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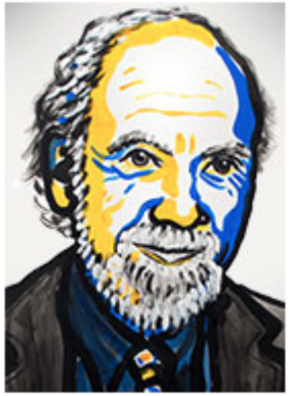
Rainer Weiss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Kip S. Thorne

THCA Student Seminar

A GLIMPSE INTO GRAVITATIONAL WAVE SCIENCE

Yukai Xia Oct. 13, 2017

Outline

- Physical Nature of GWs
- Astronomical sources of GWs
- Detection techniques
- Recent LIGO results

Part I. Physical Nature of GWs

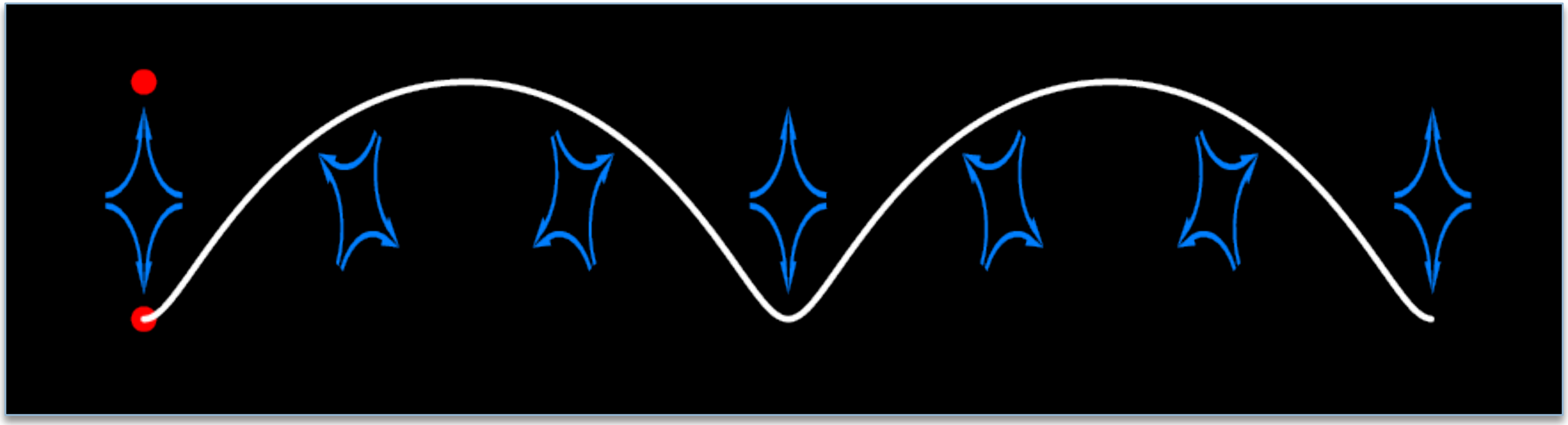
What is GW?

- ☐ **General relativity predicts:**

  Time-changing gravitational tidal field

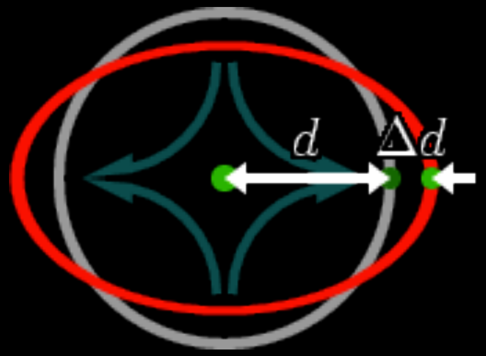
  ➡ propagates out at speed c

  ➡ gravitational radiation!



Effect of GW on test masses

- **GW “pushes and pulls” on nearby test masses**
  - The proper distance between them is changed
  - The fractional change is denoted by *h*, the “strain” field.
  - *h* is related to the metric perturbation in a full GR



$$h = \frac{2\Delta d}{d} = 2 \times \frac{\text{change in displacement}}{\text{displacement}}$$

Spin-2 nature of GW

- **A GW can have two distinct polarization states:**

h_+ polarization

$h_\times$ polarization

  - Divergence-free, pure strain
  - These states do not change under a 180 degree rotation → graviton is massless with spin 2

Quadrupole nature of GW radiation

E&M

Static coulomb field: $E \sim \frac{Q}{r^2} \rightarrow \xcancel{\frac{\dot{Q}}{r}}$

Static dipole field: $E \sim \frac{\boldsymbol{d}}{r^3} \rightarrow \frac{\dot{\boldsymbol{d}}}{r^2} \rightarrow \frac{\ddot{\boldsymbol{d}}}{r}$ **Dipole radiation!**

GW

Static monopole field: $g \sim \frac{M}{r^2} \rightarrow \xcancel{\frac{\dot{M}}{r}}$

Static dipole field: $g \sim \frac{\boldsymbol{d}}{r^3} \rightarrow \frac{\dot{\boldsymbol{d}}}{r^2} \rightarrow \xcancel{\frac{\ddot{\boldsymbol{d}}}{r}}$ momentum conservation

Static quadrupole field: $g \sim \frac{\mathcal{I}}{r^4} \rightarrow \rightarrow \frac{\dddot{\mathcal{I}}}{r}$ **Quadrupole radiation!**

Why is GW so weak?

E&M $$\frac{P}{E} \approx \frac{\langle \ddot{d}\ddot{d} \rangle}{E} \sim \frac{f^4 Q^2 s^2}{Q^2/s} \sim f^4 s^3 \sim (\lambda f)^3 \left(\frac{s}{\lambda}\right)^3 f \sim v^3 f$$

v << 1

Size of source

GHz ~ THz

GW $$\frac{P}{E} \approx \frac{\langle \dddot{\mathcal{I}}\dddot{\mathcal{I}} \rangle}{E} \sim \frac{f^6 M^2 s^4}{M^2/s} \sim f^6 s^5 \sim (\lambda f)^5 \left(\frac{s}{\lambda}\right)^5 f \sim v^5 f$$

