Panorama de la science avec les ondes gravitationnelles

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JOGLy

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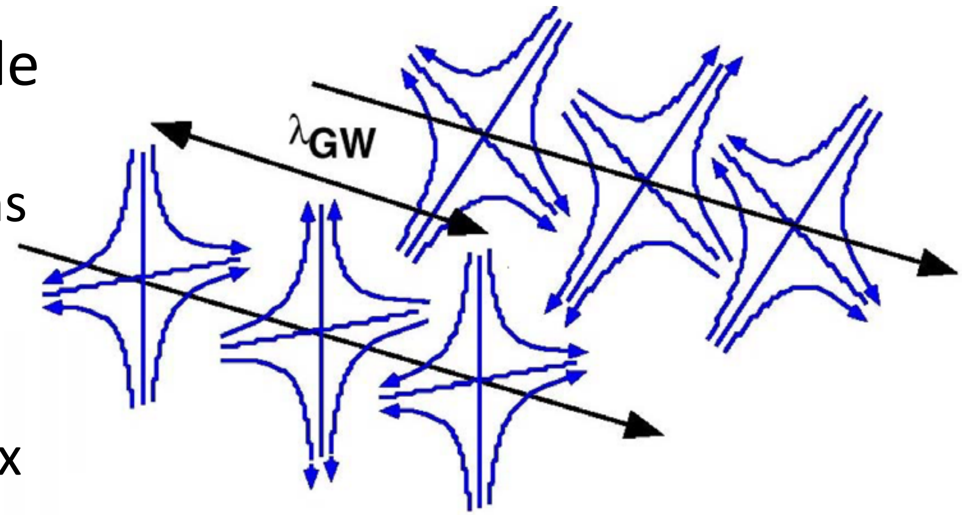
Ondes gravitationnelles

- Prédiction de la Relativité Générale (Einstein, 1916)
- Perturbations de la métrique de l'espace-temps
  - Engendrées par des accélérations de masses
  - Se propagent à la vitesse de la lumière
  - Transverses, quadripolaires, deux polarisations orthogonales



- Luminosité d'une source

$$\frac{c^5}{G} \quad \epsilon^2 \quad \left(\frac{R_S}{R}\right)^2 \quad \left(\frac{v}{c}\right)^6$$

source asymétrique — source compacte — source relativiste

➔ Sources astrophysiques

Enjeux scientifiques

Gravitation

Sources

Univers

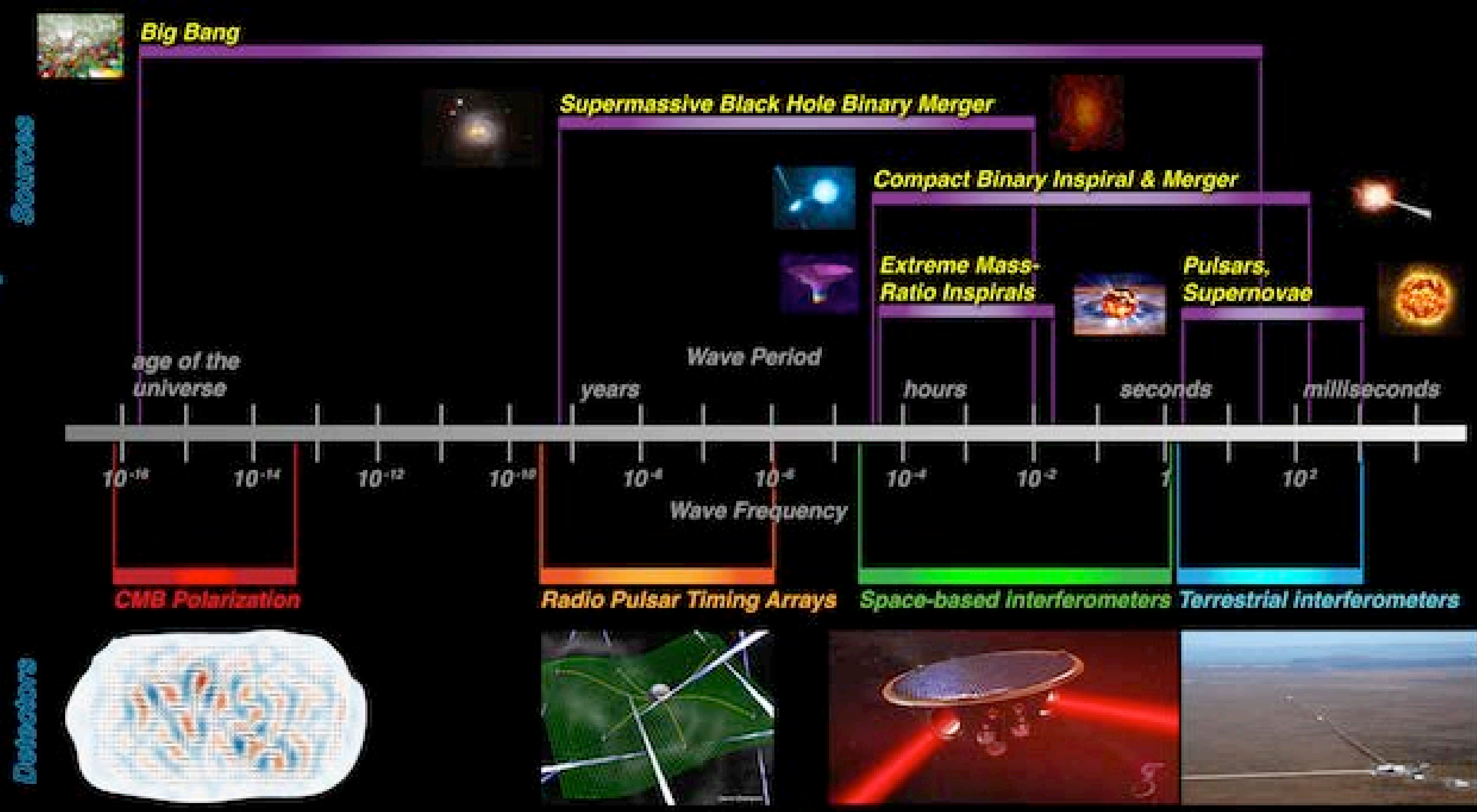
- Les ondes gravitationnelles témoignent des phénomènes les plus violents de l'Univers
  - Sondent directement la dynamique des événements
- Les ondes gravitationnelles permettent de sonder la gravitation dans un régime inédit
  - Gravitation au cœur des grandes énigmes de la physique contemporaine

Relativité Générale

Astrophysique

Cosmologie

Le spectre

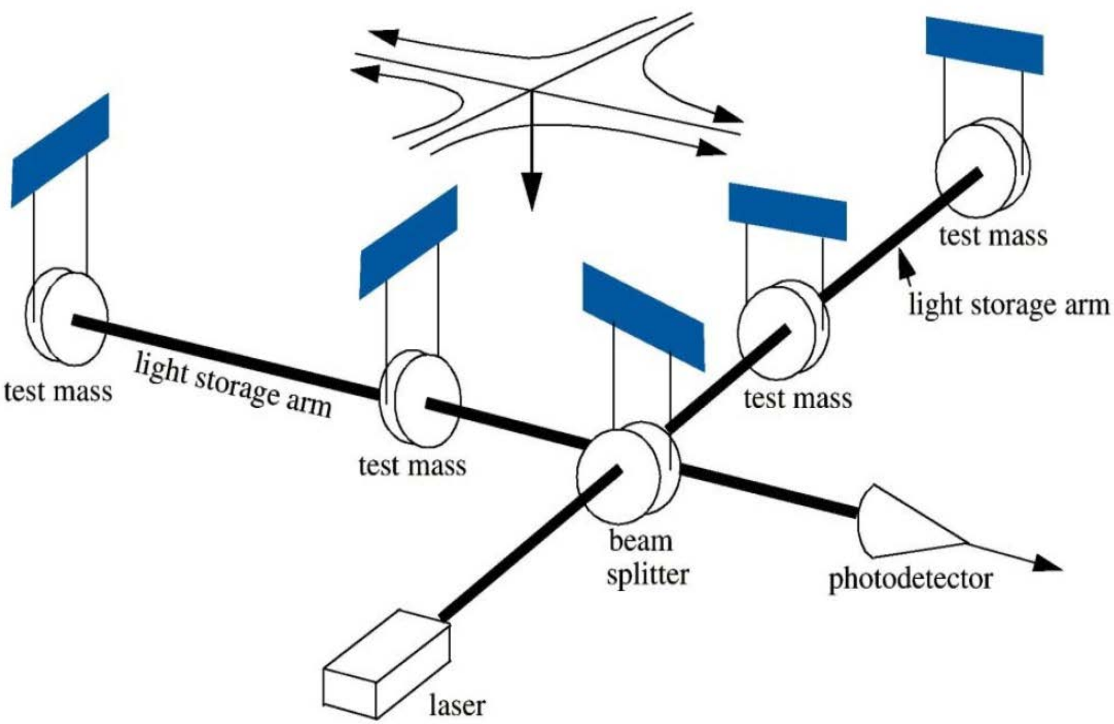


NASA/J. I.Thorpe

Détecteurs interférométriques

- Miroirs suspendus ≡ masses en chute libre dans le plan horizontal, pour f >> $f_{pendule}$
- Envergure de plusieurs kilomètres nécessaire
  - $h \sim 10^{-22}$ - 10^{-21}
  - ➔ $\delta L \sim 10^{-18}$ m
- Détecteurs large bande
  - 10 Hz – 10 kHz sur Terre

$$h = 2 \frac{\delta L}{L}$$



Configuration standard

Les paramètres évoluent avec les détecteurs…

- ❑ Réglage sur la frange noire
  - ➢ Réjection sources de bruit du mode commun
  - ➢ Meilleur rapport signal sur bruit de photons

