Gravitational wave observations: The dawn of a new era in astronomy

Ulrich Sperhake

DAMTP, University of Cambridge

King Edward VI School

Chelmsford, UK, 12 Oct 2017

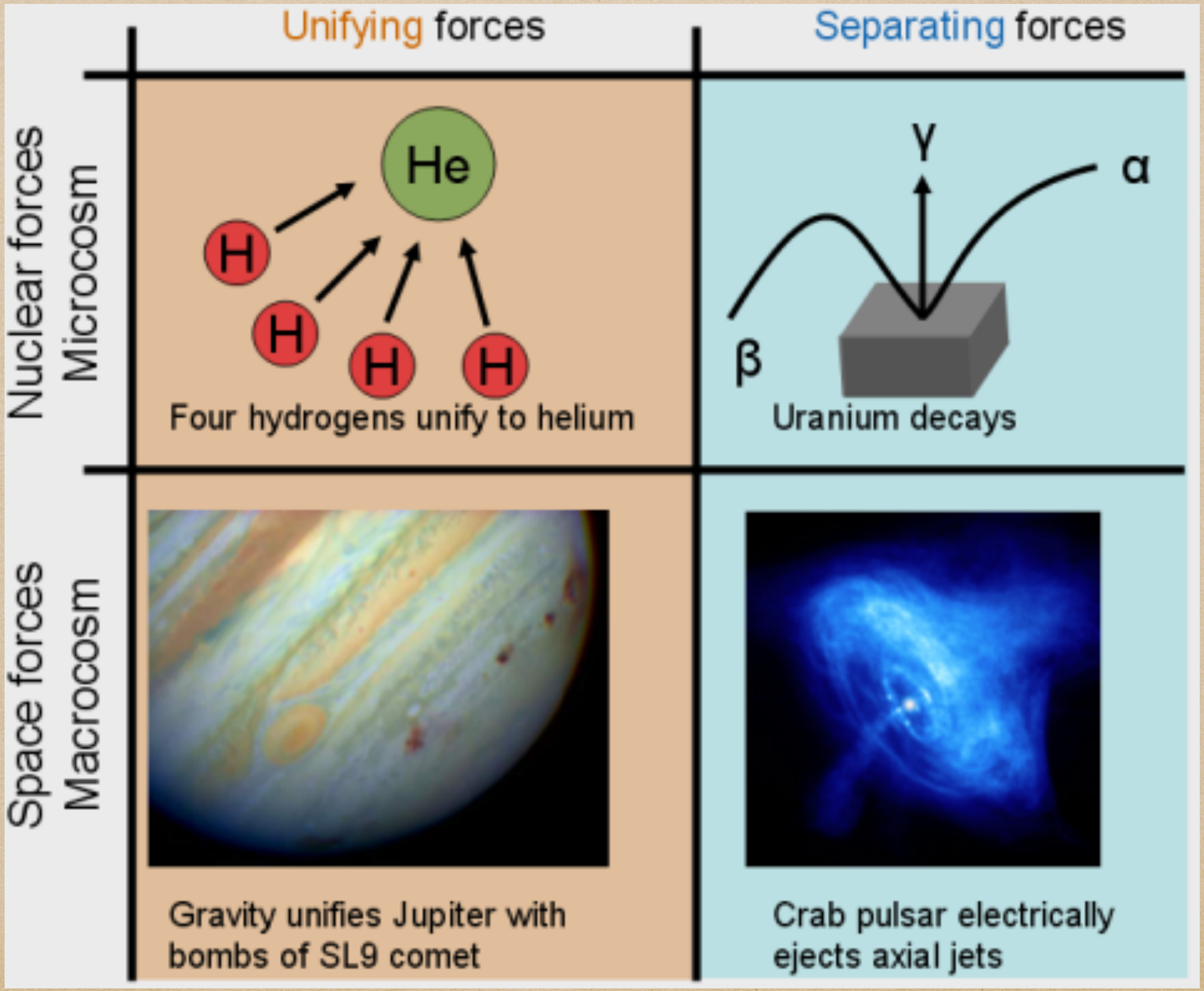
This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 690904, from H2020-ERC-2014-CoG Grant No. "MaGRaTh" 646597, from NSF XSEDE Grant No. PHY-090003 and from STFC Consolidator Grant No. ST/L000636/1.

Conclusions

- Gravity
- General Relativity
- Gravitational waves
- Searching for gravitational waves
- The Nobel Prize winning discovery
- Applications in physics and astrophysics
- Conclusions and outlook

1. Gravity

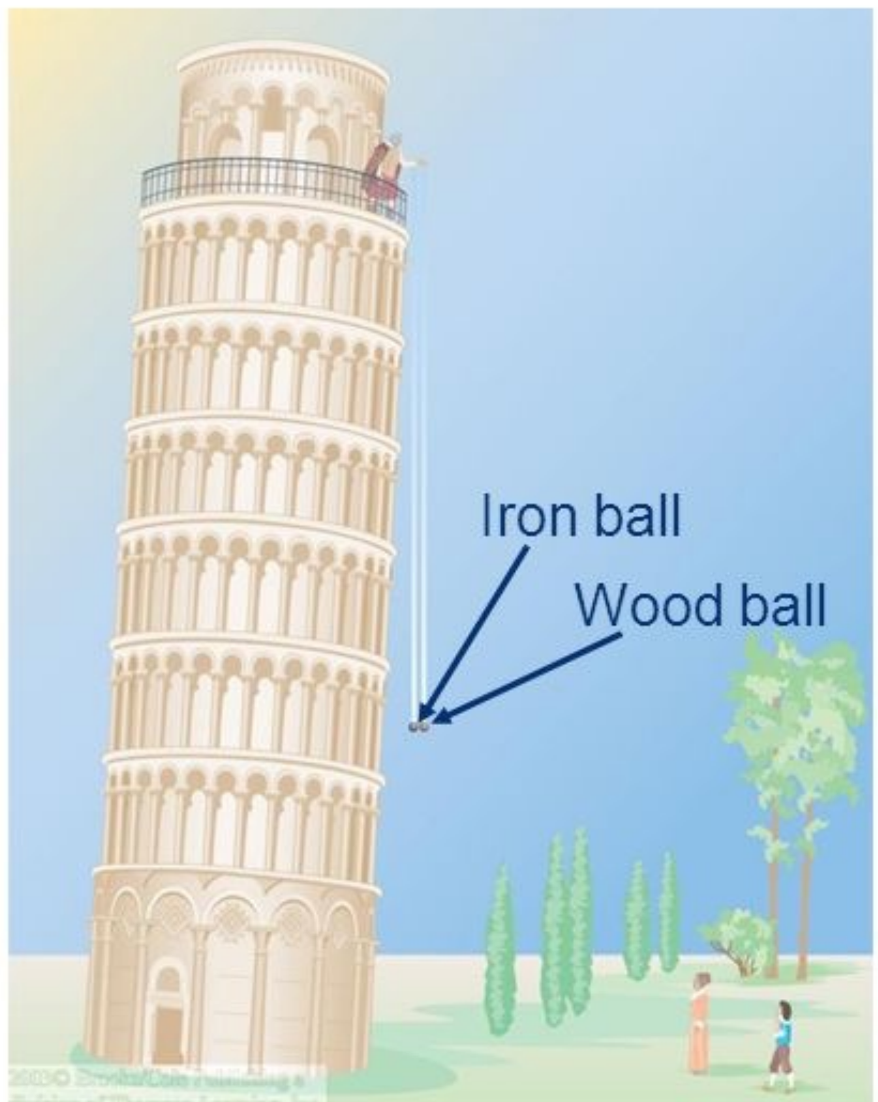
Four fundamental forces



Gravity

Galileo: Equivalence principle

Galileo and Gravity



Acceleration of gravity is independent of the mass (weight) of the falling object.

Friction interferes with falling bodies so they fall differently.

Without friction, all bodies fall at same rate near Earth's surface.

Apollo 15: Equivalence principle

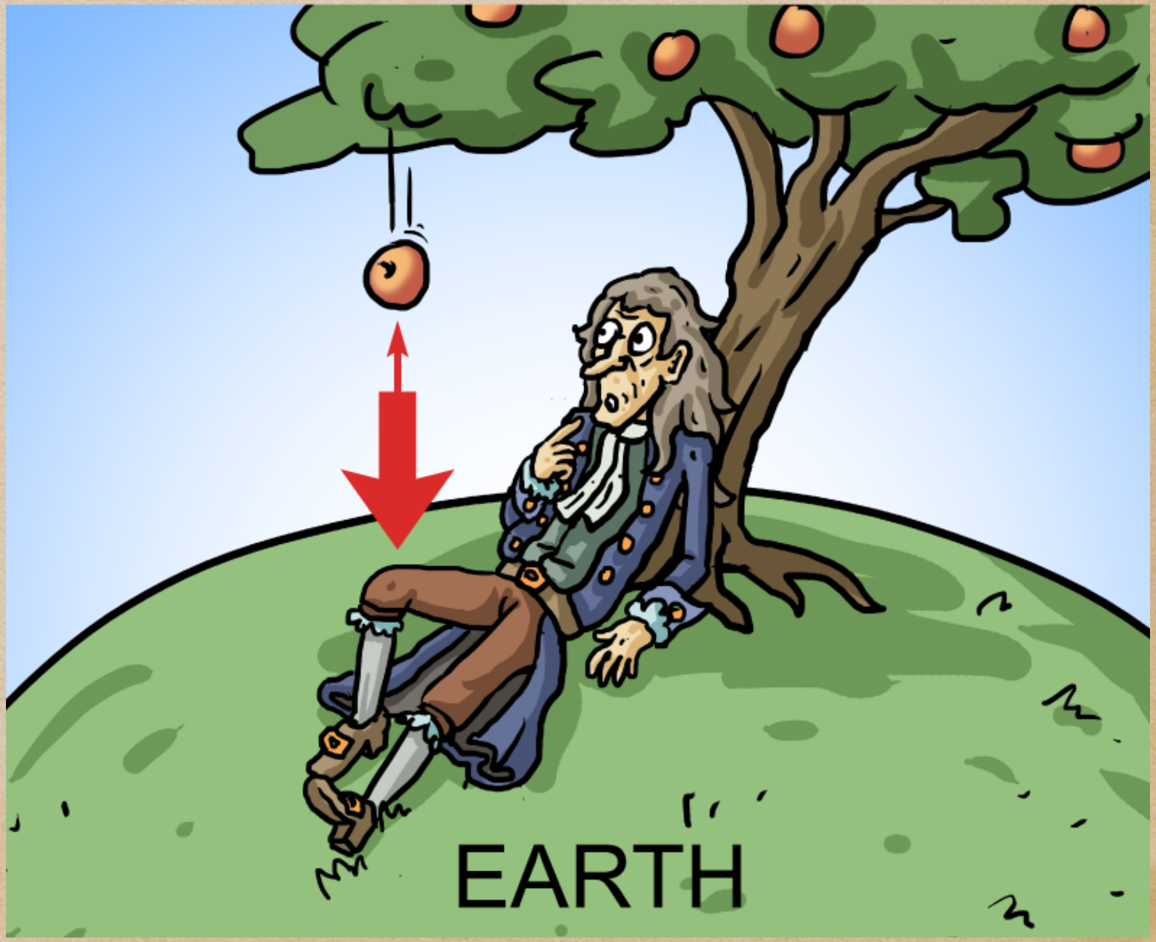
Newton's insights

- Objects at rest remain at rest and objects in motion remain in motion with constant speed and in a straight line, unless acted upon by by an external force.
- The force is the acceleration times the mass

  $\vec{F} = m\vec{a}$

- For every force, there is an equal and opposite reaction:

  actio $=$ reactio

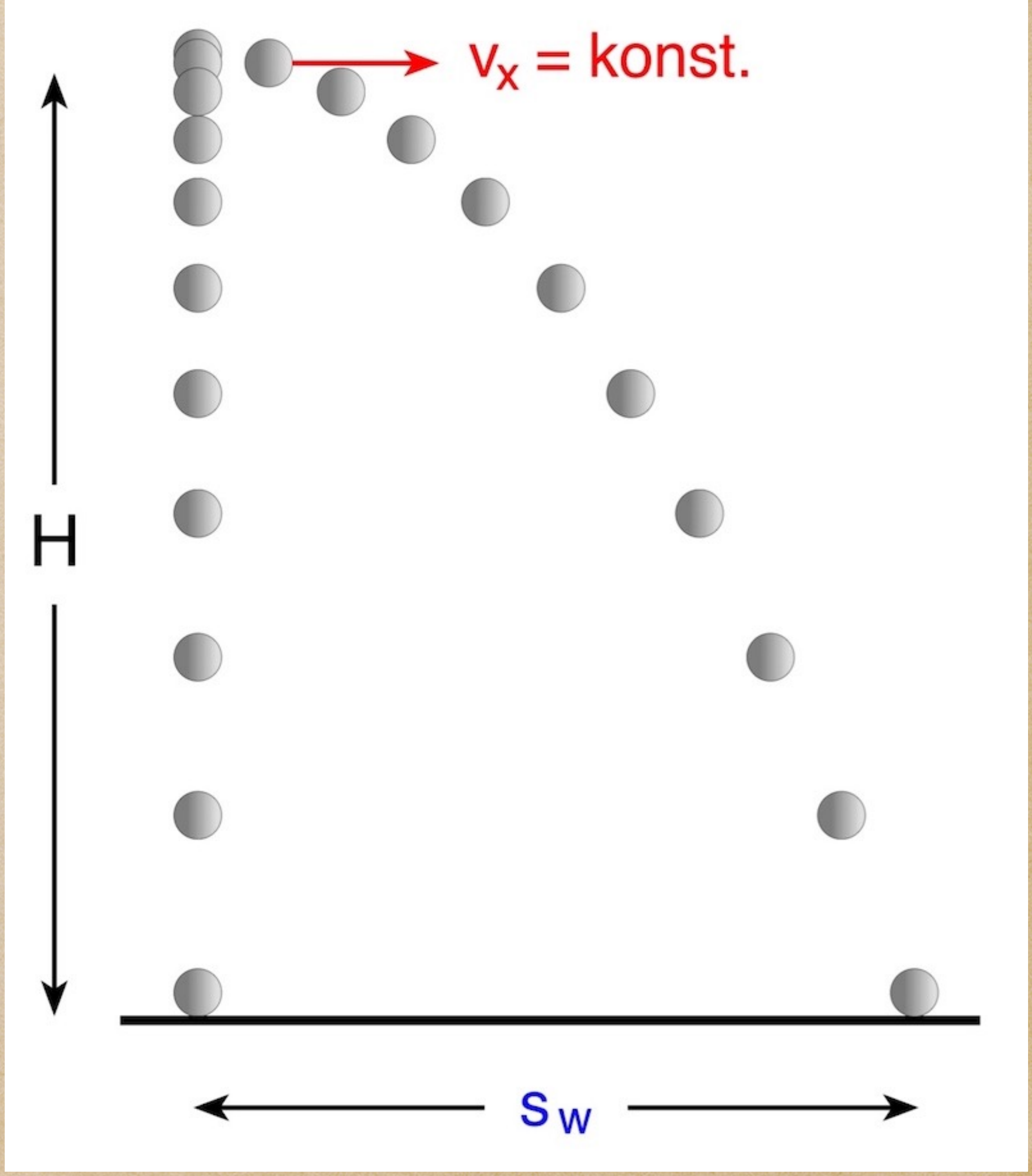


The real insight of the apple

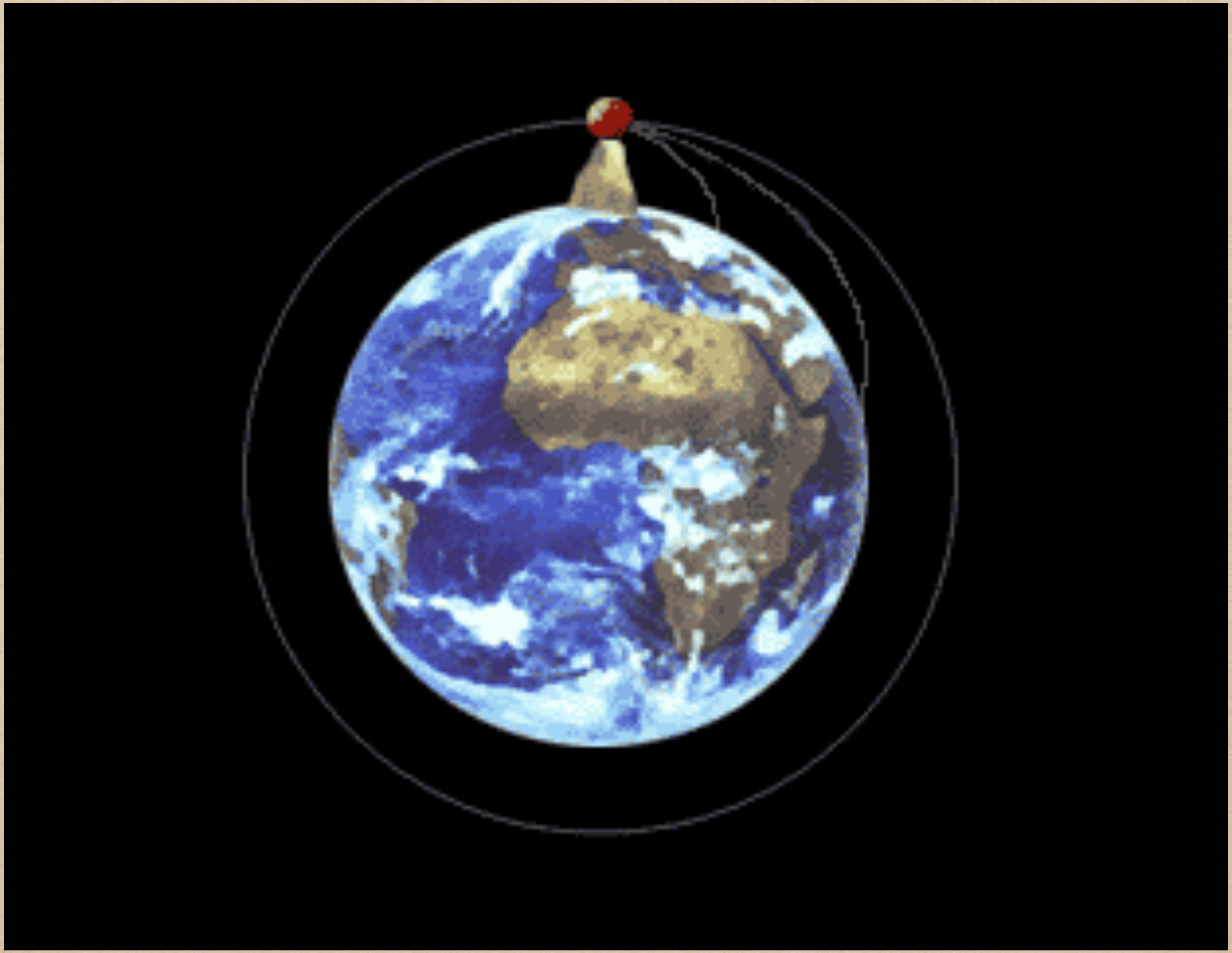
- A horizontal component has no effect on the vertical fall!
- Decompose motion