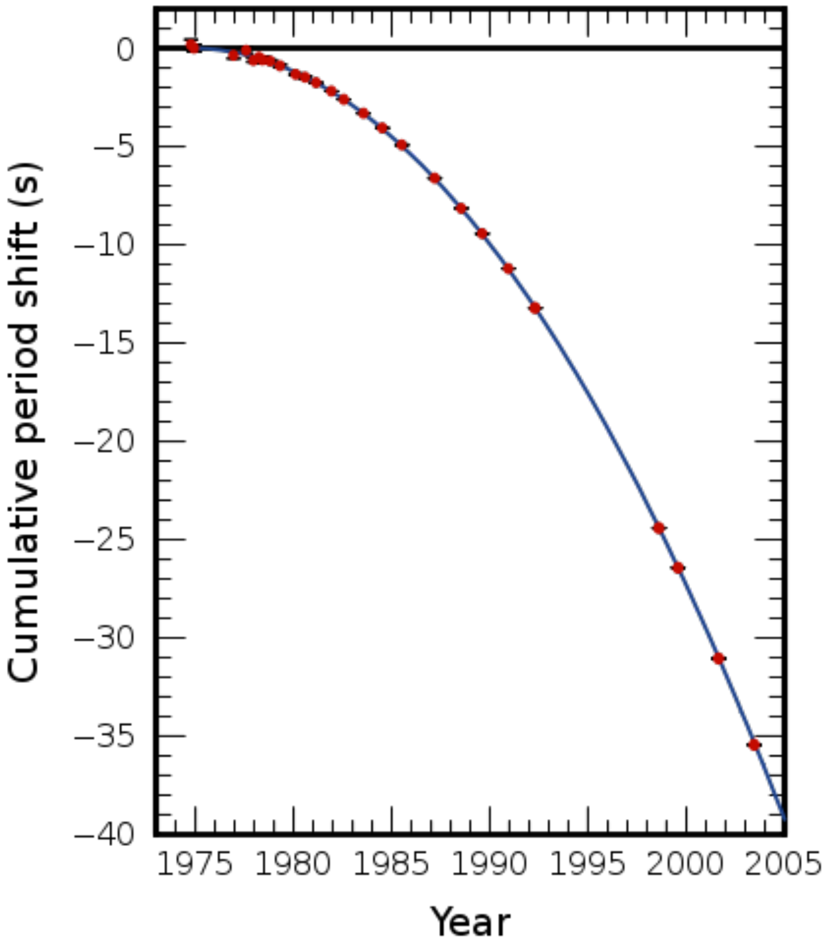
v << 1

Hz ~ kHz

- **GW also interacts very weakly with matter**
  - **Dust** or **ideal fluid:** no response to the pure strain field of GW.
  - **Viscous** or **elastic matter:** attenuation/dispersion negligible.
  - Array of good emitters (NSs): “GW blackbody”?

History note: NS-NS orbital decay

- PSR 1913+16
  (Hulse & Taylor, 1975,
  Nobel prize 1993)
  - Pulsar + NS binary
  - 1.4+1.4 solar masses
  - Orbital period 7.75hr
  - Separation ~several solar radii
  - First indirect evidence for GW
  - ~A dozen detected now by radio