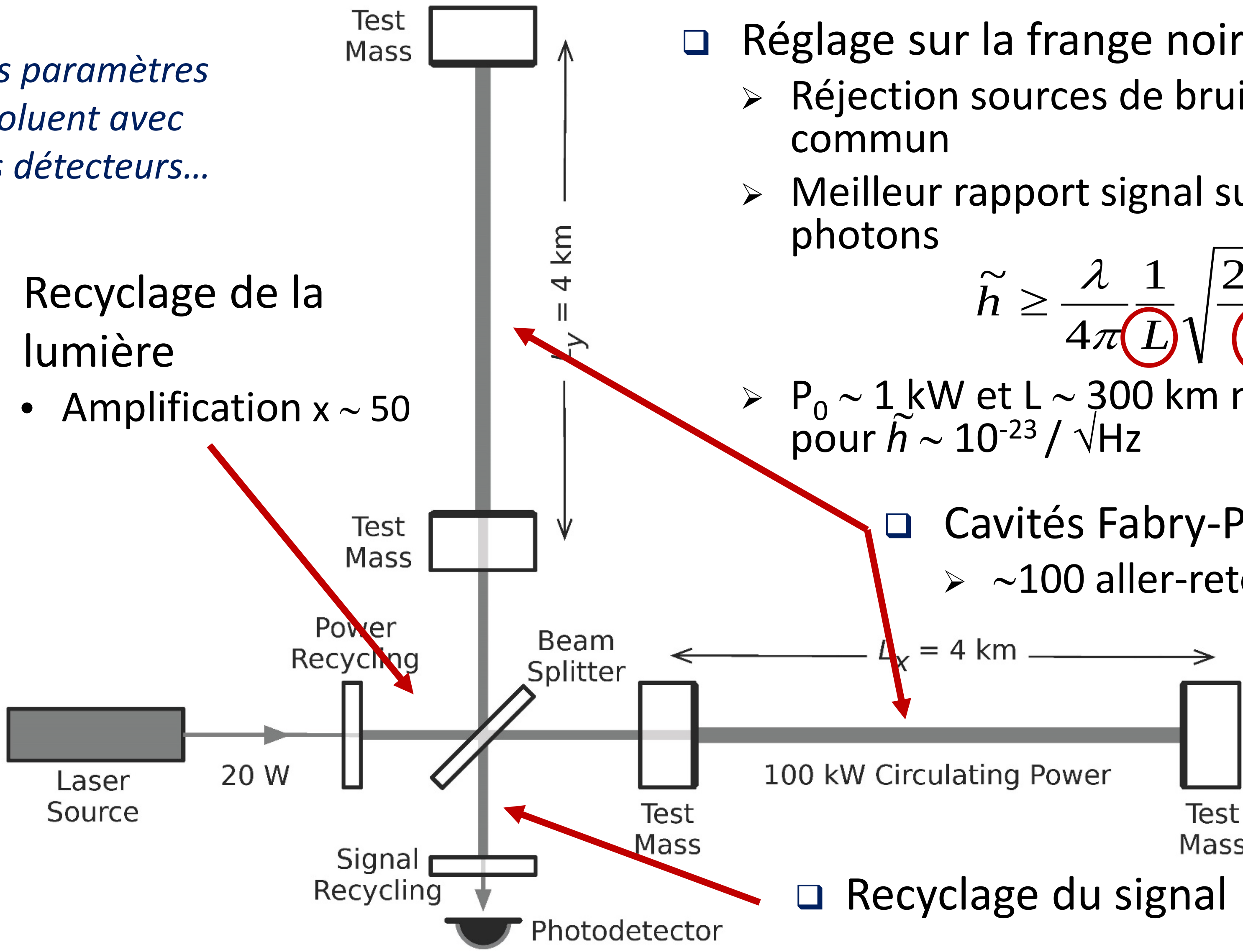
$$\tilde{h} \geq \frac{\lambda}{4\pi}\frac{1}{L}\sqrt{\frac{2h\nu}{P_0}}$$

  - ➢ $P_0 \sim 1$ kW et $L \sim 300$ km nécessaires pour $\tilde{h} \sim 10^{-23} / \sqrt{\text{Hz}}$

- ❑ Recyclage de la lumière
  - Amplification x ~ 50

- ❑ Cavités Fabry-Perot
  - ➢ ~100 aller-retour

- ❑ Recyclage du signal



Les détecteurs

Ground-based GW detectors

- 1st generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

  - Enhanced LIGO, Virgo+

Improved sensitivity

Laid ground for multi-messenger astronomy

- 2nd generation detectors
  - Advanced LIGO, Advanced Virgo, KAGRA

VOUS ÊTES ICI

First detections

Toward routine GW observation
Multi-messenger astronomy

2.5 G

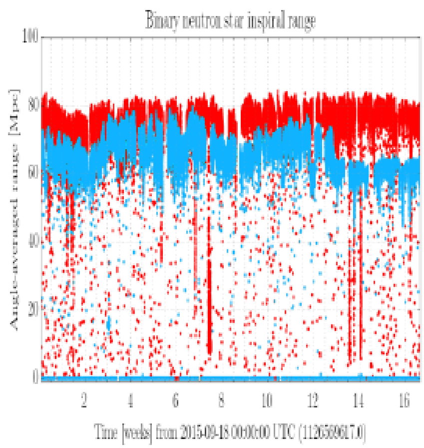
A+
AdV+
Voyager

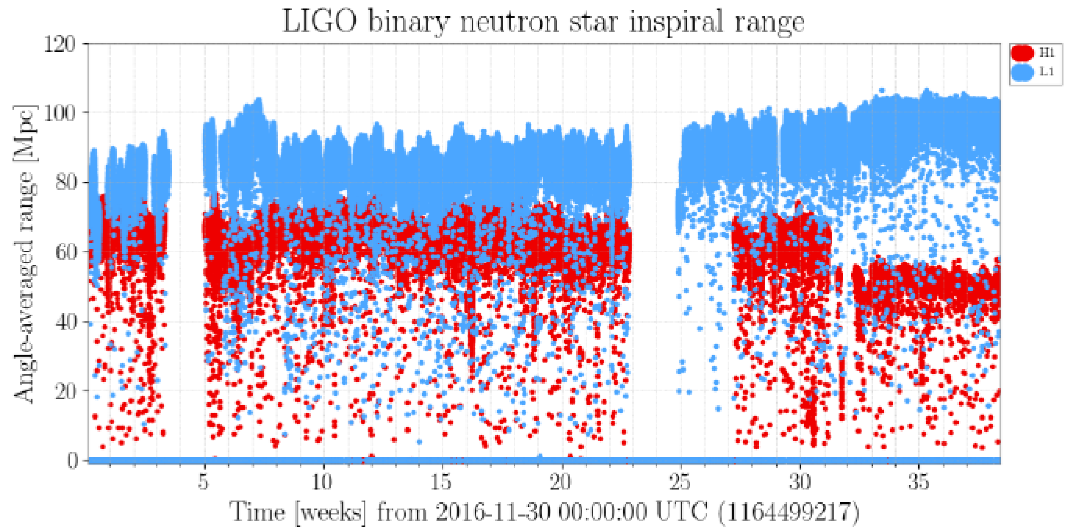
- 3rd generation detectors
  - Einstein Telescope, Cosmic Explorer

Thorough observation of Universe with GW

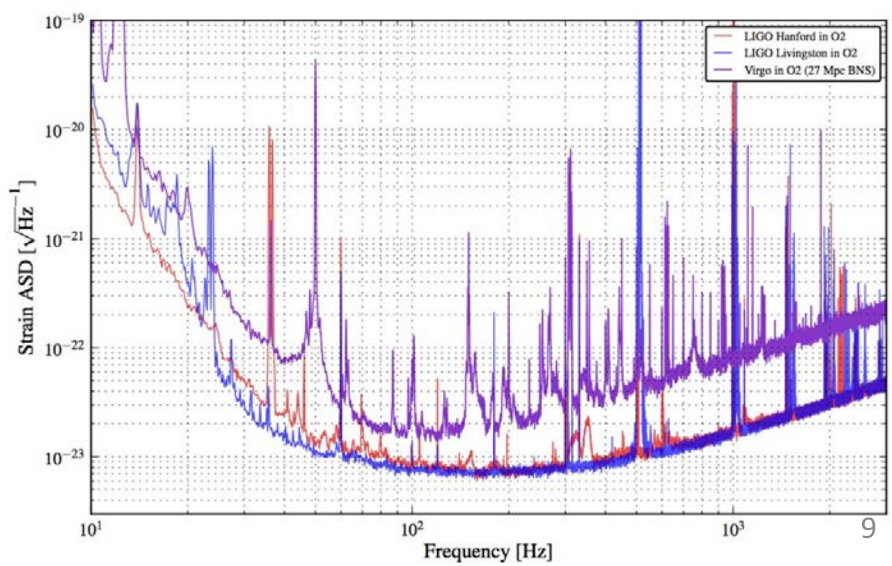
O1 & O2 Observing Runs

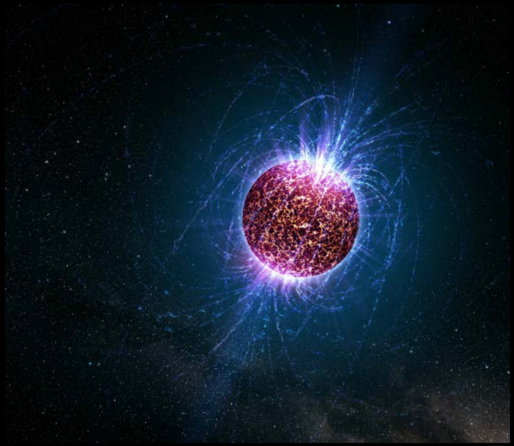
LIGO
2010
★





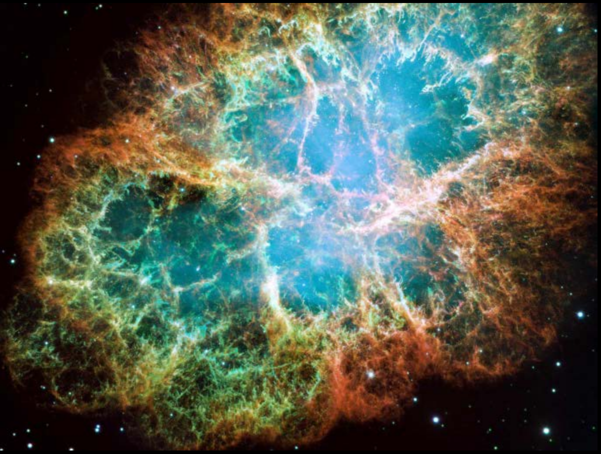
- Binary neutron star range
  - Average horizon distance
  - Horizon ~ 2.26 x range
- O1: 16 weeks
- O2: 37 weeks
- Virgo joined for last month of O2

