Overview of Current Research in Gravitational Astronomy

International Centre for Theoretical Studies

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  - In this lecture we will discuss what gravitational waves are and how they can be used to explore the dark and dense Universe

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- This lecture will take you on a tour of what this window is all about and what it might tell us about the Universe

What are Gravitational Waves?

In Newton's law of gravity the gravitational field satisfies the Poisson equation:

$$\nabla^2\Phi(t,\mathbf{X}) = 4\pi G\rho(t,\mathbf{X})$$

Gravitational field is described by a scalar field, the interaction is instantaneous and no gravitational waves.

In general relativity for weak gravitational fields, i.e.

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}, \quad |h_{\alpha\beta}| \ll 1$$

in Lorentz gauge, i.e. $\bar{h}^{\alpha\beta}{}_{,\beta} = 0$, Einstein's equations reduce to wave equations in the metric perturbation:

$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right)\bar{h}^{\alpha\beta} = -16\pi T^{\alpha\beta}.$$

Here $\bar{h}_{\alpha\beta} = h_{\alpha\beta} - \frac{1}{2}\eta_{\alpha\beta}\eta^{\mu\nu}h_{\mu\nu}$ is the trace-reverse tensor.

Transverse–Traceless Gauge and Number of Degrees of Freedom

Plane–wave solutions:

$$\bar{h}^{\alpha\beta} = A^{\alpha\beta}\exp(2\pi\imath k_\mu x^\mu), \quad k_\alpha k^\alpha = 0$$

Gravitational waves travel at the speed of light.

Gauge conditions imply that $A^{\alpha\beta}k_\beta = 0$. Further gauge conditions

1. $A^{0\beta} = 0 \quad \Rightarrow \quad A^{ij}k_j = 0$: *Transverse* wave; and
2. $A^j{}_j = 0$: *Traceless* wave amplitude.

For a wave traveling in the z–direction then $k_z = k,\ k_x = k_y = 0$.

Gauge conditions, transversality and traceless conditions imply

$$A^{0\alpha} = A^{z\alpha} = 0,\ A^{xy} = A^{yx},\ \ A^{yy} = -A^{xx}.$$

Only two independent amplitudes. Two independent degrees of freedom for polarization: plus–polarization and cross–polarization.

Tidal Effect of Gravitational Waves

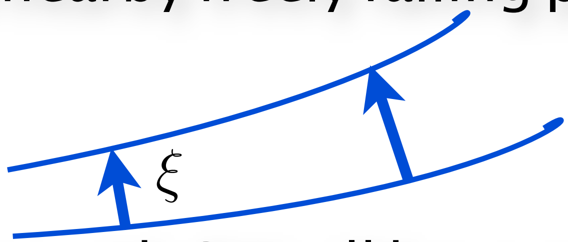
In the TT gauge, the effect of a wave on a particle at rest

$$\frac{d^2}{d\tau^2}x^i = -\Gamma^i{}_{00} = -\frac{1}{2}\left(2h_{i0,0} - h_{00,i}\right) = 0.$$

So a particle at rest remains at rest. TT gauge is a coordinate system that is comoving with freely falling particles.

The waves have a tidal effect which can be seen by looking at the change in distance between two nearby freely falling particles:

$$\frac{d^2}{d\tau^2}\xi^i = R^i{}_{0j0}\xi^j = \frac{1}{2}h_{ij,00}\xi^j.$$

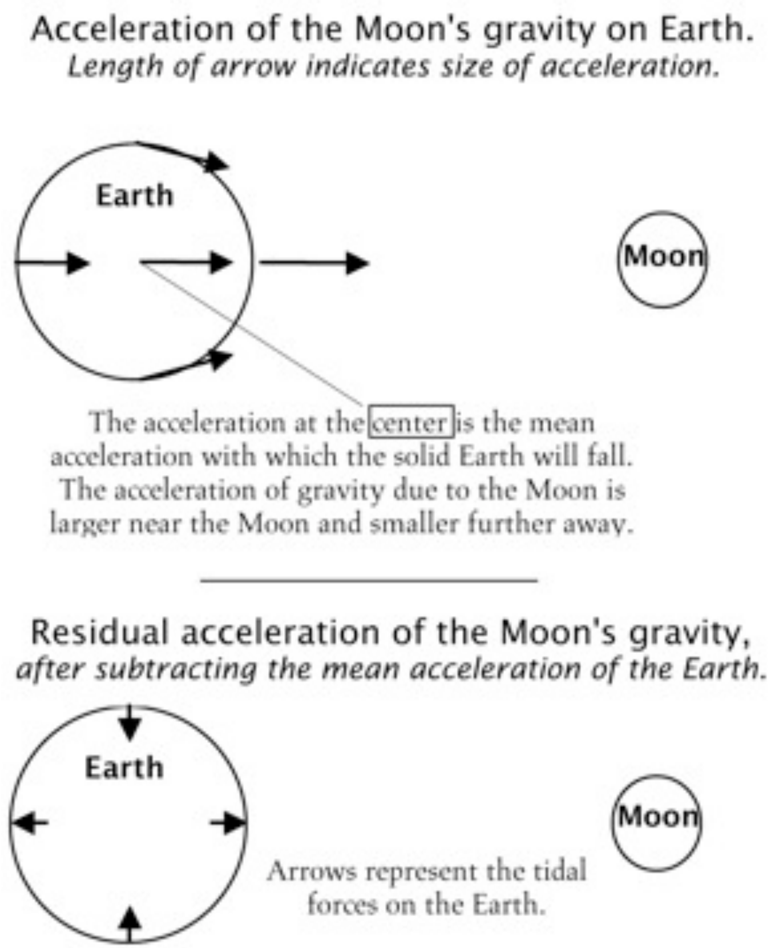


Isaacson showed that a spacetime with GW will have curvature with the corresponding Einstein tensor given by

$$G_{\alpha\beta} = 8\pi T^{(GW)}_{\alpha\beta} \qquad T^{(GW)}_{\alpha\beta} = \frac{1}{32\pi} h^{TT}_{\mu\nu}{}_{,\alpha} h^{TT\mu\nu}{}_{,\beta}.$$

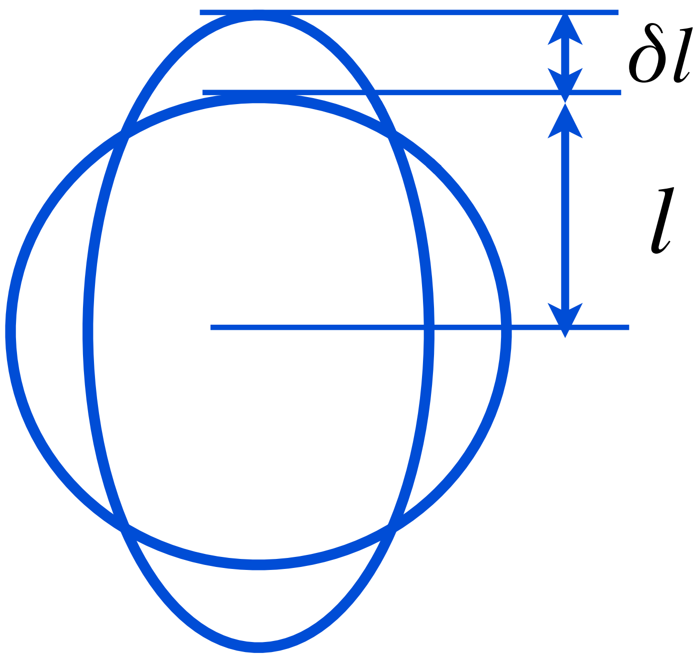
Tidal Gravitational Forces

- Gravitational effect of a distant source can only be felt through its tidal forces
- Gravitational waves are traveling, time-dependent tidal forces.
- Tidal forces scale with size, typically produce elliptical deformations.



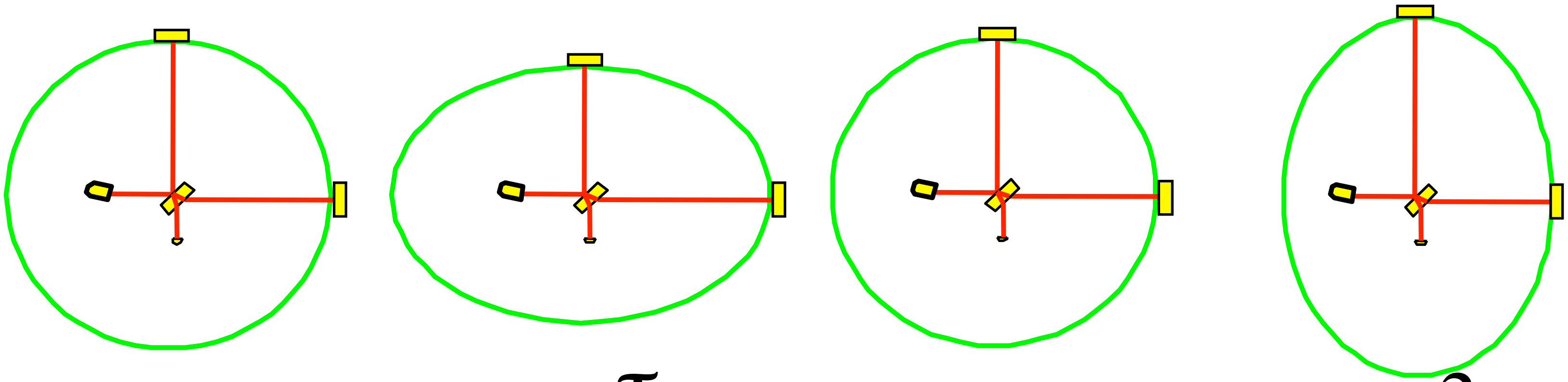
GW Amplitude – Measure of Strain

- Gravitational waves cause a strain in space as they pass
- Measurement of the strain gives the amplitude of gravitational waves



