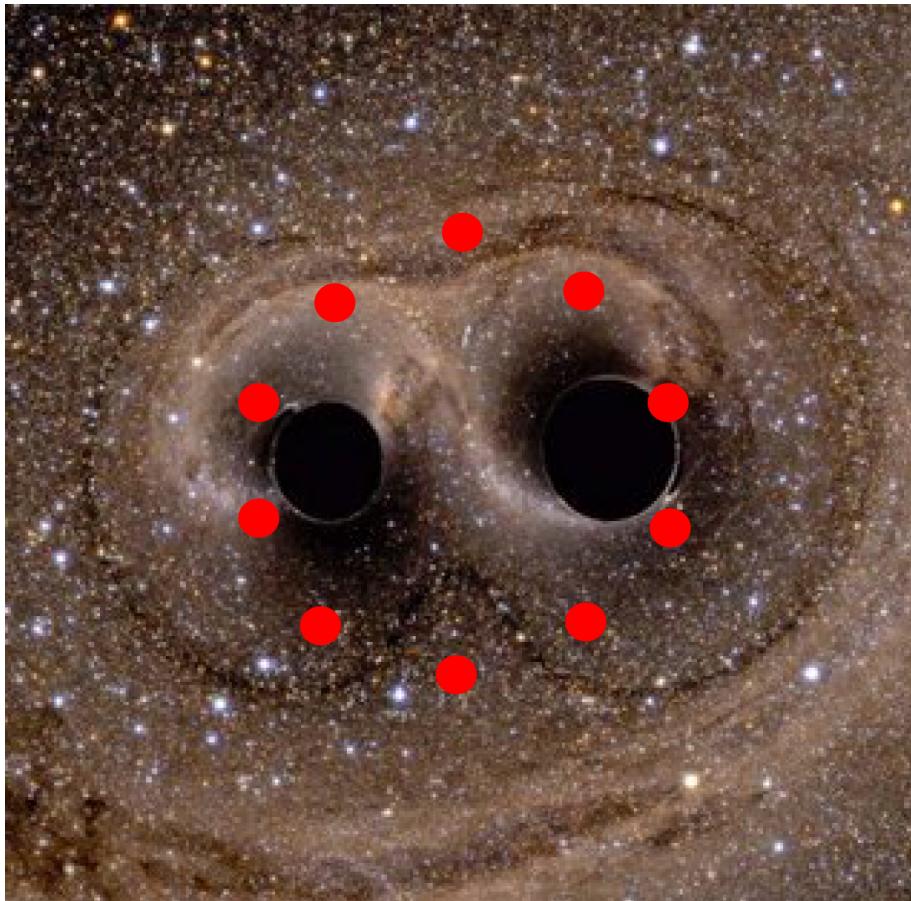
What do Gravitational Waves Feel Like?



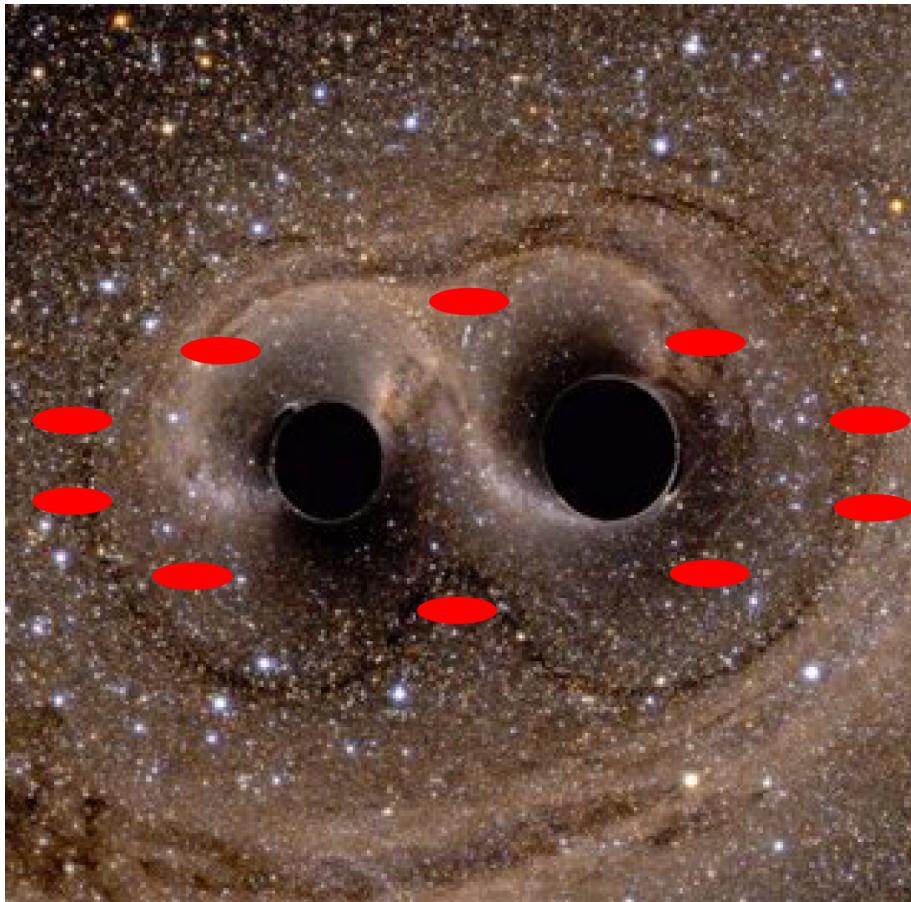
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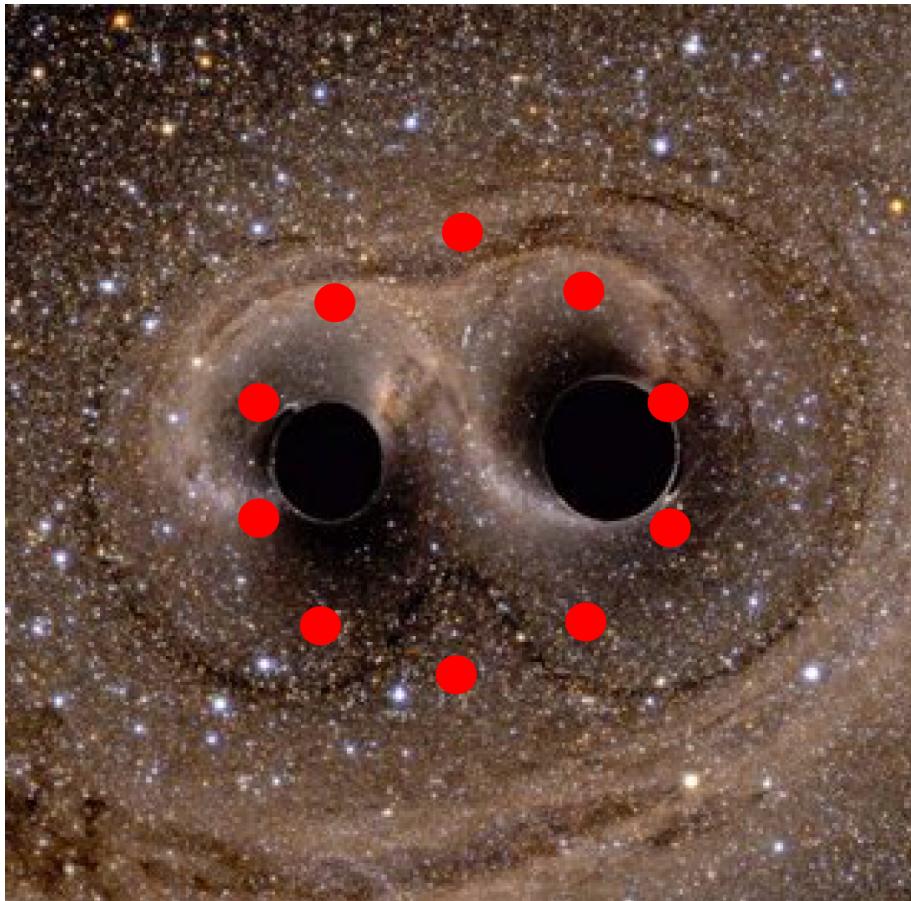
What do Gravitational Waves Feel Like?