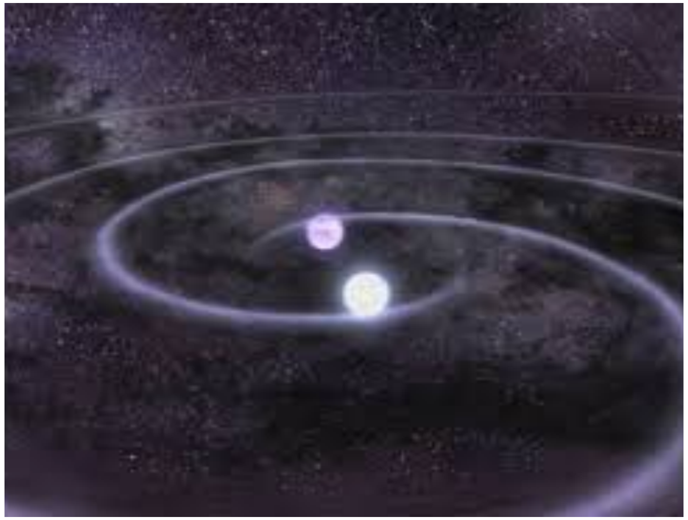
Calculating the strain of a GW

$$g \approx \frac{\dddot{I}}{r} \Rightarrow h \approx \frac{\ddot{I}}{r}$$

$$h \approx \frac{M s^2 f^2}{r} = \frac{r_{\mathrm{sch}} s^2}{r (cT)^2}$$

At the **end of its life**

r_{sch} ~ 3km, s ~ 30km, T ~ 10^{-3} s



For a system in our own galaxy (r ~ 10kpc): h ~ 10^{-18}

For a system in Virgo cluster (r ~ 10Mpc): h ~ 10^{-21}

Part II. Astronomical sources of GWs

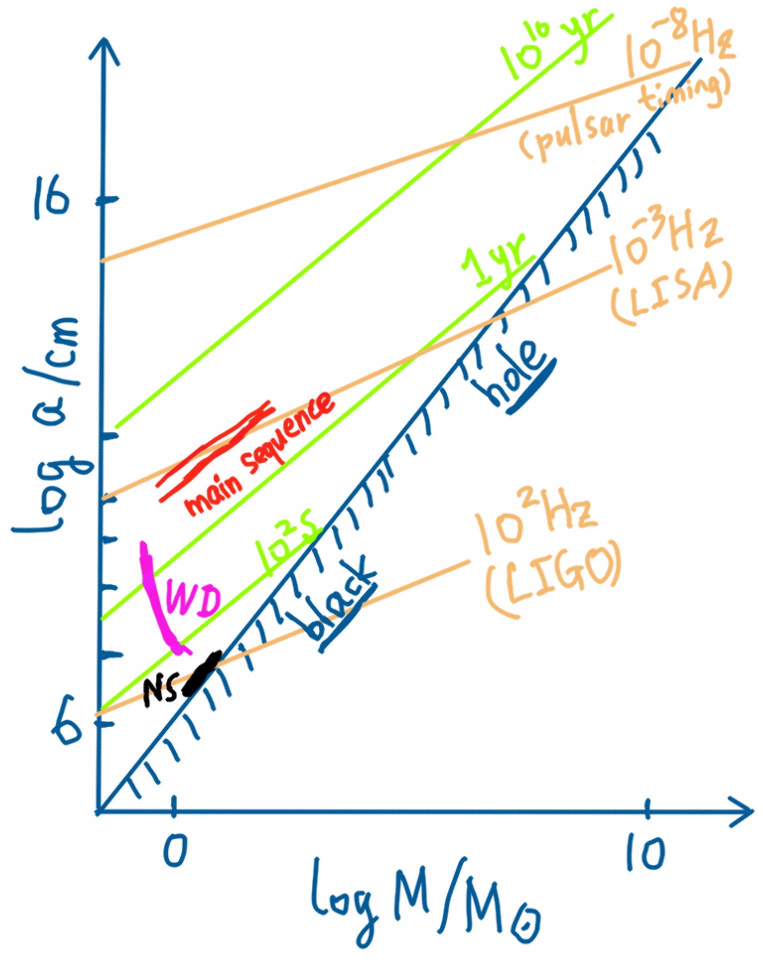
Binary GW sources

$$f_{\rm GW} = 2/P_{\rm orb}$$

$$t_{\rm merger} \propto M^{-5/3} f_{\rm GW}^{-8/3}$$

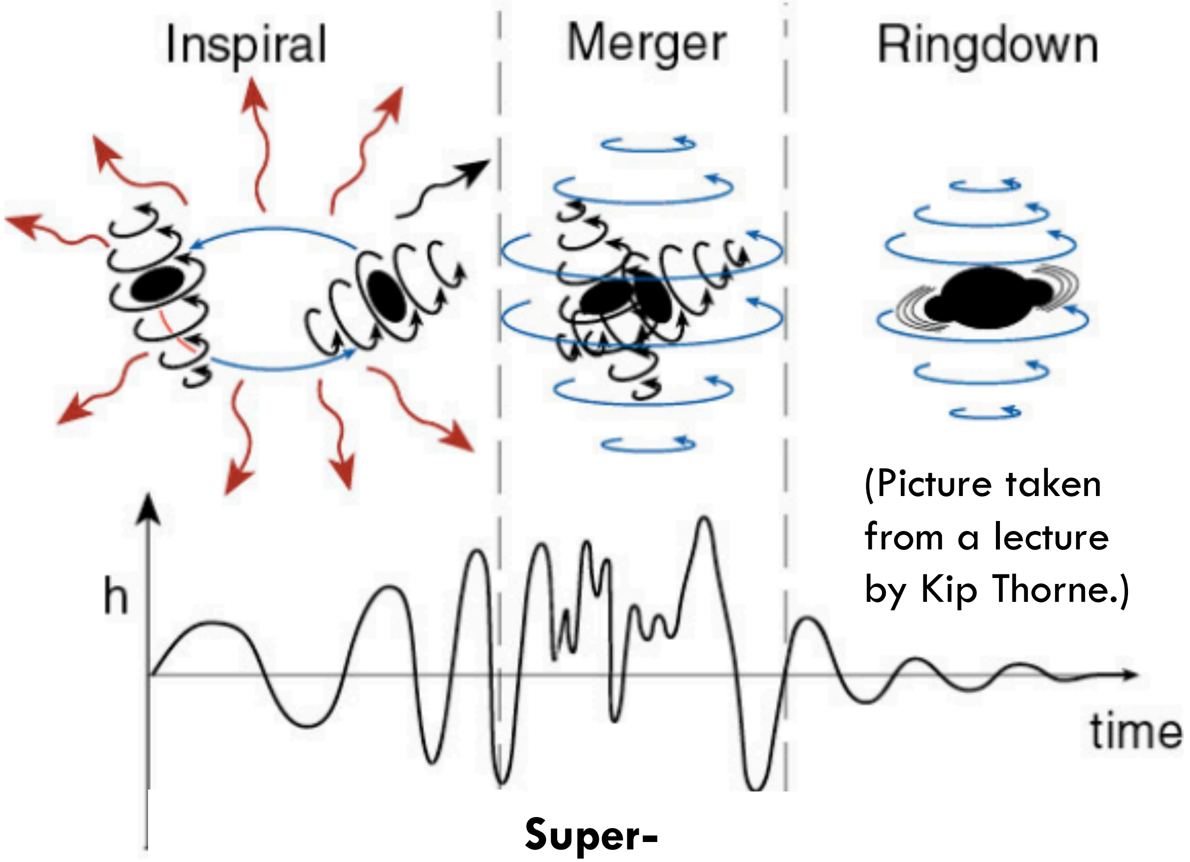
For a $1M_\odot + 1M_\odot$ binary

GW frequency	Merger time
4.5 * 10^{-5} Hz	10^{10} yr
4.5 * 10^{-2} Hz (LISA band)	10^{2} yr
45 Hz (LIGO band)	300s



(Adapted from an online talk by Sterl Phinney)

BH-BH merger



(Picture taken from a lecture by Kip Thorne.)

Post-Newtonian approximation

Super-computer simulation

BH perturbation theory

BH-BH merger: numerical simulation

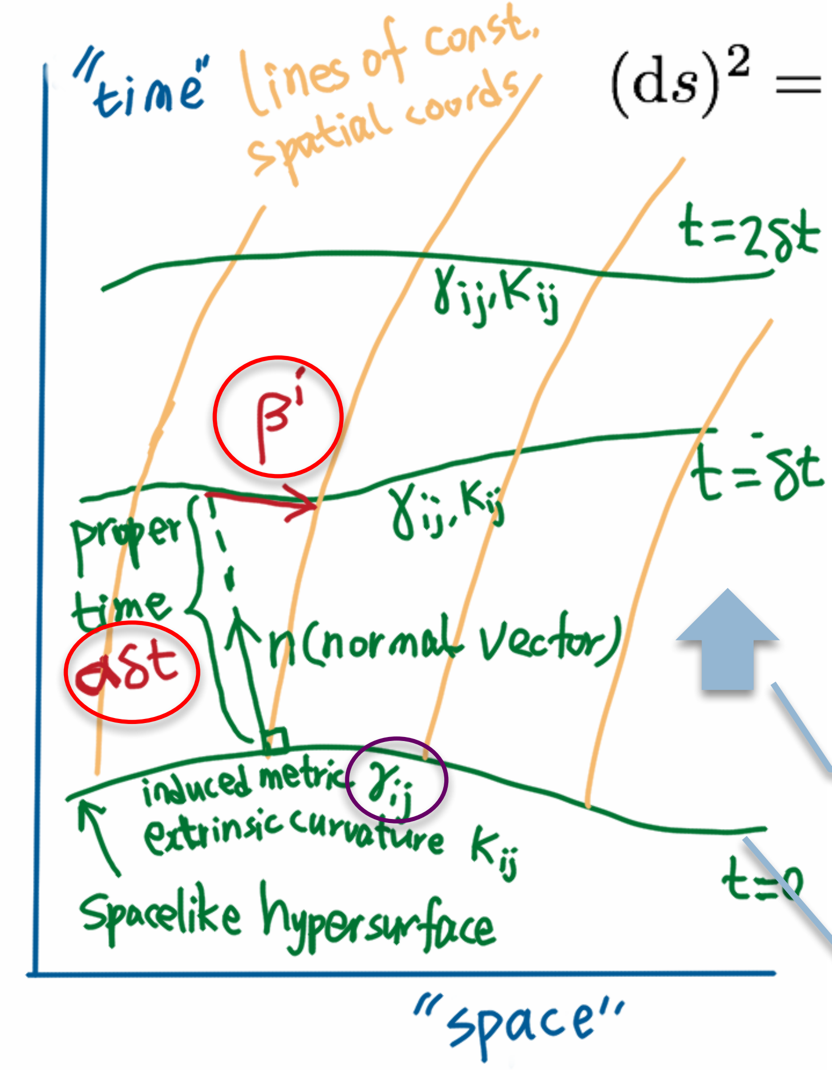
“3+1” decomposition scheme

$$(\mathrm{ds})^2 = -\alpha^2 \mathrm{d}t^2 + \gamma_{ij}(\mathrm{d}x^i + \beta^i \mathrm{d}t)(\mathrm{d}x^j + \beta^j \mathrm{d}t)$$

No equations for α and β^i! (freedom in choice of coords, needs a gauge)