$$v_x(t), \quad x(t)$$

$$v_y(t), \quad y(t)$$

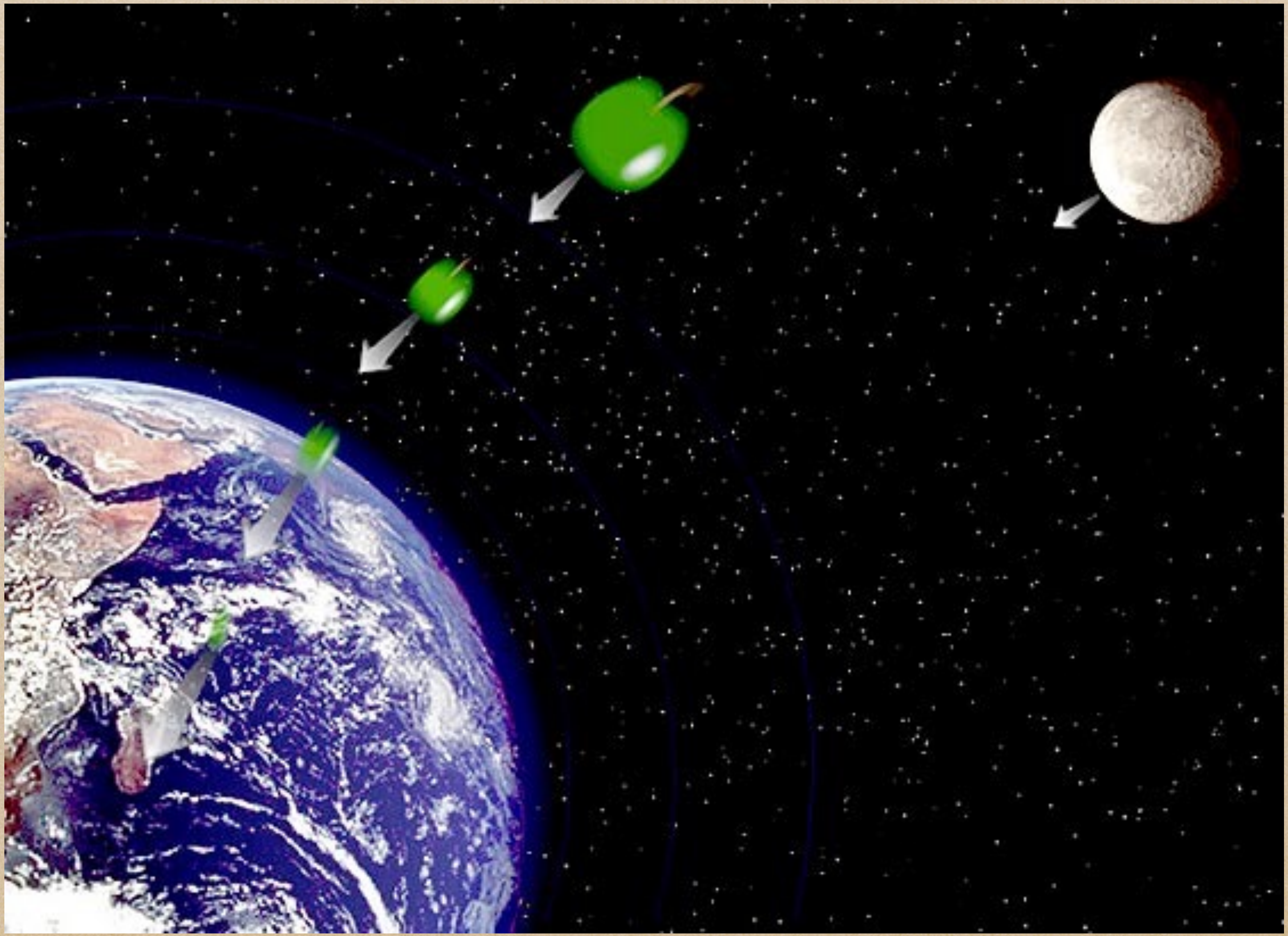


The real insight of the apple



The real insight of the apple

- The force on the apple and the moon are the same: Gravity!



Summary so far

- Gravity operates throughout the universe and is far reaching
- All objects fall the same way!
- Gravitational charge = inertial mass: $m\vec{a} = m\vec{g}(\vec{r}, t) \quad \Rightarrow \quad \vec{a} = \vec{g}(\vec{r}, t)$

  cf. electric field: $m\vec{a} = e\vec{E}(\vec{r}, t)$
- (Weak) Equivalence Principle:

  Freely falling small bodies with negligible self-interaction follow the same path if they have the same initial velocity and position.
- **Einstein: Gravity is a feature of the spacetime!**
- Flat Spacetime: Objects move on straight lines

  Curved spacetimes: Objects move on curved lines

2. General Relativity

Curvature

- A map of Cambridge

Curvature

- A map of Cambridge
- Grafton Centre -

  Trinity College -

  St.Catherine's College
- Pythagoras works well!

Curvature

- A map of the Earth: Pythagoras doesn't really work…

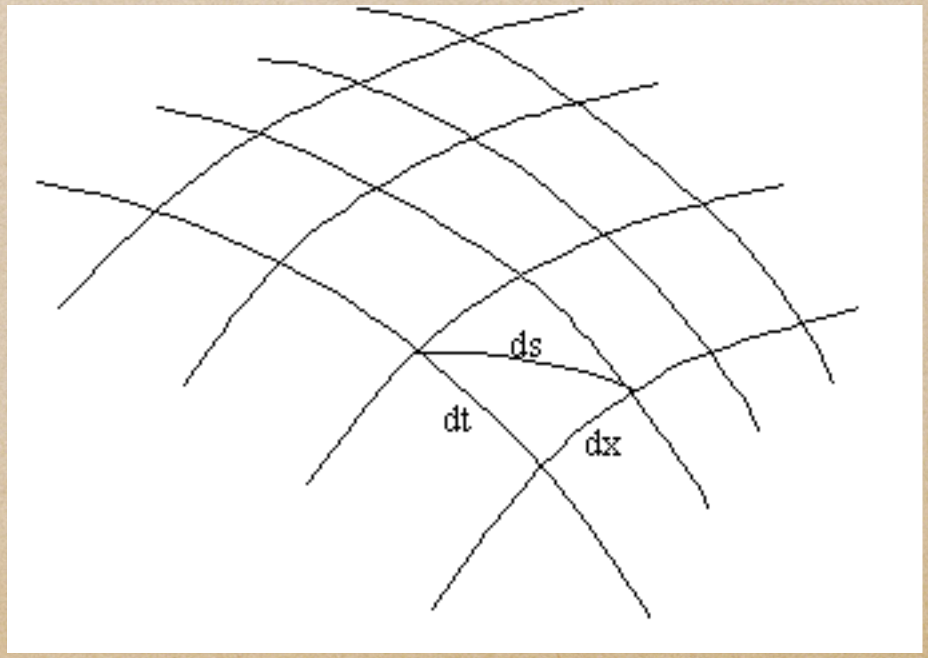
Differential geometry: Non-flat manifolds

- Manifold: A set of points labeled by coordinates $x^\alpha\,, \quad \alpha = 0 \ldots n-1$
- Think of house numbers in a street!
- Measure for real distance: Metric
- E.g. 2D Euclidean: $ds^2 = dx^2 + dy^2 = dr^2 + r^2 d\phi^2$
- In general: $n \times n$ matrix valued function
- Time directions count negative:

  Special relativity: $ds^2 = -dt^2 + dx^2 + dy^2 + dz^2 = \eta_{\alpha\beta} dx^\alpha dx^\beta$

$$\eta_{\alpha\beta} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$dx^\alpha = \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$



General relativity

- Spacetime as a curved manifold
- Key quantity: spacetime metric $g_{\alpha\beta}$
- Curvature, geodesics etc. all follow
- Einstein equations

$$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R + \Lambda g_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

10 non-linear PDEs for $g_{\alpha\beta}$

$T_{\alpha\beta} =$ Matter fields

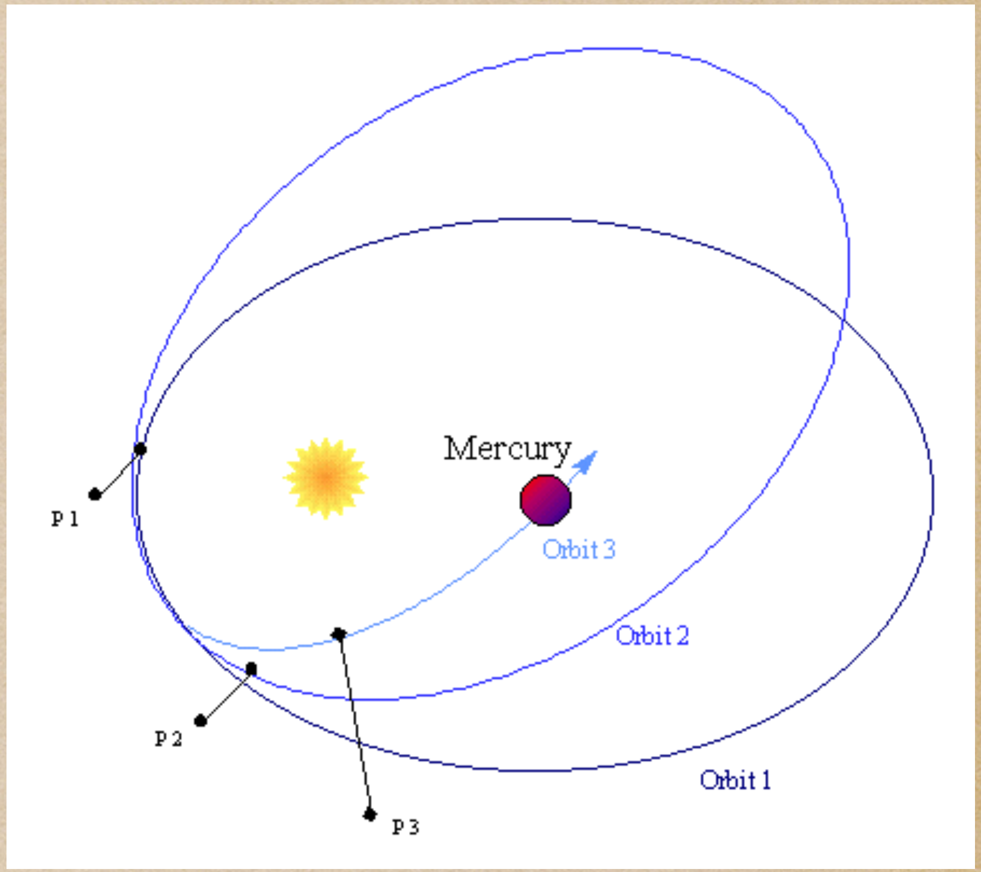
- Conceptually simple, hard in practice
- E.g. Schwarzschild

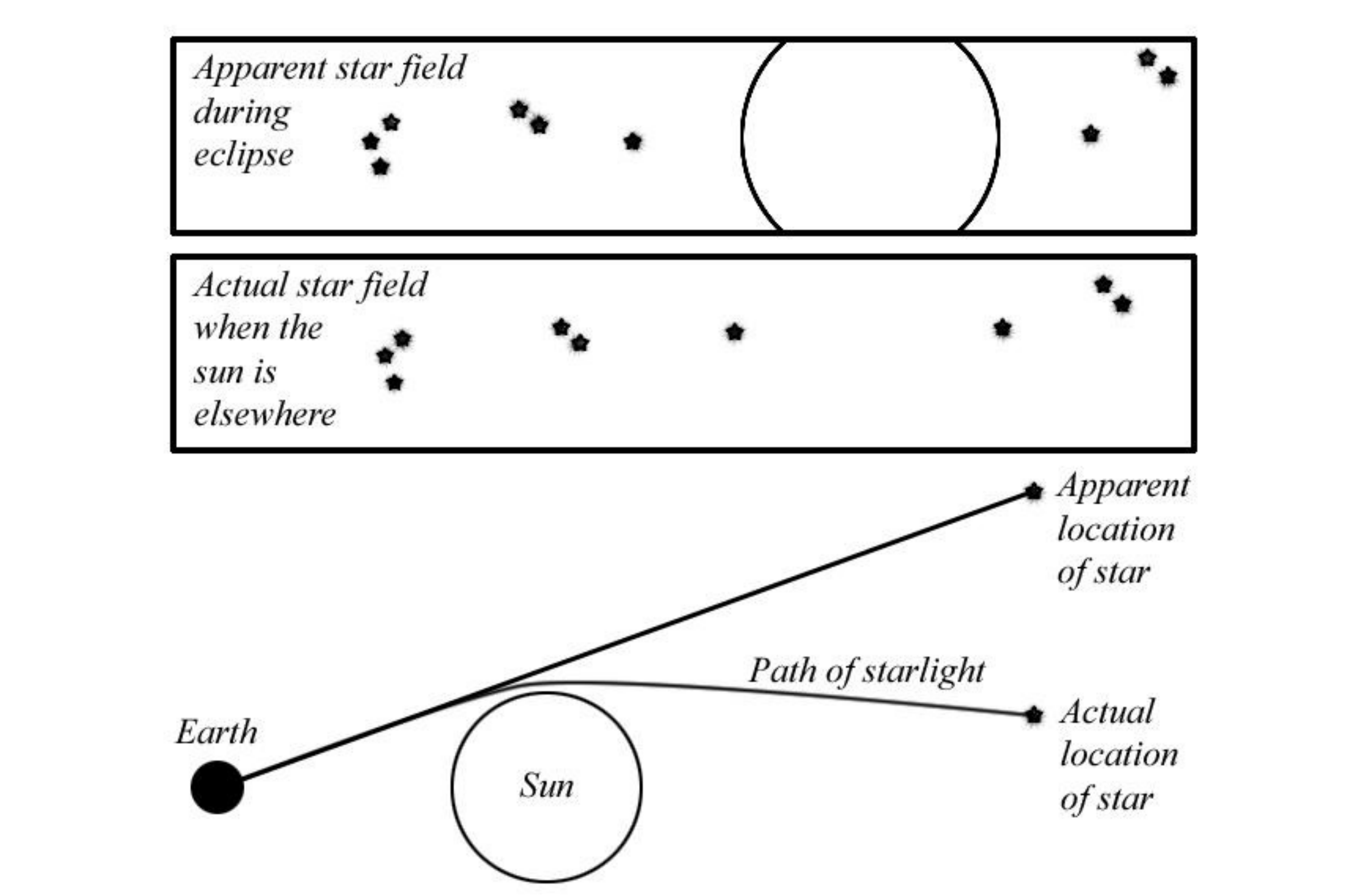
$$g_{\mu\nu} = \begin{pmatrix} \left(1 - \frac{2GM}{rc^2}\right) & 0 & 0 & 0 \\ 0 & -\left(1 - \frac{2GM}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin^2\theta \end{pmatrix}$$

$$ds^2 = c^2 dt^2 \left(1 - \frac{2GM}{rc^2}\right) - \frac{dr^2}{1 - 2GM/rc^2} - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2$$

Classical tests of general relativity

- Light bending
- Gravitational redshift
- Mercury's perihelion precession
- Shapiro time delay





General relativity is non-linear!