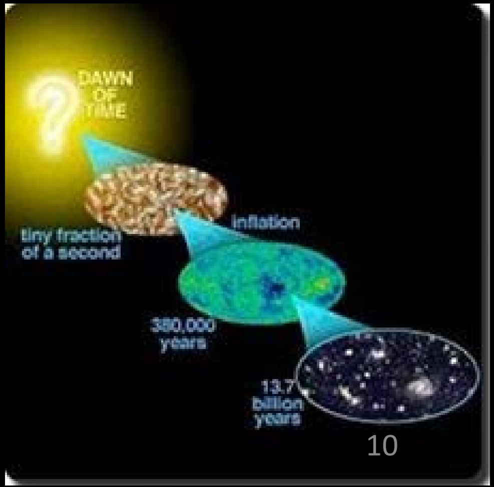




Sources

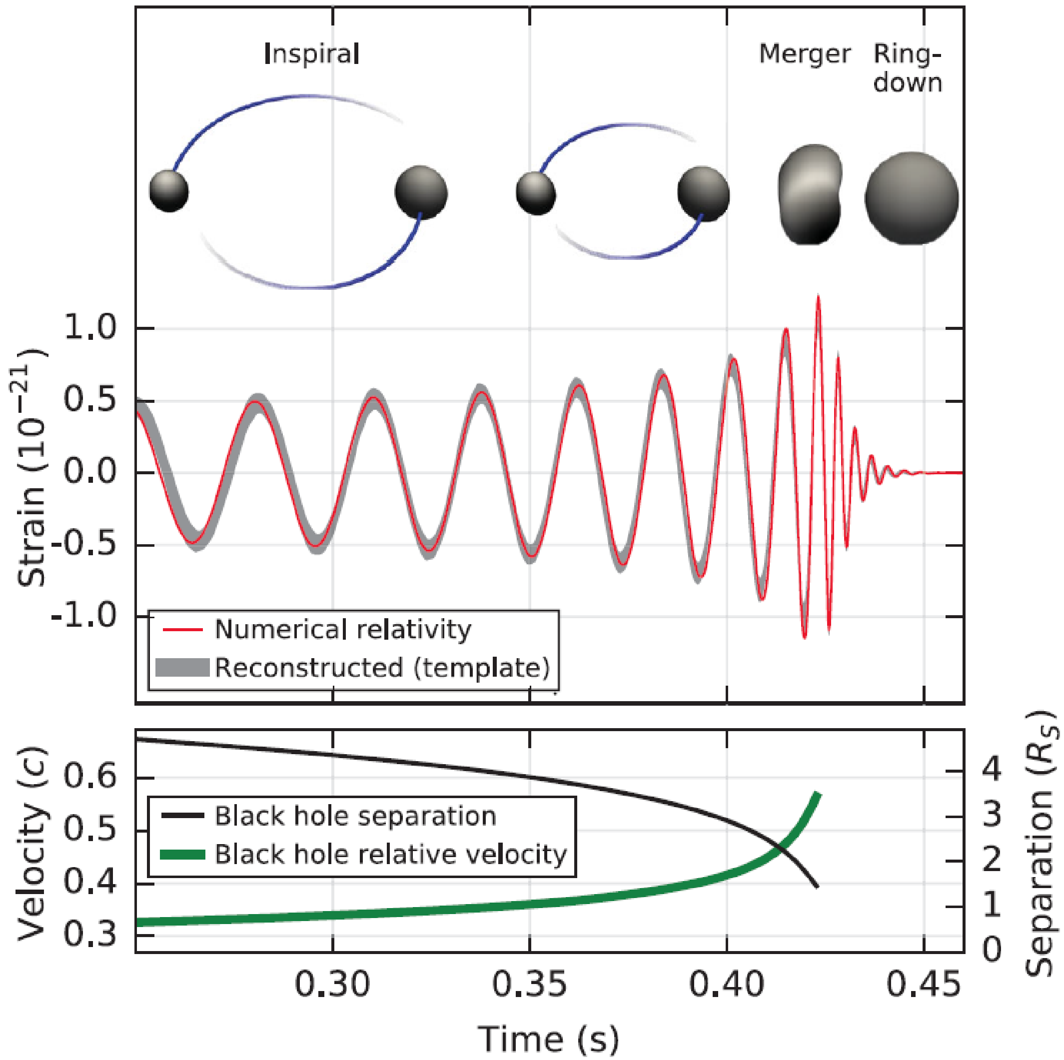
- ❑ Transient sources
  - Compact binary coalescences
  - Other “bursts”, e.g. supernovae
- ❑ Persistent sources
  - Rotating neutron stars
  - Stochastic background



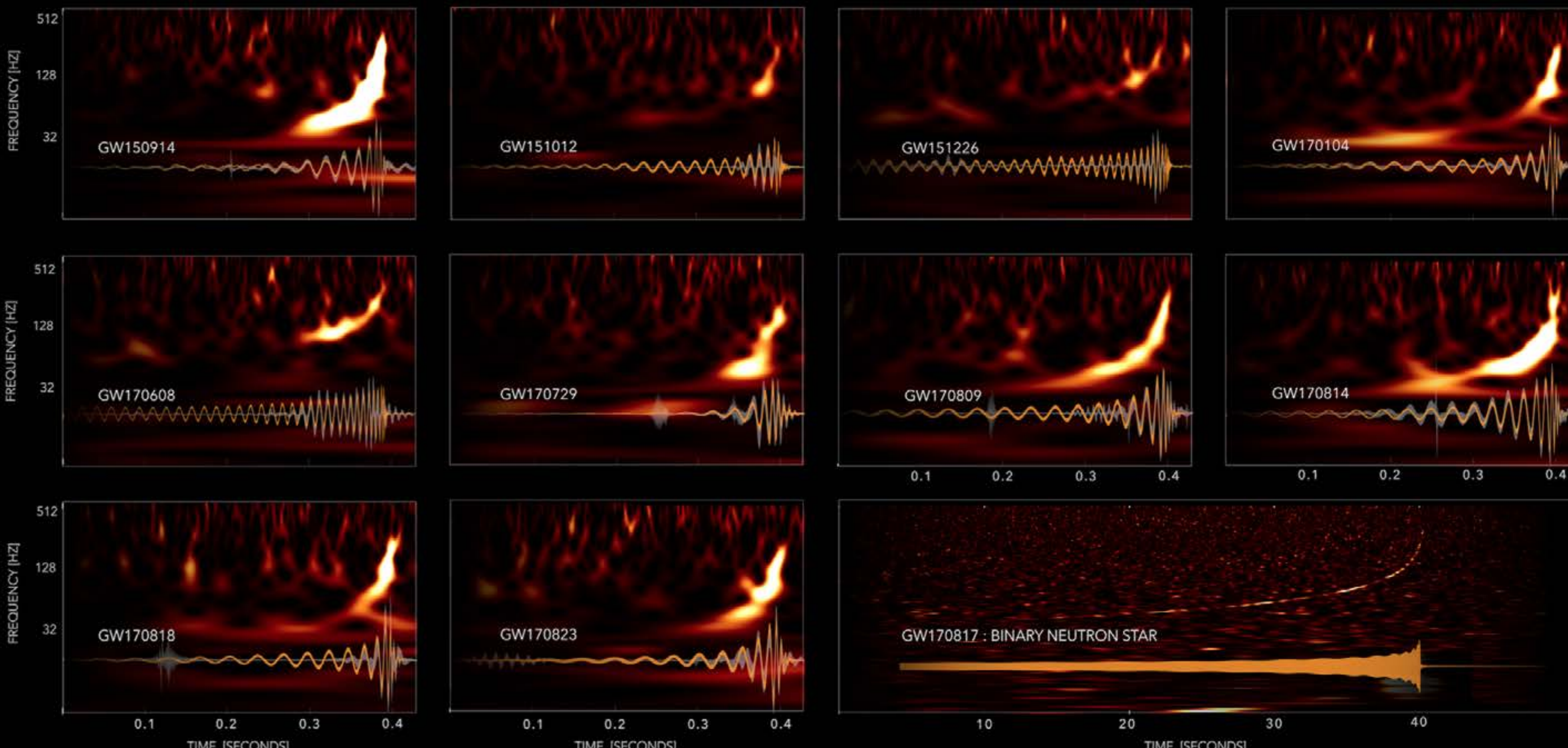


Compact Binary Coalescences

- BH + BH, NS + NS, NS + BH systems
- Waveform models from analytical and numerical relativity
- Event dynamics probes strong field gravity
- Standard candles
- Rare events
  - Rates now measured
  - R_{BBH} = 12 - 213 $Gpc^{-3}\ yr^{-1}$
  - R_{BNS} = 320 - 4740 $Gpc^{-3}\ yr^{-1}$



Gravitational-Wave Transient Catalog-1



LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23 WAVELET (UNMODELED) EINSTEIN'S THEORY IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

Do we understand the progenitors?