Only 2 stable evolution schemes known

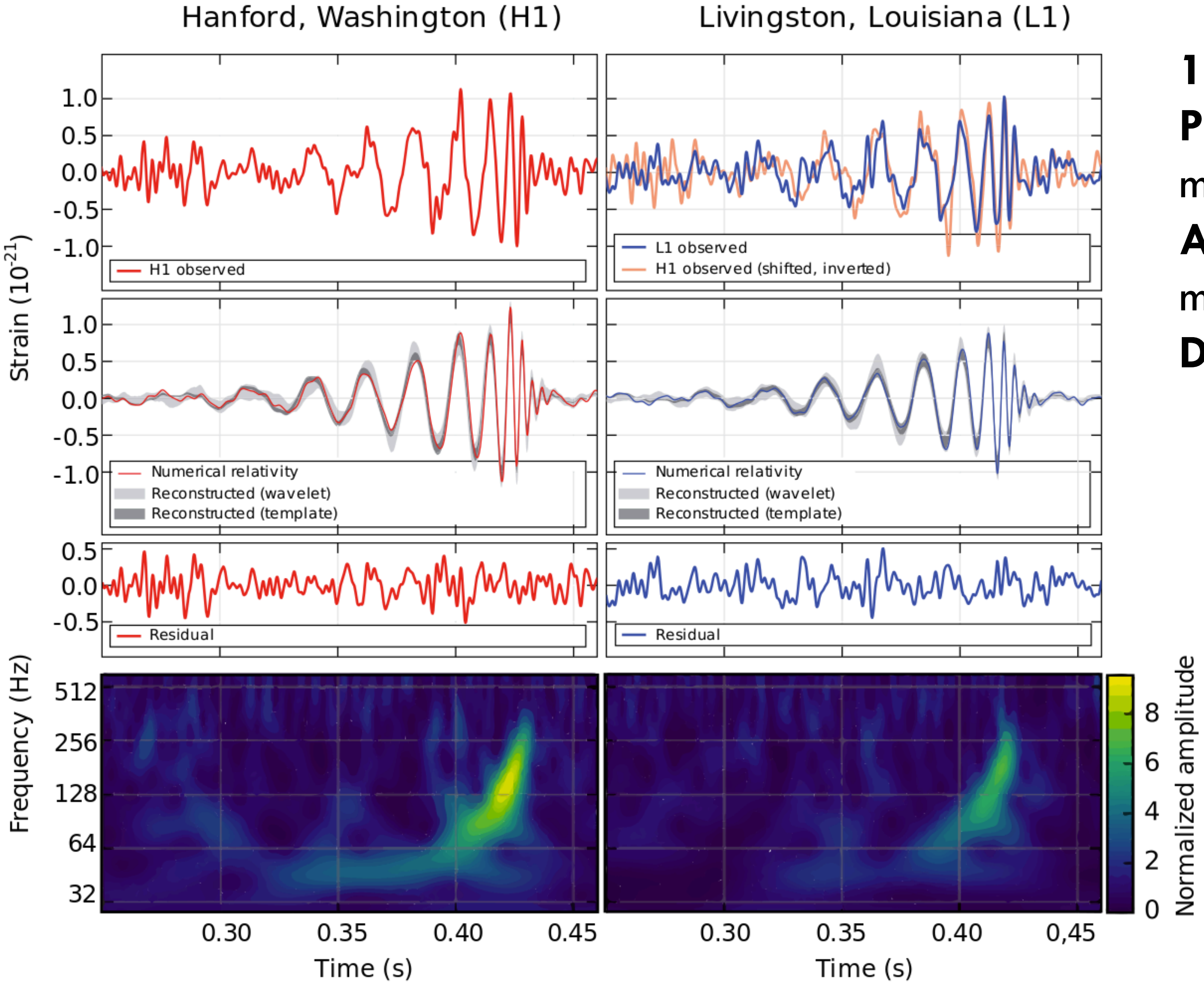
- Harmonic coordinates (Pretorius 2005, first success)
- Baumgarte-Shapiro-Shibata-Nakamura (Baker et. al.; Campanelli et. al., 2006)



Evolution equations (hyperbolic)

Constraint equations (elliptic)

GW150914: first LIGO detection



14 Sep. 2015

Pre-merger: 35+30 solar masses

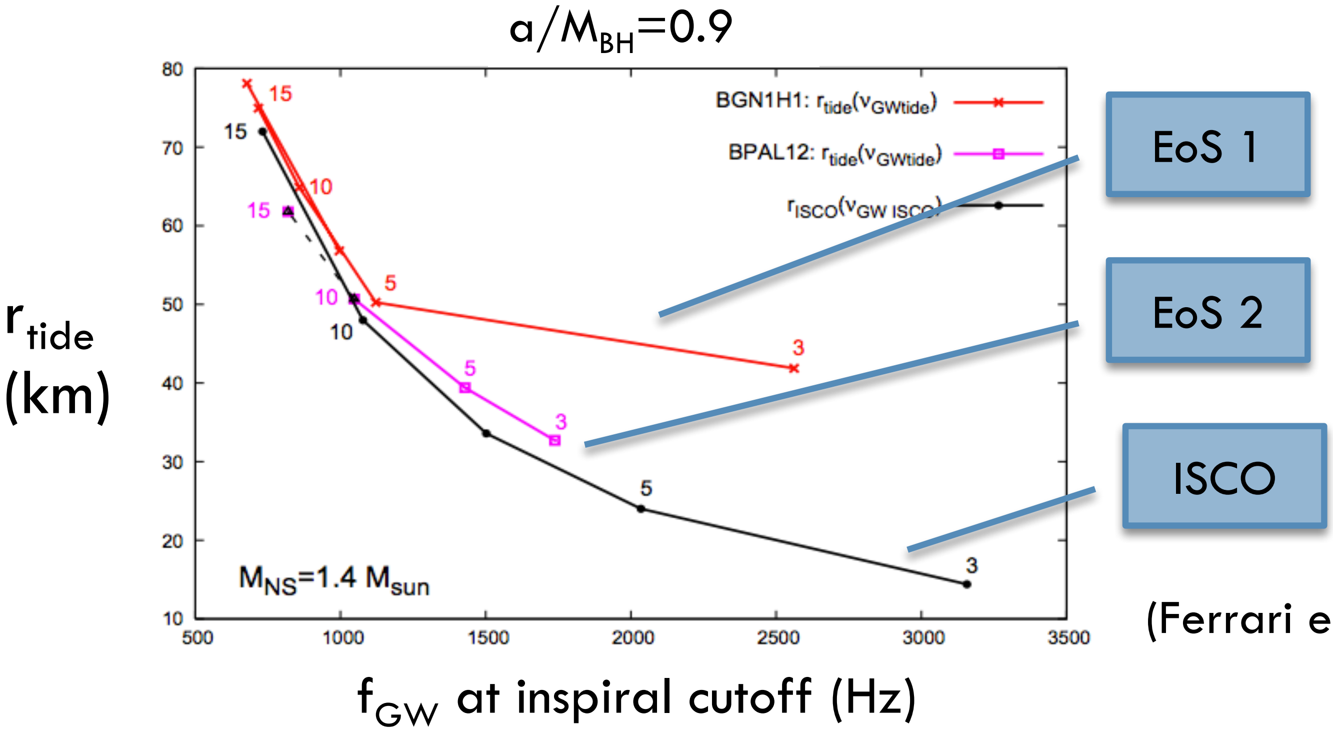
After merger: 62 solar masses, spin 0.68