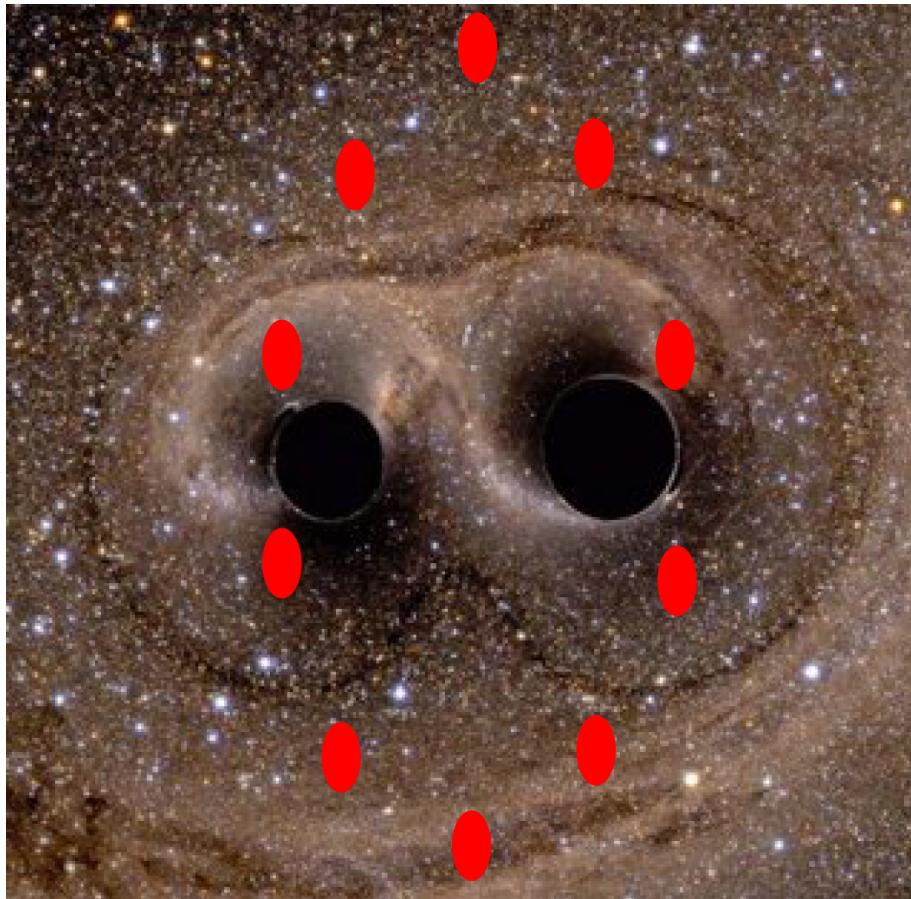
What do Gravitational Waves Feel Like?



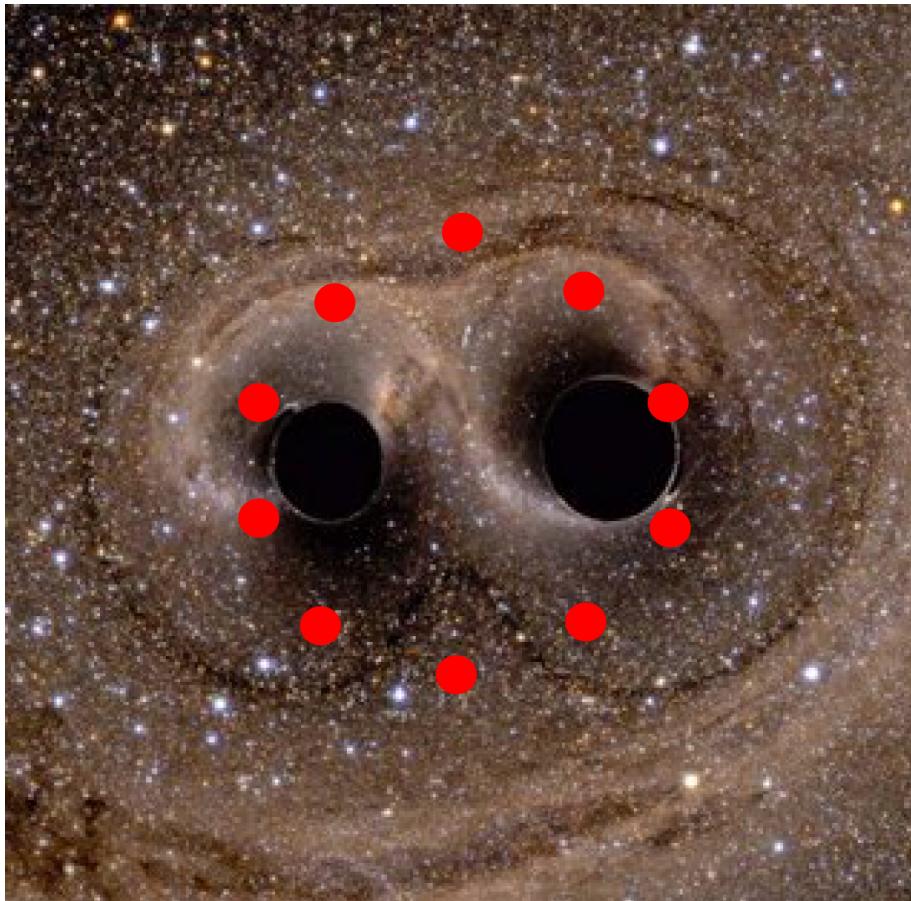
What do Gravitational Waves Feel Like?



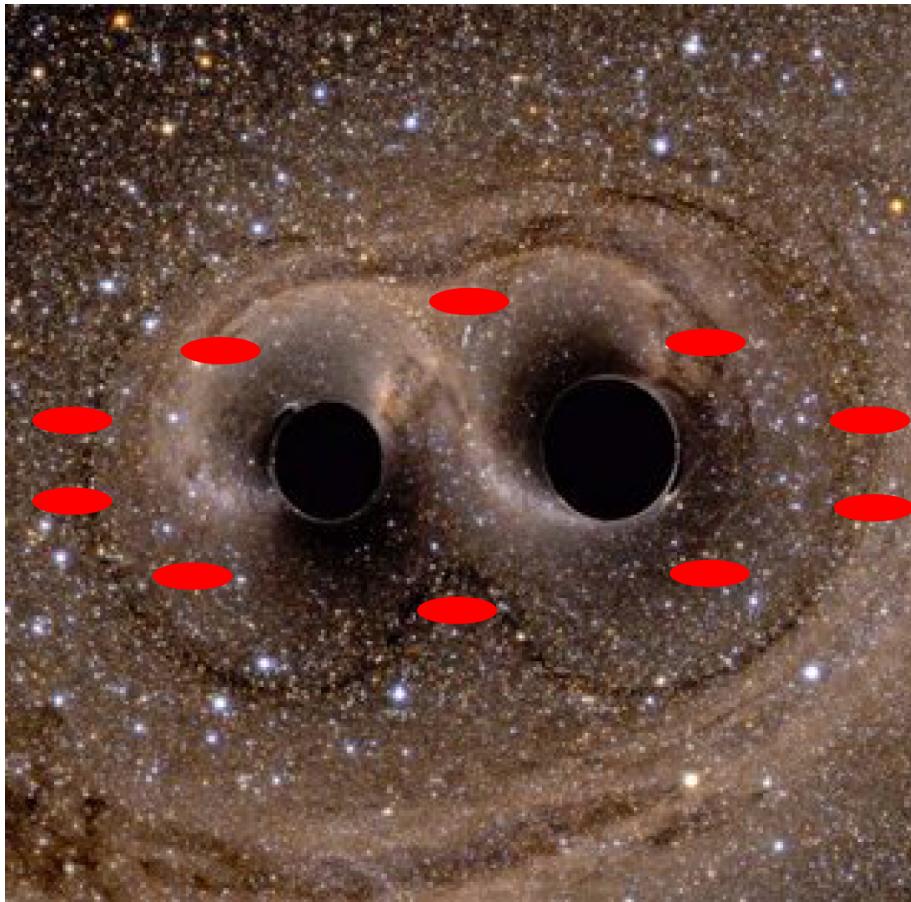
What do Gravitational Waves Feel Like?