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

Interferometric gravitational_wave detectors



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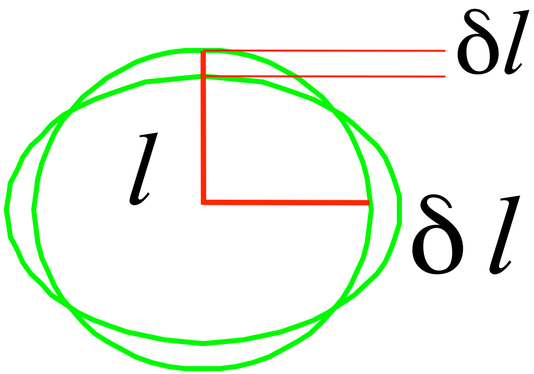

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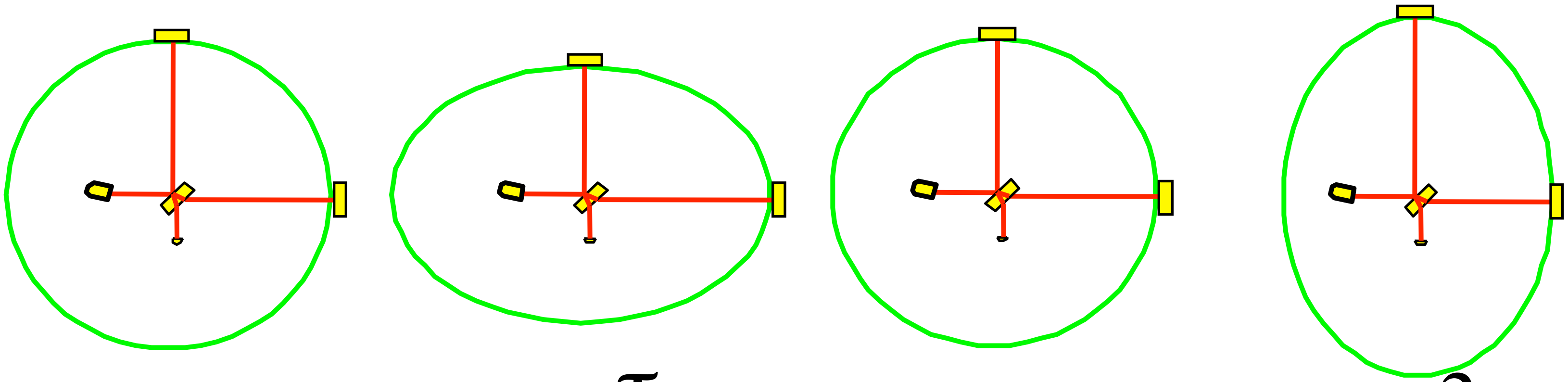

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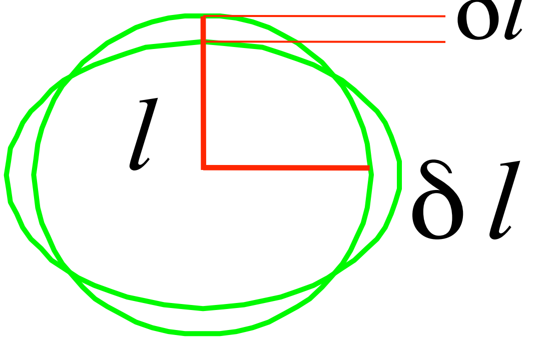

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For Typical Astronomical sources

$$h = \frac{2\delta l}{l} \leq 10^{-22}$$

Gravitational Wave Flux

Flux of gravitational waves can be shown to be

$$\langle T^{(GW)0z} \rangle = \frac{k^2}{32\pi}(A_+^2 + A_\times^2)$$

where $k = 2\pi f$ is the wave number. For a wave with an amplitude h in both polarizations the energy flux is

$$F_{gw} = \frac{\pi}{4} f^2 h^2.$$

$$F_{\rm gw} = 3 \text{ mW m}^{-2} \left[\frac{\rm h}{1 \times 10^{-22}}\right]^2 \left[\frac{\rm f}{1 \text{ kHz}}\right]^2$$

This is a large flux (twice that of full Moon) for even a source with a very small amplitude! Integrating over a sphere of radius r and assuming that the signal lasts for a duration τ gives the amplitude in terms of energy in GW

$$h = 10^{-21} \left[\frac{E_{gw}}{0.01 M_\odot c^2}\right]^{1/2} \left[\frac{r}{20 \text{ Mpc}}\right]^{-1} \left[\frac{f}{1 \text{ kHz}}\right]^{-1} \left[\frac{\tau}{1 \text{ ms}}\right]^{-1/2}.$$

Understanding Sources of Gravitational Waves

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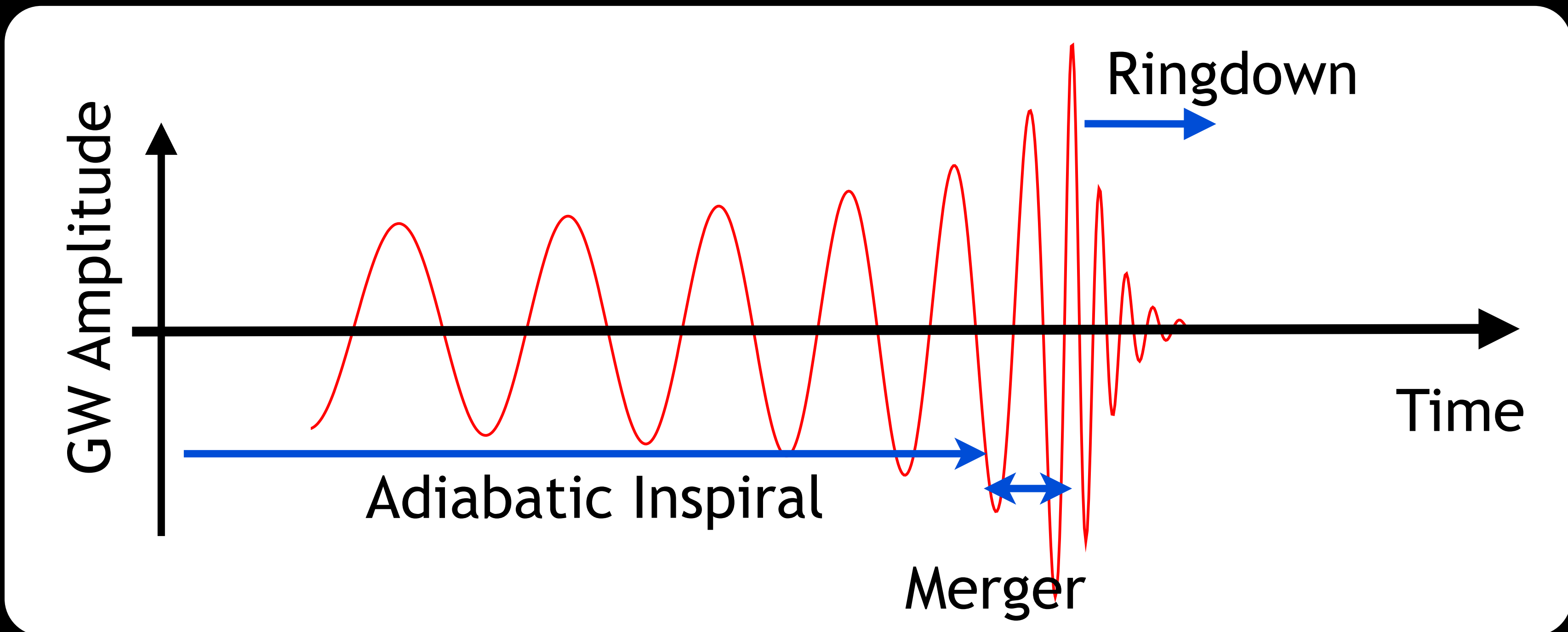

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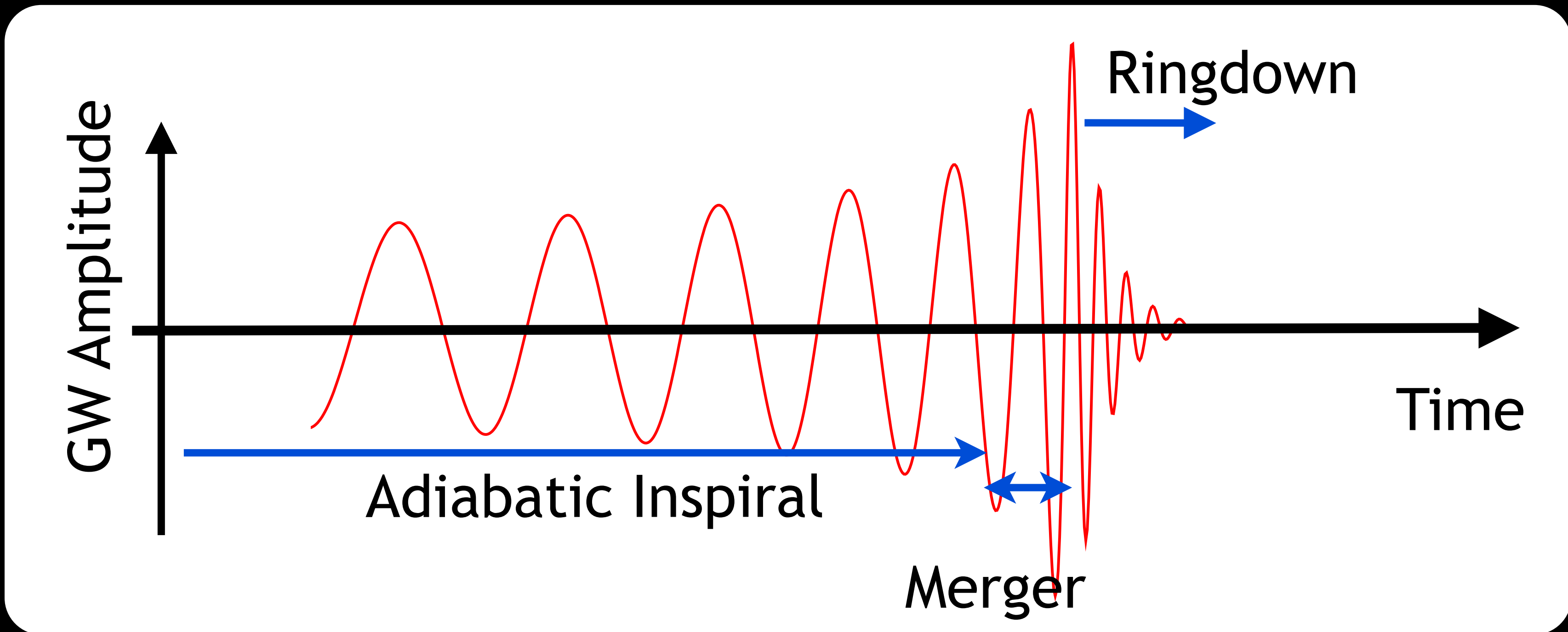