Distance: 440 Mpc

Abbott et. al.,
Phys. Rev. Lett.
116, 061102 (2016)

NS-BH tidal disruption

- Happens when BH tidal field pulls NS apart
- Can tell by inspiral cutoff
- Can be used to probe NS equation of state

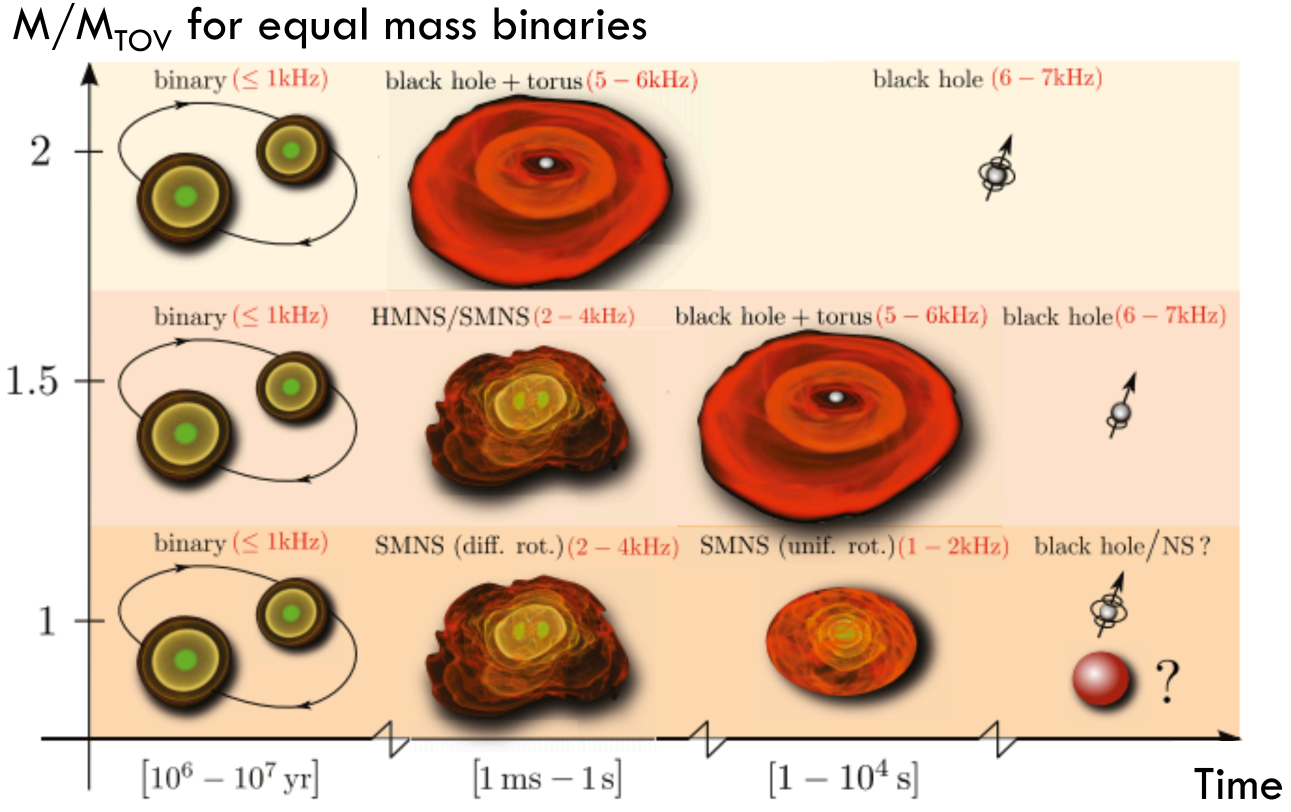


(Ferrari et. al., 2010)

- Possibly associated with GRB

NS-NS merger

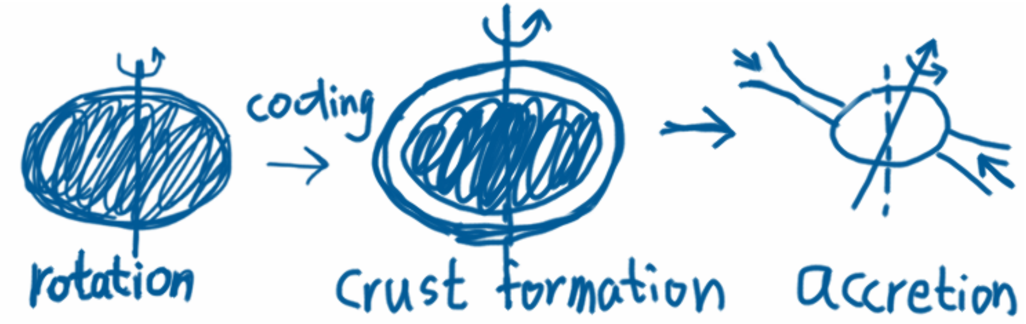
- NS EoS, GRB association?



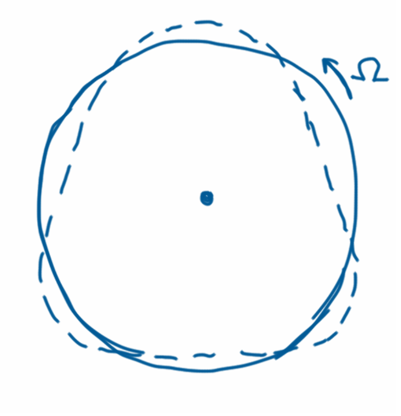
(Baiotti & Rezolla, 2017)

NS spin & pulsation (in our own galaxy)