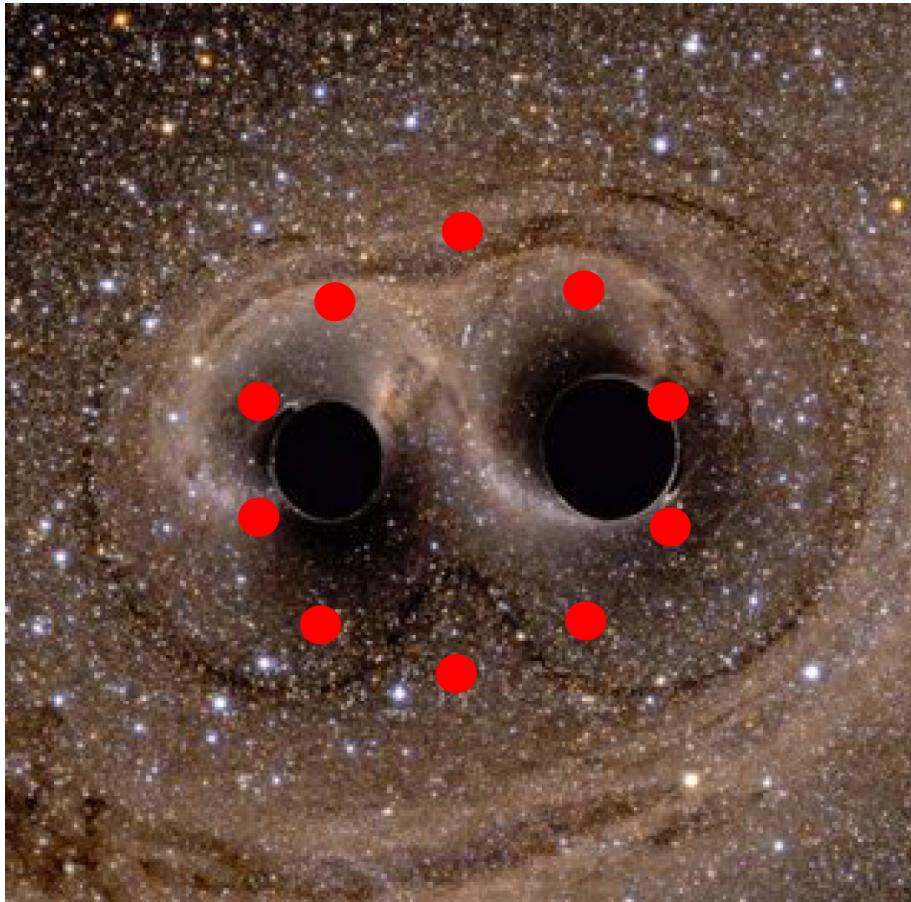
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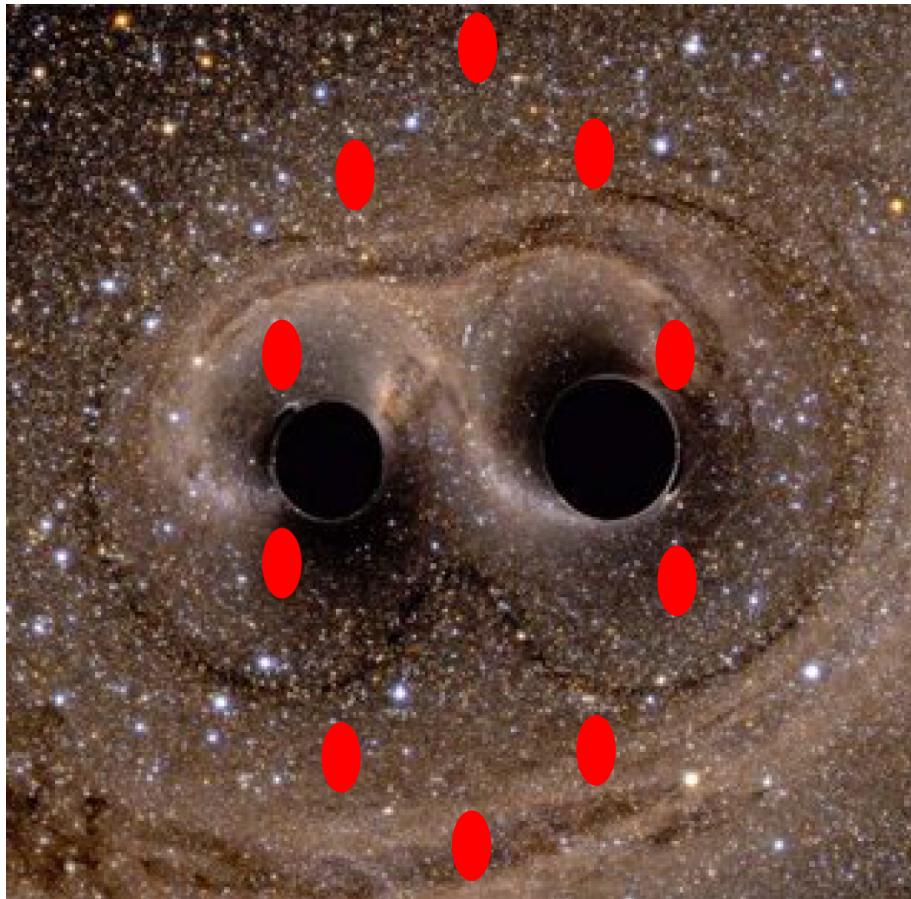
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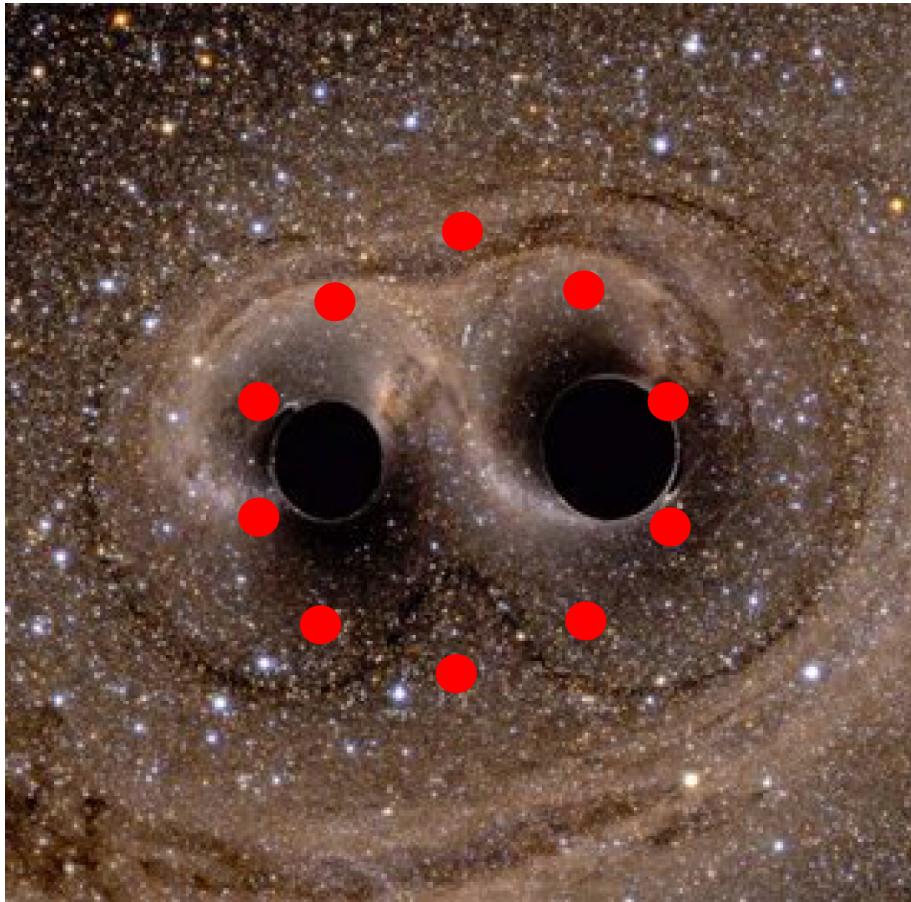
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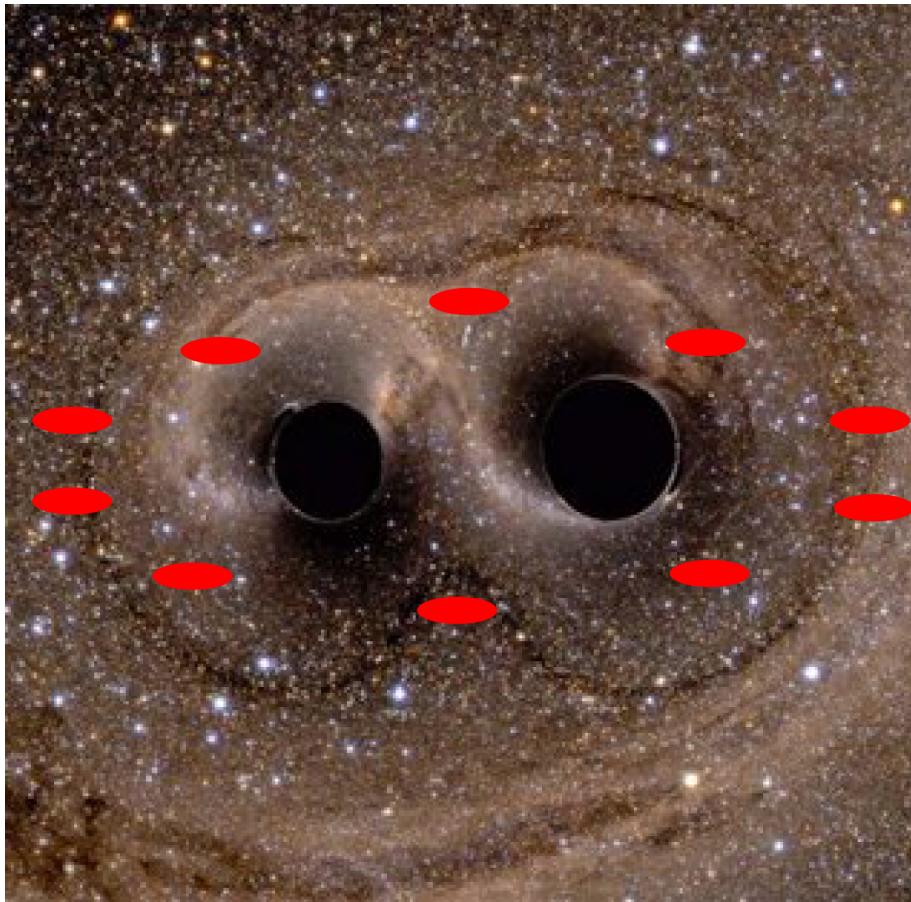