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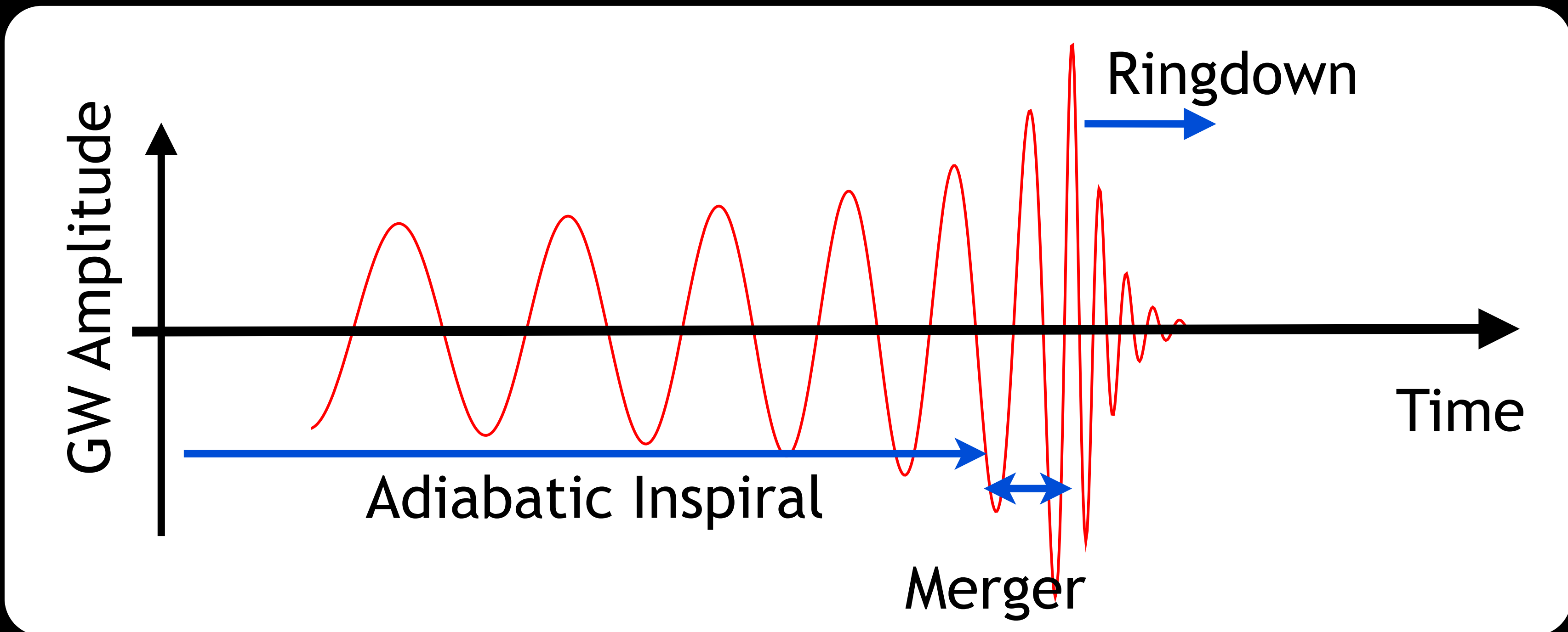

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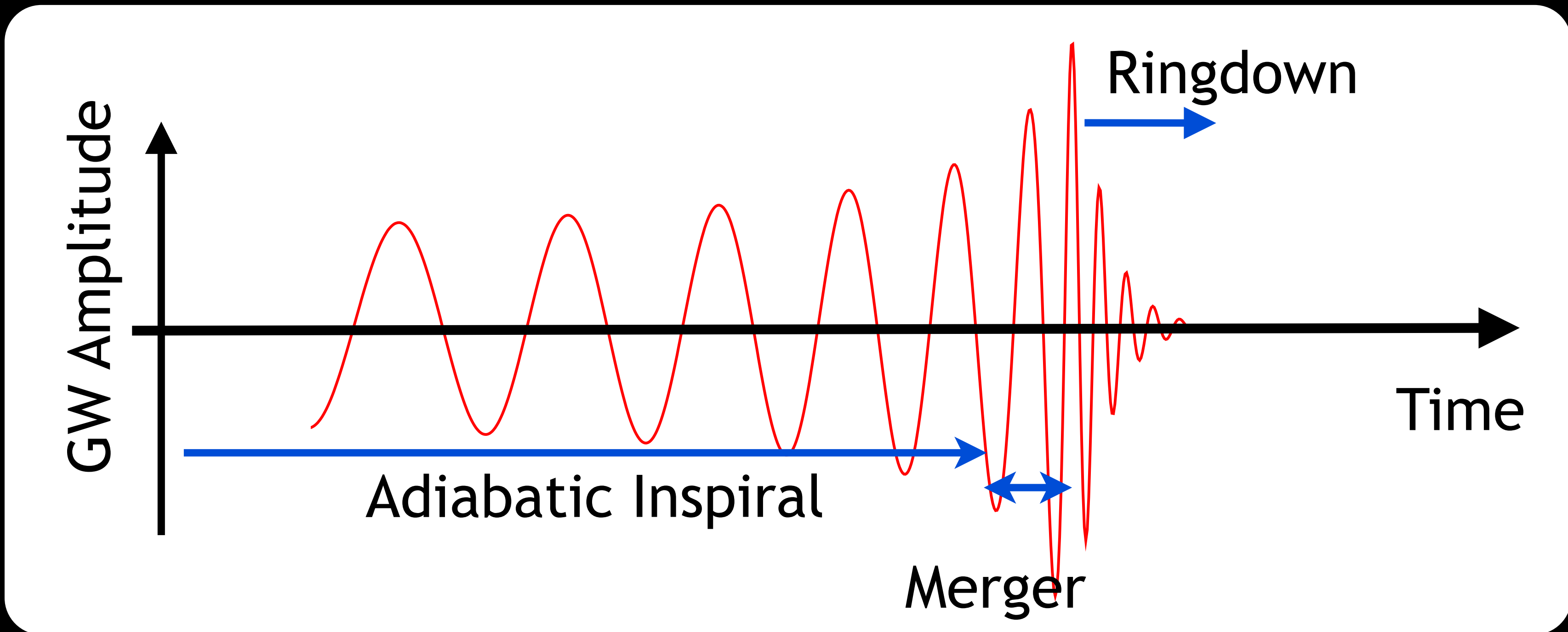

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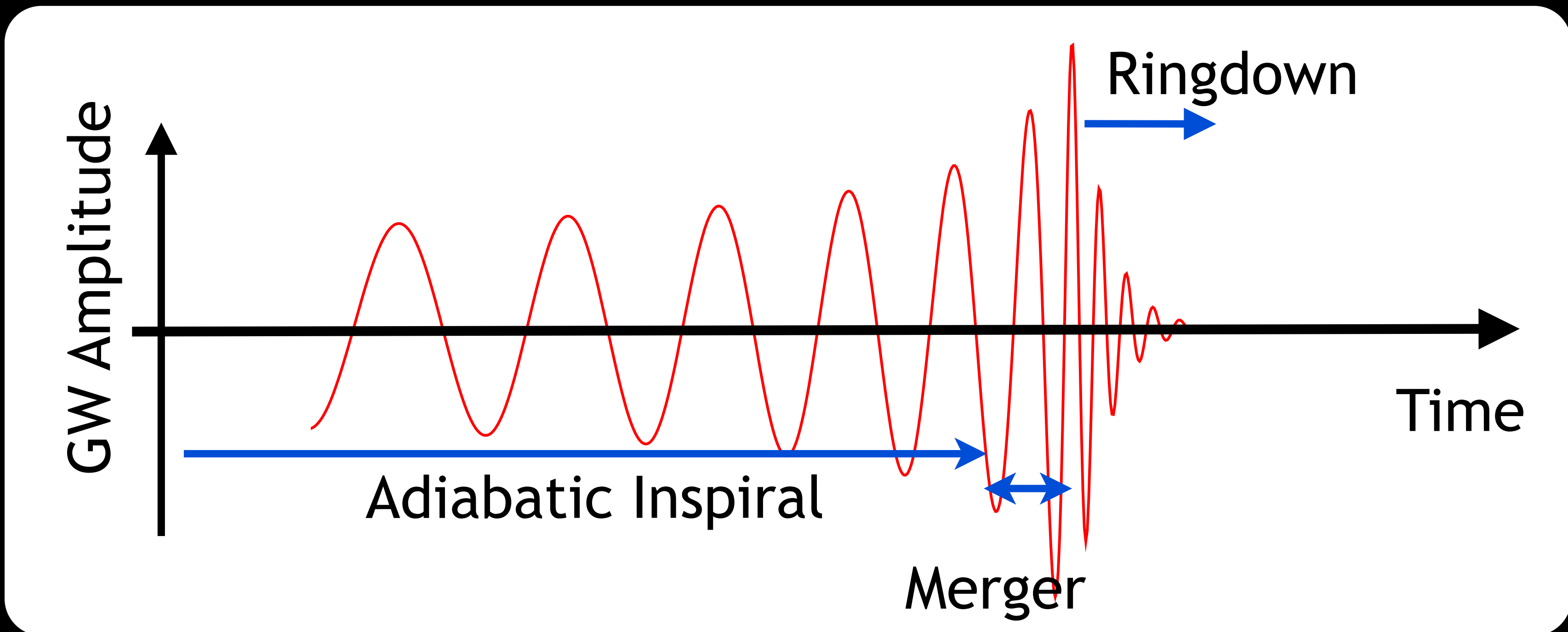