Stellar evolution

Source population

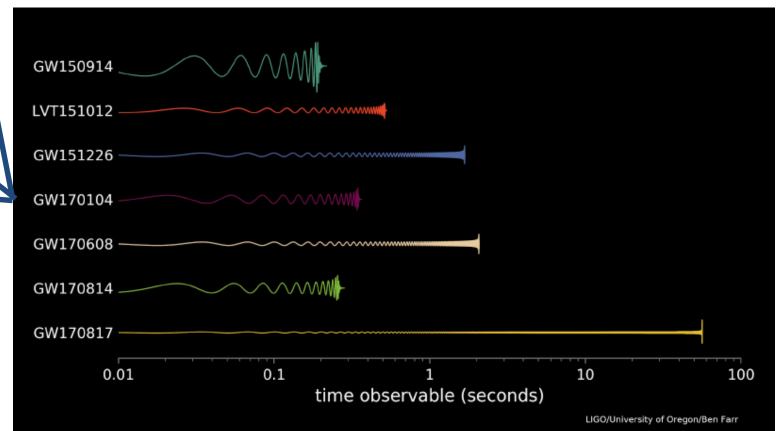
Binary formation and evolution

Masses

Spins

Merger rates

Tidal deformability

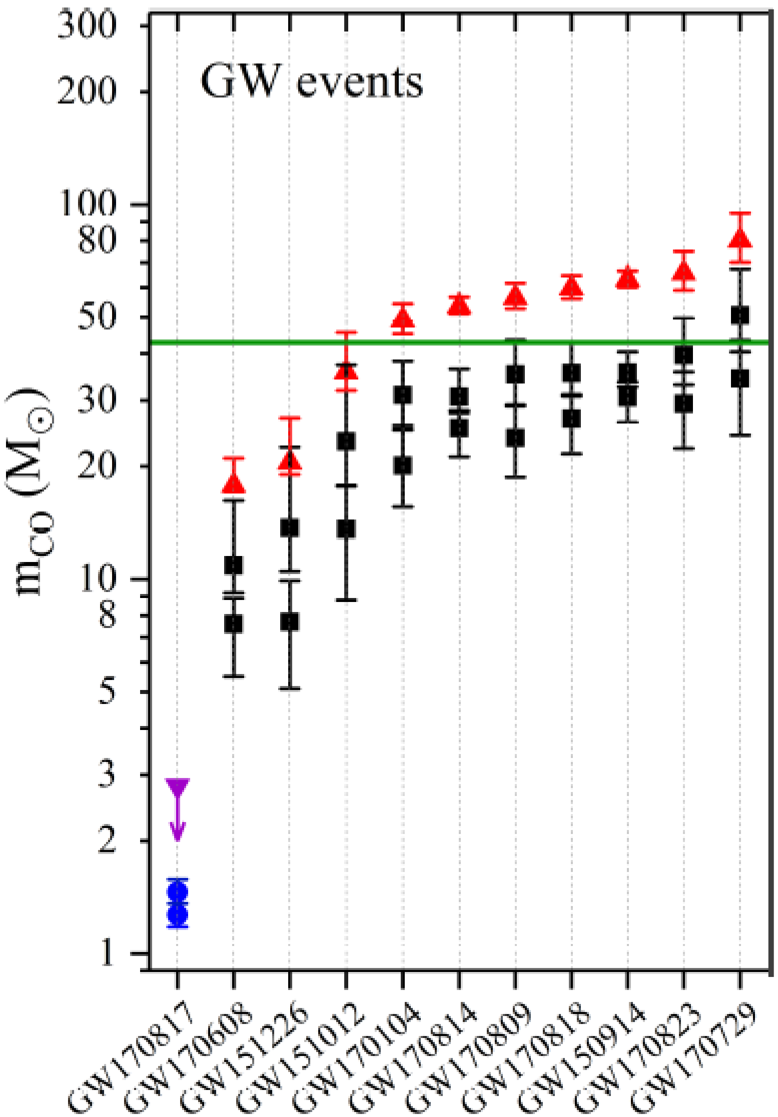


Neutron stars
What is their structure?

Black holes
Are they the BH of GR?

Masses

arXiv:1811.12940

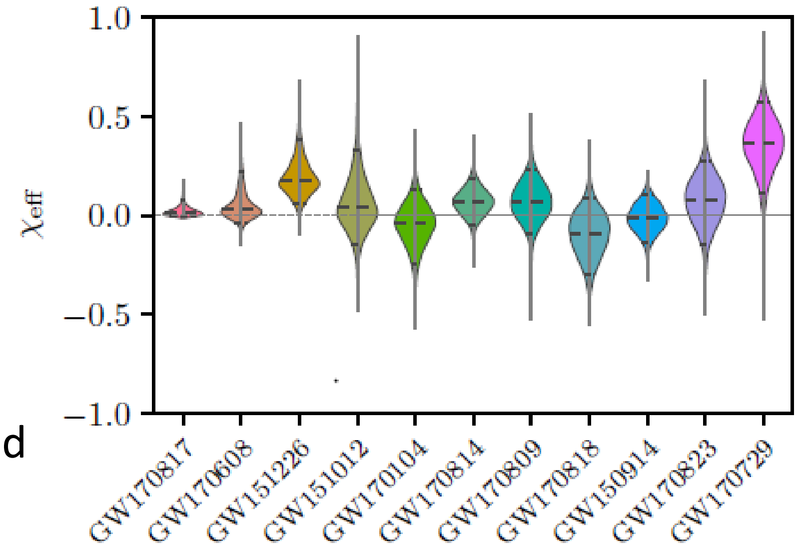


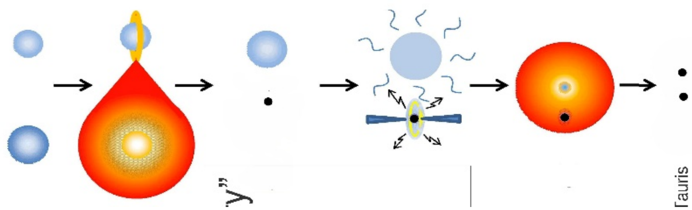
- Heavy stellar mass BHs (> 25 $M_\odot$)
  - Heavier than BHs observed in X-ray binaries
  - Weak massive-star winds due to low-metallicity environment
- Evidence for upper cutoff in BBH mass spectrum at 45 $M_\odot$
  - Might be a consequence of pair-instability supernova
- Mass gap between NS and BH ?
- GW170817 remnant
  - Lightest BH or heaviest NS known

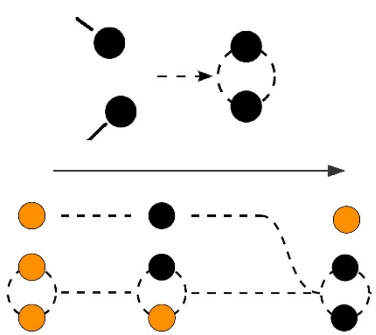
Spins

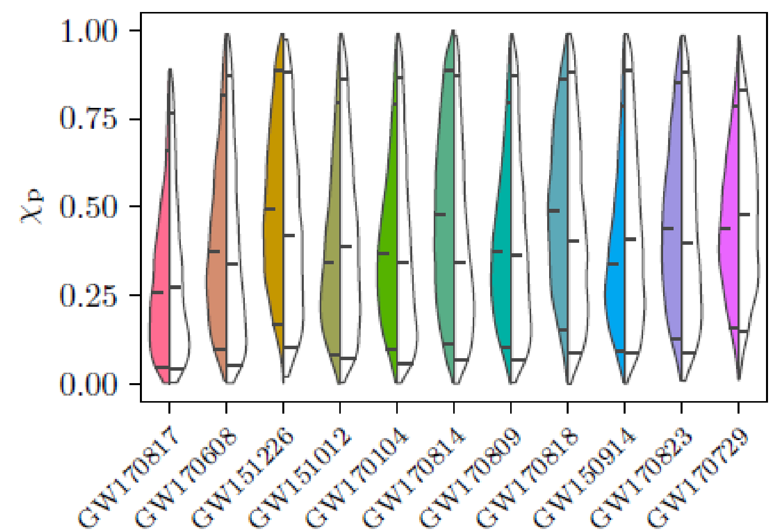
arXiv:1811.12907

- Spins difficult to measure – sub-dominant effect on waveforms
- Spins possible discriminator for BBH formation history
  - BHs in dynamically formed binaries in dense stellar environments expected to have spins distributed isotropically
  - For field populations, stellar evolution expected to induce BH spins preferentially aligned with the orbital angular momentum

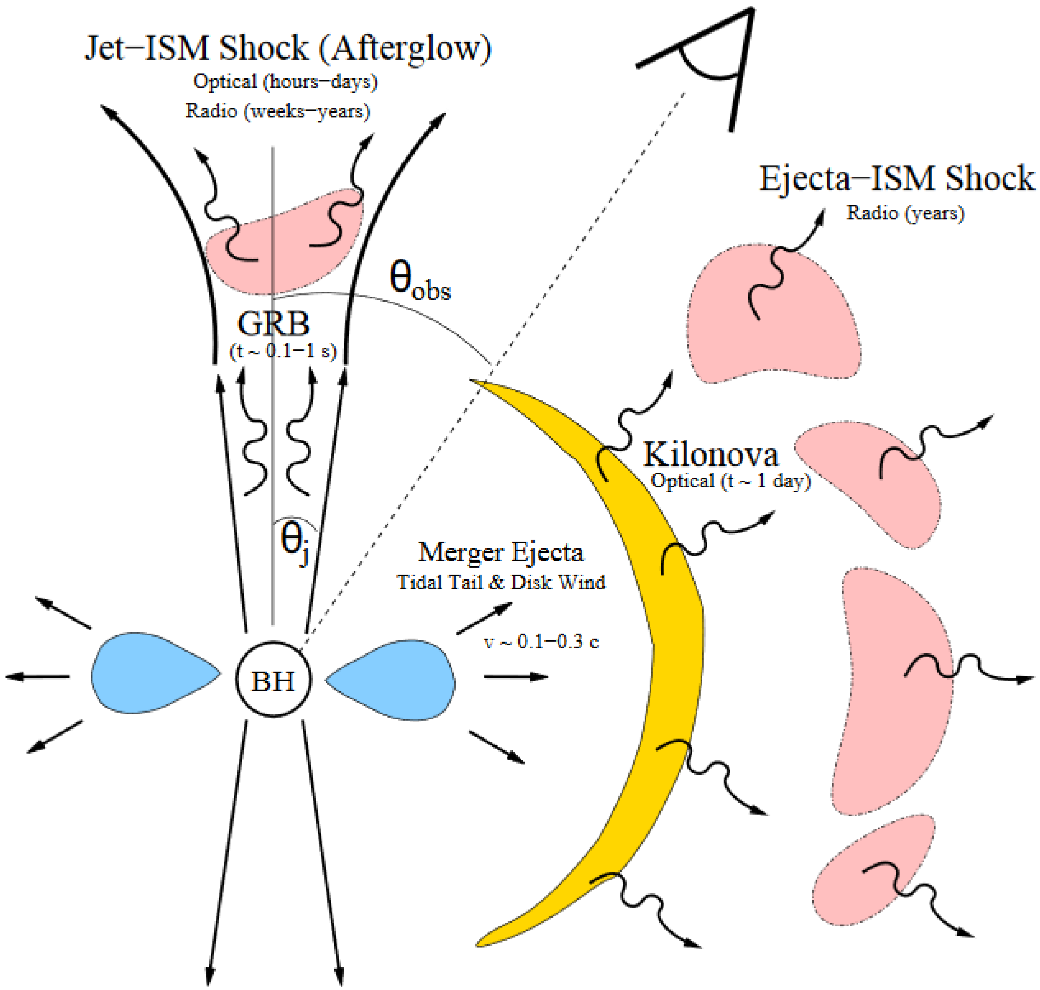








Do we understand the ejecta?