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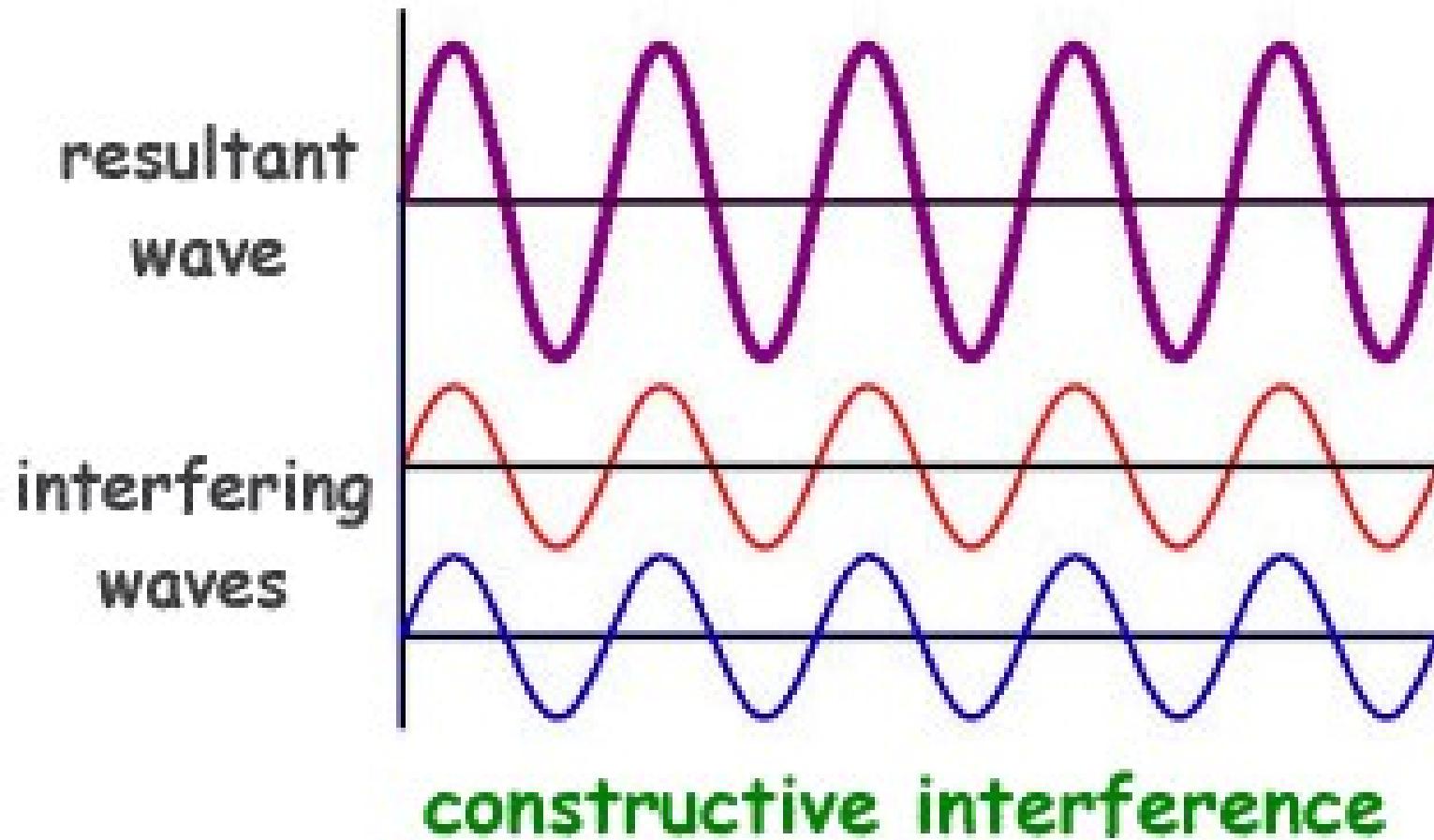
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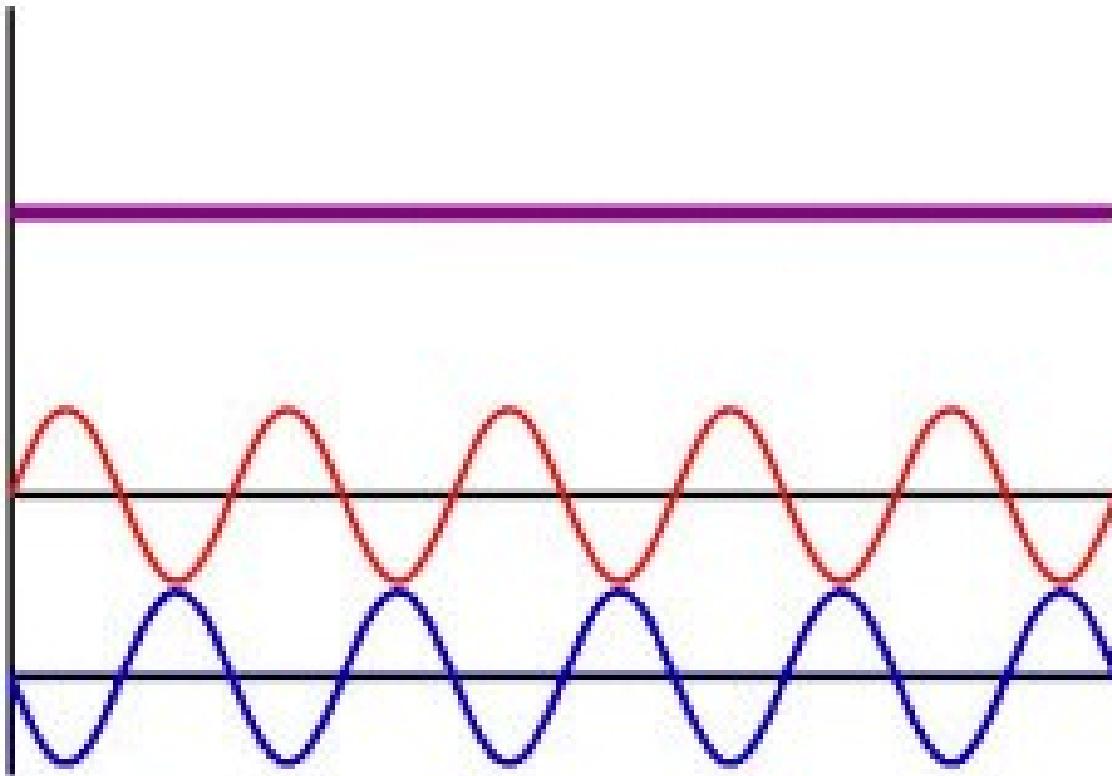
Laser Interferometer Gravitational Wave Observatory (LIGO)