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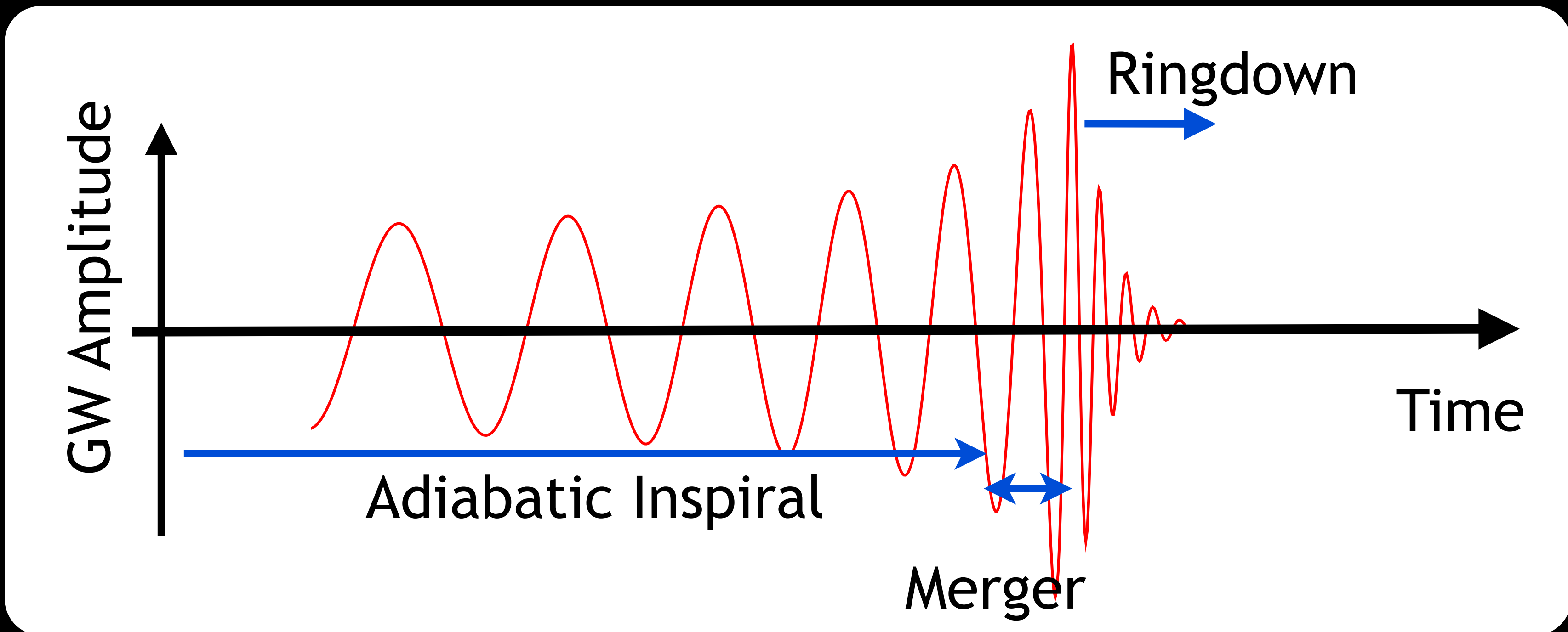
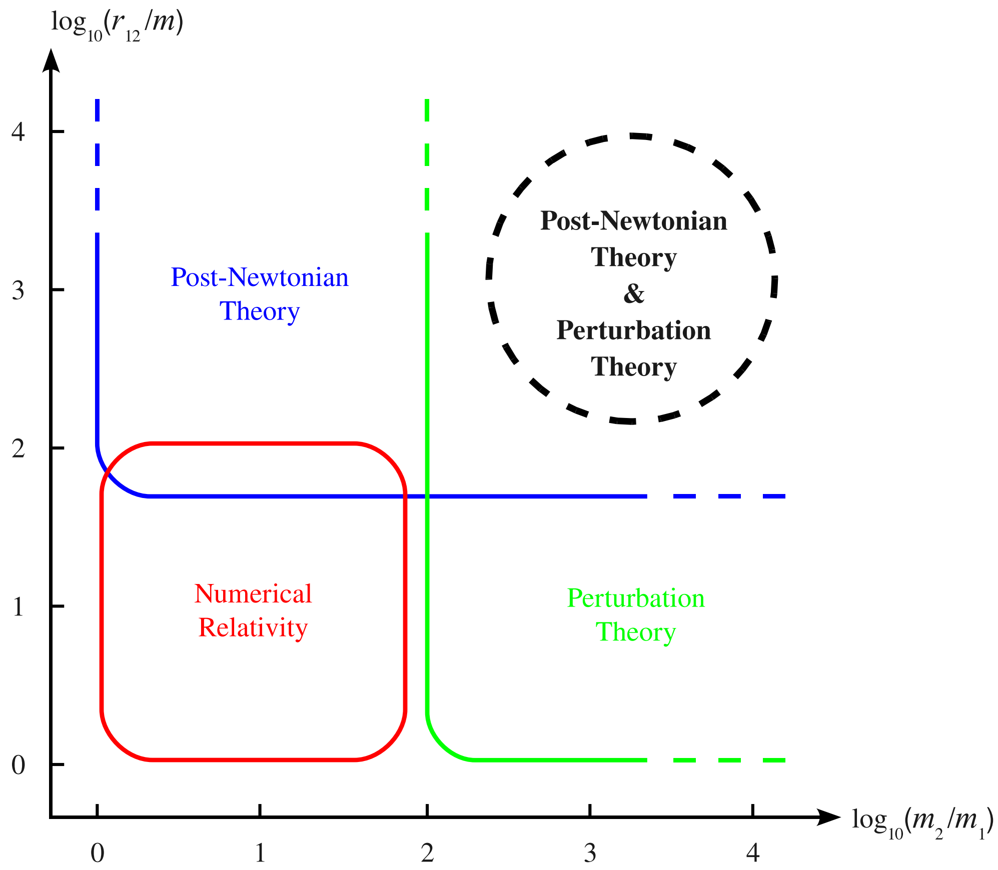
- The shape of the signal contains information about the binary



Two–Body Problem in General Relativity: Application of Various Methods



[Blanchet et al. 10]

- Two parameters determine the range of validity of each method:

$$\frac{G\,m}{r_{12}\,c^2} \sim \frac{v^2}{c^2}\,, \qquad \frac{m_2}{m_1}$$

- EOB formalism can incorporate results of different methods. It can span the entire parameter and provide GW detectors with faithful templates.

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  - Need long NR simulations and better analytical models

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  - Phenomenological waveforms, effective one–body model, numerical simulations

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Analytical Models of Inspiral and Merger

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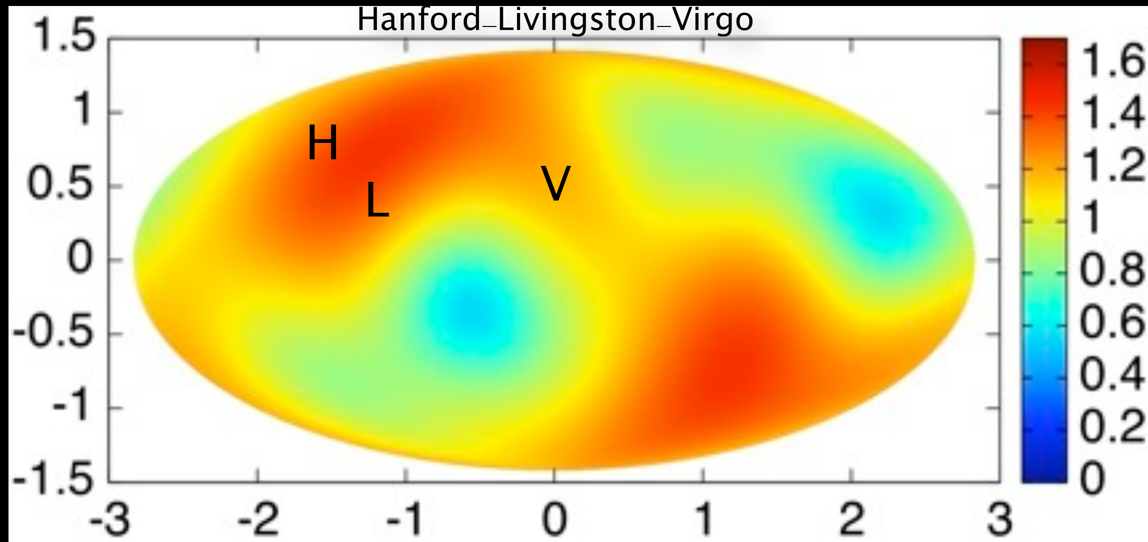
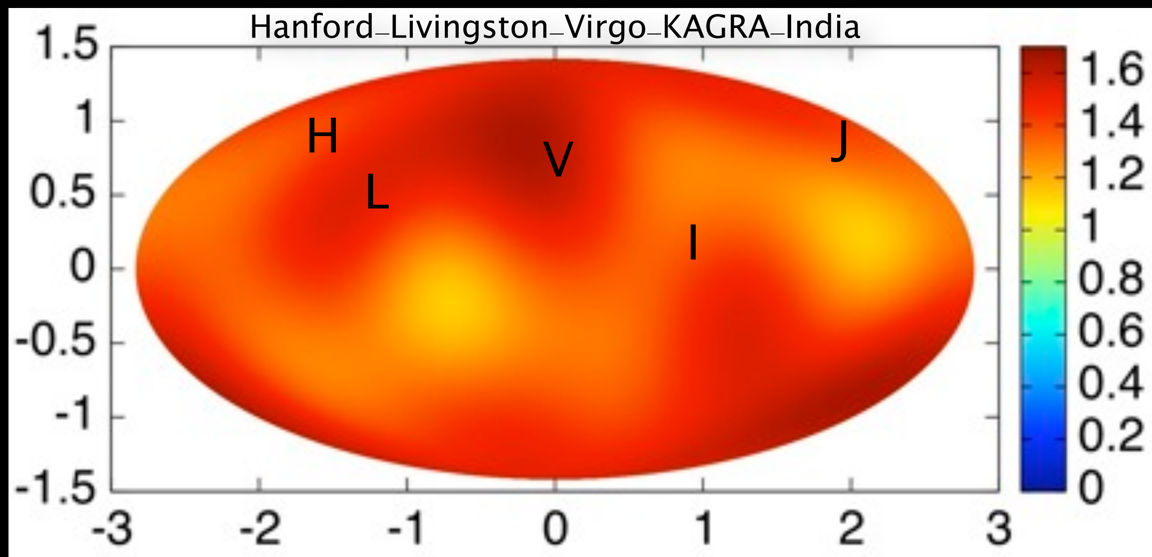
Challenges of Gravitational Wave Searches