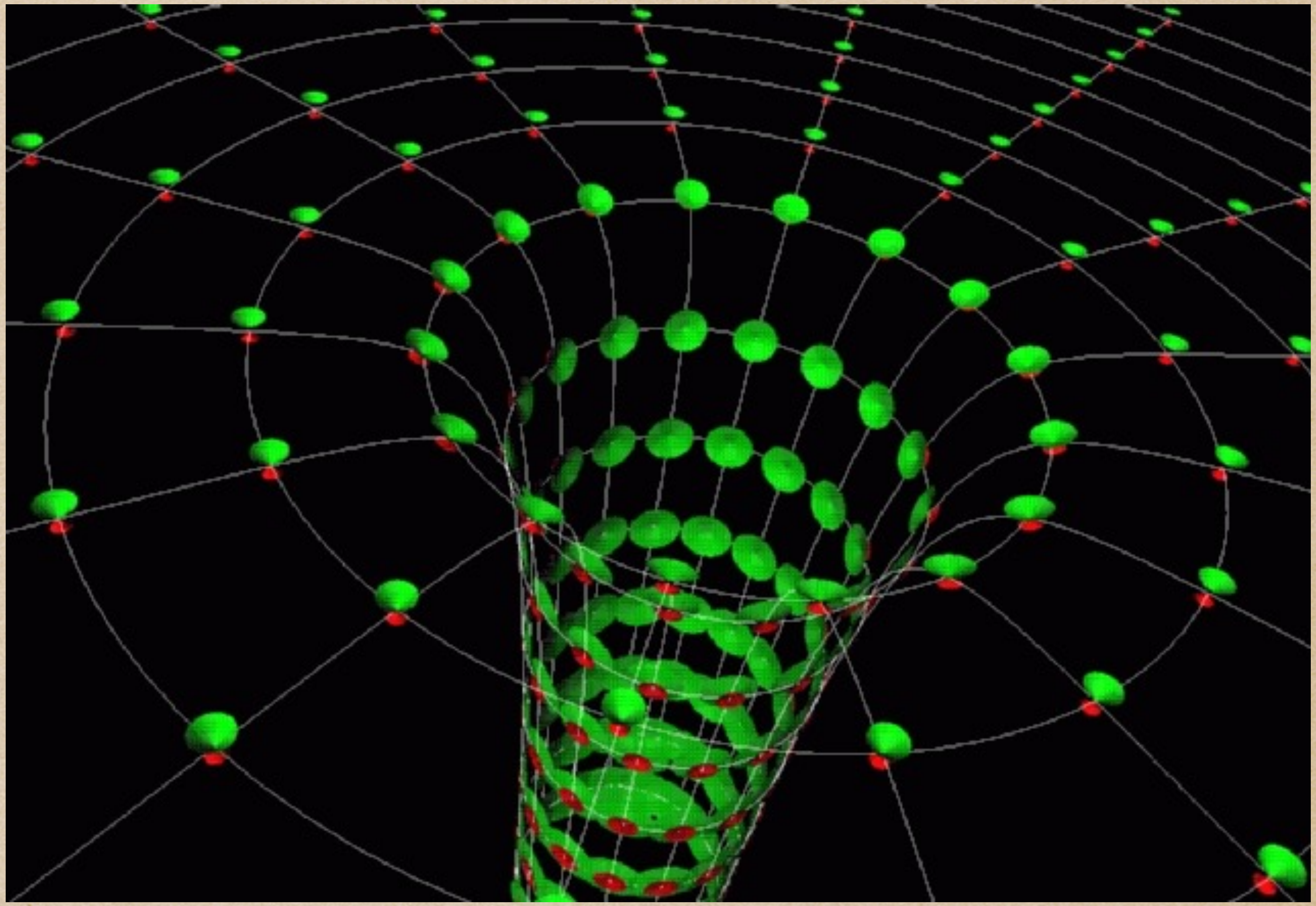
- John Wheeler: Spacetime tells matter how to move; matter tells spacetime how to curve
- What is non-linearity? Think of the stock market

$\Rightarrow$ linear

$\Rightarrow$ NON-LINEAR!

Strongest gravity: Black Holes

- Time goes upwards
- Green = Future
- Red = Past



- Strong curvature $\Rightarrow$ Everything moves inwards

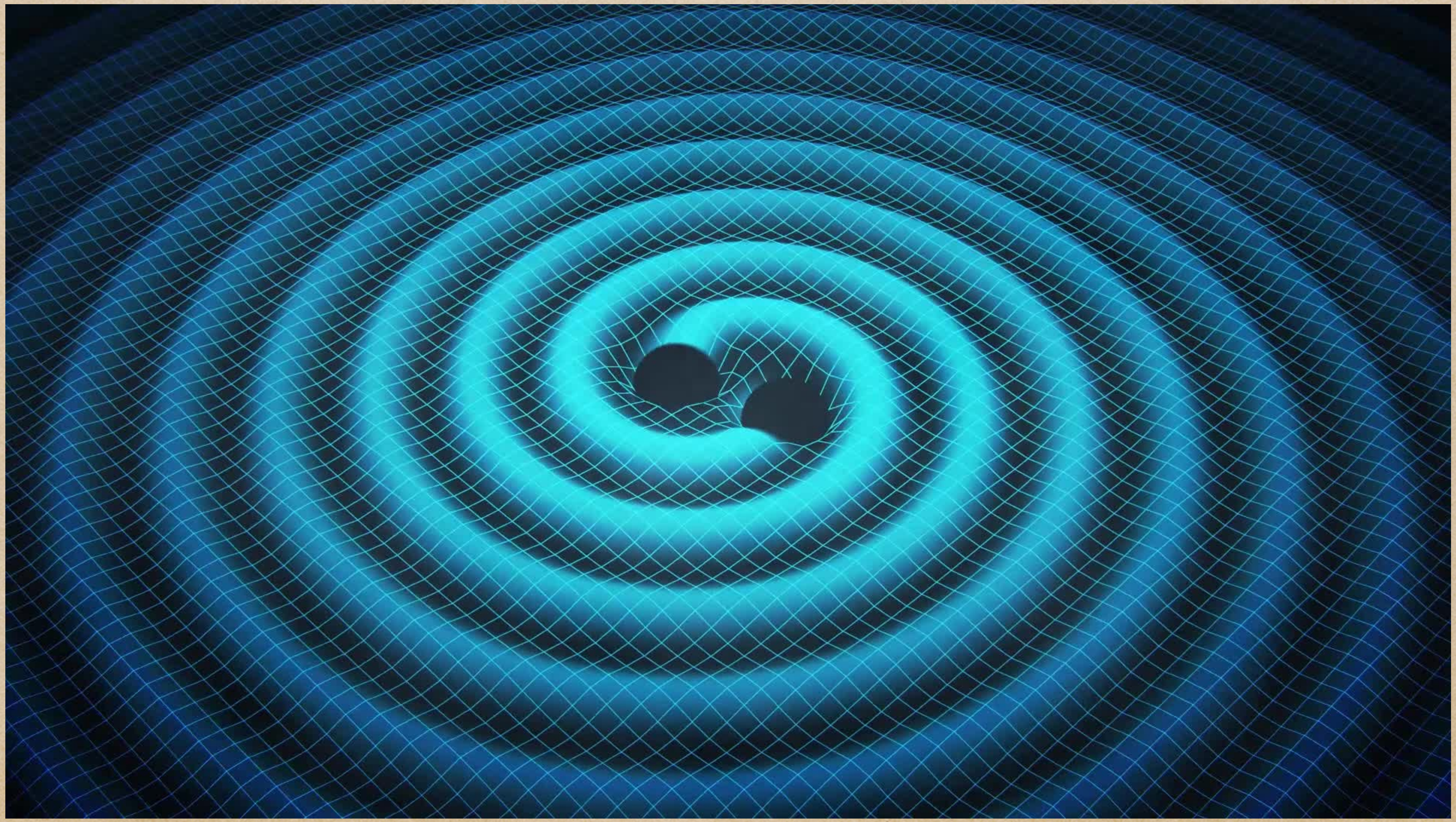
  Black hole!

Black Hole Analogy

3. Gravitational Waves

Gravitational Waves: non-mathematical

- Black-hole / Neutron-star binaries generate ripples in spacetime
- These hit the Earth $\Rightarrow$ Changes in length: $<$ atomic nucleus per km
- Indirect evidence: 1993 Nobel Prize Hulse & Taylor



Gravitational waves: mathematical

- Consider small deviations from Minkowski in Cartesian coordinates

  "Background": Manifold $\mathcal{M} = \mathbb{R}^4, \quad \eta_{\mu\nu} = \mathrm{diag}(-1, 1, 1, 1)$

  "Perturbation": $h_{\mu\nu} = \mathcal{O}(\epsilon) \ll 1 \quad \Rightarrow \quad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

- Coordinate freedom: "Transverse-traceless (TT)" gauge

$$h^{\mu}{}_{\mu} = 0, \quad \partial^{\nu} h_{\mu\nu} = 0$$

- Vacuum, no cosmological constant: $T_{\mu\nu} = 0, \quad \Lambda = 0$
- Einstein's eqs.: $\Box h_{\mu\nu} = 0$
- Plane wave solution in z direction: $h_{\mu\nu} = H_{\mu\nu} e^{i k_{\sigma} x^{\sigma}}$

$$k^{\mu} = \omega(1, 0, 0, 1) \qquad H_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & H_{+} & H_{\times} & 0 \\ 0 & H_{\times} & -H_{+} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Effect on particles

- Geodesic eq.

  Particle at rest at x^μ stays at $x^\mu = \text{const}$ in TT gauge

- Proper separation:

$$ds^2 = -dt^2 + (1+h_+)\,dx^2 + (1-h_+)\,dy^2 + 2h_\times\,dx\,dy + dz^2$$

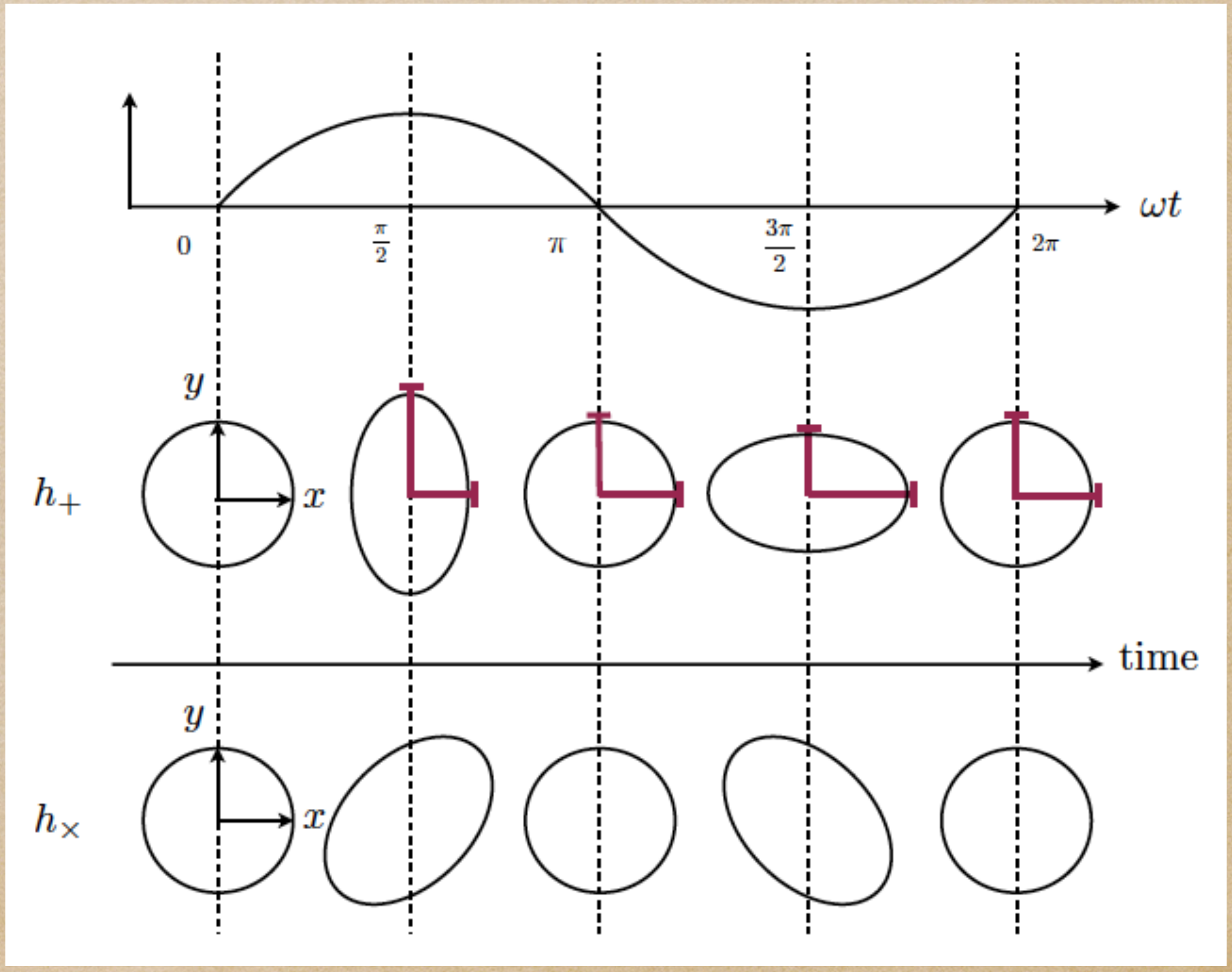
- Effect on test particles:

  Mirshekari 1308.5240

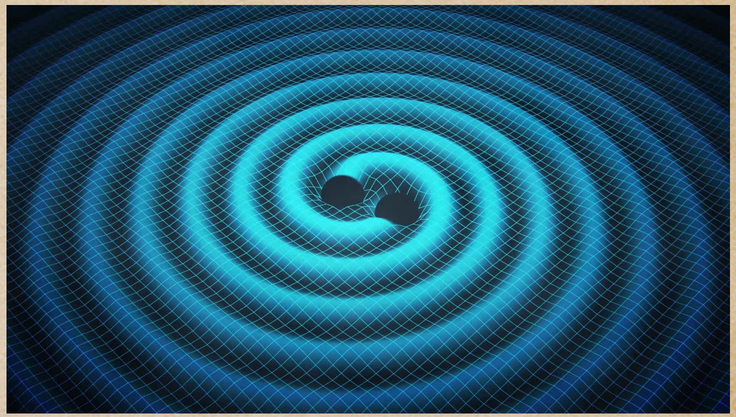
- Debate on physical

  reality until late 1950s

  e.g.Saulson GRG (2011)