- Emission of GW from rotation of solid NS crust

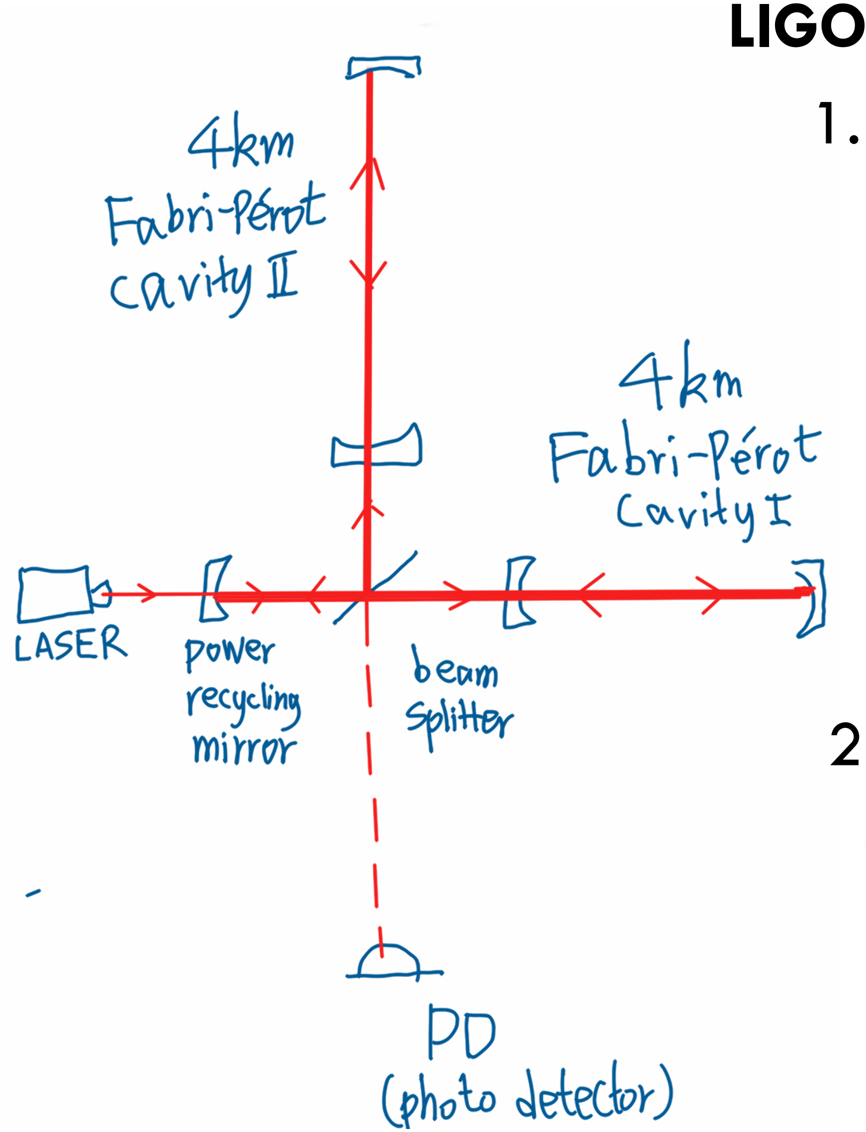


- Emission of GW from NS pulsation
  - Modes damped down by GW and viscosity?
  - Look for unstable modes in fast-rotating NSs
    - Dynamical instabilities (hydrodynamic in origin)
    - Secular instability (driven by dissipation)



Part III. GW detection techniques

LIGO (Laser Interferometer GW Observatory)



LIGO's Two key challenges

1. Phase difference:

10^{-22}

4km

$$\Delta\Phi = khL = \frac{2\pi}{\lambda_E}hL \sim 10^{-12}$$

10^{-4} cm

Solution: use a Fabri-Pérot cavity
(store light for a time $\sim T_{\rm GW}/2$)

2. The energetic quantum limit:

$\propto \sqrt{I_0}$

$$\Delta E \cdot \Delta t \geq \hbar$$

$\propto \Delta\Phi$

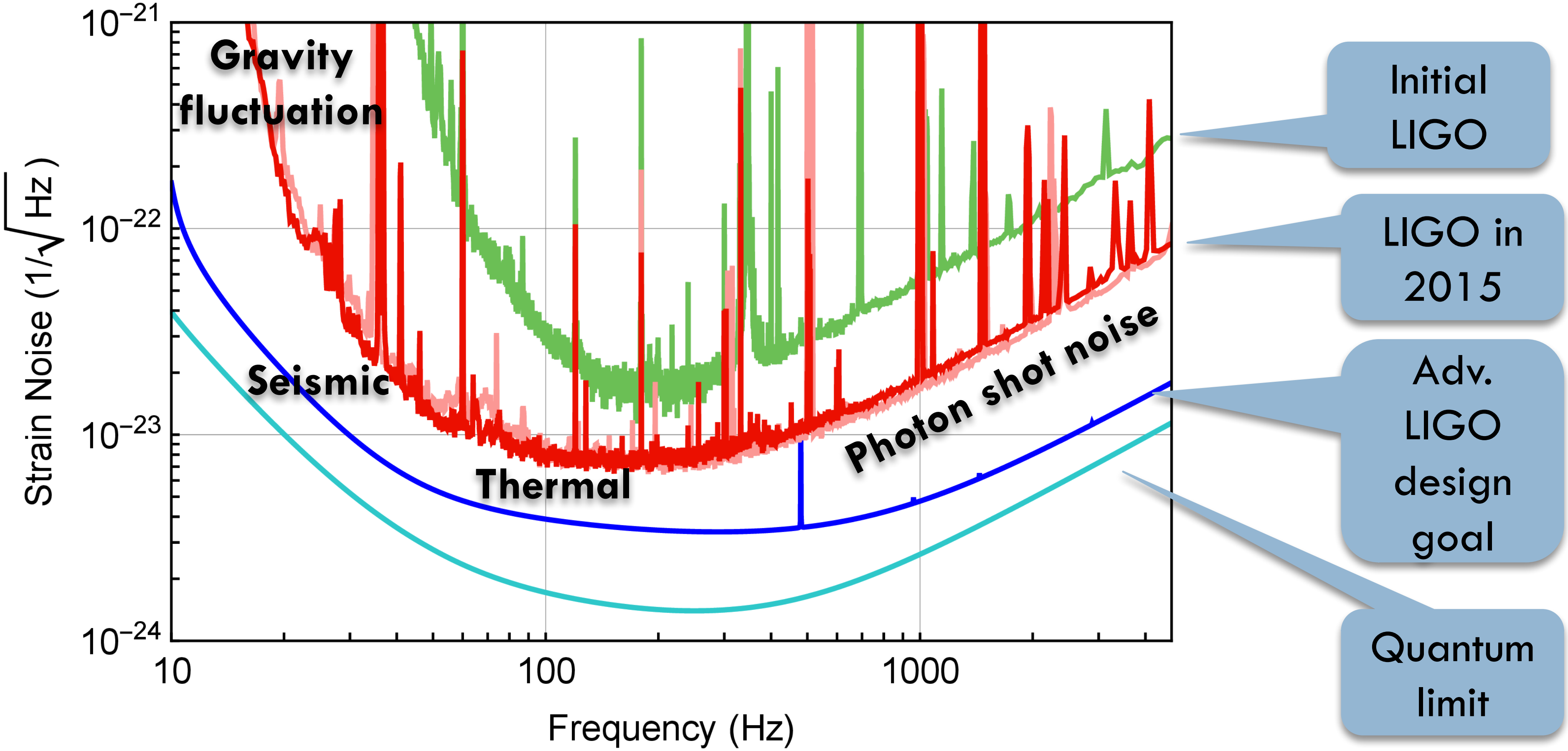
Needs I_0>100W

Solution: use a power recycling mirror

Everything seems impossible in LIGO

- Noises, noises, noises!!!
- Noises that affect the position of the mirror
  - Seismic vibrations (**~10^{-4} cm**)
  - Thermal vibrations of the mirror
    - Brownian motion of CM (**~10^{-10} cm**)
    - Fluctuation of mirror surface (**~10^{-14} cm**)
- Noises that affect the ability to measure the position of the mirror
  - Scattering by residual gas in the vacuum system
  - Photon shot noise
  - Radiation pressure