- By the time they reach earth, this stretching and squashing changes distances by about 1 part in 10^{21}
- This is roughly equivalent to the diameter of a human hair (micrometres) compared to the distance to Alpha Centauri (4.35 lightyears)
- How do we go about measuring these kinds of differences?

Brief Aside: Interference

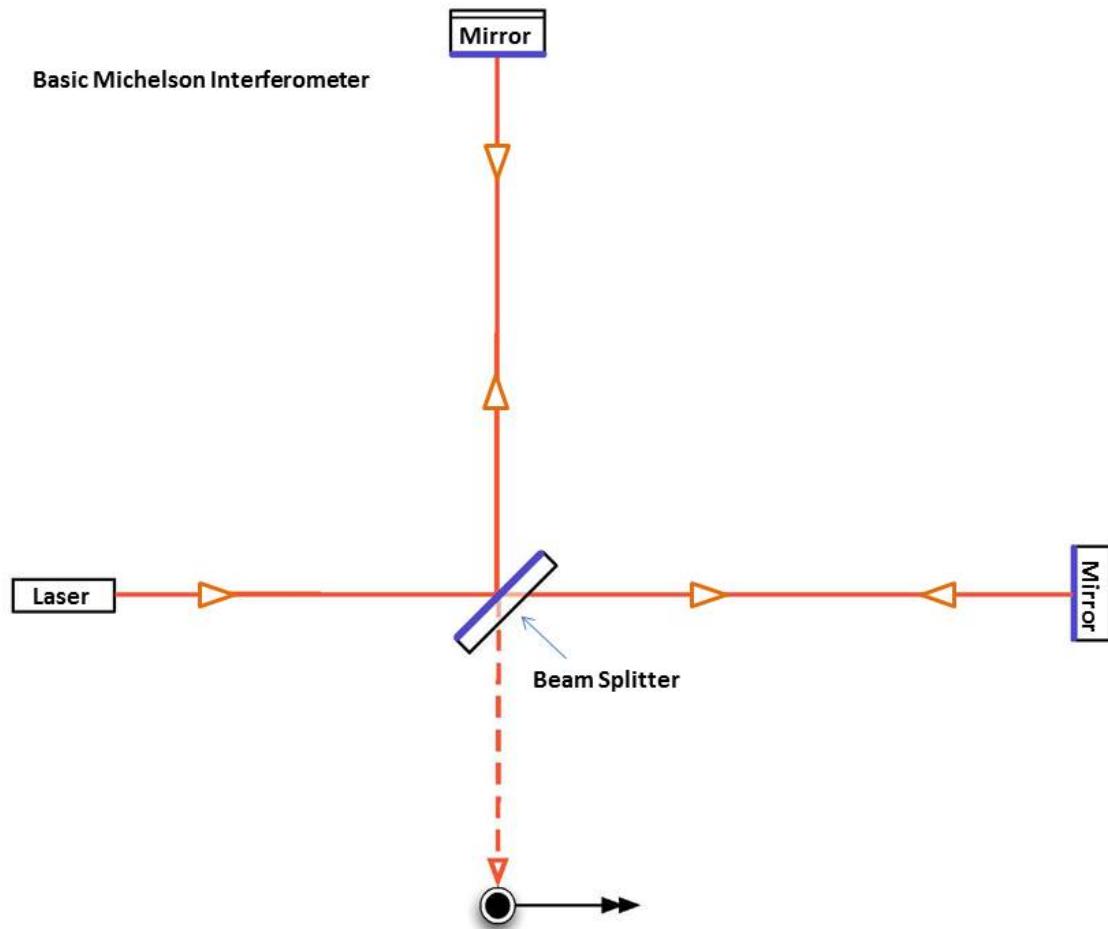


Brief Aside: Interference



destructive interference

Michelson Interferometer



Question

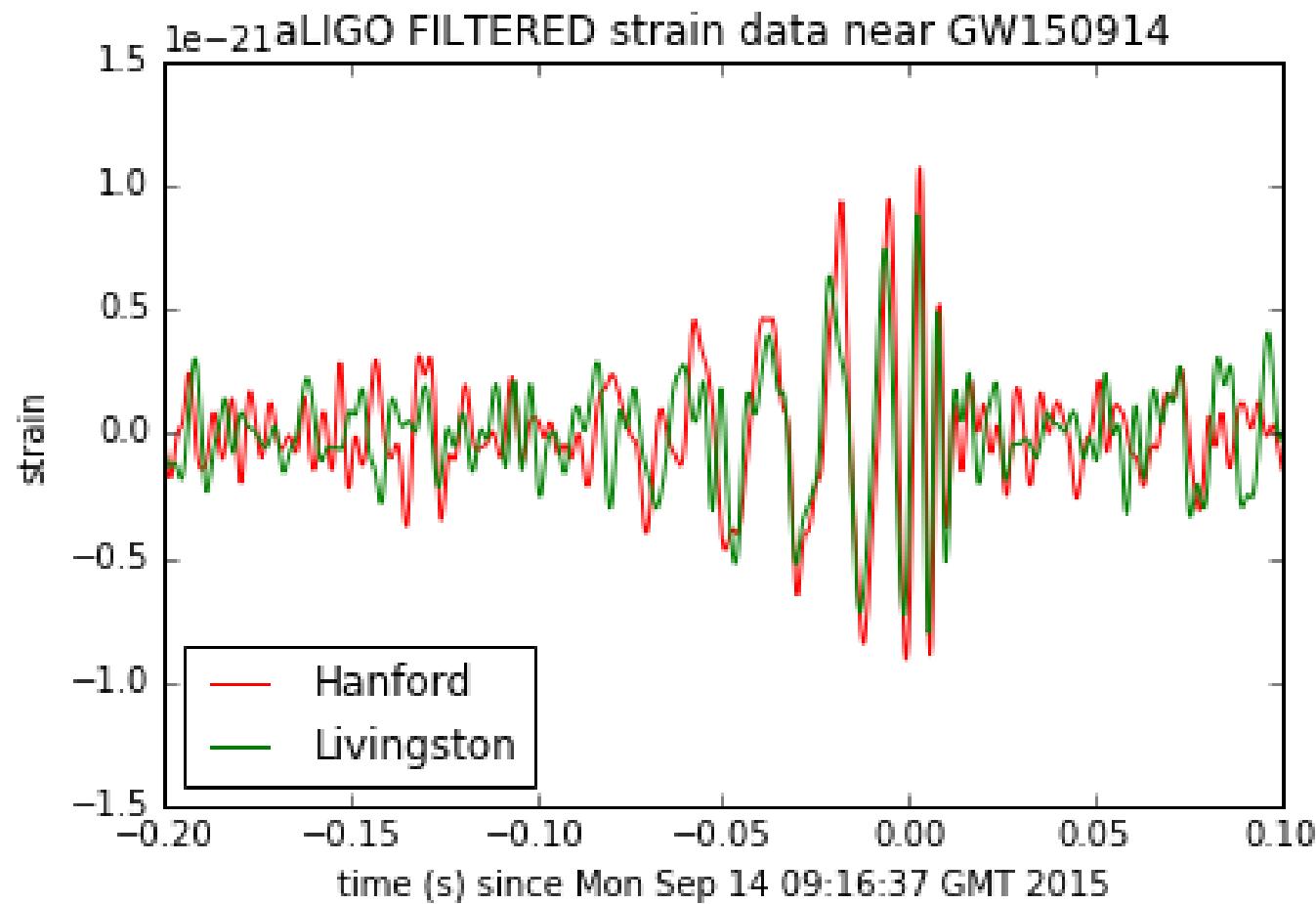
What's better than a laser
interferometer for
detecting gravitational
waves?