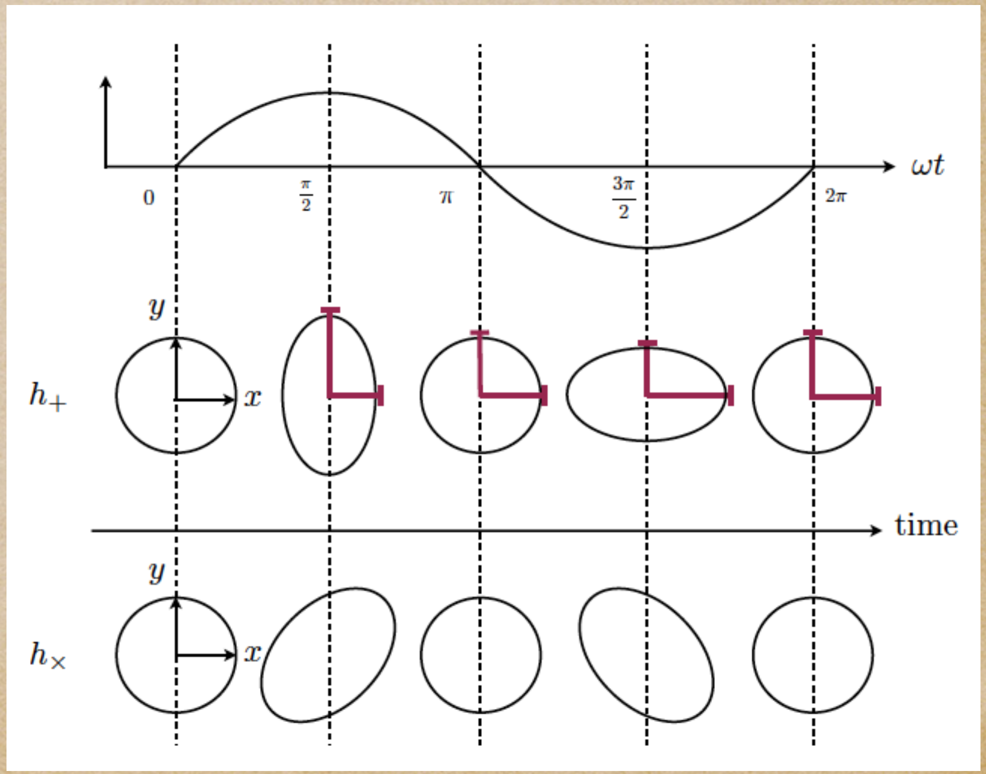


The search for GWs in the data stream



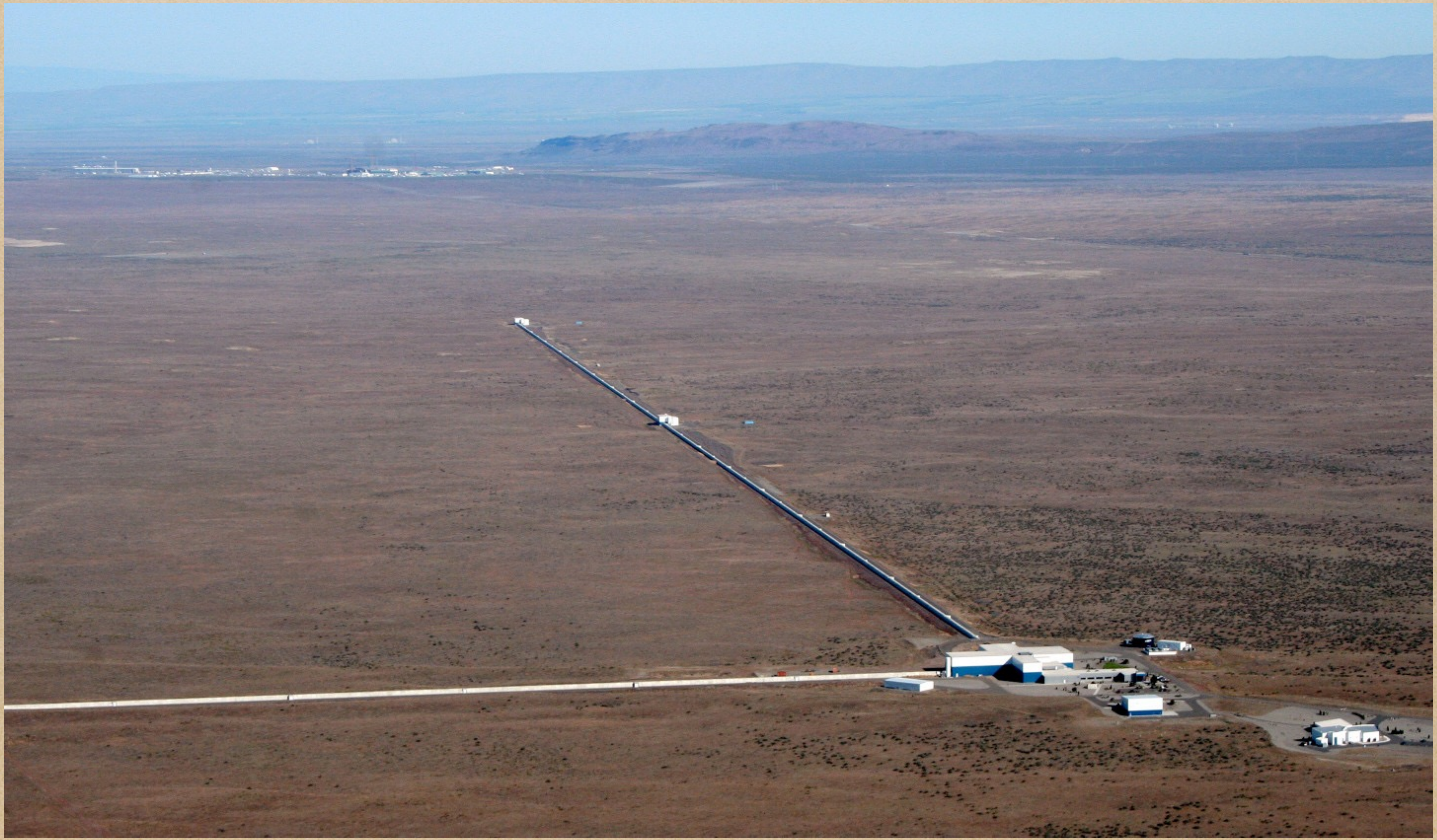
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}\,; \qquad \frac{8\pi G}{c^4} = 2.07 \times 10^{-43}\,\frac{\mathrm{s}^2}{\mathrm{m\,kg}}$$

- Weak effect of matter on geometry
- GWs carry huge energy but barely interact with anything
- Induced changes in length: < atomic nucleus / km