Metzger & Berger 2012

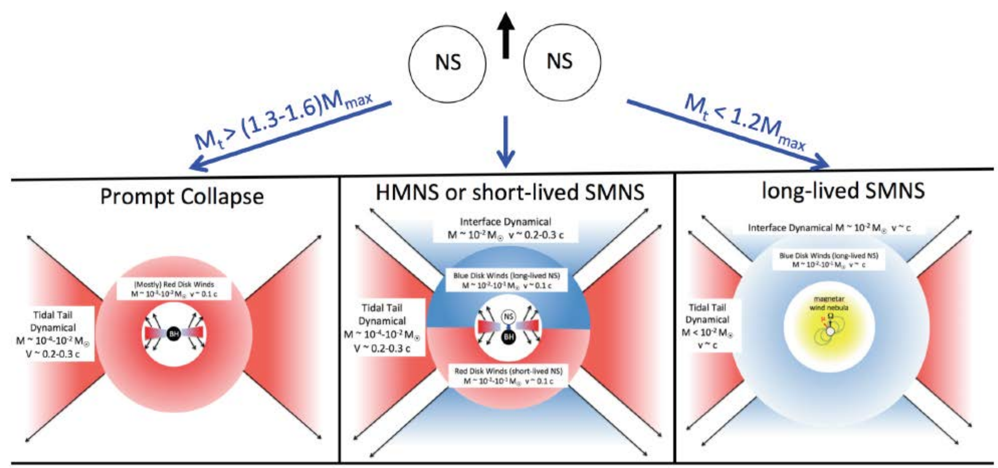
- Connection of short GRBs to BNS mergers confirmed
  - But GRB170817 not a typical short GRB ?
- Kilonova powered by radioactive decay of r-process nuclei synthesized in ejecta
  - Accumulated nucleosynthesis could account for all heavy elements in Galaxy
    - Depends on ejecta mass and composition, and on merger rate

Do we understand the remnants?

- ❑ Not very well – yet – for lack of sensitivity at high frequency

- ❑ Kerr nature of CBC remnant can be shown by observing multiple quasinormal modes in post-merger signal
  - ➢ Well modelled but low SNR

- ❑ Fate of BNS remnant should leave prints in both GW and EM signals
  - ➢ But difficult to observe and read the prints



Margalit & Metzger

More exotic questions

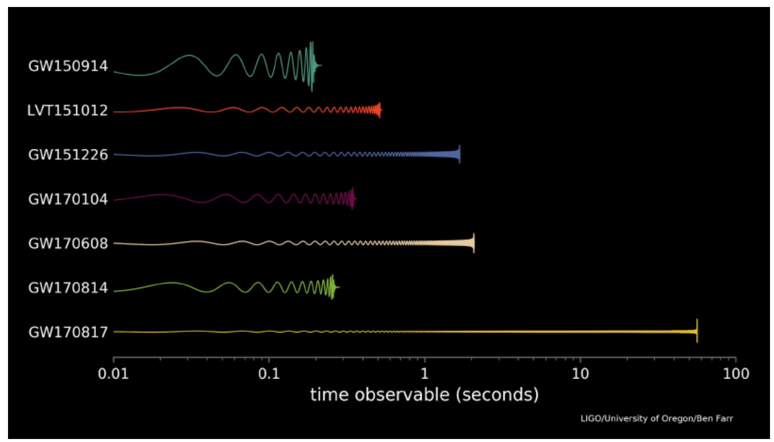
- Might BBHs be part of a primordial BH population in the early Universe and constitute a significant fraction of dark matter?
- Might some BBH signals be twin detections of strong-lensed distant sources?
- « Yes » not the most likely answer, but fun scenarios to explore

Are GWs as predicted by GR ?

Polarization modes

Propagation speed

Binary dynamics



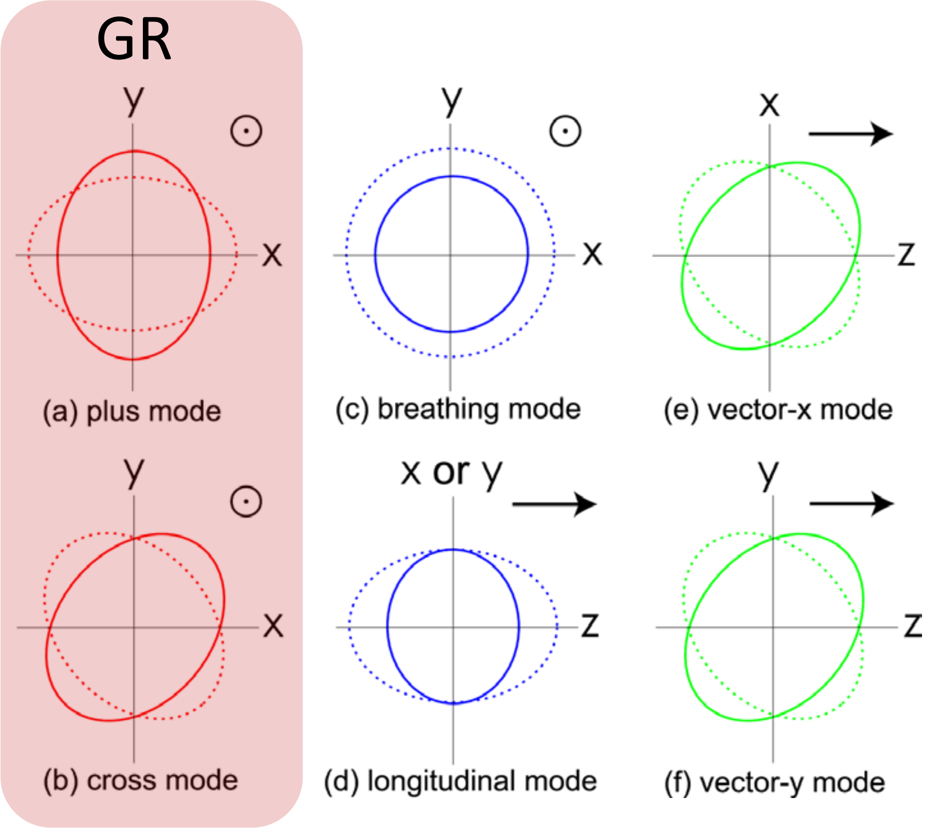
Graviton mass

Lorentz invariance

Equivalence principle

GW Polarizations

- Generic metric theories of gravity allow up to six polarizations
- GR allows two tensor polarizations, + and x
- LIGO instruments have similar orientation ➔ record same combination of polarizations
- Virgo has different orientation ➔ breaks degeneracy



- GW geometry probed directly through projection of metric perturbation onto detector network
- GW170814: pure tensor polarization strongly favored over pure scalar or vector polarizations

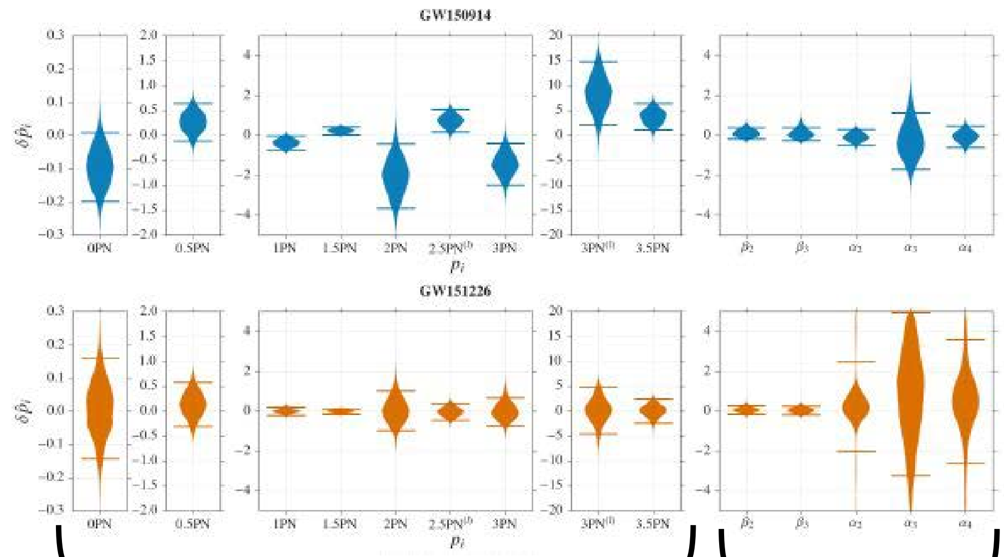
Testing GR with CBC

- Most relativistic binary pulsar known today
  - J0737-3039, orbital velocity

    $v/c \sim 2 \times 10^{-3}$
- BBH / BNS mergers
  - Strong field, non linear, high velocity regime

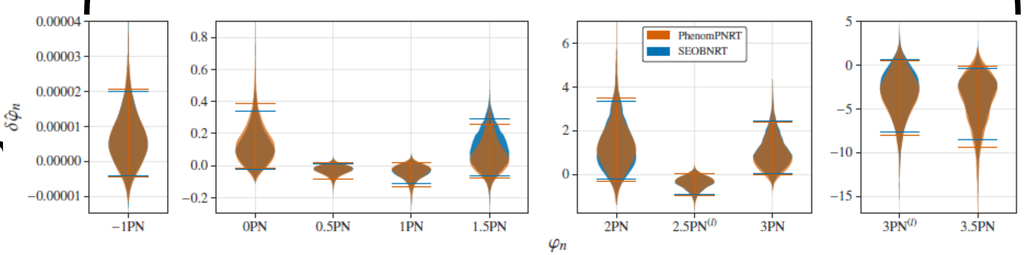
    $v/c \sim 0.5$
- No evidence for deviation from GR in waveform, place empirical bounds on high order post-Newtonian coefficients