Challenge of Gravitational Wave Searches





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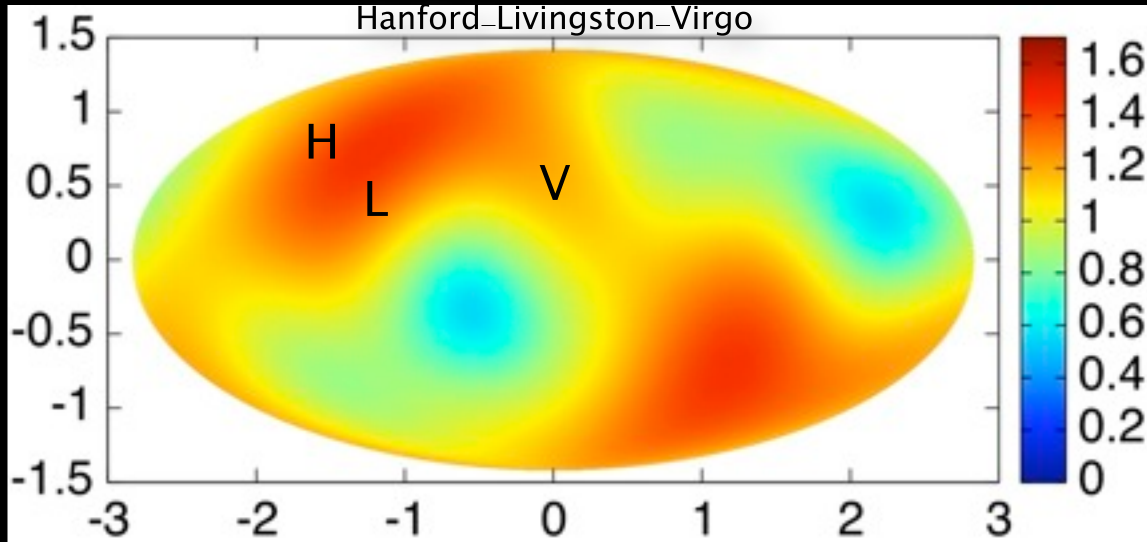

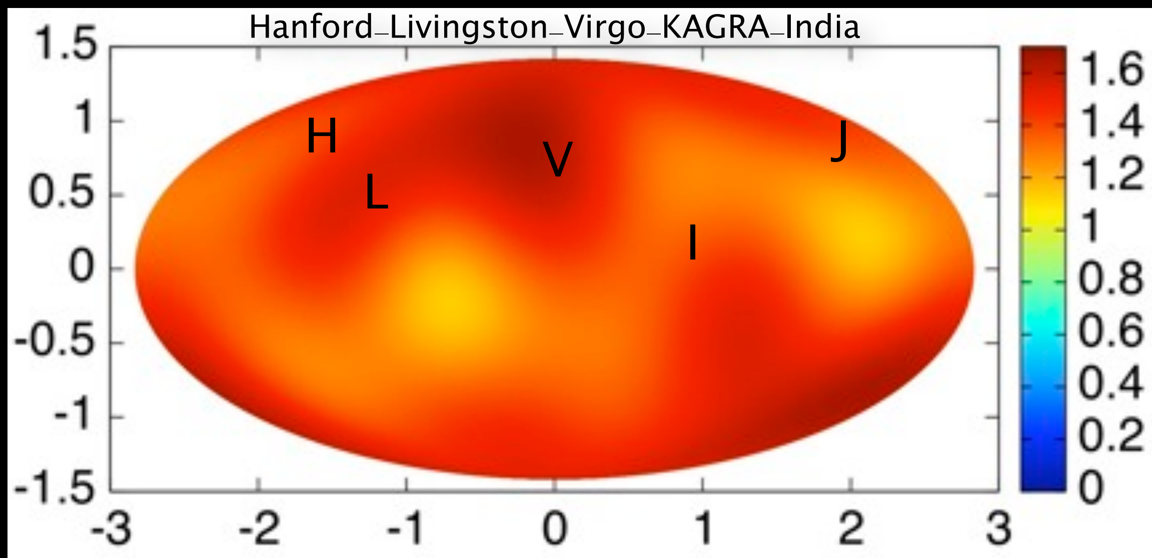

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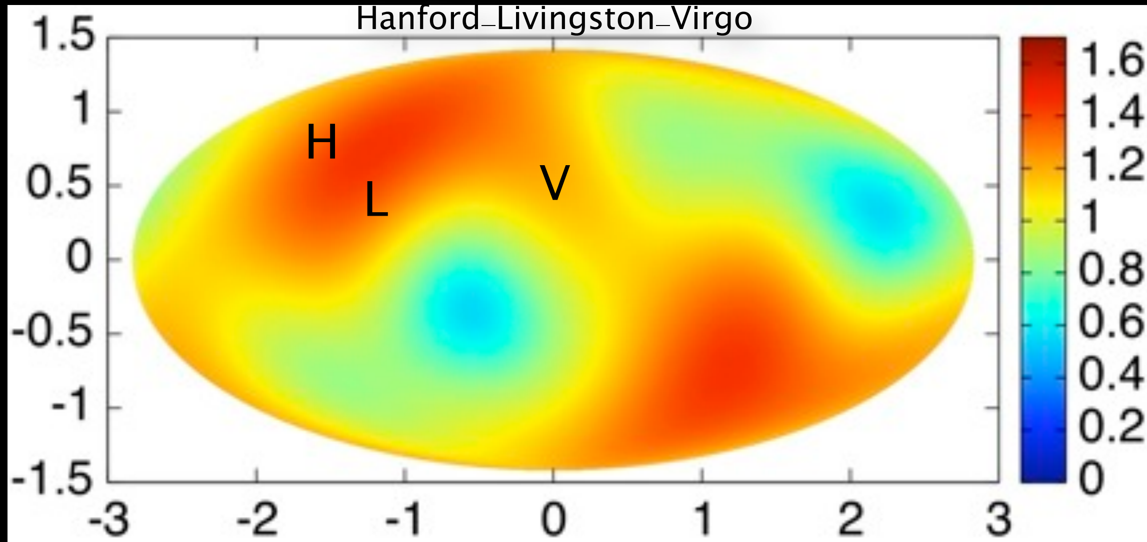

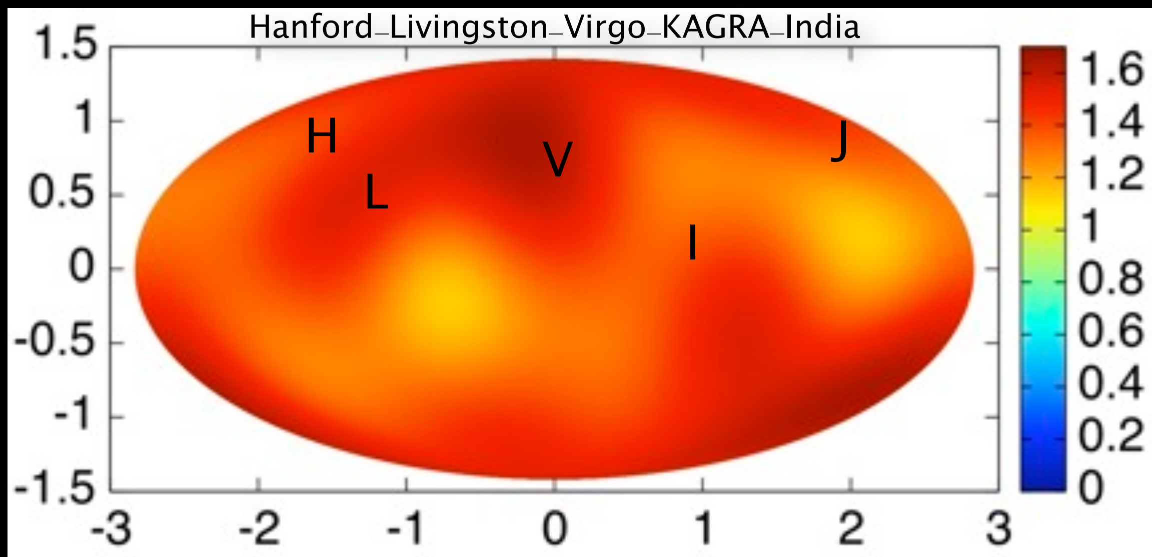

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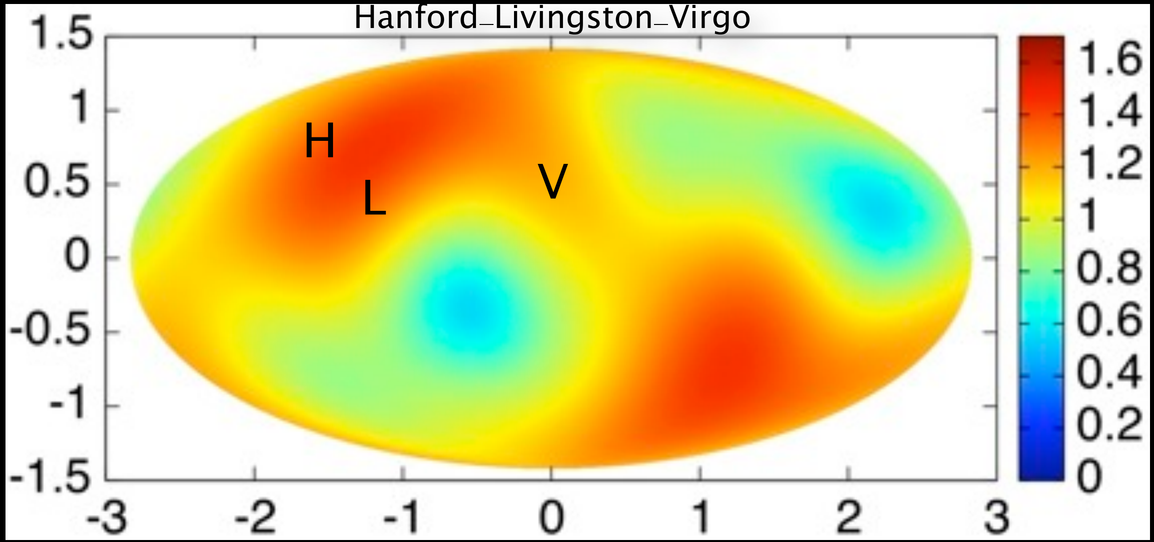