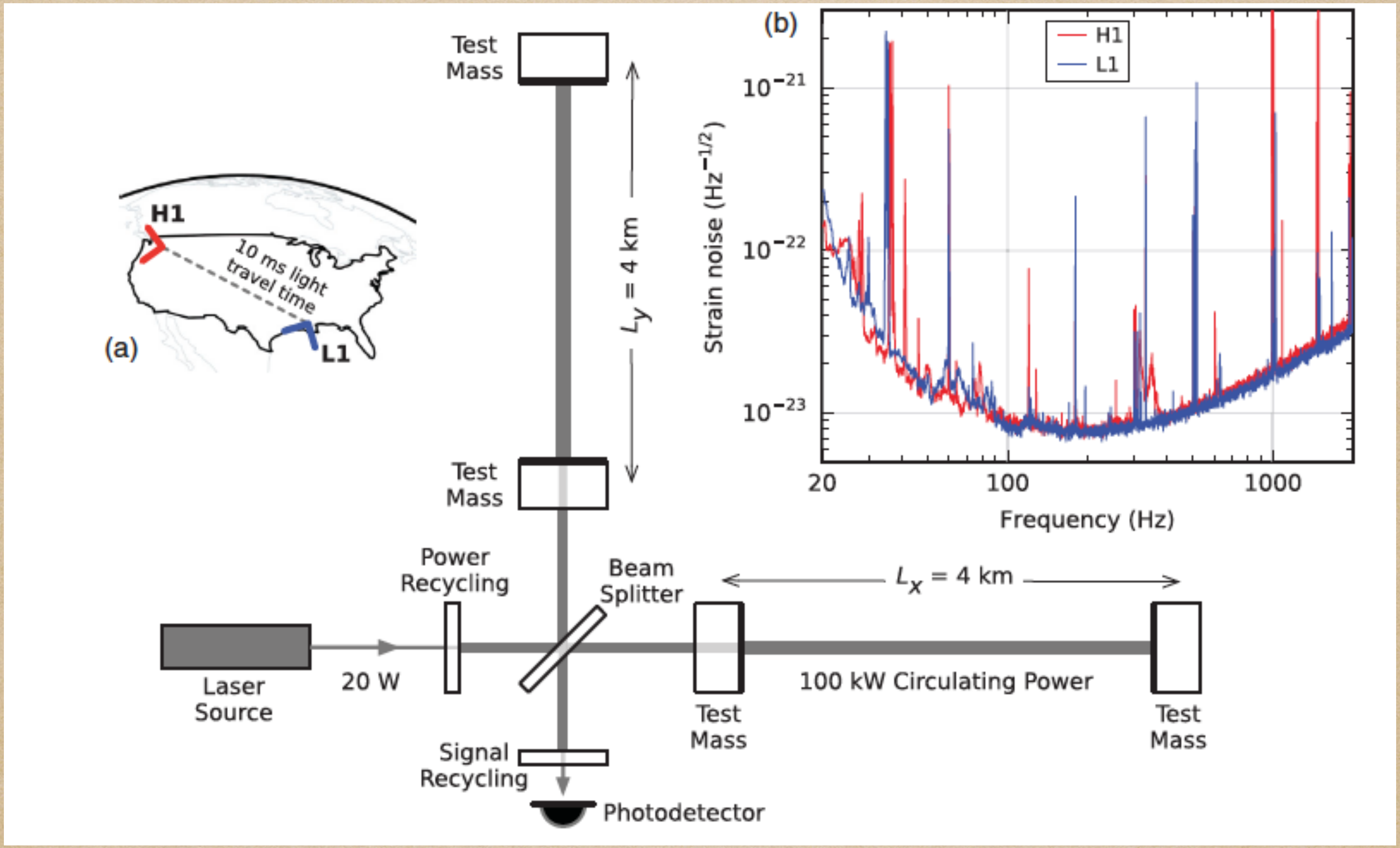


Effect on particles

- Measure this effect; Michelson-Morley type interferometer



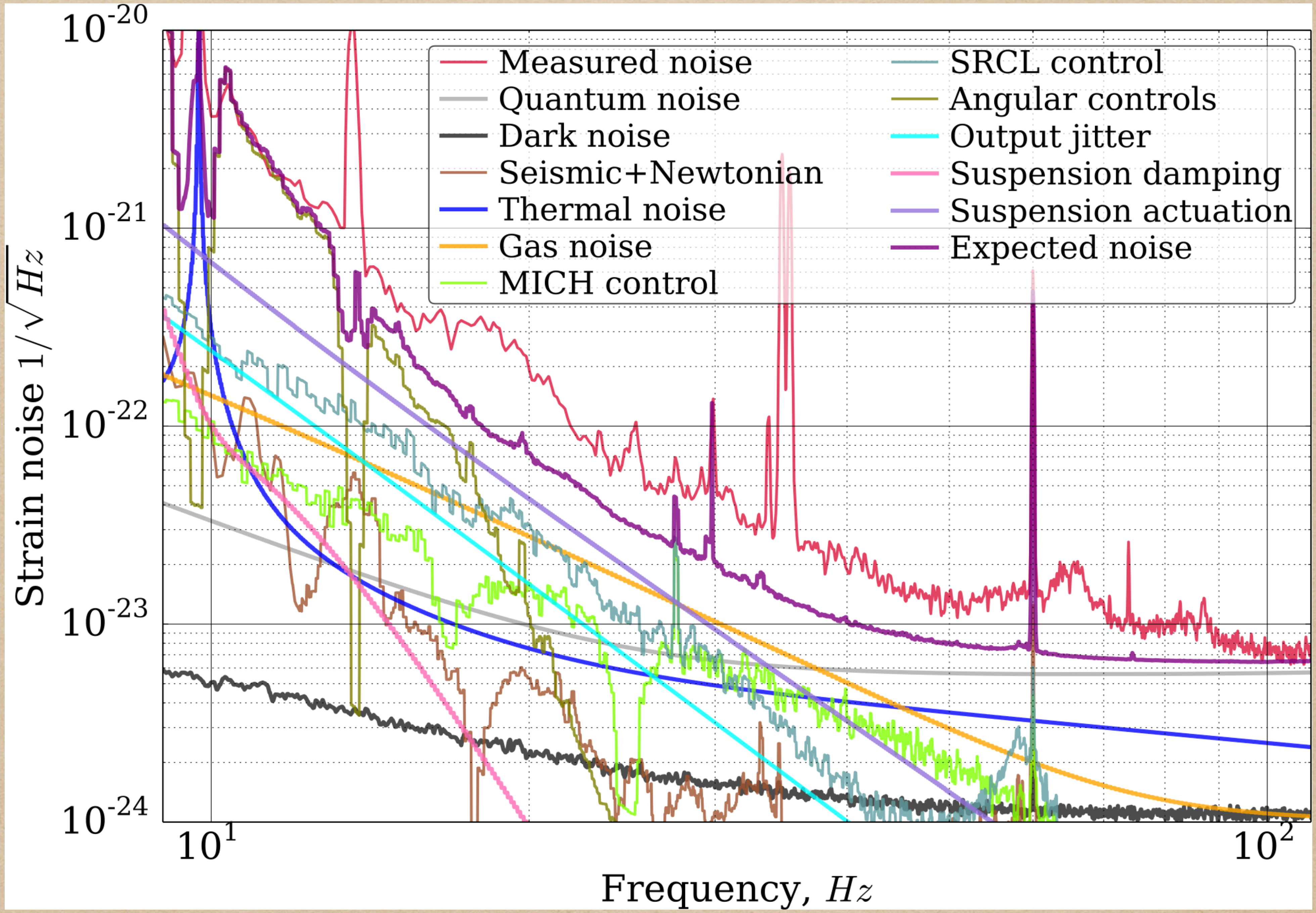
The interferometer diagram: LIGO



Abbott et al, PRL 116 (2016) 061102

Seismic, thermal, shot noise

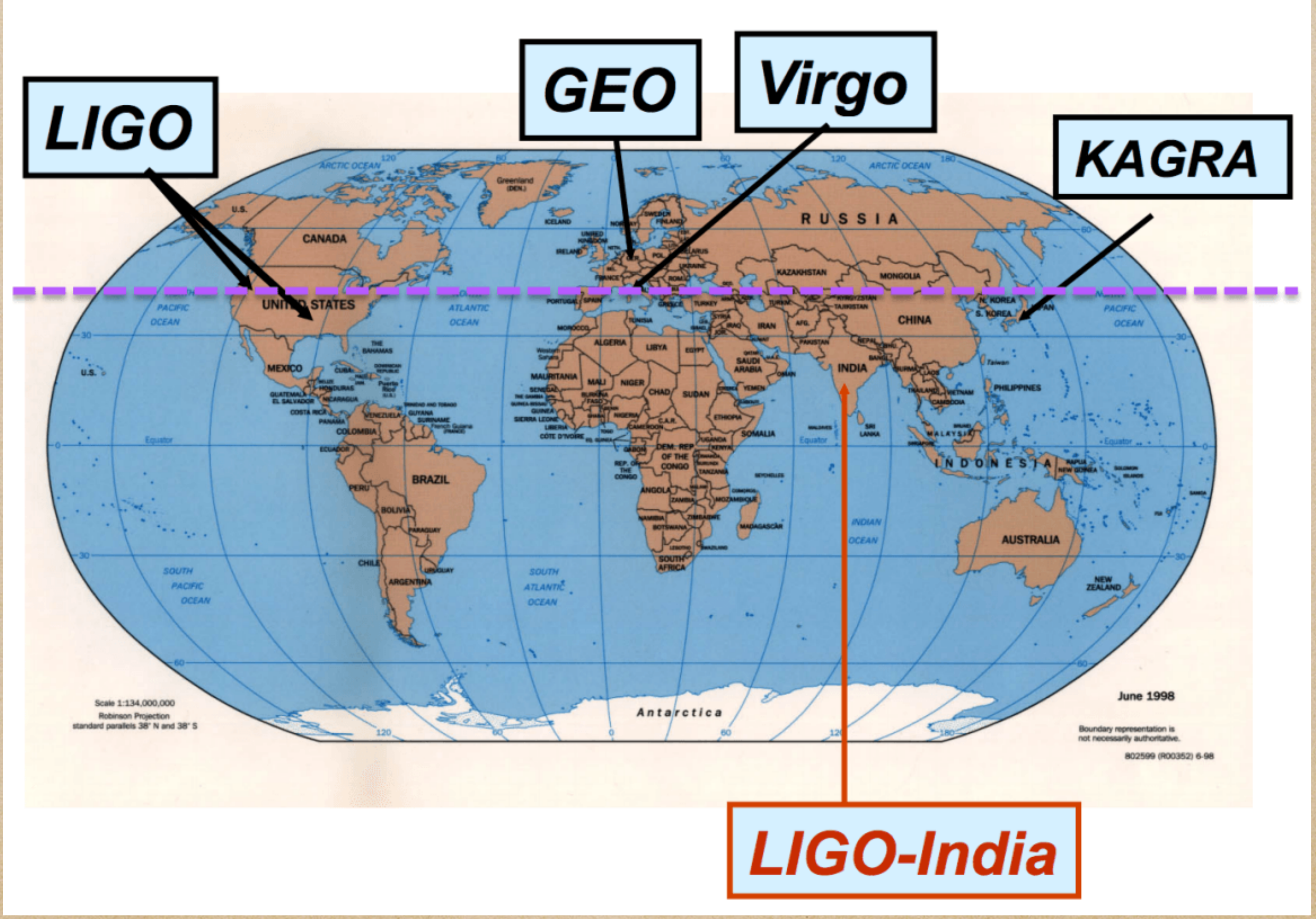
LIGO: Sources of noise



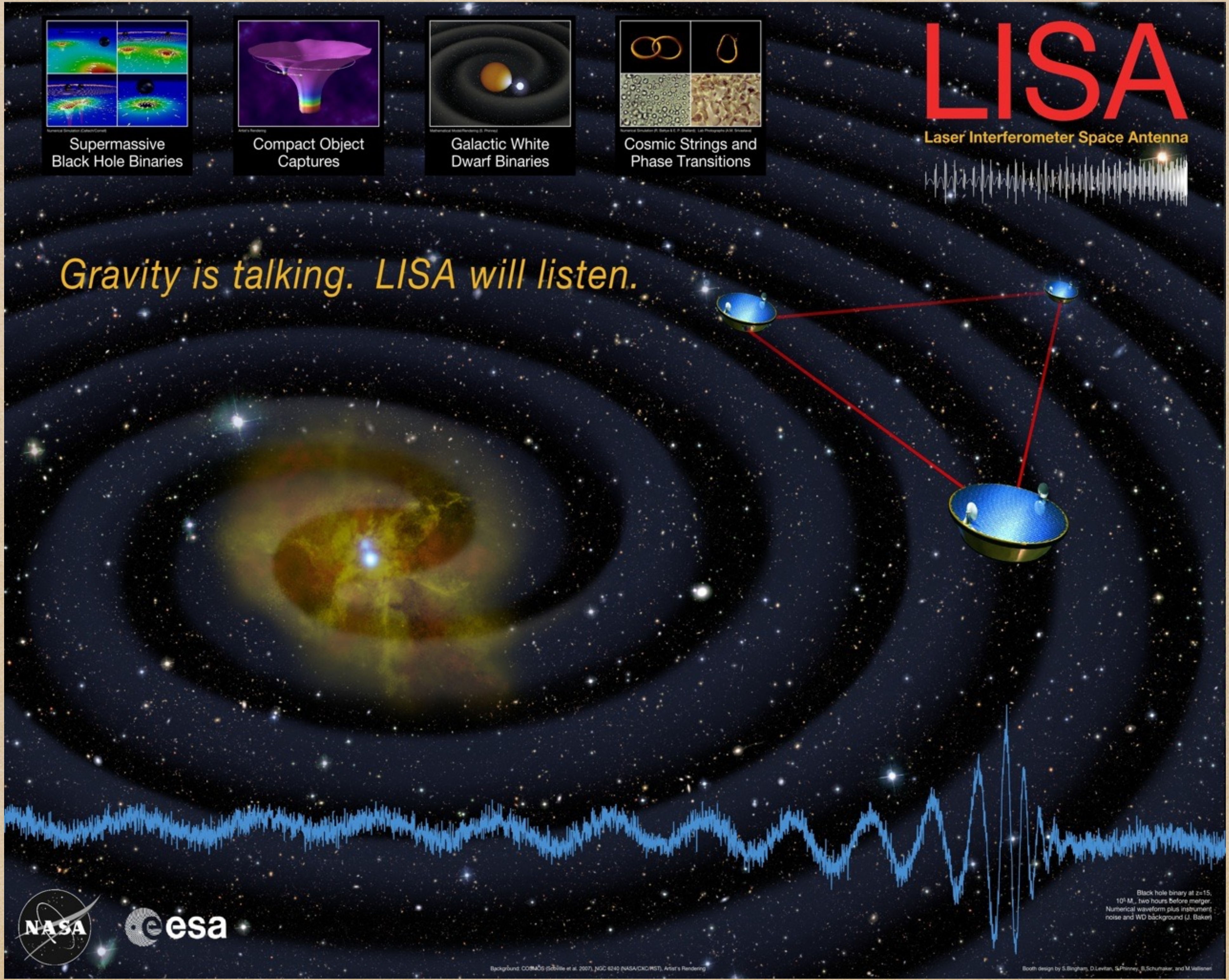
- Shot noise at high frequencies

The high frequency regime

- Interferometry with $\sim \mathrm{km}$ arms
- Detector: 2 LIGO, Virgo (2016), GEO600, KAGRA (2018), LIGO-India



The low frequency regime



4. Searching for gravitational waves

Detection and parameter estimation

Generic transient search

- No specific waveform model
- Identify excess power in detector strain data
- Use multi detector maximum likelihood   Klimenko et al. 1511.05999

Detection and parameter estimation

Generic transient search

- No specific waveform model
- Identify excess power in detector strain data
- Use multi detector maximum likelihood   Klimenko et al. 1511.05999

Binary coalescence search

- "Matched Filtering"
- Compare data stream with GW templates ("Finger print search")
- Bayesian analysis: Prior $\longrightarrow$ Posterior

The low frequency regime

- Interferometry with $\sim 10^6$ km arms
- Realm of space missions
- LISA: L3 mission of ESA's "Cosmic Vision" Launch: ~ 2034
- Configuration still uncertain:

  2 arms vs. 3 arms

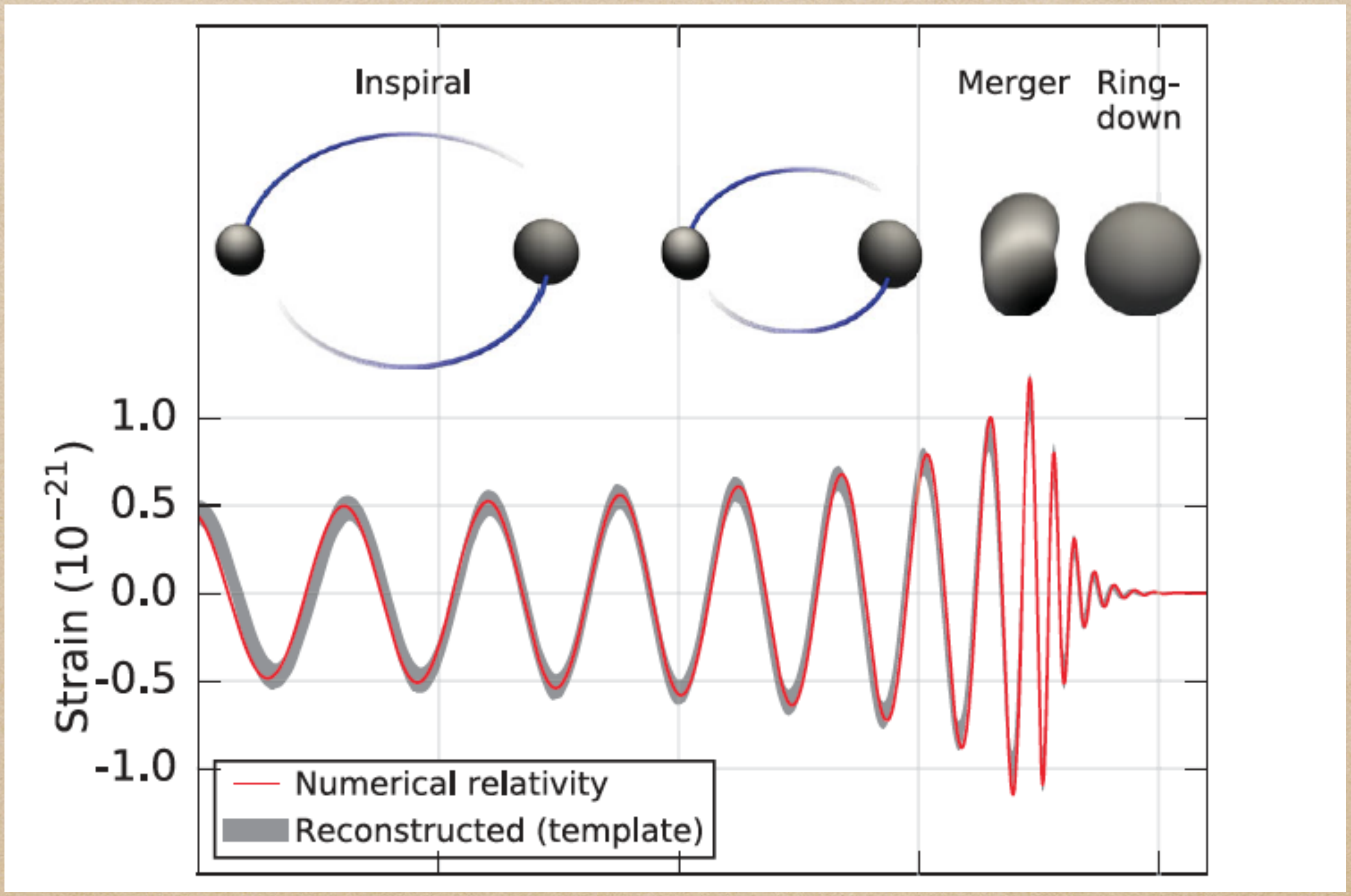
  10^6 km vs. 5×10^6 km

  2 yr vs. 5 yr life span
- Calibration binaries (WDs)
- Outstanding SNR
- LISA Pathfinder: Test mission

  Launched 3 Dec 2015

Modeling of GW sources

- Neutron star / Black hole binaries
- Others: Supernovae, cosmic strings, neutron star “mountains” etc.



Abbott et al, PRL 116 (2016) 061102

Black-hole binaries: parameters

- 8+2 Intrinsic parameters

  Masses $m_1 \, , \, m_2$

  Spins $\boldsymbol{S}_1 \, , \, \boldsymbol{S}_2$

  Eccentricity (often ignored; GW emission circularizes orbit)

- 7 Extrinsic parameters

  Location: Luminosity distance D_L , Right ascension α , Declination δ

  Orientation: Inclination ι , Polarization ψ

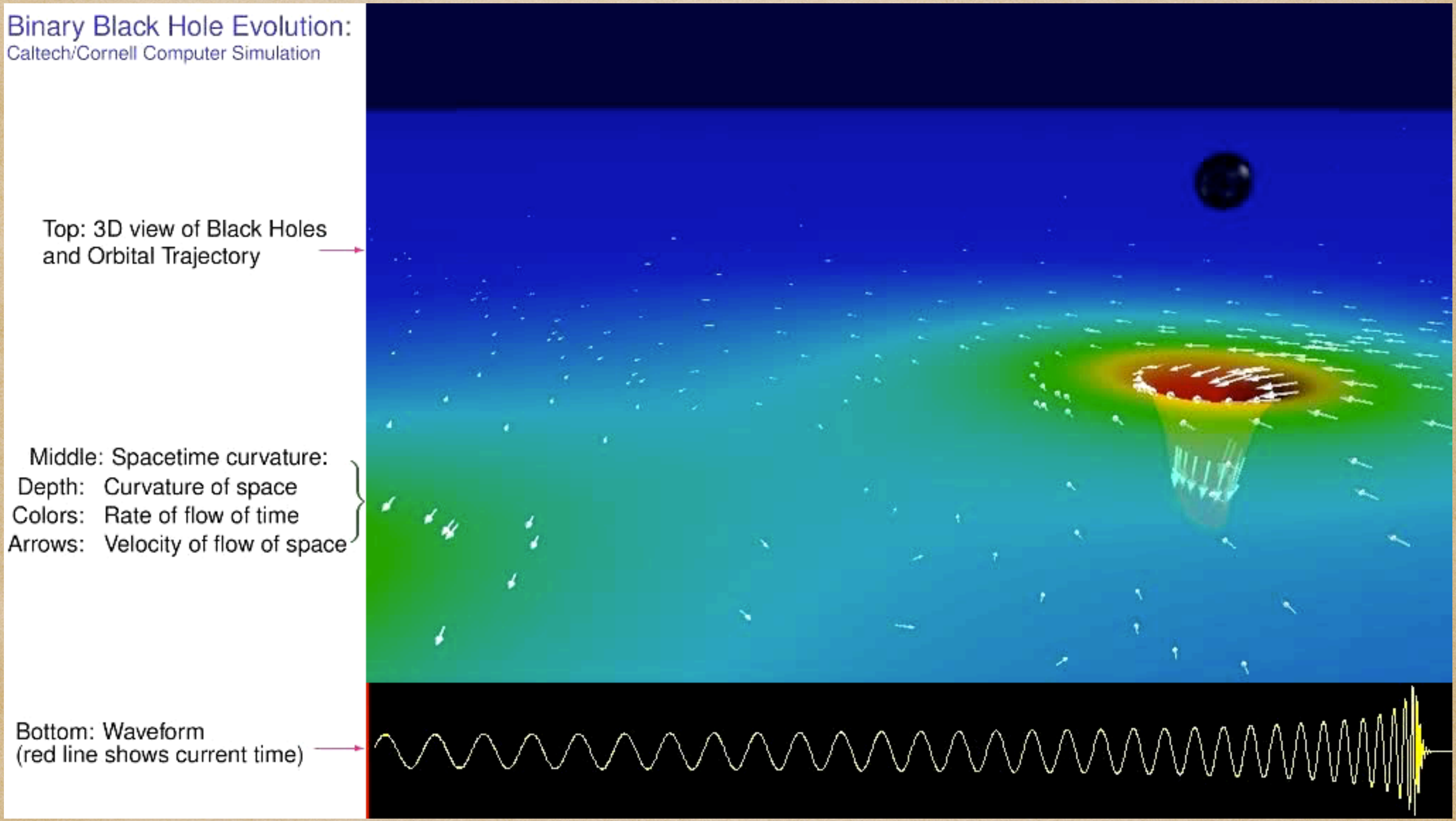
  Time t_c and Phase ϕ_c of coalescence

GW source modeling

- Key requirement for matched filtering: GW template catalog
- Model black holes in general relativity
  - Post Newtonian theory $\rightarrow$ Inspiral   Blanchet Liv.Rev.Rel. 2006
  - Numerical relativity $\rightarrow$ final orbits, merger

    Pretorius PRL 2005, Baker et al PRL 2006, Campanelli et al PRL 2006
  - Perturbation theory $\rightarrow$ Ringdown
- Need supercomputers!

Anatomy of a BHB coalescence



Thanks to Caltech-Cornell groups

5. The Nobel Prize winning discovery

Gravitational Waves: Ripples in spacetime

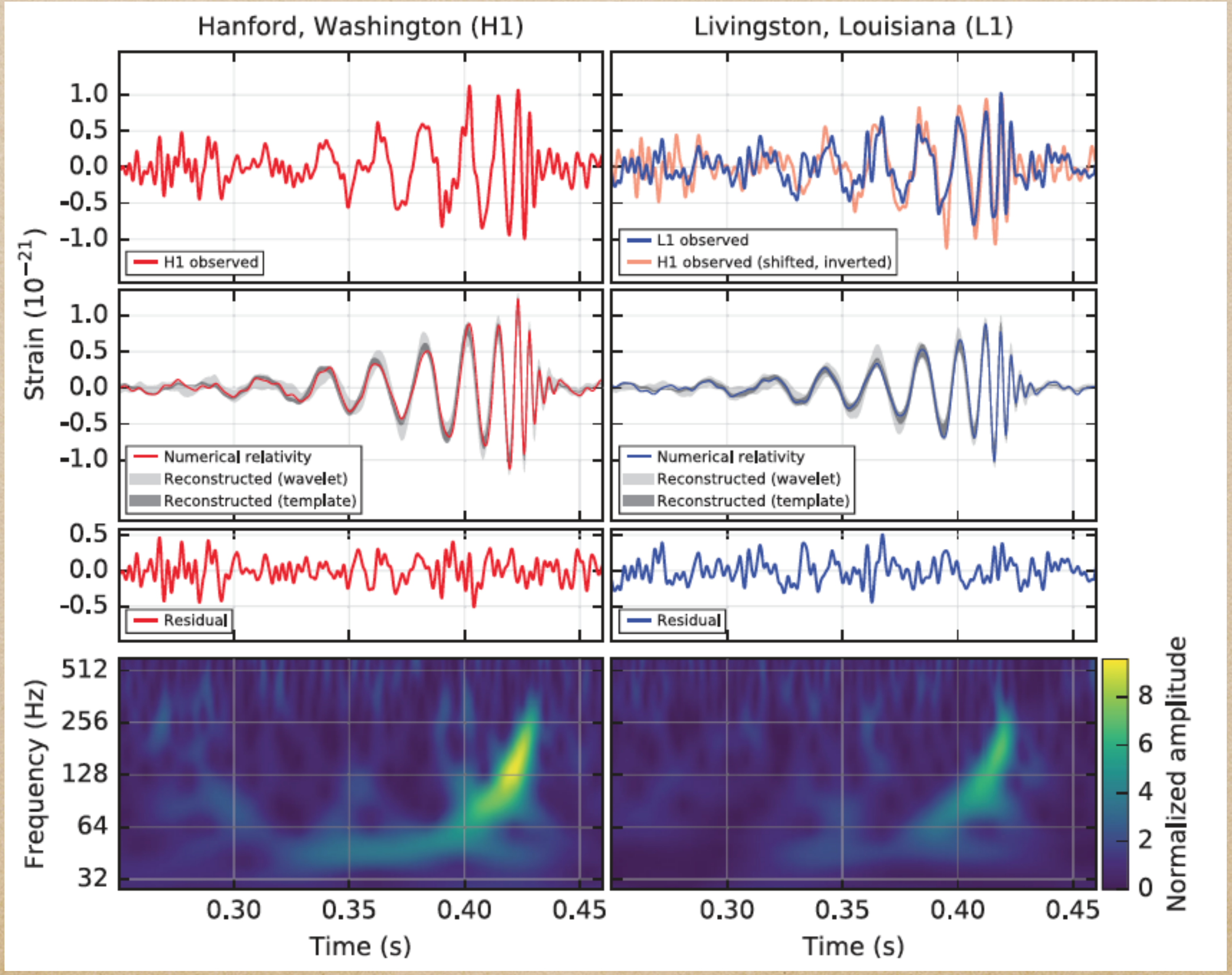
- Unusual news headlines on 11/12 February 2016
- First direct detection of gravitational waves: GW150914

So, what happened?