PHYSICAL REVIEW X 6, 041015 (2016)



inspiral

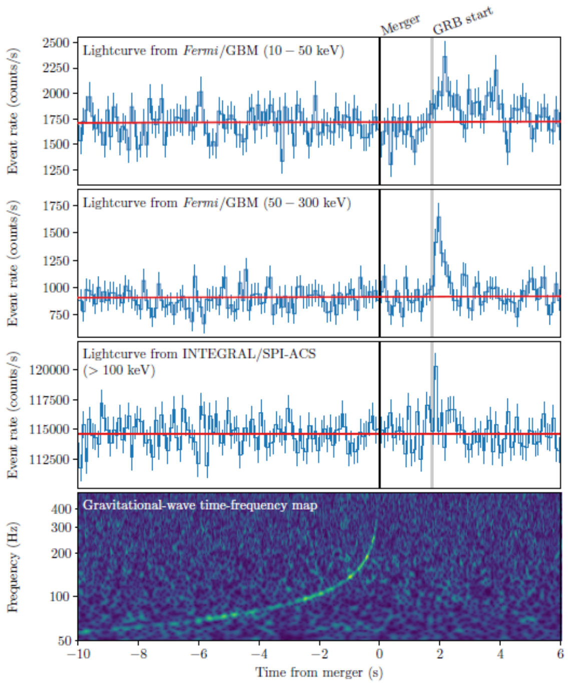
merger/ringdown



GW170817

arXiv:1811.00364

Testing some GR cornerstones (I)



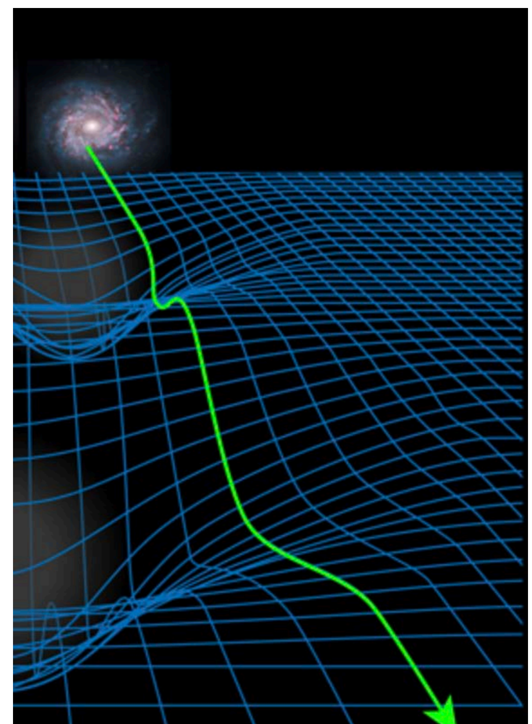
- GW propagation speed
  - GW170817 – GRB 170817A: delay of 1.74 ± 0.05 s over > 85 million years propagation
  - Assume Gamma emission delayed by [0,10]s

$$-3 \times 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq 7 \times 10^{-16}$$

- Equivalence principle
  - EM radiation and GWs affected by background gravitational potentials in the same way ?
  - Shapiro delay $\delta t_S = -\frac{1+\gamma}{c^3} \int_{\mathbf{r}_e}^{\mathbf{r}_o} U(\mathbf{r}(l))dl$

$$-2.6 \times 10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2 \times 10^{-6}$$

- Many alternative theories of gravity ruled out



APS/Alan Stonebraker

Testing some GR cornerstones (II)

- Lorentz invariance: Look for possible dispersion in signal propagation

$$\left(\frac{v}{c}\right)^2 = 1 - \left(\frac{hc}{\lambda_g E}\right)^2$$

- GW150914 + GW151226 + GW170104

PRL 118, 221101 (2017)

$$\lambda_g > 1.6 \times 10^{13}\, km$$

  - Bound graviton mass $m_g \leq 7.7 \times 10^{-23}\, eV/c^2$
  - More constraining than bounds from Solar System and binary pulsar observations
  - Less constraining than model dependent bounds from large scale dynamics of galactic clusters and weak gravitational lensing observations

Cosmology with CBC

- GW waveform provides luminosity distance
- GW waveform typically does not provide redshift
  - Full mass-redshift degeneracy for inspiral
- How do we get the redshift ?
  - From possible electromagnetic counterpart

Measuring the Hubble Constant

- GW17081 – AT2017gfo
  - GW only
    - Luminosity distance = 40^{+8}_{-14} Mpc at 90% CL
  - Assuming sky position of AT2017gfo
    - $d = 43.8^{+2.9}_{-6.9}\,\mathrm{Mpc}$ at 68% CL
  - H_0 uncertainty from statistics, geometrical degeneracy with system inclination, and galaxy peculiar velocity

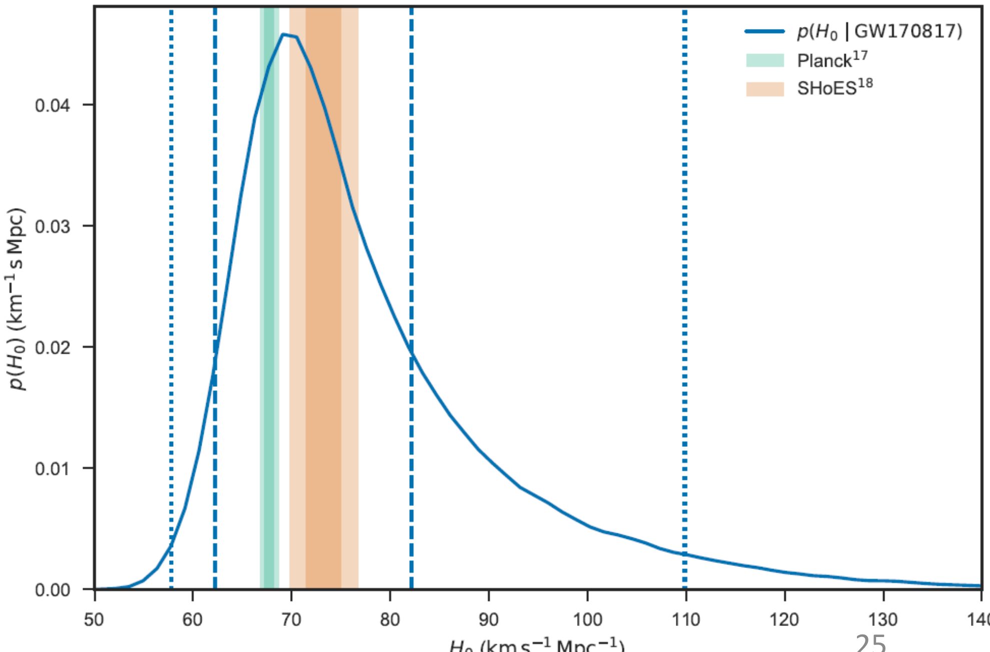
$$v_H = H_0 d$$

Hubble flow velocity from host galaxy NGC4993

Distance from GW

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Independent of any cosmic distance ladder



Nature 551, 85 (2017)

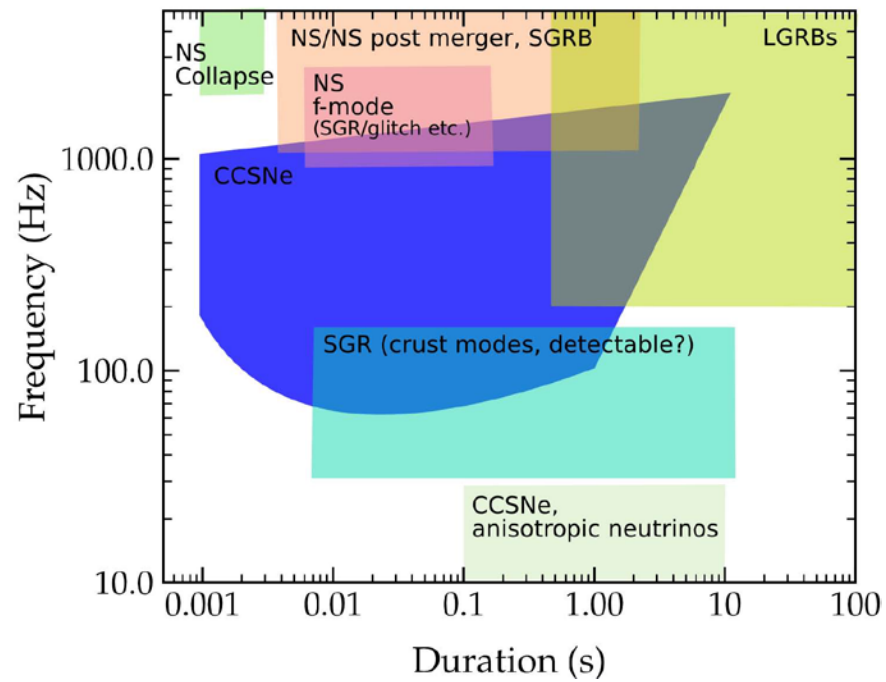
Cosmology with CBC

- GW waveform provides luminosity distance
- GW waveform typically does not provide redshift
  - Full mass-redshift degeneracy for inspiral
- How do we get the redshift ?
  - From possible electromagnetic counterpart
  - Statistically, from reliable galaxy catalog
  - From tidal effects if NS equation of state is known
  - From post-merger signal if observed and NS EoS is known
  - Statistically, from known features in NS / BH mass distribution
- High statistics will provide precise measurements

Burst sources

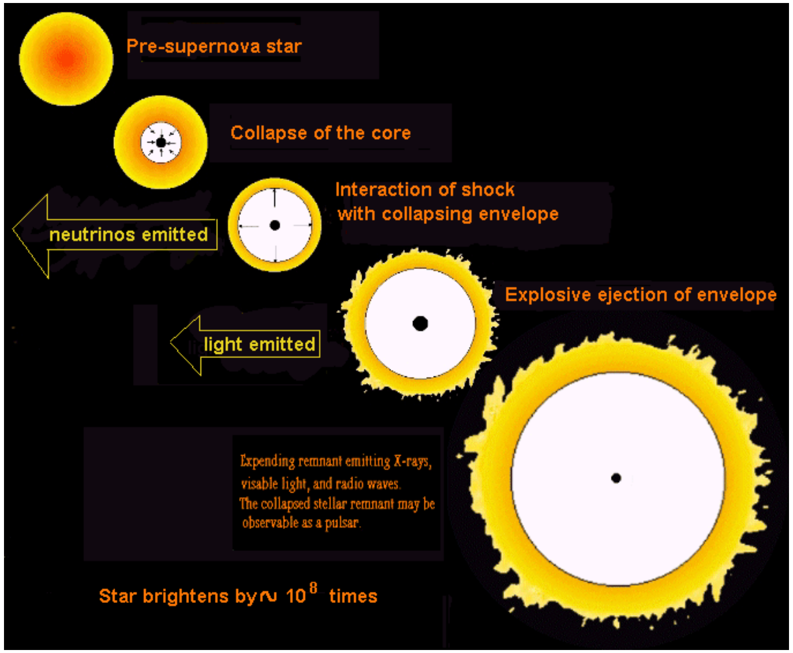
- Generic GW Bursts with < ~1 – 10 s duration
  - Some long-lived transient signals considered too, duration < 10^4 s
- Many poorly modeled transient sources
  - CBC post-merger signal
  - Core-collapse supernovae in or near the galaxy
  - Long GRBs
  - Neutron star instabilities
  - Soft gamma-ray repeater flares
  - …