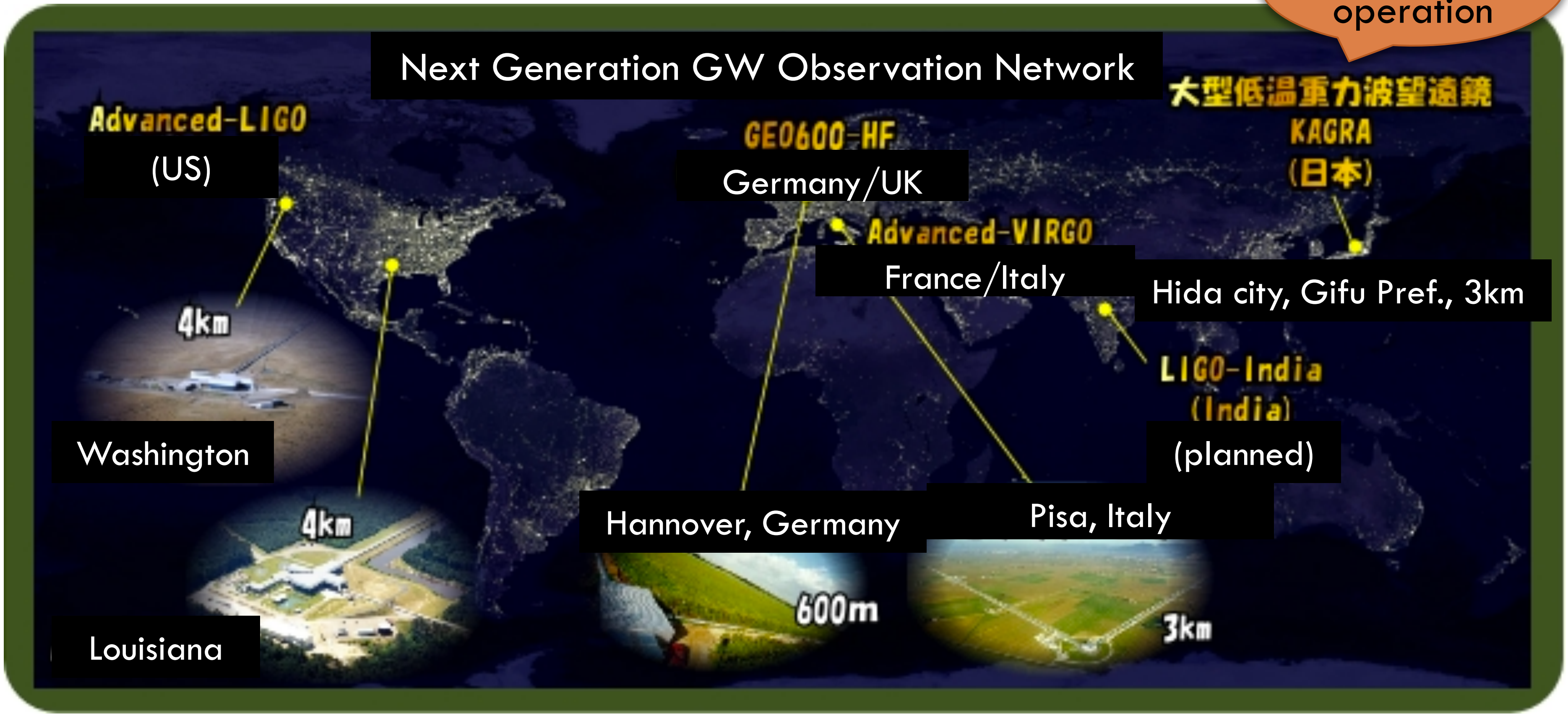
LIGO sensitivity curve



Abbott et. al., *Phys. Rev. Lett.* 116, 131103 (2016)

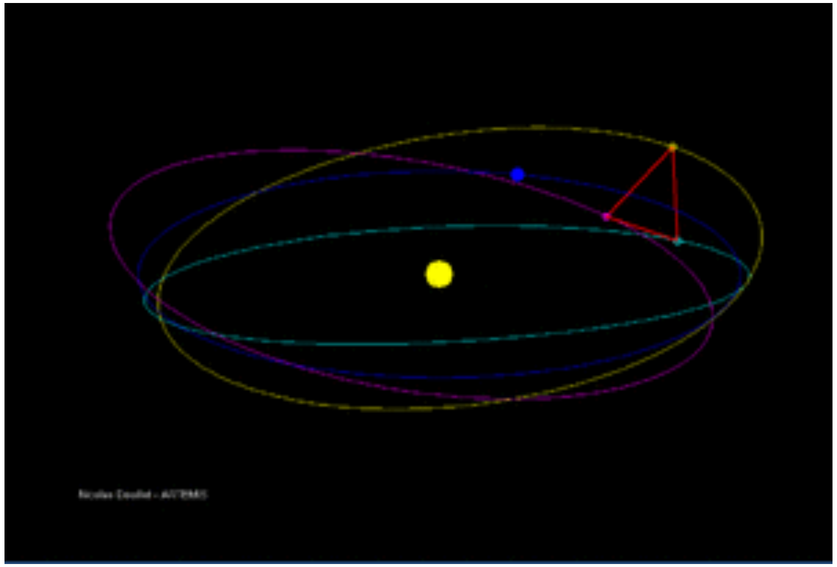
LIGO-like projects around the world

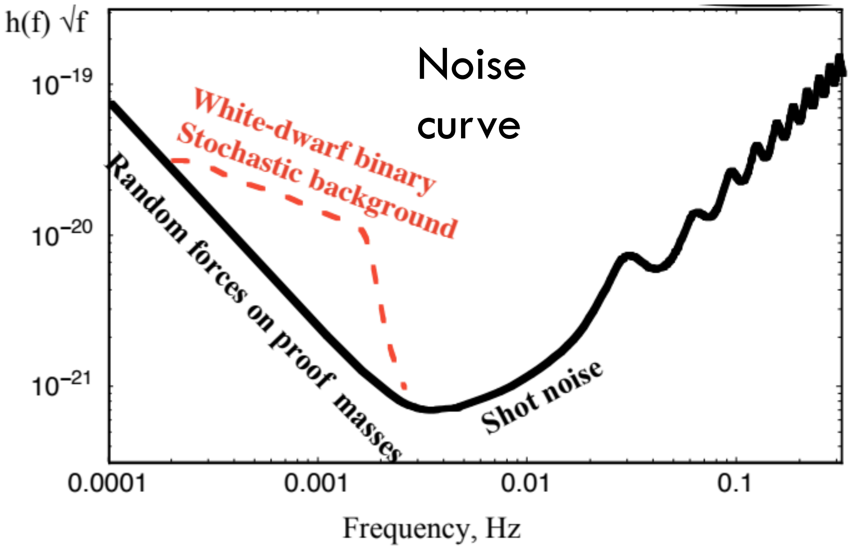
Cryogenic operation



Next Generation GW Observation Network

LISA (Laser Interferometer Space Antenna)