- Sep 14, 2015 at 09:50:45 UTC: SNR ~ 24

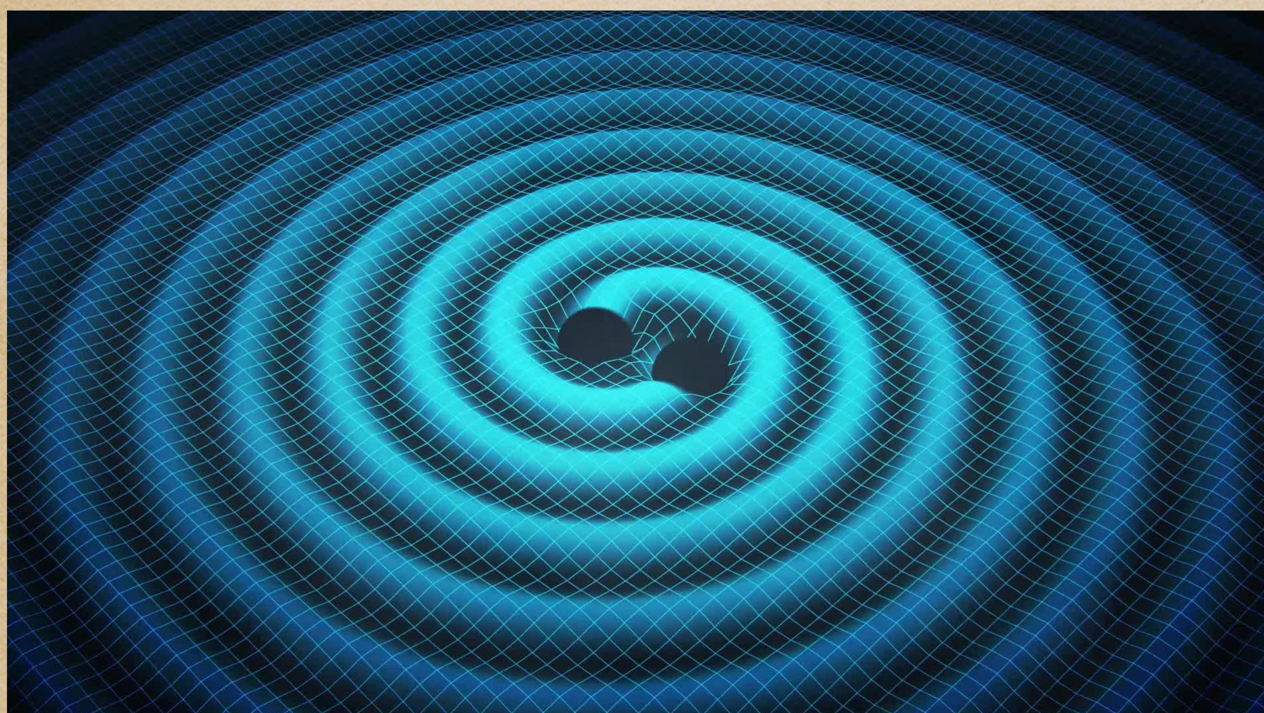
  Abbott et al. PRL 2016, Abbott et al. 1606.01210

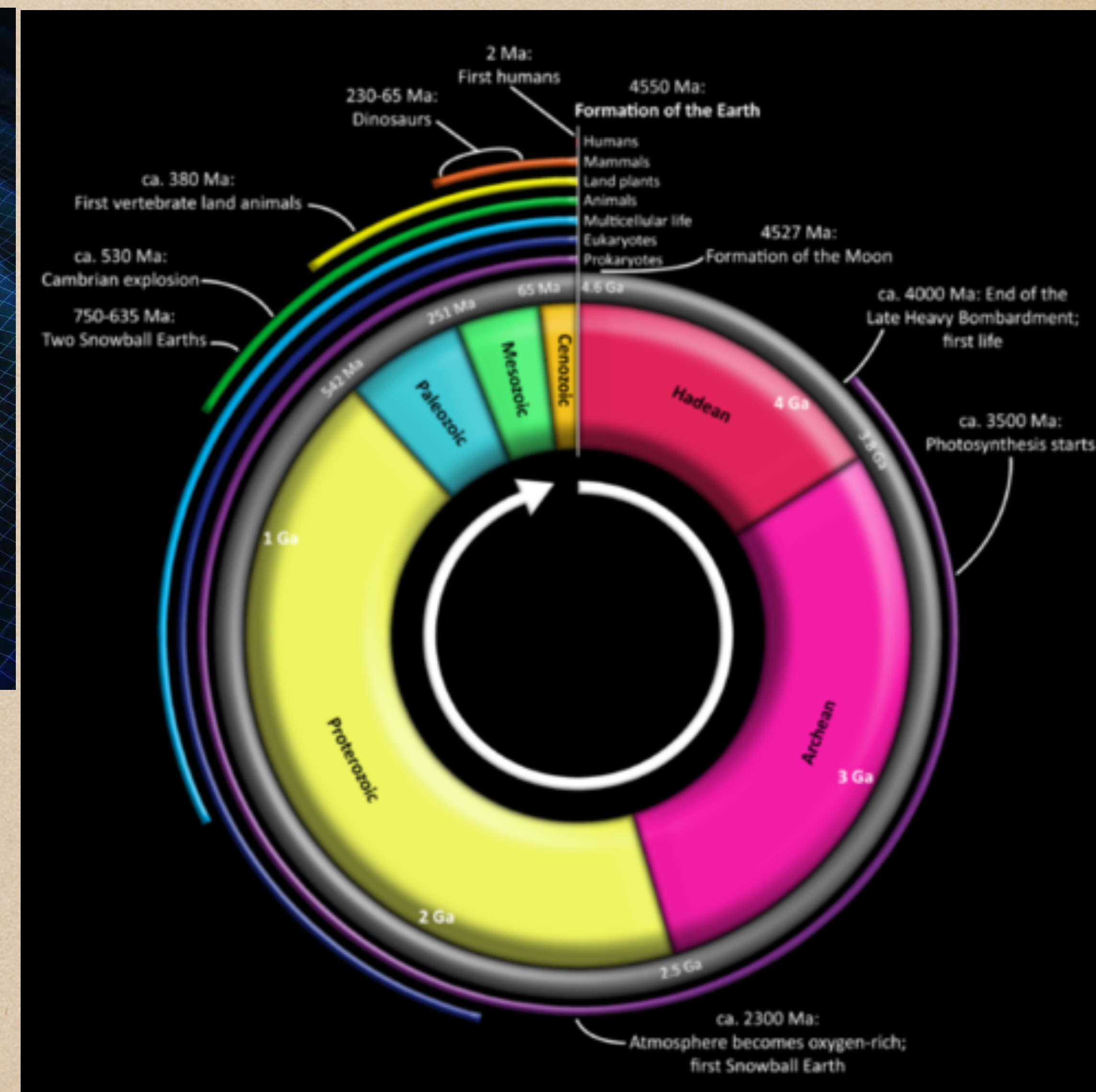
- BBH inspiral, merger and ringdown: $m_1 = 35^{+5}_{-3}\, m_\odot\,,\quad m_2 = 30^{+3}_{-4}\, M_\odot$



What really happened…

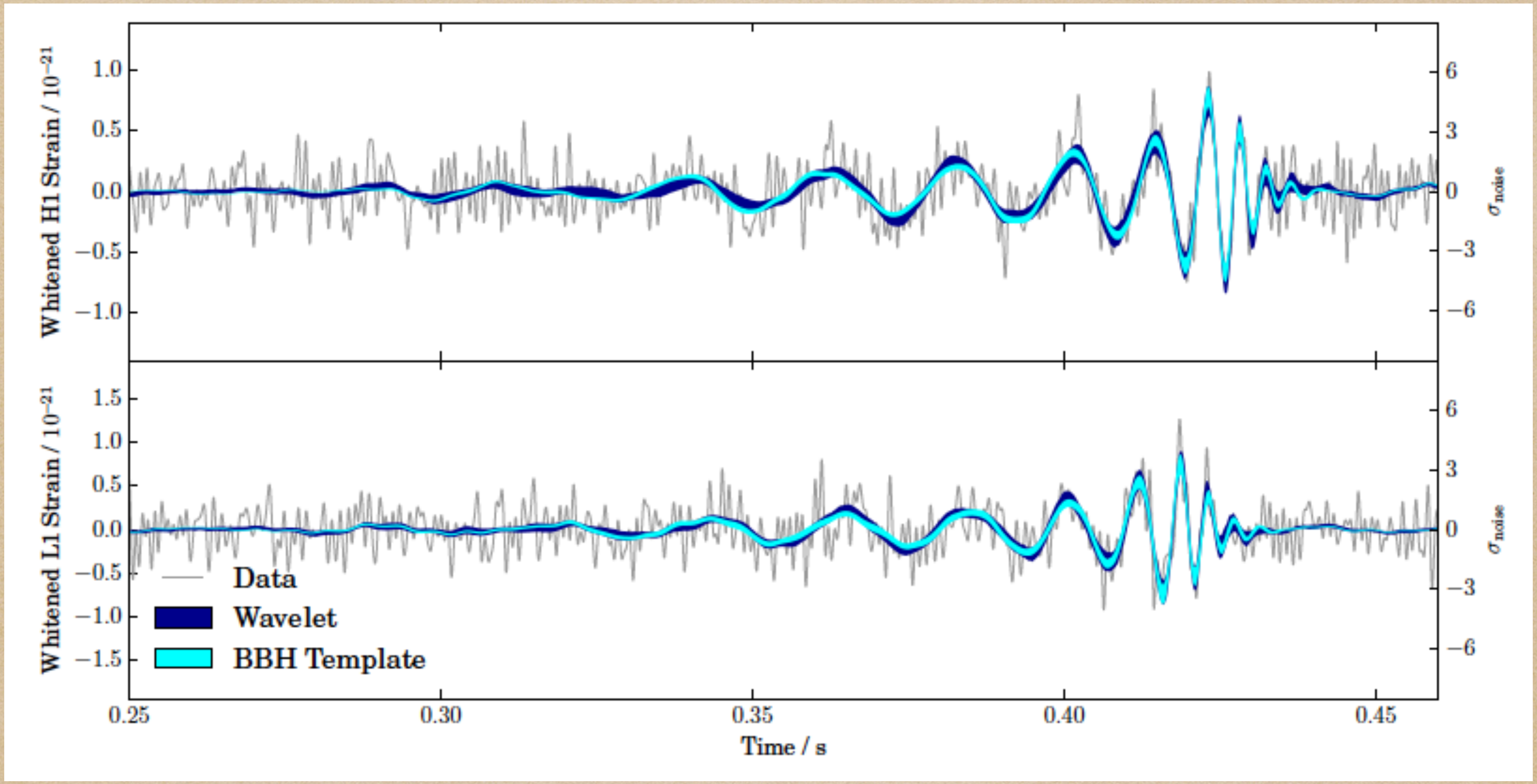
- Once upon a time: $1.34^{+0.52}_{-0.59}$ Gyr ago, somewhere in the universe





- Deep Precambrian

GW150914: The signal



Abbott et al 1602.03840

- Whitened by power spectral density
- Wavelet = Linear combination of sine-Gaussian pieces

GW150914: BH masses

- Source frame
- 2 Waveform models

Abbott et al. 1602.03840

$$m_1 = 36^{+5}_{-4}\ M_\odot$$

$$m_2 = 29^{+4}_{-4}\ M_\odot$$

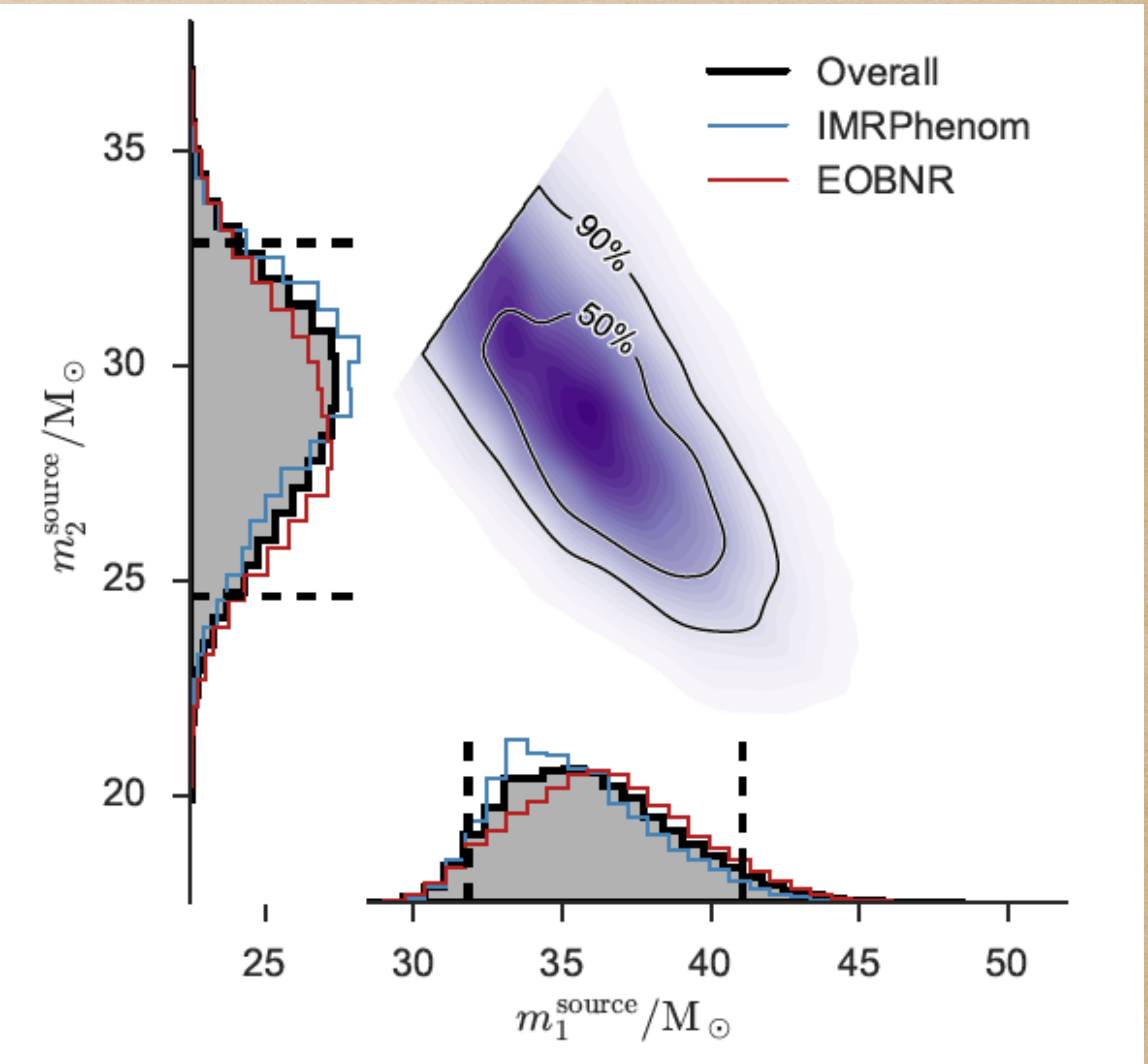
$$M_{\rm fin} = 62^{+4}_{-4}\ M_\odot$$

- Deficit in GWs!