Question

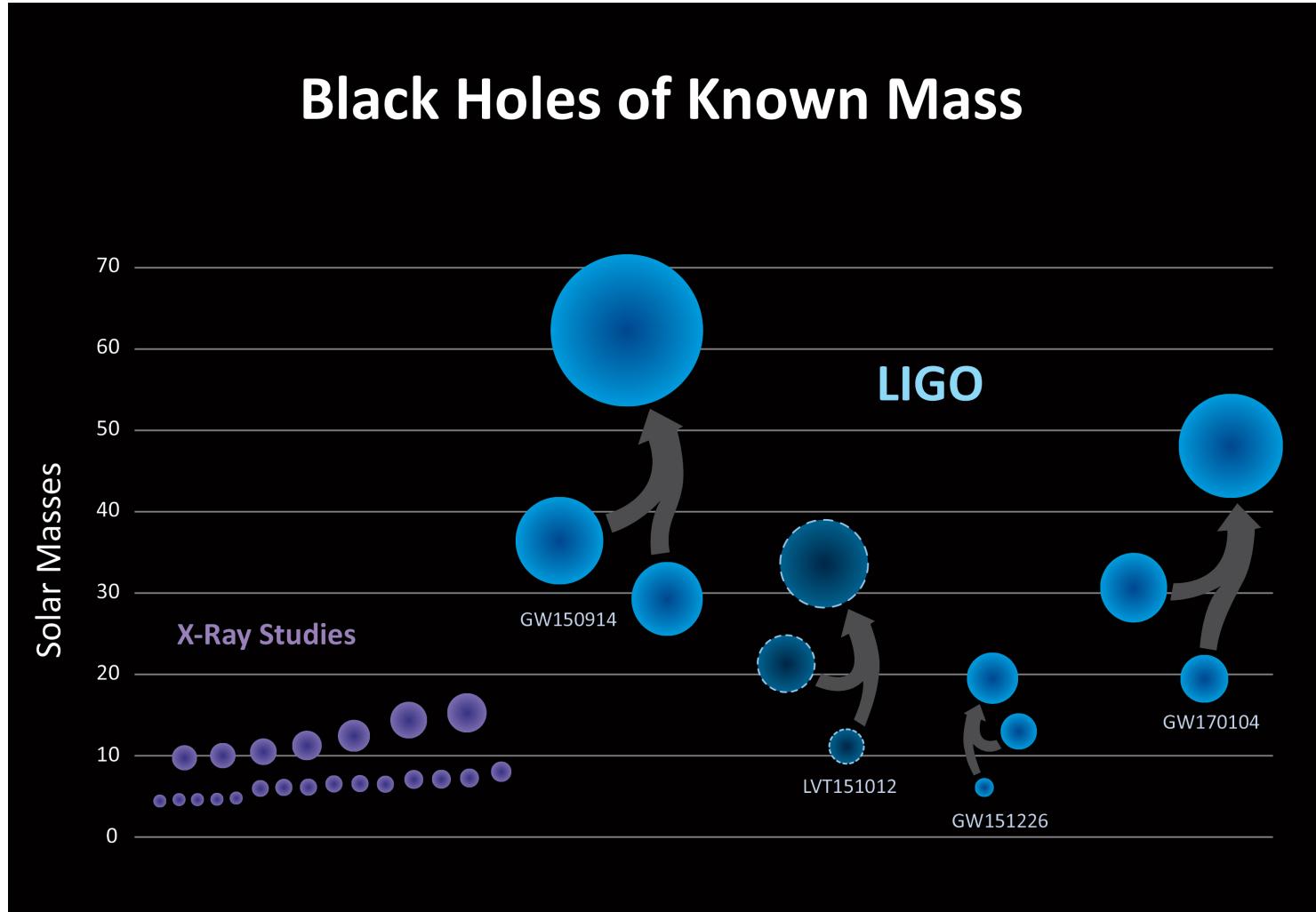
Two Interferometers!



GW150914



Other Gravitational Waves



Some Gossip - GW170818(ish)



J Craig Wheeler
@ast309

 Follow

New LIGO. Source with optical counterpart. Blow your
sox off!