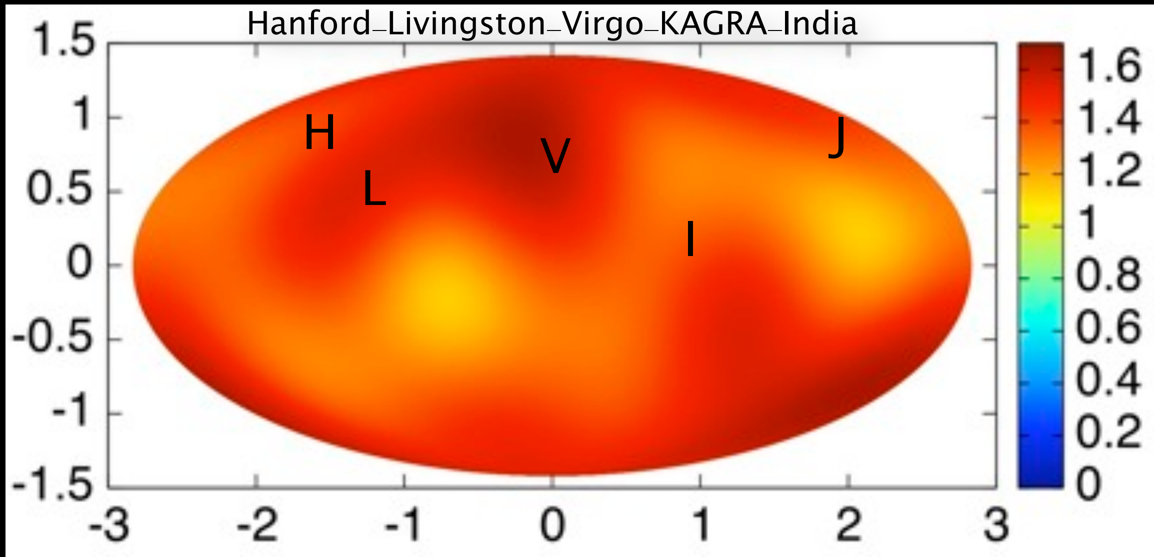

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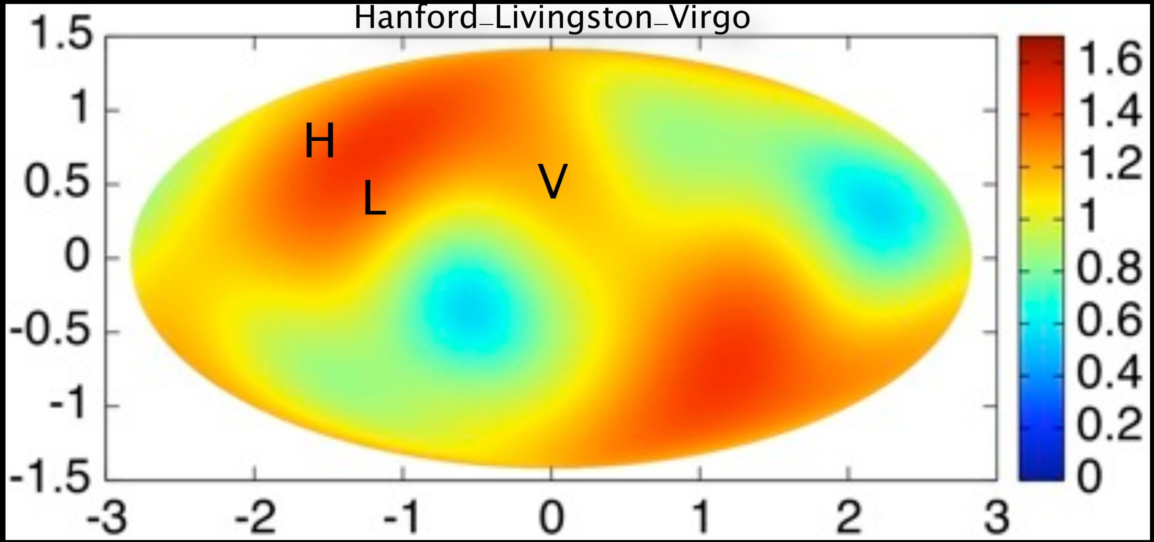

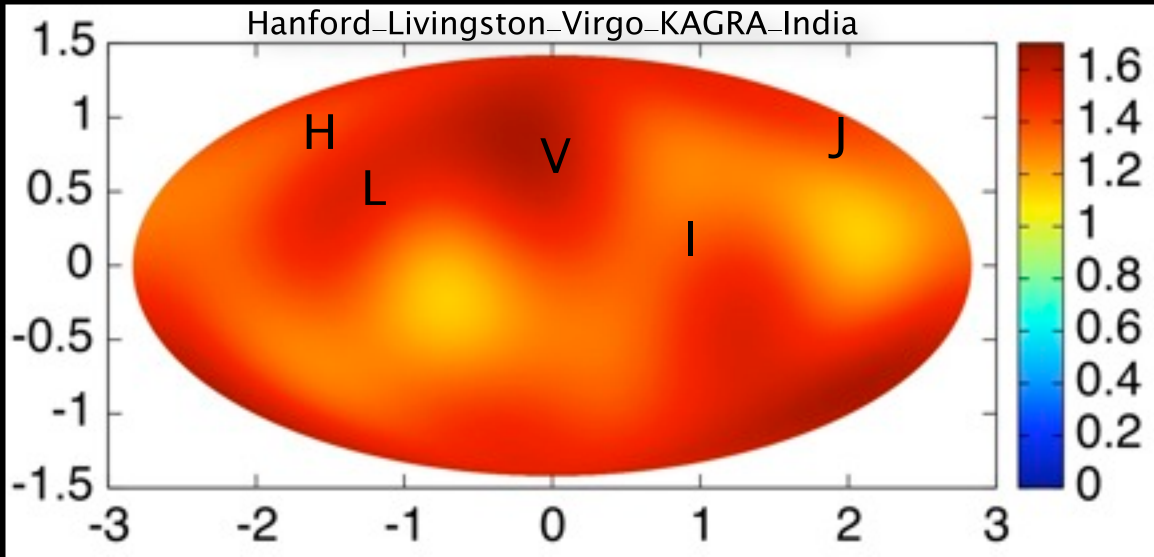

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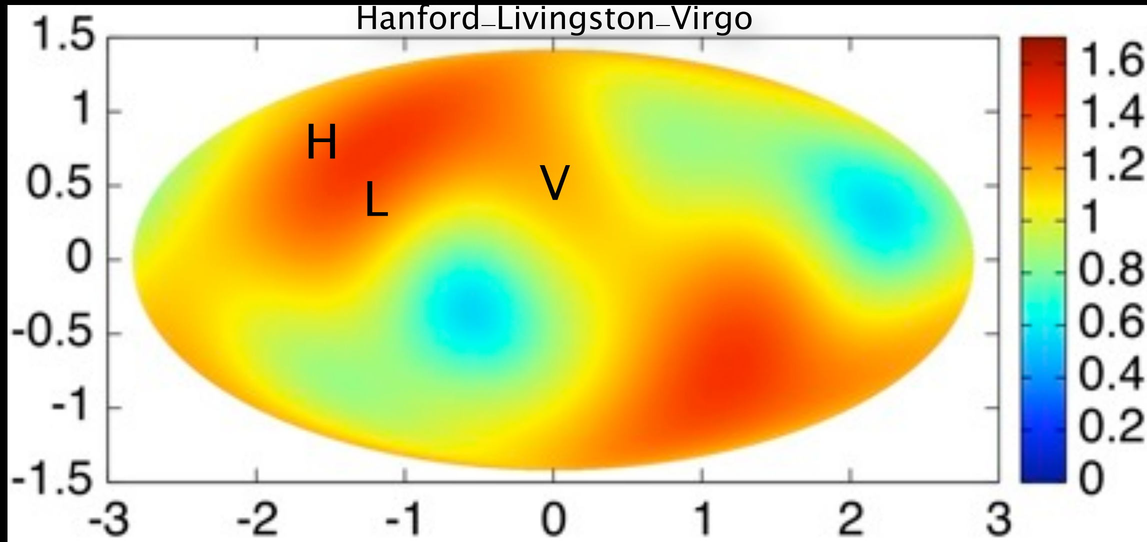