$$\Delta M \approx 3\ M_\odot$$

$$\approx 5.4 \times 10^{54}\ \text{erg}$$

$$L_{\rm max} \approx 3.6 \times 10^{56}\ \text{erg/s}$$



Abbott et al 1602.03840

GW150914: BH parameters

- Mass ratio $q \equiv \frac{m_2}{m_1} = 0.65 \pm 0.03$

- Spins harder to measure: few cycles, no full-precession catalog

  $$\chi_1 = \frac{|\boldsymbol{S}_1|}{m_1^2} < 0.7\,, \quad \chi_2 = \frac{|\boldsymbol{S}_2|}{m_2^2} < 0.9$$

  $$\chi_{\rm fin} = 0.67^{+0.05}_{-0.07}$$

- Luminosity distance $D_L = 410^{+160}_{-180}\ \mathrm{Mpc}$

- Source redshift $z = 0.088^{+0.031}_{-0.038}$

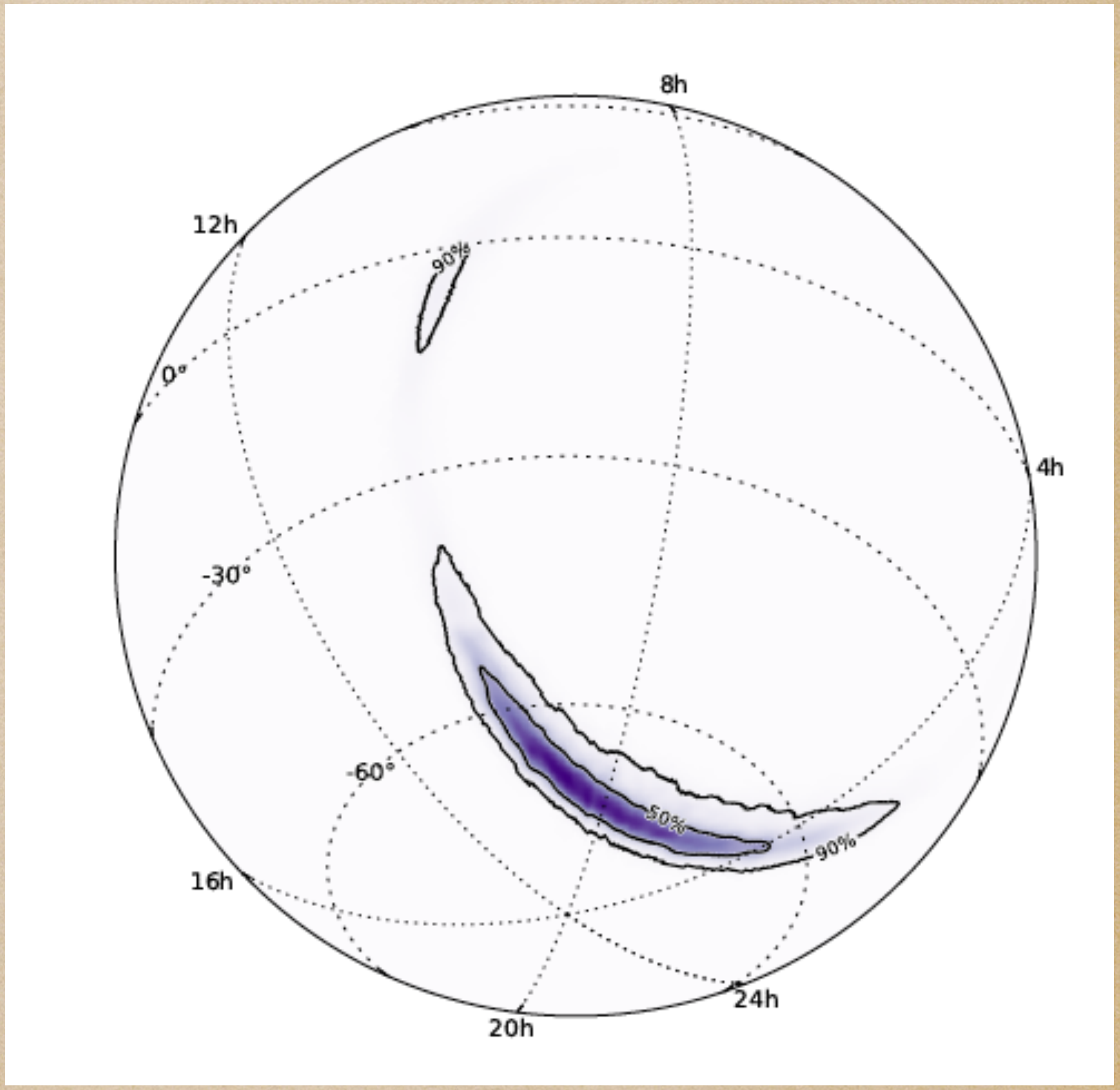
GW150914: Sky location

- Important for EM follow-up
- GW detectors are all-sky
- Via triangulation
- 2 detectors

  $\sim 590 \ \mathrm{deg}^2$

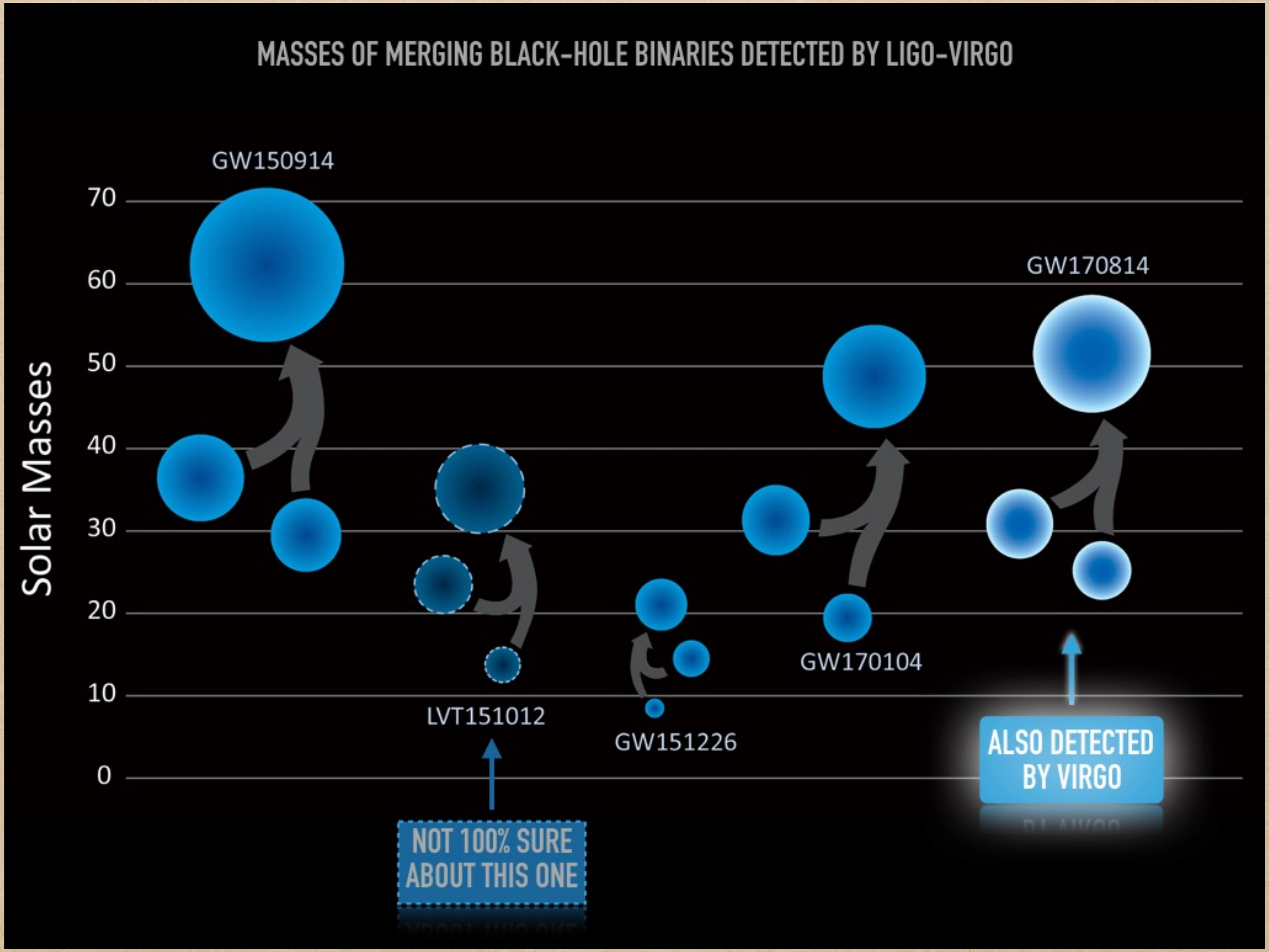
  Southern hemisphere
- To improve with

  Virgo, KAGRA, LIGO India

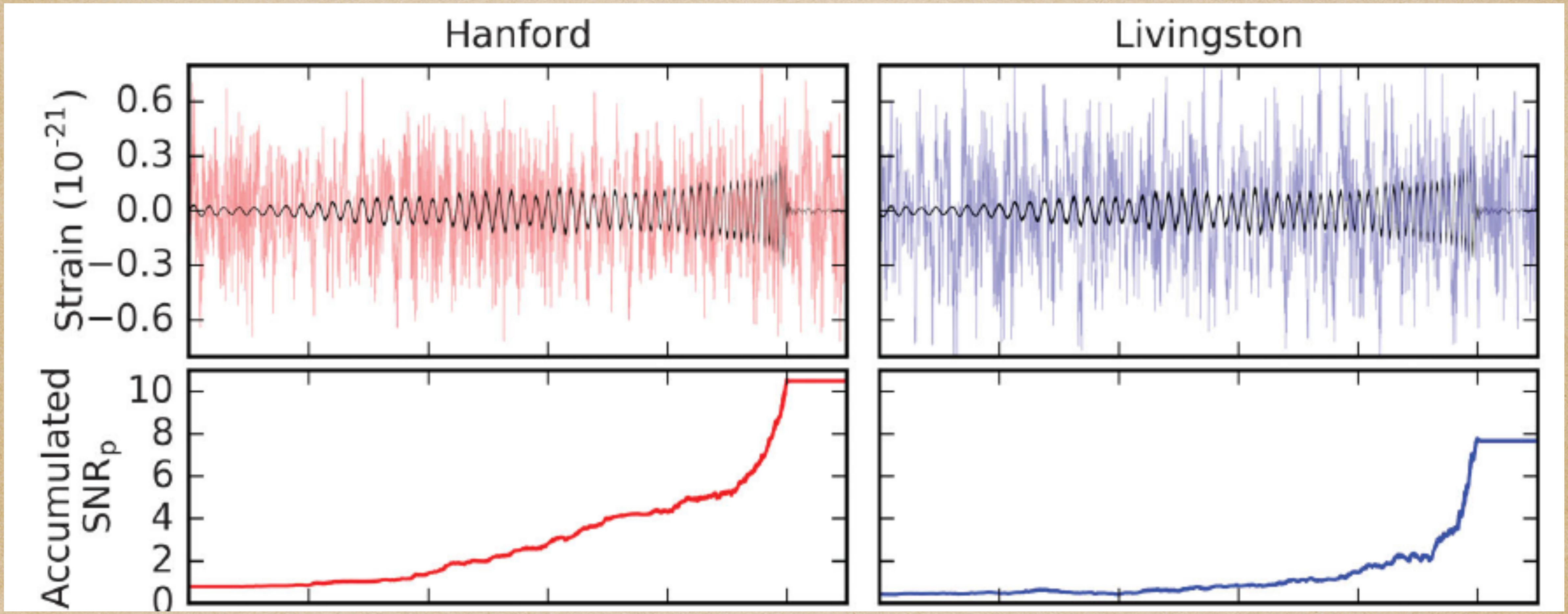


Abbott et al 1602.03840

4 (+1) BBH detections so far



GW151226: The signal



Abbott et al 1606.04855

- Filtered by $30 - 600\ \mathrm{Hz}$ band pass
- Duration $\sim 1\ \mathrm{s}$; ~ 55 orbits; $f \approx 35 \ldots 450\ \mathrm{Hz}$

GW151226: BH masses

- Source frame
- 2 searches

Abbott et al. 1606.04855

$$m_1 = 14.2^{+8.3}_{-3.7}\ M_\odot$$

$$m_2 = 7.5^{+2.3}_{-2.3}\ M_\odot$$

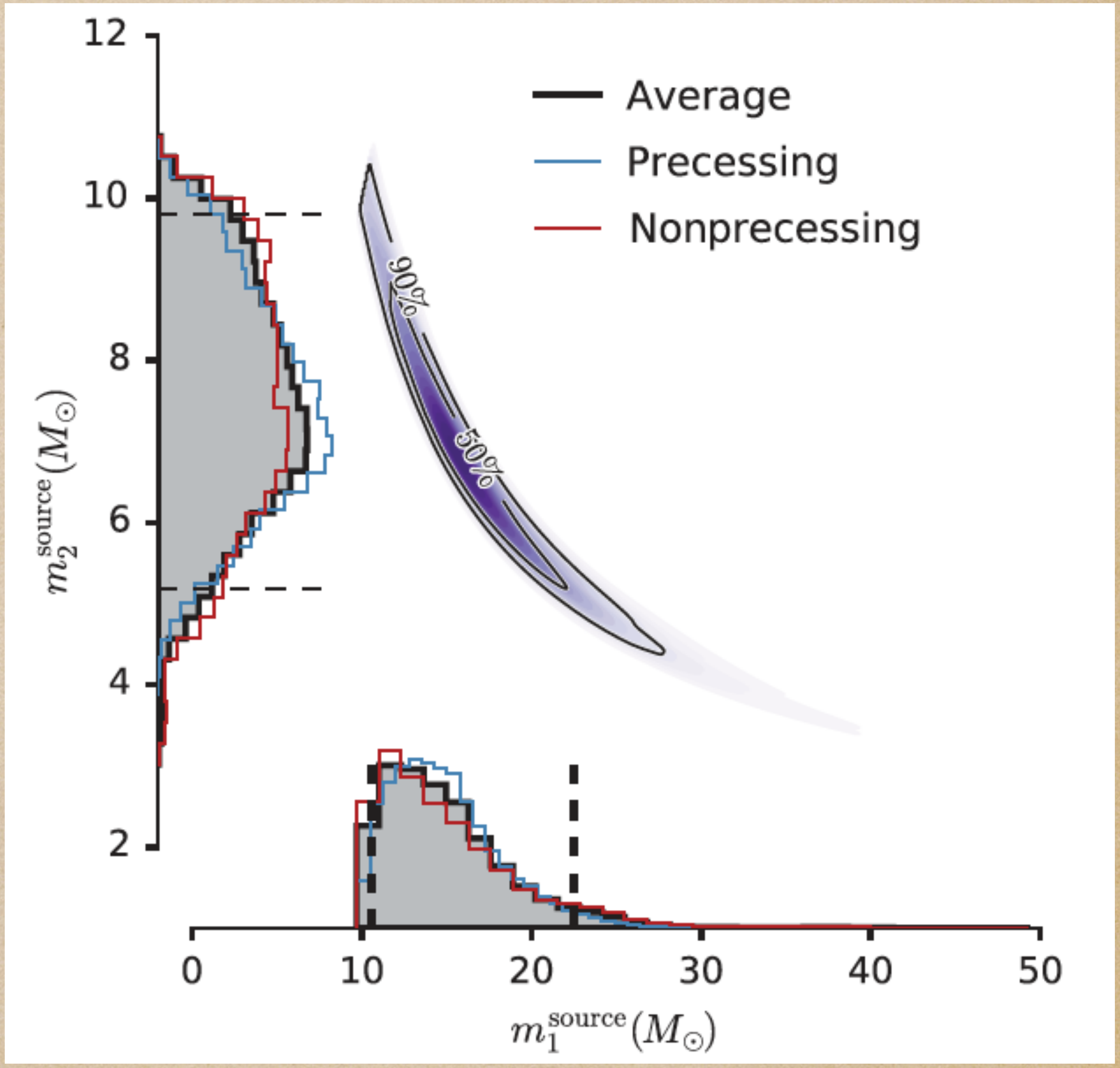
$$M_{\rm fin} = 20.8^{+6.1}_{-1.7}\ M_\odot$$

- Deficit in GWs!

$$\Delta M \approx 1.0^{+0.1}_{-0.2}\ M_\odot$$

- Spins:

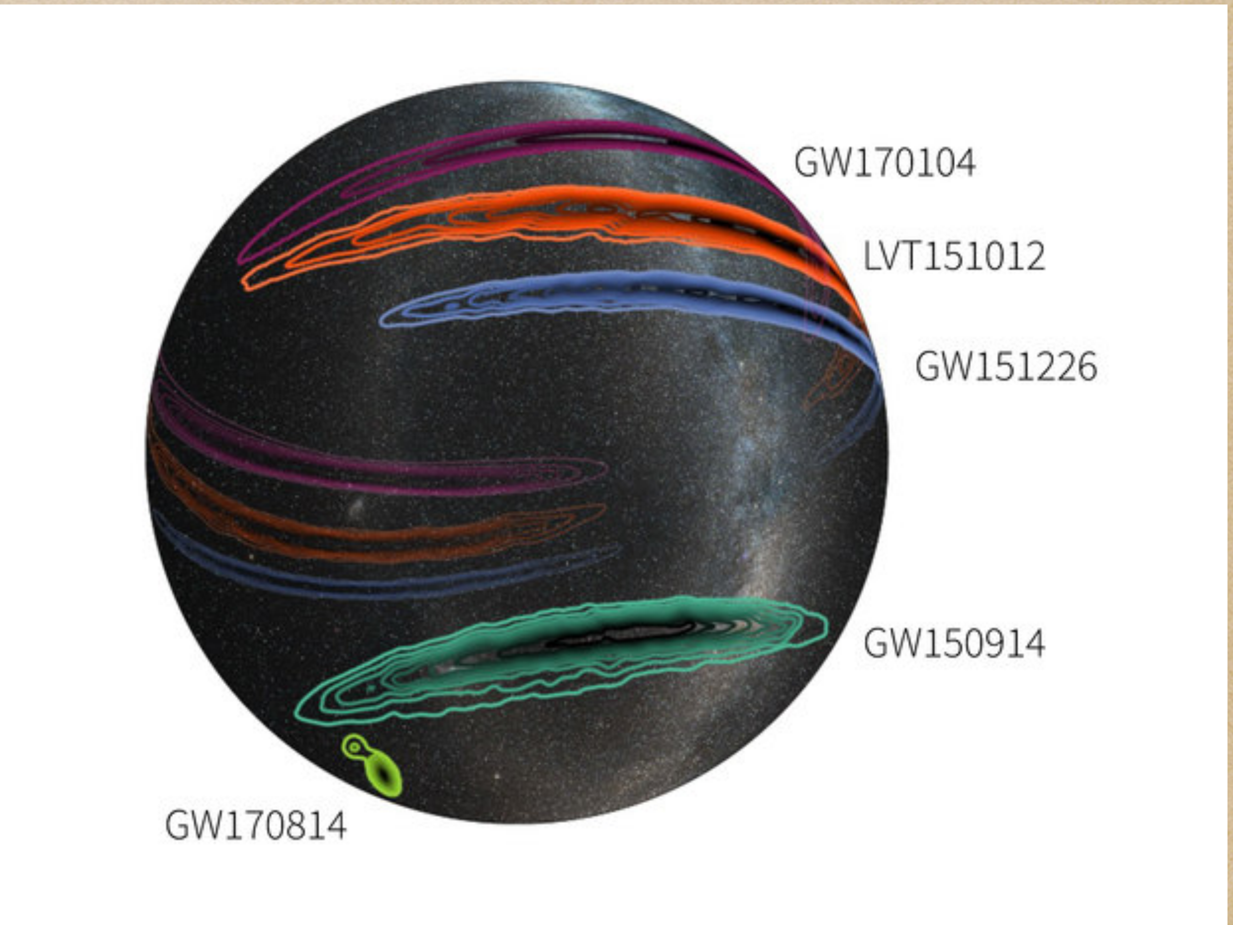
$$\chi_{\rm eff} \sim 0.25\,, \quad \chi_p \sim 0.5$$