6:25 PM - Aug 18, 2017

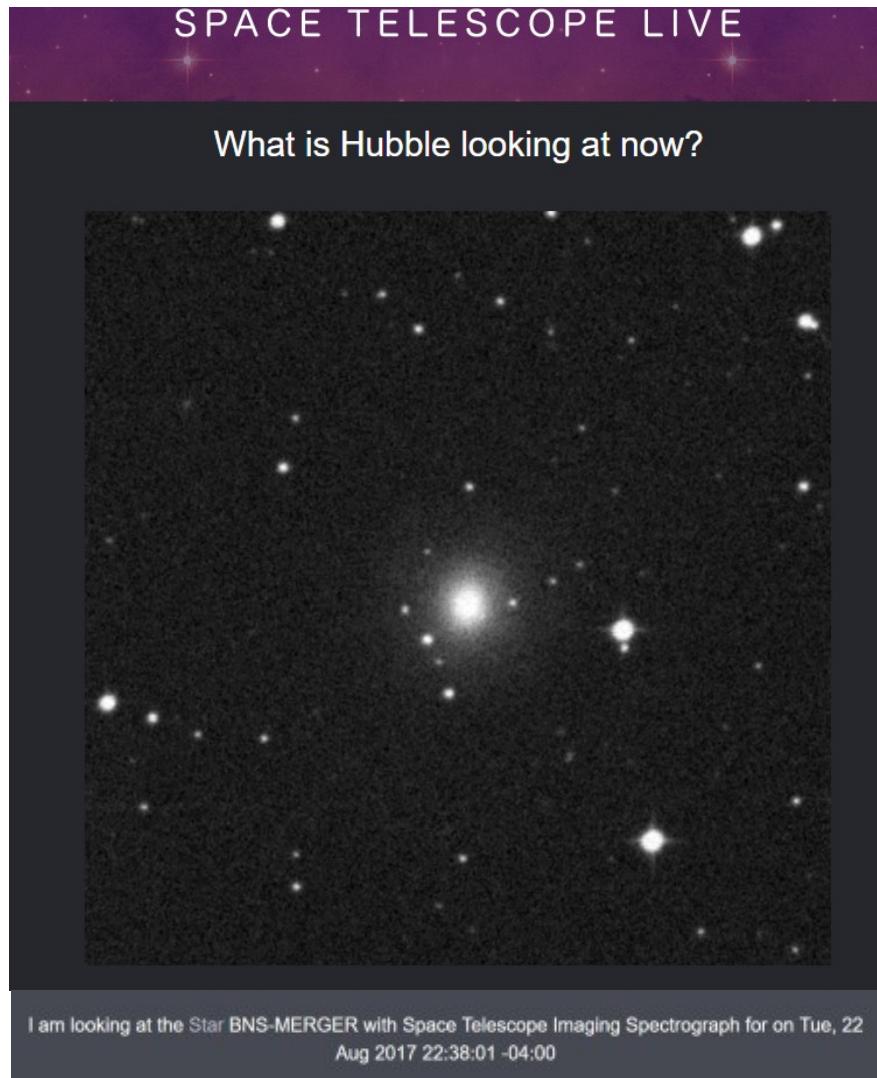
3

45

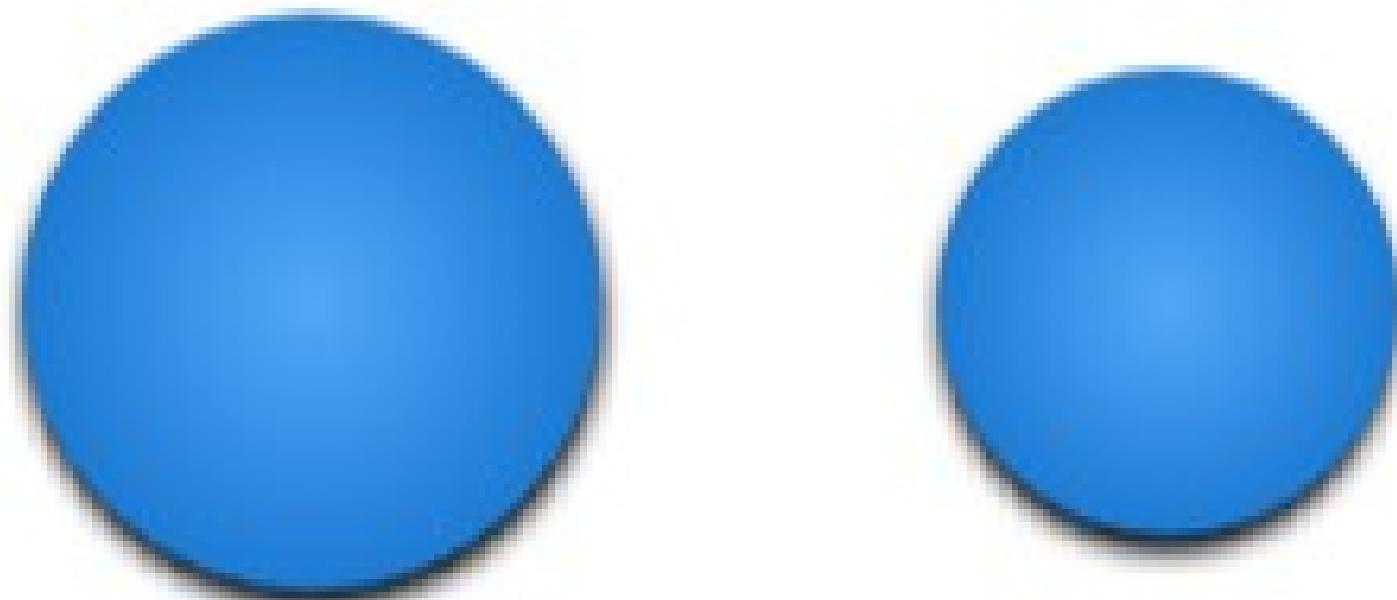
86



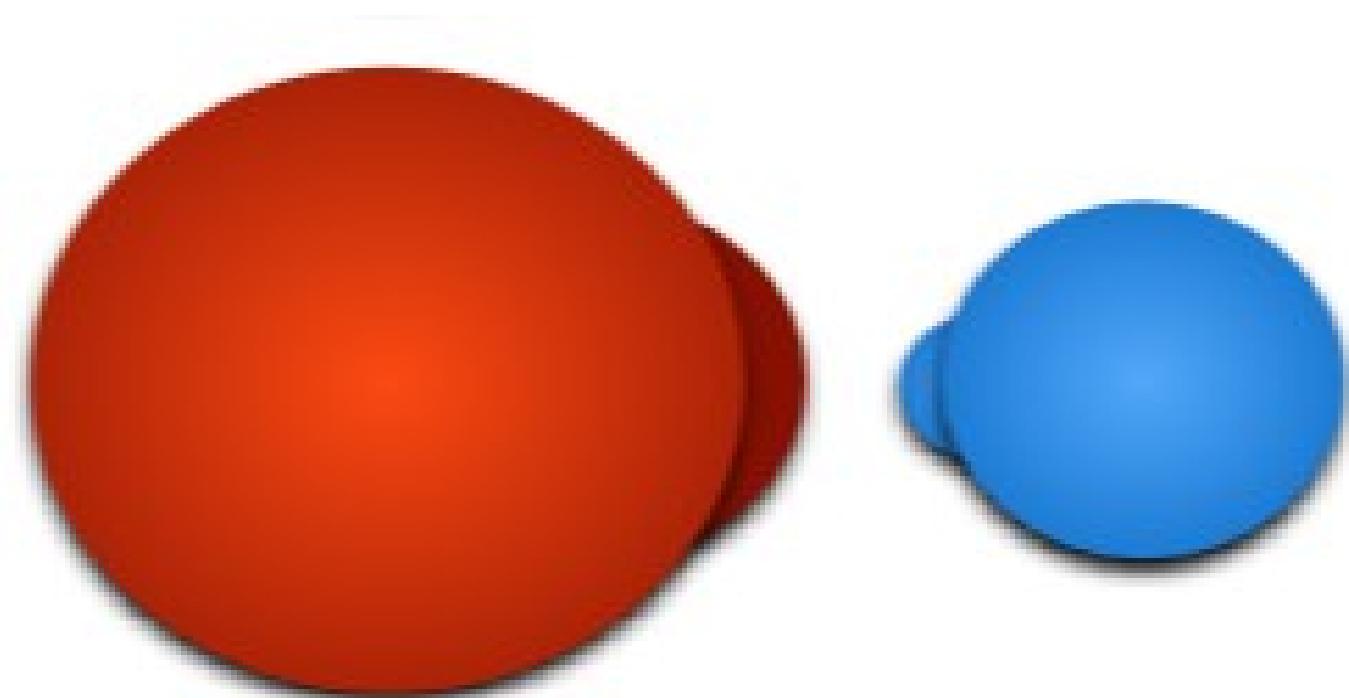
Some Gossip - GW170818(ish)