Ott 2010



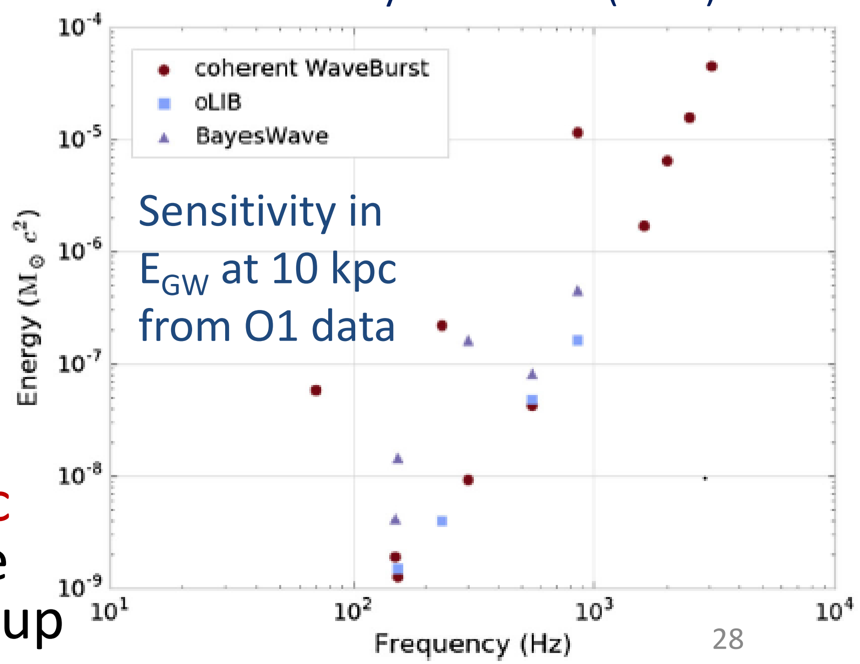
- Some well modeled sources too
  - Cosmic strings
    - Cusps h ∝ $f^{-4/3}$, Kinks h ∝ $f^{-5/3}$

Core-Collapse Supernovae



- Collapse dynamics & GW waveform hard to predict
  - Efficiency of GW emission strongly model dependent $E_{GW} \sim 10^{-11} – 10^{-7}\ M_\odot c^2$

Phys. Rev. D 95 (2017) 042003



- Advanced detectors probe
$$h_{\rm rss} = \sqrt{\int |h_+(t)|^2 + |h_\times(t)|^2} \sim 10^{-23}\ \mathrm{Hz}^{-1/2}$$
- $E_{GW} \sim 10^{-9}\ M_\odot c^2$ at 10 kpc, 100-200 Hz
- Should detect GW signal from a galactic supernova / Put constraints on extreme scenarios for supernova in the local group

Multi-messenger searches

- Triggered searches
  - Search for GW signals in coincidence wit remarkable events
    - GRBs, Magnetar flares, Pulsar glitches, Supernovae, High energy neutrinos…
  - Are more sensitive than their all-sky counterparts

- The electromagnetic follow-up program
  - MoUs with partners allowed successful follow-up in O1/O2
    - Spectacular results for GW170817
  - Moving to open public alerts from O3 on

Continuous wave sources

- GW signal from non axisymmetric rotating neutron star
  - O(10^6 - 10^7) neutron stars within 5 kpc
  - ~2000 known pulsars, ~10% in frequency band of ground-based detectors

$$h = 3.10^{-27} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{10 \text{ kpc}}{D}\right) \left(\frac{I}{10^{45} \text{ g cm}^2}\right) \left(\frac{f}{200 \text{ Hz}}\right)^2$$

- Amplitude of GW signal driven by ellipticity, many uncertainties
  - Maximum sustainable ε depends on NS structure $\epsilon \leq 10^{-7}$–10^{-5}
  - Processes to produce/sustain ε
    - NS born with bumpy crust
    - Strong internal magnetic fields
    - Accretion ± unstable r-mode oscillations
    - Free precession

$$\sim 10^{-12} < \epsilon <\sim 10^{-5}$$

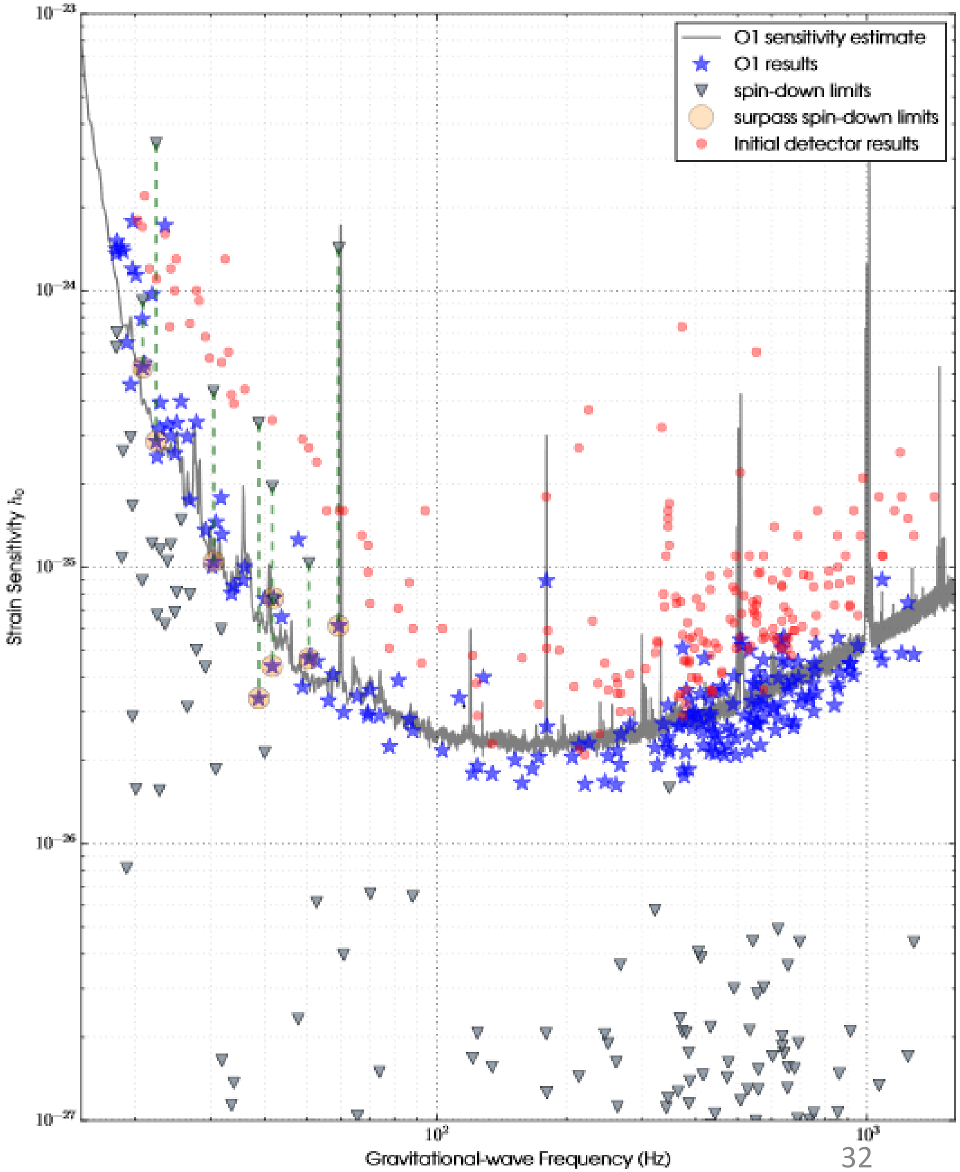
- Emission frequency
  - Depends on emission mechanism $f = 2\ f_{\text{rot}}, f_{\text{rot}} \ldots$

CW search challenges

- Computationally limited searches
  - Need to scan an enormous parameter space
    - Sky location x Frequency x Frequency derivative(s) x Inclination x Polarization
  - Coherent analysis is expensive
    - Cost α (coherence time)^6 x (band upper frequency)^3
- Pick your battles: choose your search mix well
  - Coherent / Semi-coherent, Targeted/Directed/All sky, Isolated neutron stars / In binaries (accretion!)
- Data quality
  - Chase wandering lines of instrumental or environmental origin
- Electromagnetic information
  - Pulsar ephemerides, glitches…