Abbott et al 1606.04855

2017: Virgo joins O2

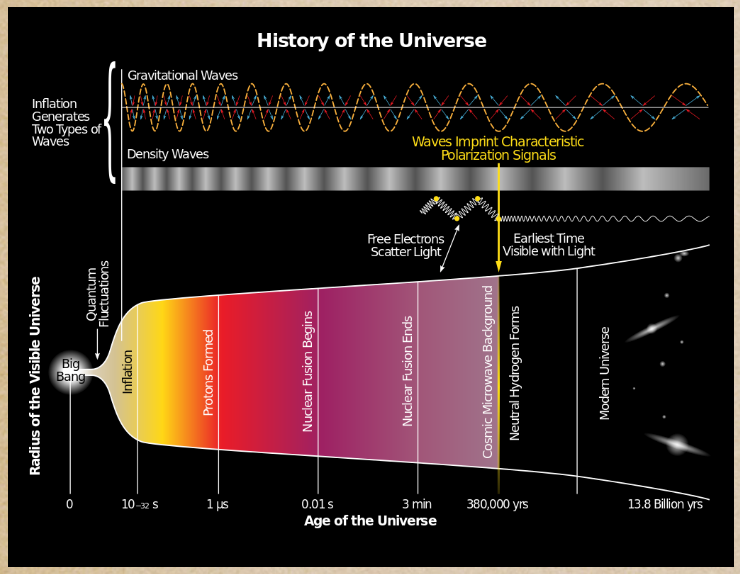
- 3 detectors
- much improved sky location!
- First triple coincidence detection GW170814



6. Applications in physics & astrophysics

Overview

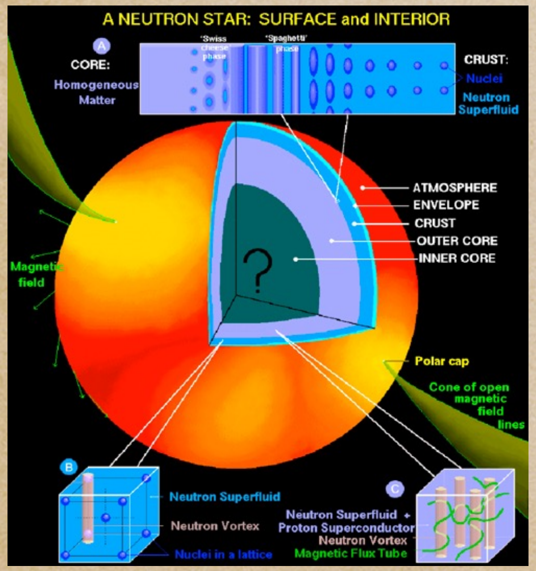
Early Universe



Testing Einstein's theory

Galaxy history

Equation of state



BH populations

The unknown…

Testing GR with GW150914: Graviton mass

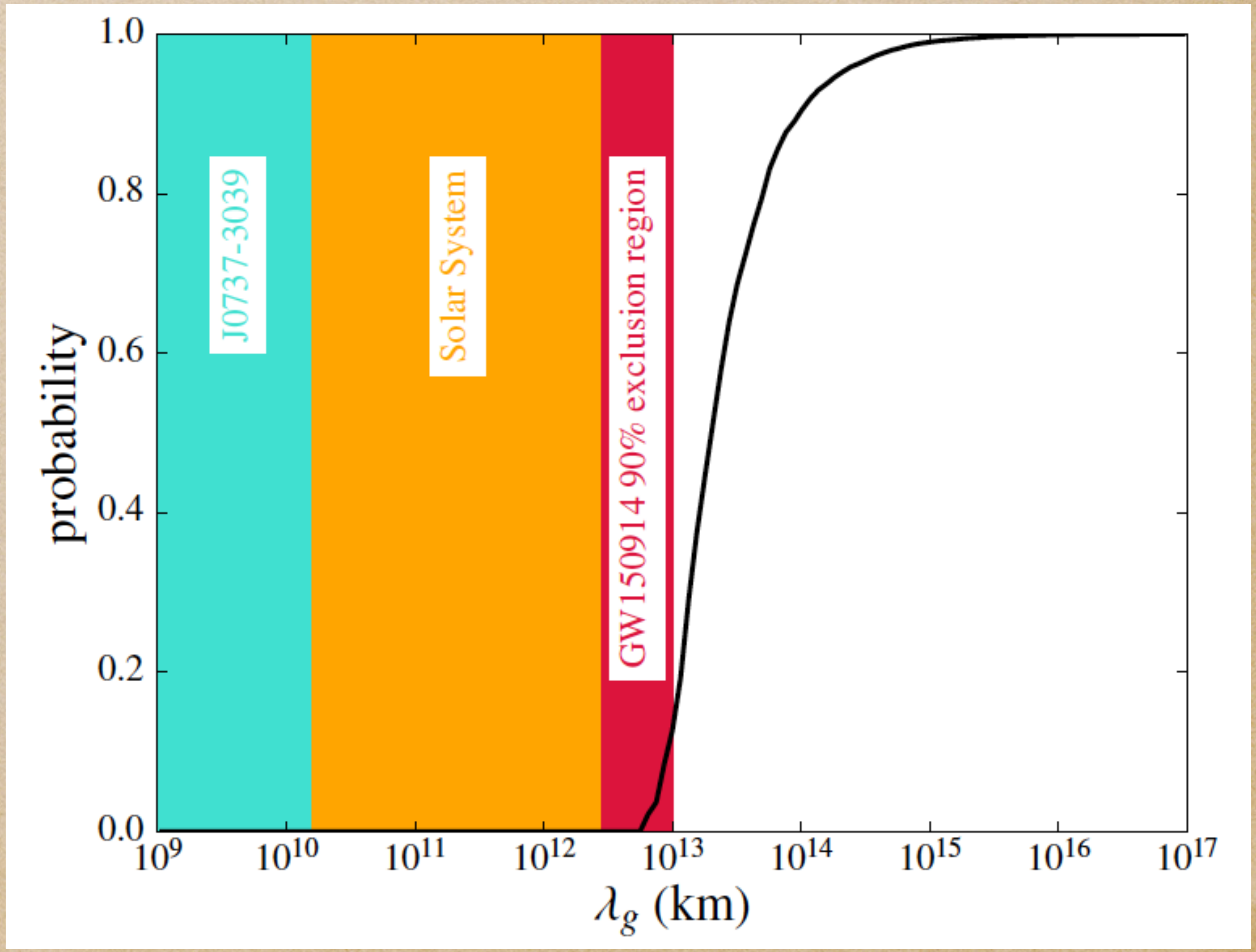
- Phenomenological model
- Massive graviton ⇒ Compton wavelength $\lambda_g = \dfrac{h}{m_g c}$
- Dispersion relation: $\dfrac{v_g^2}{c^2} = 1 - \dfrac{h^2 c^2}{\lambda_g^2 E^2}$
- ⇒ Quasi-1PN phase term

$$\phi_{\rm MG}(f) = -\frac{\pi D c}{\lambda_g^2 (1+z) f}$$

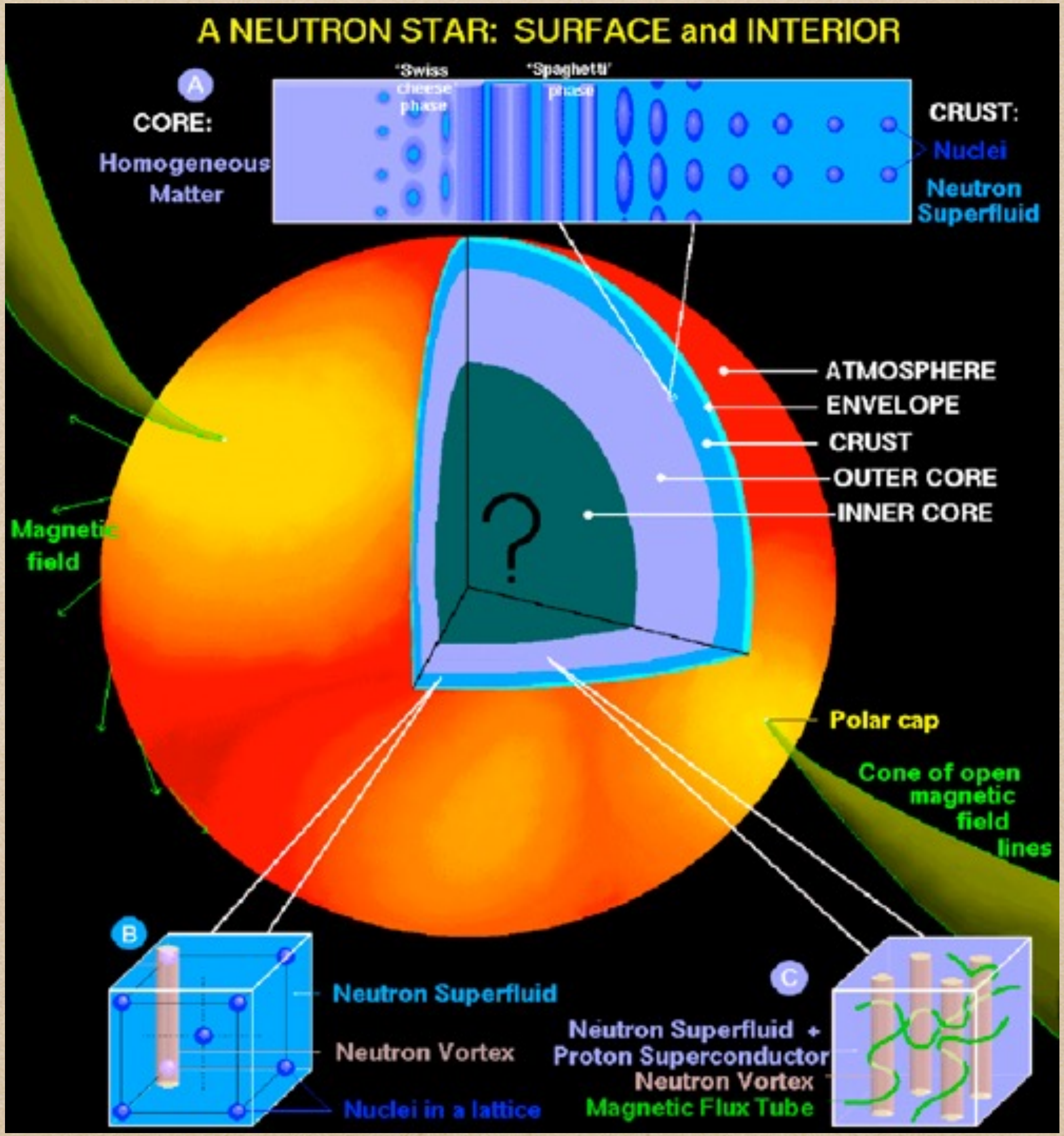
Will 1998 PRD

$$\boxed{m_g \leq 1.2 \times 10^{-22}\ {\rm eV}/c^2}$$

Abbott et al 1602.03841

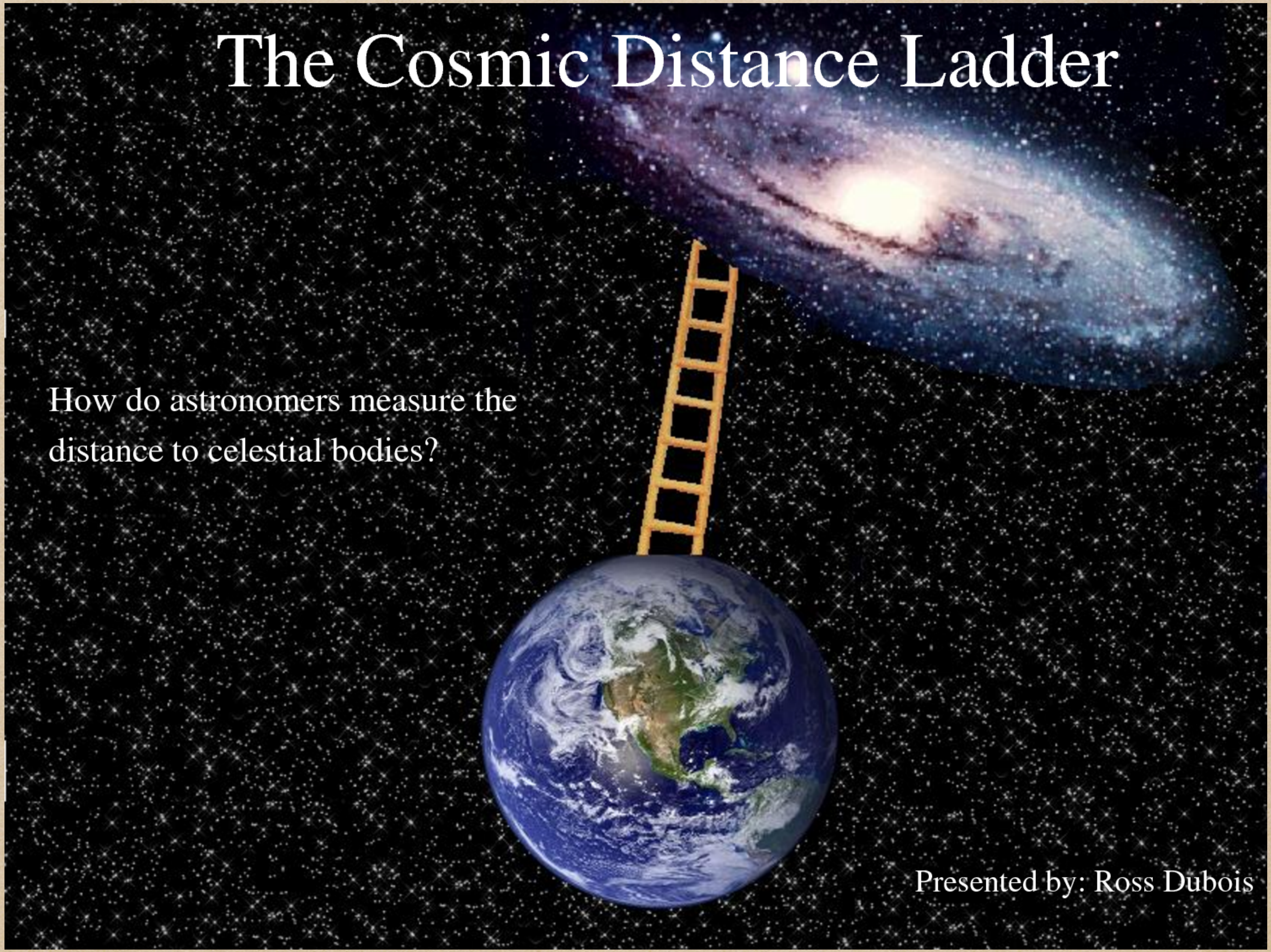


Equation of state of matter



- E.g. through tidal effects

Cosmological distance ladder



- Need electromagnetic counterpart!

Conclusions

Conclusions

- Gravity is a manifestation of spacetime geometry
- General Relativity predicts gravitational waves
- Huge effort to build detectors and model GW sources
- First detection: GW150914 (2017 Nobel Prize)
- New window to the Universe
- It has just started!
- Scheduled: Upgrade of LIGO, Virgo

  Under construction: KAGRA, LIGO India

  Space detector: LISA

  Pulsar Timing Arrays