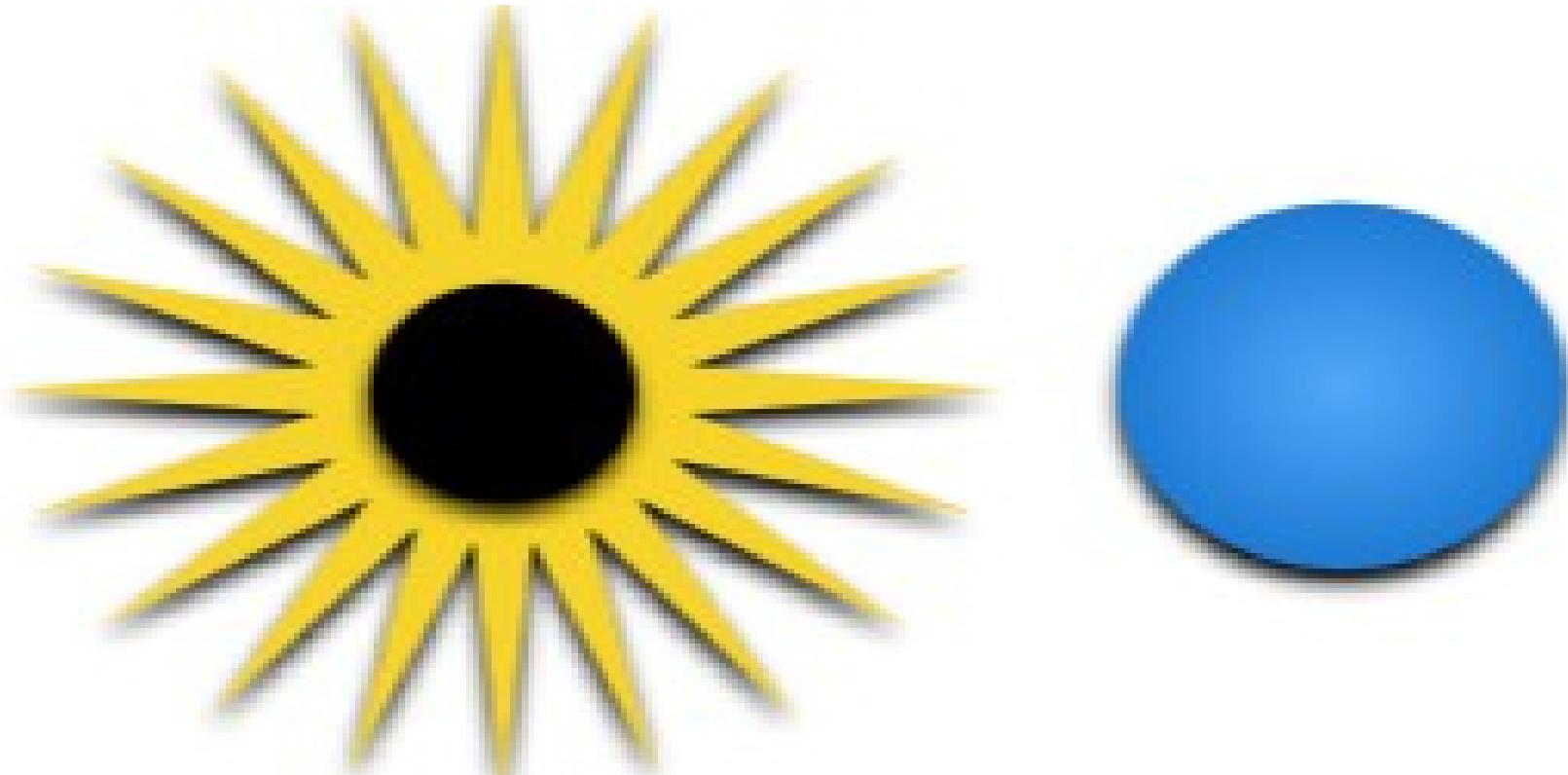
Shameless Self Plug – Binary Evolution



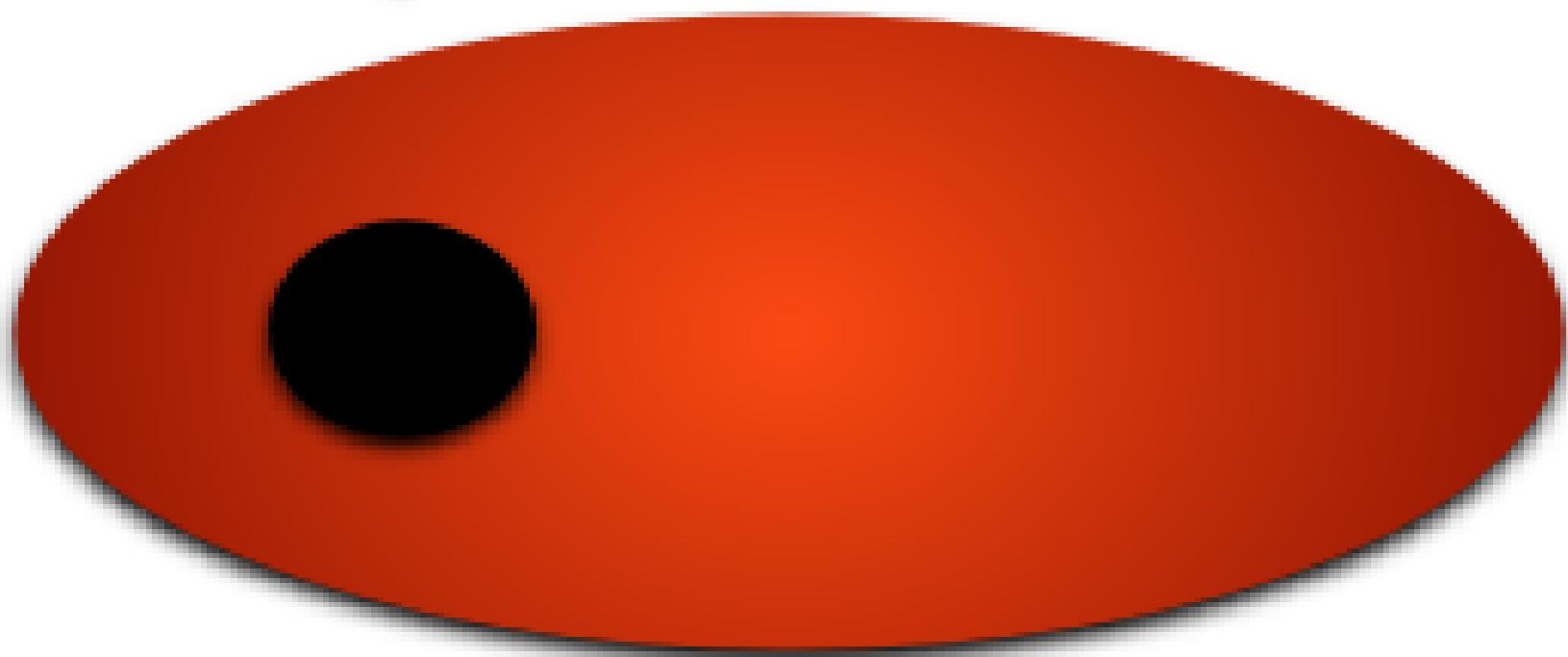
Shameless Self Plug – Binary Evolution



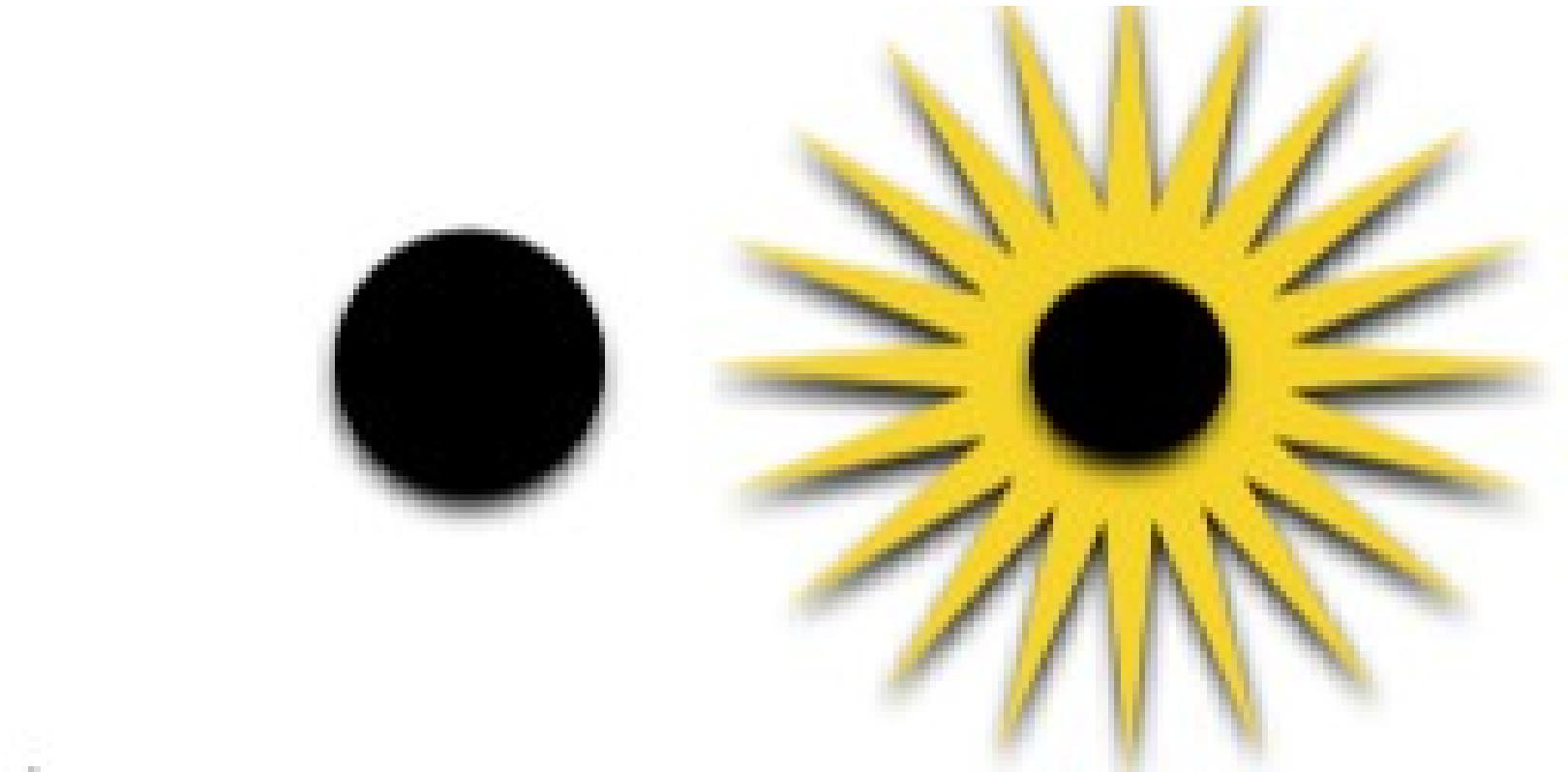
Shameless Self Plug – Binary Evolution



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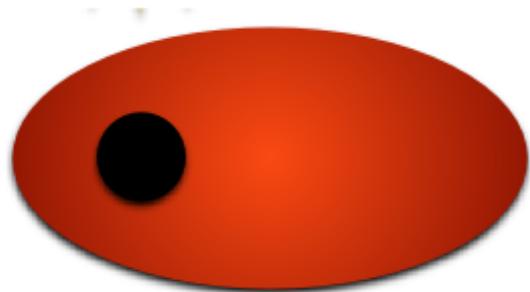
Shameless Self Plug – Binary Evolution



Shameless Self Plug – Binary Evolution



?



Shameless Self Plug – Binary Evolution

```
8 ~/COMPAS/CompasPython/COMPAS/compasGaussianProcess.py - Sublime Text (UNREGISTERED)
File Edit Selection Find View Goto Tools Project Preferences Help
setup.py x selection_effects.py x delayTimeToRedshift.py x cosmologicalintegrator.py x compasGaussianProcess.py x forTsunami.py x plotting.py x
211 bestParams = None
212 bestLikelihood = -np.inf
213 successes = []
214
215 for i in range(nRepeats):
216     gp = george.GP(self._initialiseRandomKernel())
217     gp.compute(inputs,yerr=errors)
218
219     def nll(p):
220         gp.set_parameter_vector(p)
221         ll = gp.lnlikelihood(outputs,quiet=True)
222
223         return -ll if np.isfinite(ll) else 1e25
224
225     def grad_nll(p):
226         gp.set_parameter_vector(p)
227         return gp.grad_lnlikelihood(outputs,quiet=True)
228
229     p0 = gp.get_parameter_vector()
230     results = spop.minimize(nll,p0,jac=grad_nll,method=method)
231
232     likelihood = -1. * nll(results.x)
233
234     if likelihood > bestLikelihood:
235         bestLikelihood = likelihood
236         bestParams = results.x
237
238     successes.append(results.success)
239
240     verboseMessage = "repeat " + str(i+1) + "; success = " + str(results.success) + "; likelihood = " + str(likelihood)
241
242     self._verbosePrint(verboseMessage)
243
244     if not np.any(successes):
245         raise ValueError("none of the optimisers converged for one of the GPs")
246
247     self._verbosePrint(verboseMessage)
248
249     if not np.any(successes):
250         raise ValueError("none of the optimisers converged for one of the GPs")
251
252     return bestParams
253
254 def _initialiseRandomKernel(self):
255
256     inputs = self._trainingInputs
257
258     mean = np.mean(inputs, axis=0)
259     std = np.std(inputs, axis=0)
260
261     if self.kernelType == "squaredExponential":
262
263         startingPosition = []
264
265         for m,s in zip(mean,std):
266             startingPosition.append(np.random.randn()*s + m)
267
268         startingPosition = 0.1*np.abs(np.array(startingPosition))
269
270         kernel = george.kernels.ExpSquaredKernel(startingPosition, ndim=self.nInputDimensions)
271
272     elif self.kernelType == "matern32":
273
274         startingPosition = []
275
276         for m,s in zip(mean,std):
277             startingPosition.append(np.random.randn()*s + m)
```



Questions?