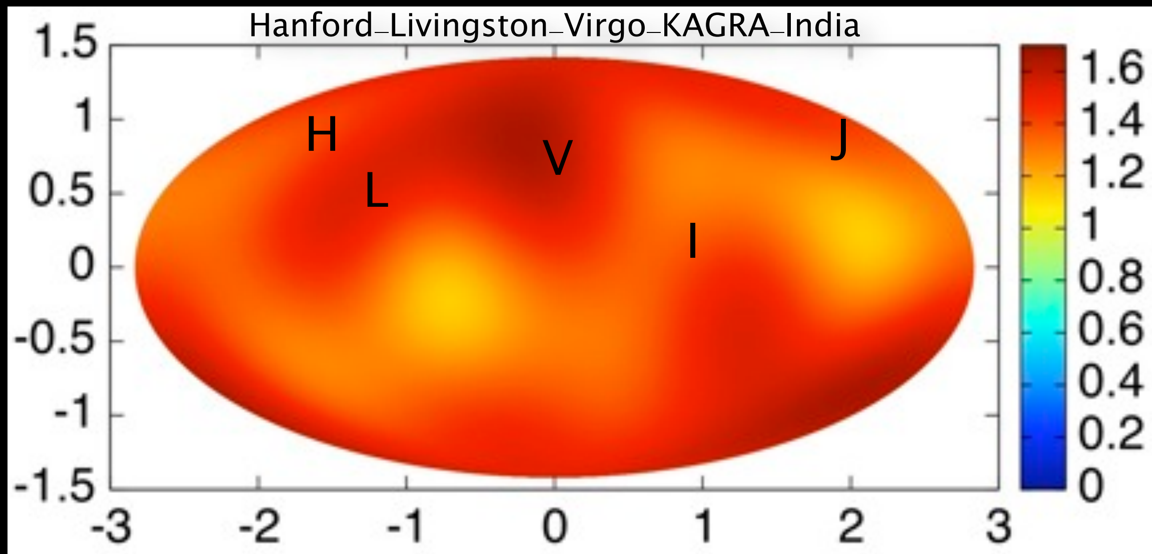

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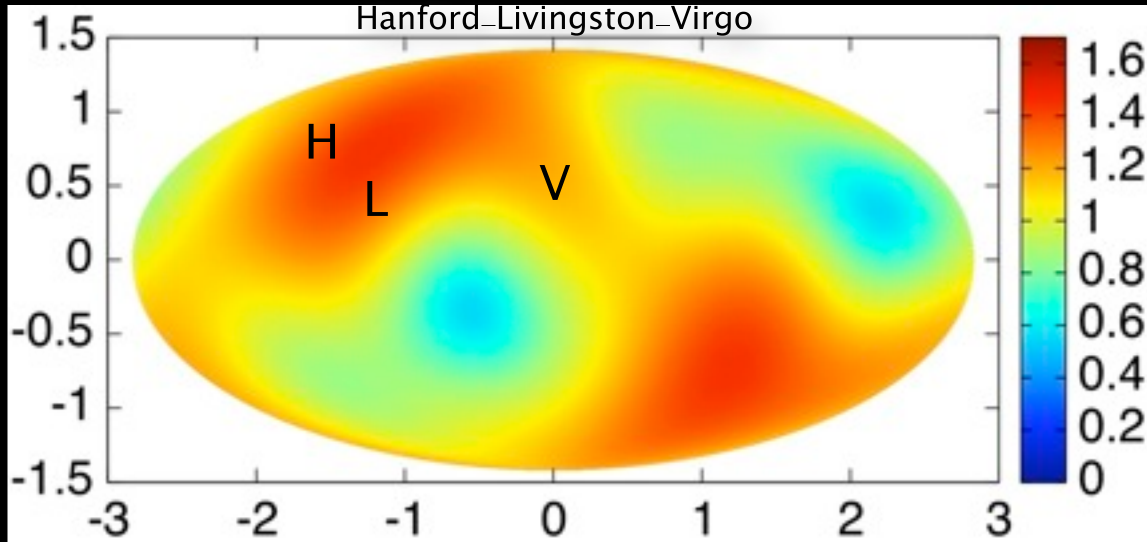

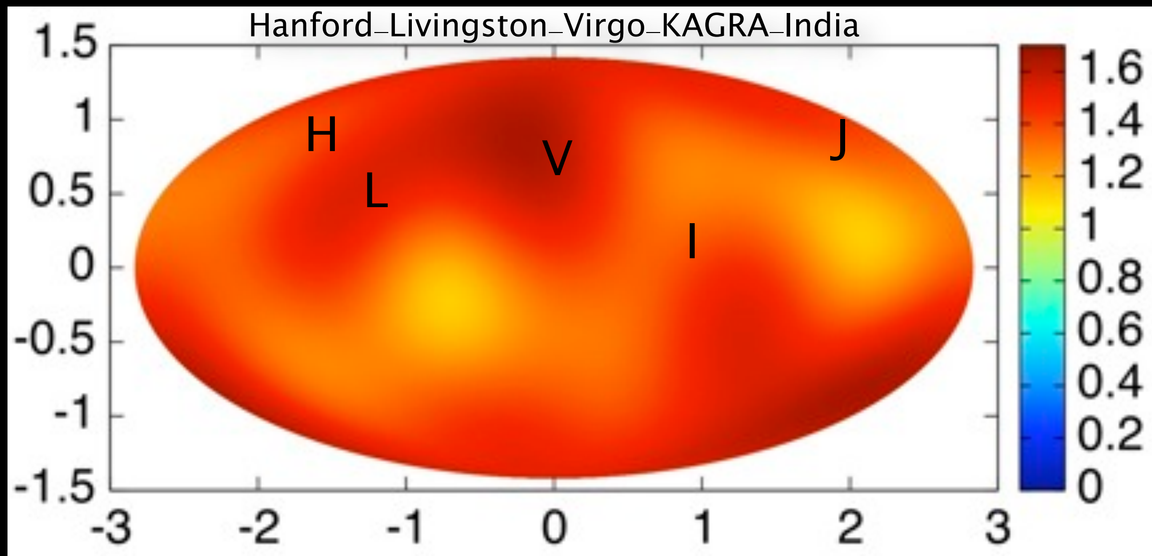

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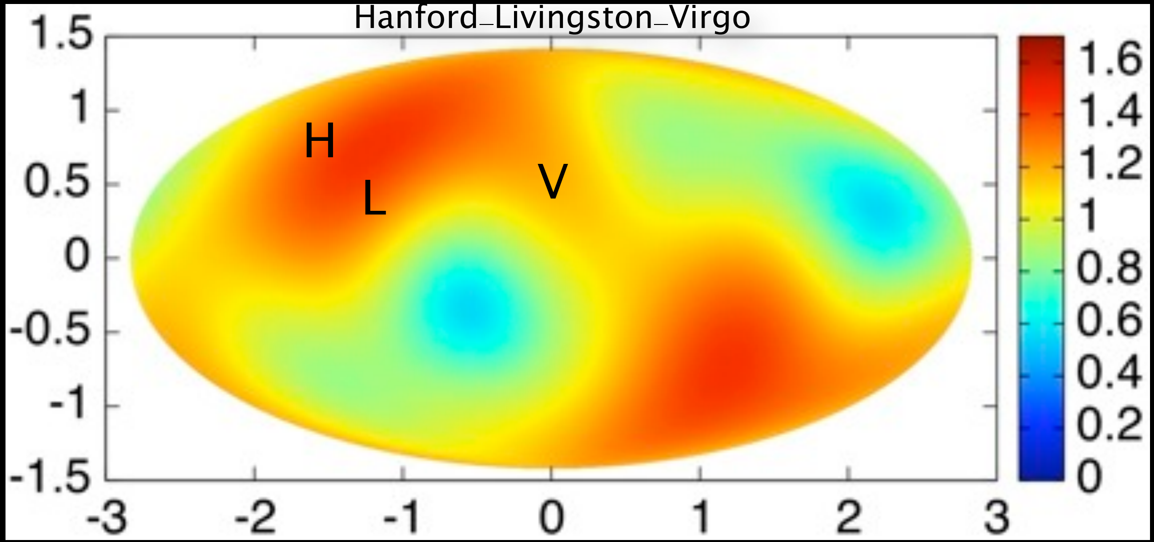
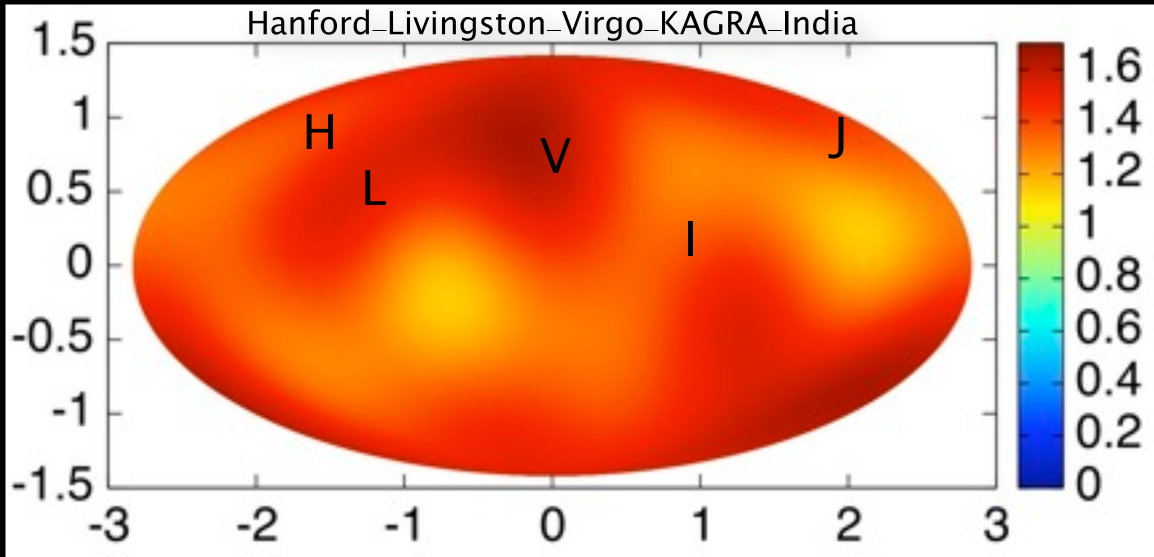
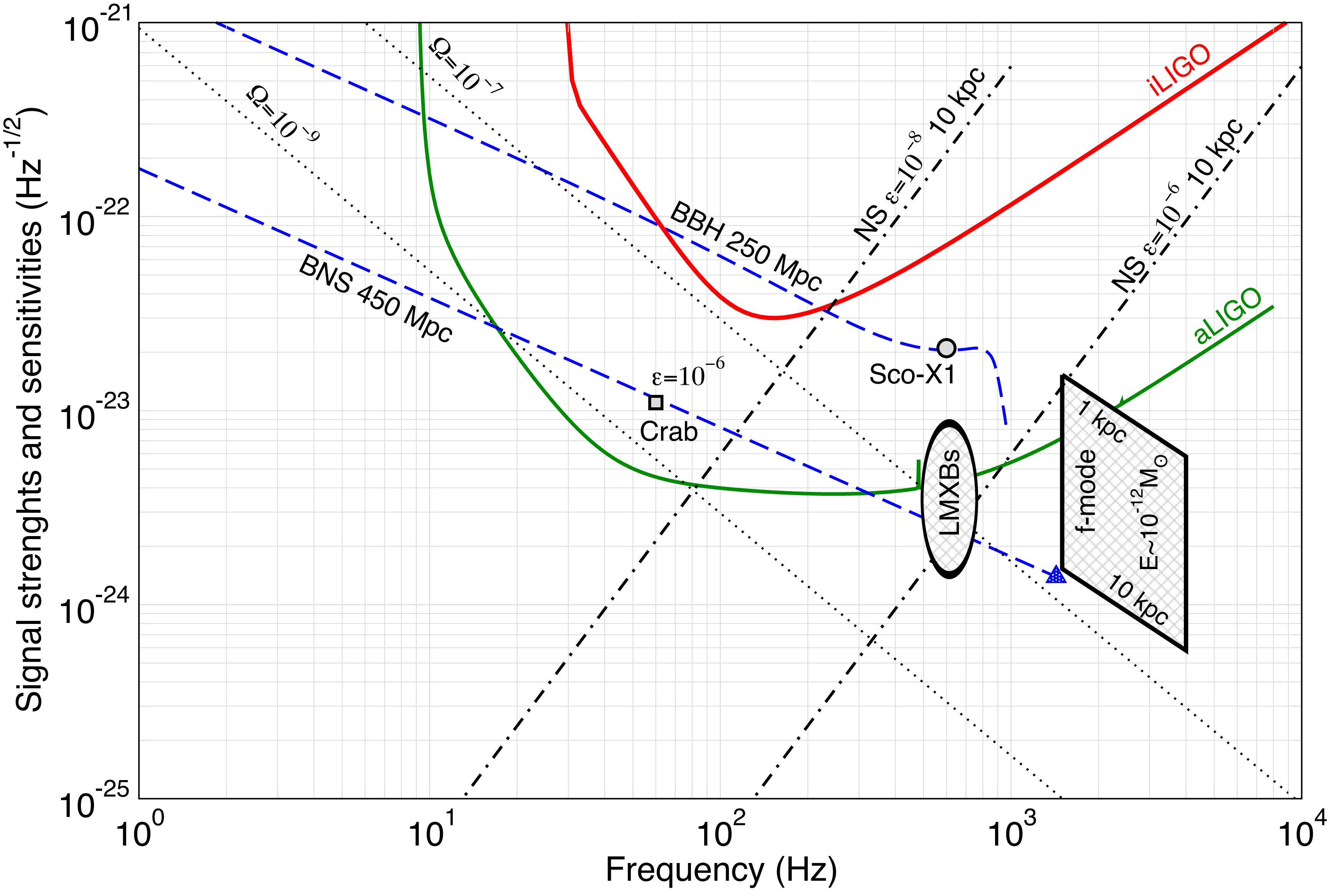