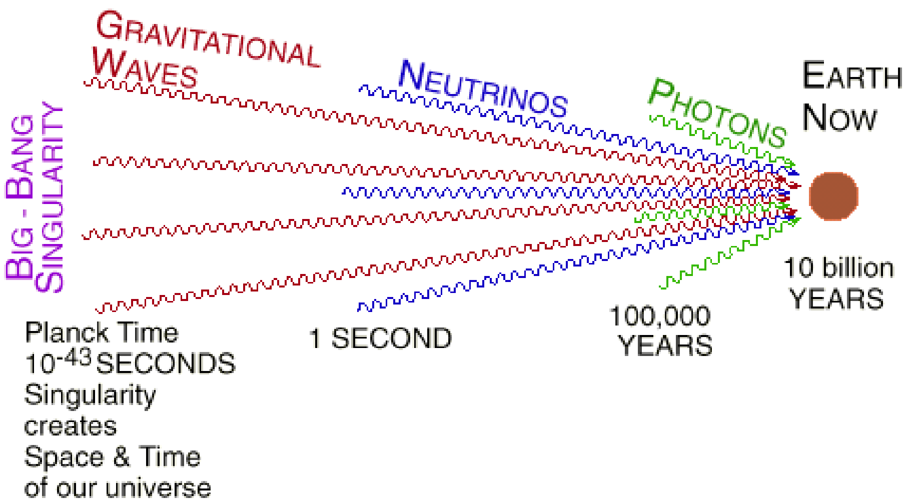
CW: From initial to advanced detectors

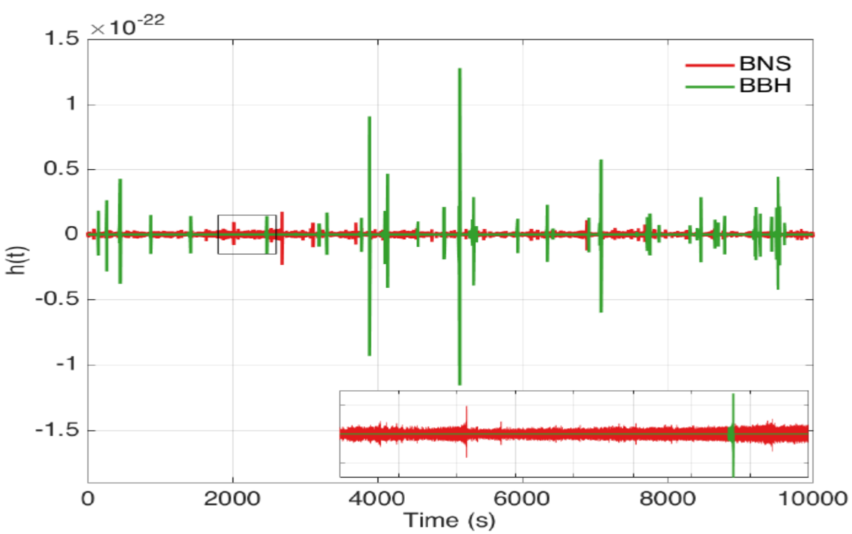
- GW emission <0.2% (1%) of spin-down luminosity for Crab (Vela)
- 8 pulsars constrained below spin-down limit, 32 within factor 10
- Lowest amplitude upper limit $h < 1.6\ 10^{-26}$ (J1918-0642)
- Lowest ellipticity upper limit $\varepsilon < 1.3\ 10^{-8}$ (J0636+5129)



Astrophys. J. 839 (2017)

Stochastic Gravitational Wave Background

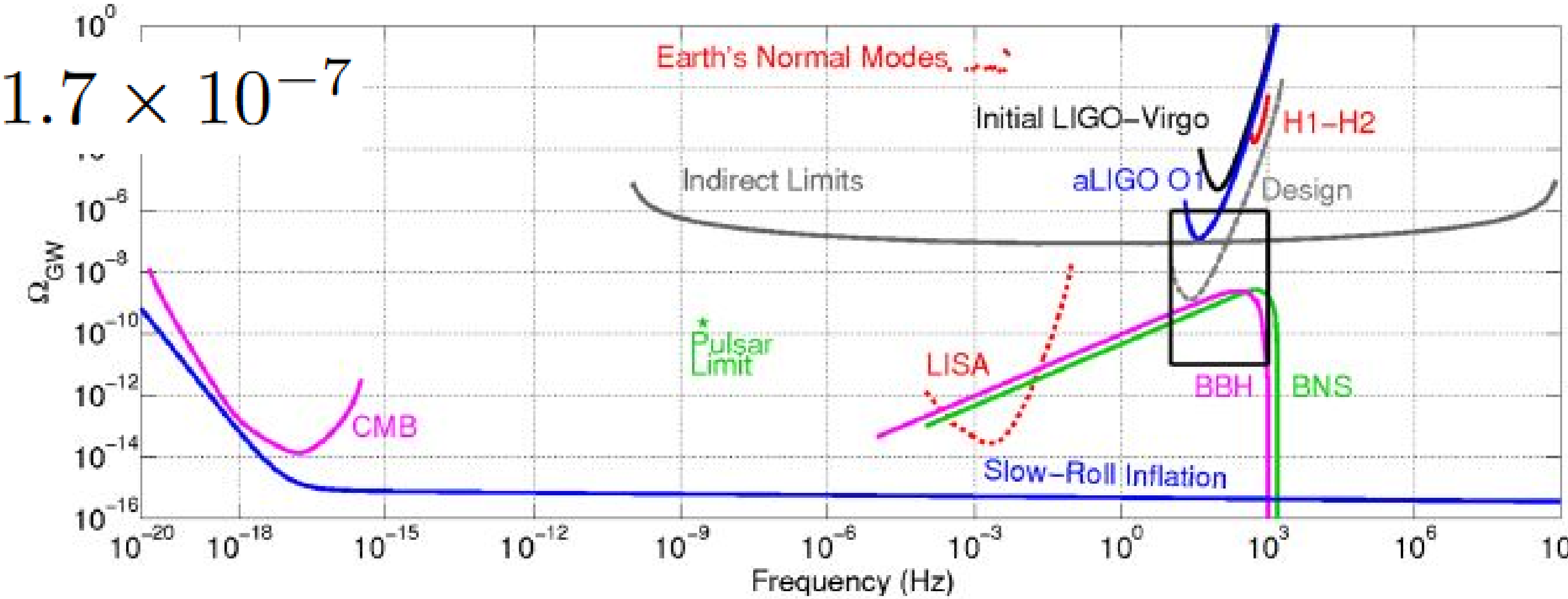




- Stochastic gravitational-wave background expected from
  - Cosmological sources
    - Inflation models, Cosmic strings, Phase transitions…
  - Astrophysical sources
    - Superposition of unresolved sources
- Spectral content carries signatures of underlying physics

SGWB energy density upper limits (O1)

$$\Omega_0 < 1.7 \times 10^{-7}$$



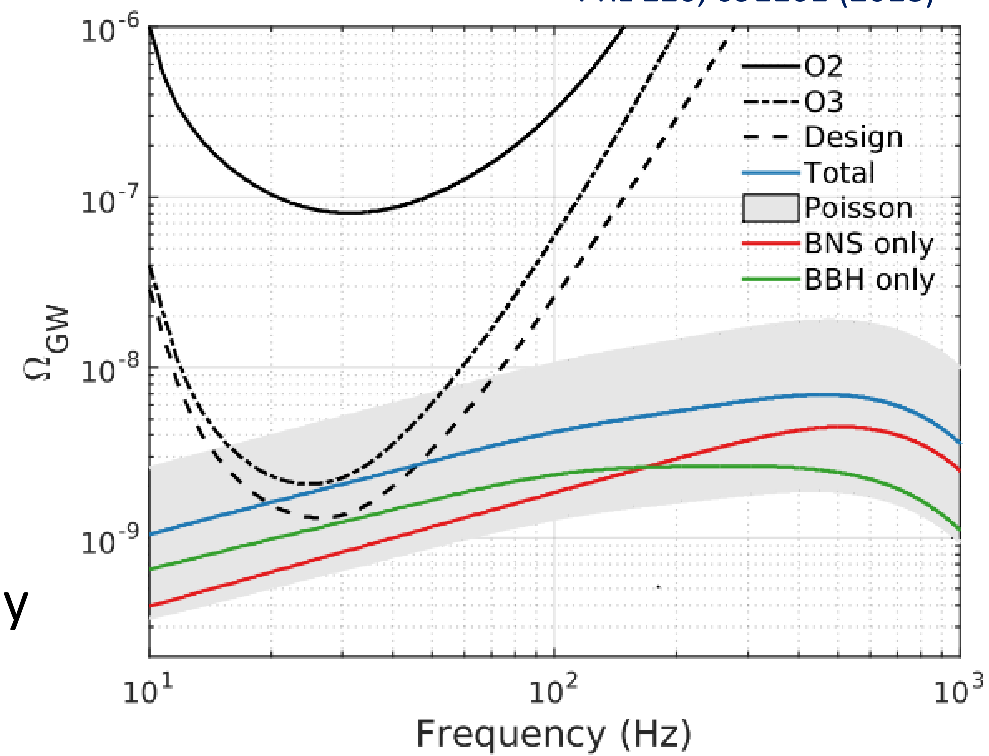
PRL 118, 121101 (2017)

- 4 orders of magnitude improvement in Ω_{GW} sensitivity expected with advanced detectors
  - 2 from detector sensitivity
  - 2 from detector bandwidth
- Future measurements can probe the physics of inflation and very high energy processes
  - $10^6 - 10^7$ TeV

Expected SGWB from CBC mergers

- First detections suggest population of BBH with relatively high mass
- SGWB from BBH could be higher than expected
  - Incoherent superposition of all merging binaries in Universe
  - Dominated by inspiral phase
- Significant contribution from BNS background
- Estimated energy density
  - $\Omega_{GW} \sim 2 \cdot 10^{-9}$ at 25 Hz
- Statistical uncertainty due to poorly constrained merger rate currently dominates model uncertainties
- Background potentially detectable by Advanced LIGO / Advanced Virgo

PRL 120, 091101 (2018)



Science prospects ↔ Instrumental challenges

- ❑ Sensitivity
  - ➢ Captured by BNS range
  - ➢ More events to explore source population
  - ➢ More SNR for exceptional events
- ❑ Bandwidth
  - ➢ Low frequency sensitivity
    - ▪ Higher mass BBH mergers
    - ▪ CBC parameter accuracy
  - ➢ High frequency sensitivity
    - ▪ CBC post-merger signal
- ❑ Network size

- ❑ Robustness
  - ➢ Duty cycle
  - ➢ 3 detector operation
    - ▪ Sky localization
- ❑ Data quality
- ❑ Calibration
- ❑ Open public alerts

Prospects for Near Future

- O2: 1/2 – 1/4 of the design sensitivity of Advanced LIGO and Advanced Virgo
- Currently both LIGO and Virgo improving sensitivity of instruments
- Next: ~1 year long O3 run
  - Start April 2019
  - LIGO BNS range ~ 120 Mpc, Virgo ~ 60 Mpc
  - KAGRA hopes to join before the end of O3
- Best guesses for O3
  - BBH: Several per month to several per week
  - BNS: 1 to 10 in the year-long run
  - NSBH: N=0 not ruled out in any scenario, most give ~50% N>0
- More events, more physics… more breakthroughs?
  - Eagerly waiting for next galactic supernova