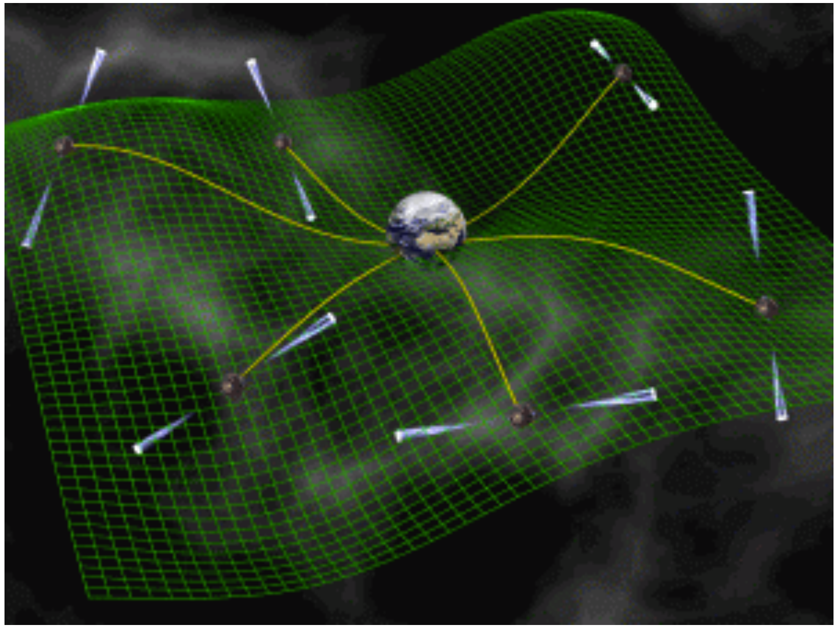




- LISA is back!! (planned 2034)
  - 3-spacecraft constellation
  - Arm length = 2.5 million km
  - No Fabri-Pérot cavity
  - Much lower frequency band
  - Much lower temperature

Pulsar timing

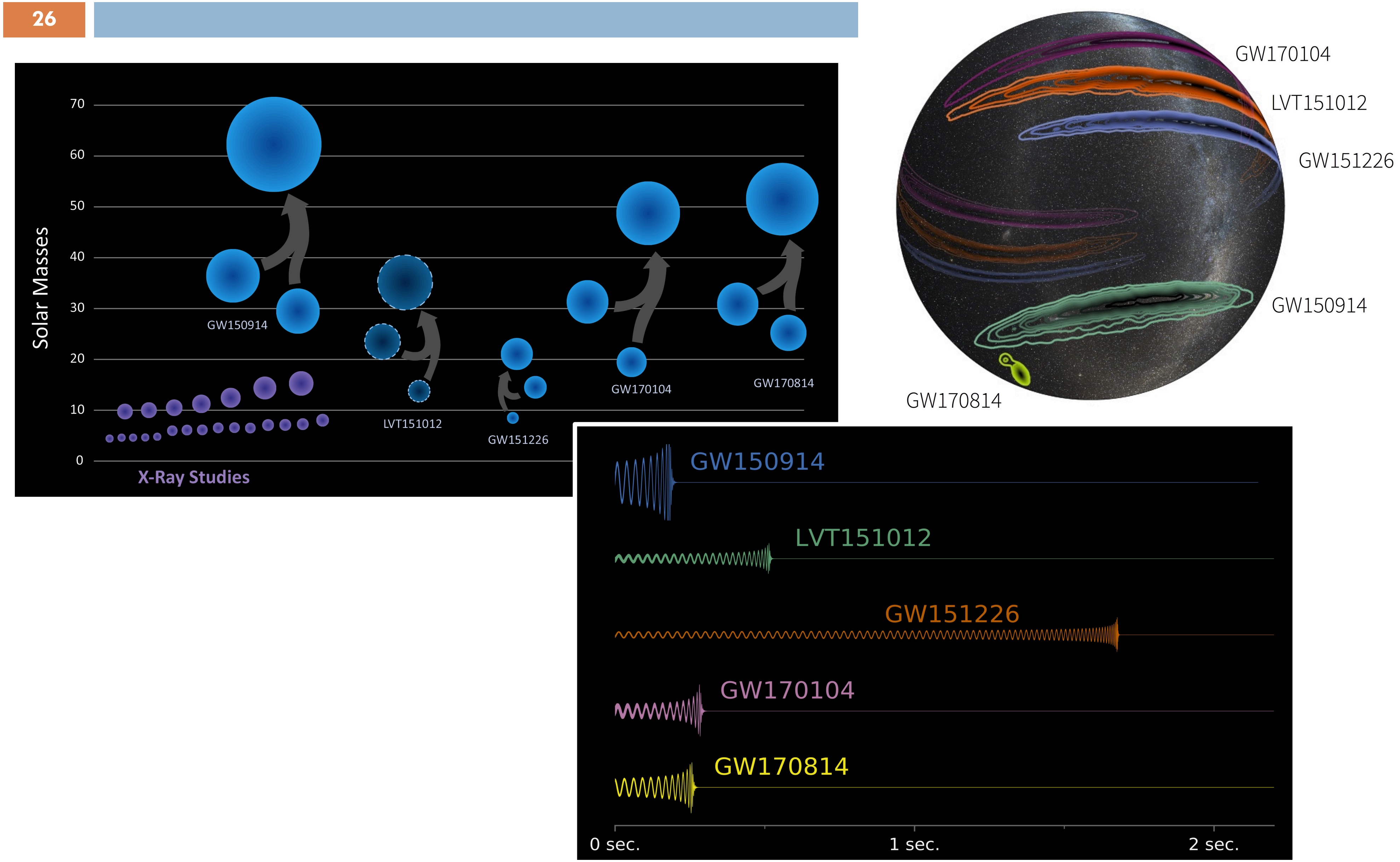
- GW passing earth can cause correlated changes in pulse arrival times
- Suitable for detecting very low frequency GWs
  - e.g. SMBH inspiral & merger
- For $h \sim 10^{-13}$, $T_{GW} \sim 1$yr, arrival time change$\sim 10^{-6}$s



credit: David J. Champion

Part IV. LIGO findings

Up till now: 4 BH-BH merger events



GW170817: NS-NS merger?

- Both LIGO and VIRGO detected a new kind of signal on August 17th
  - Optical counterpart (SSS17a) seen from NGC 4993 (40 Mpc away)
  - Chandra observed SGRB170817A from the same position on Aug. 19th
  - If real, first confirmation that short GRB can come from merging neutron stars.

This is the end. THANK YOU!