Sources in advanced detectors



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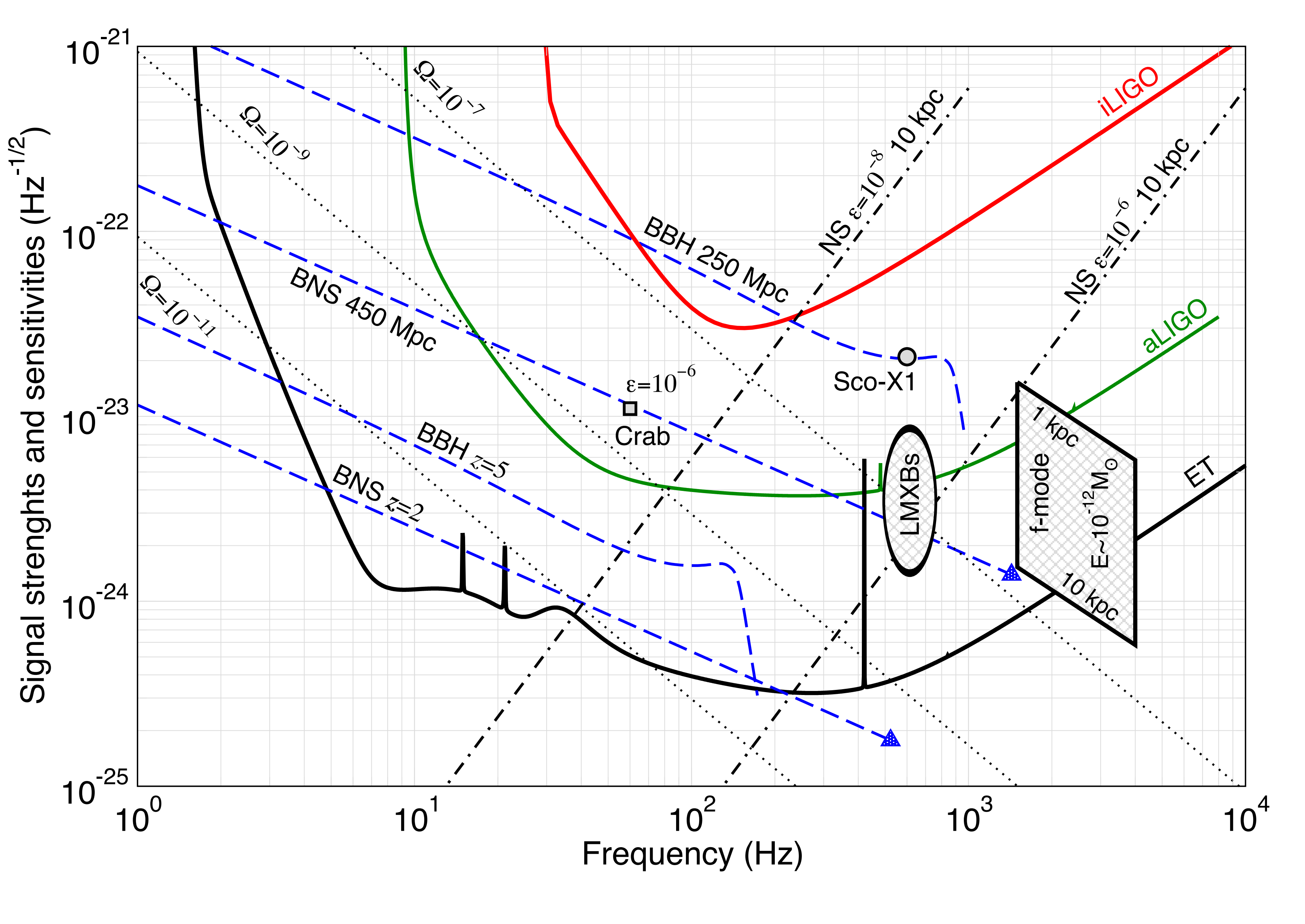
Sources in Einstein Telescope



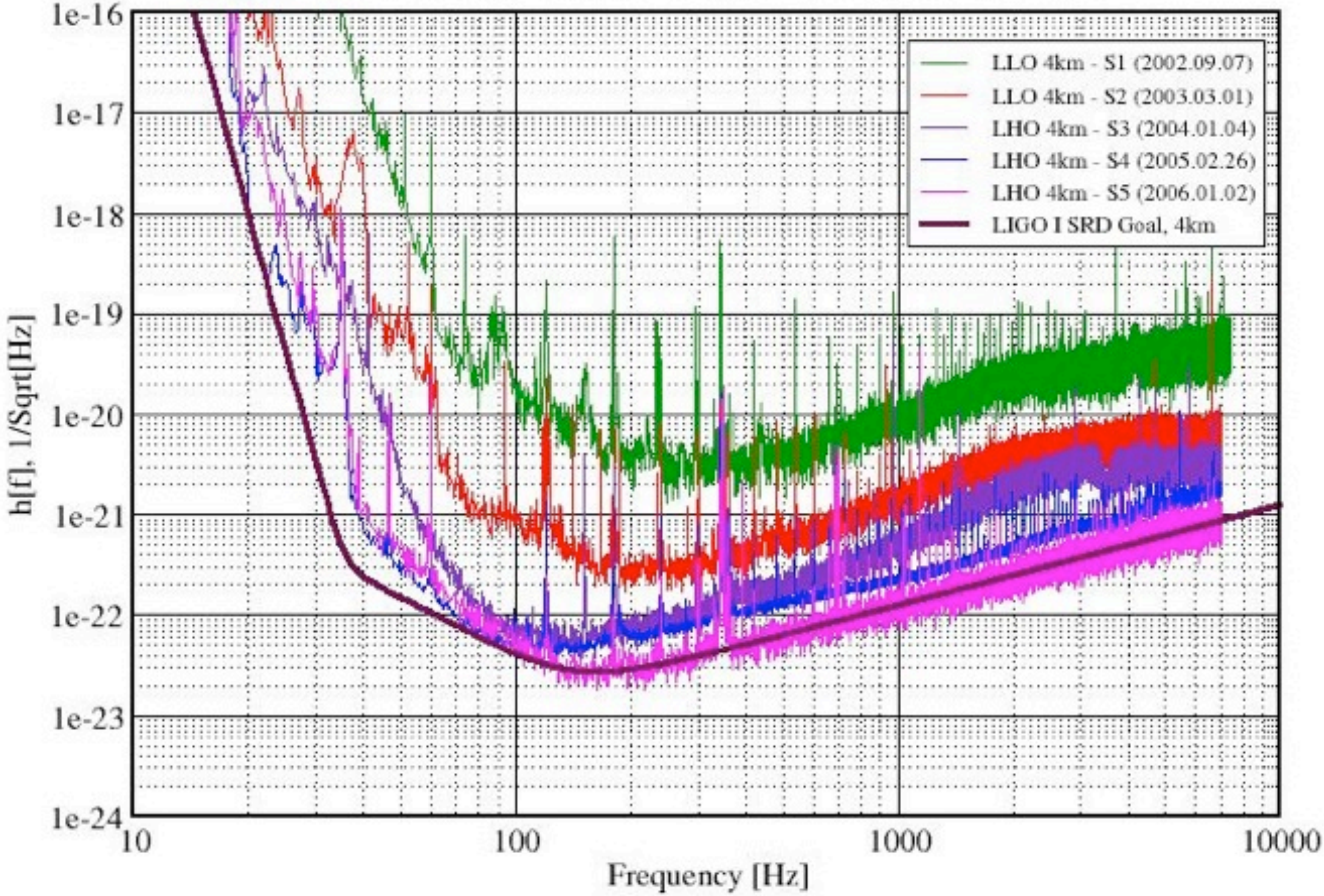
Wednesday, 26 June 2013

Current Status of Gravitational Observations:

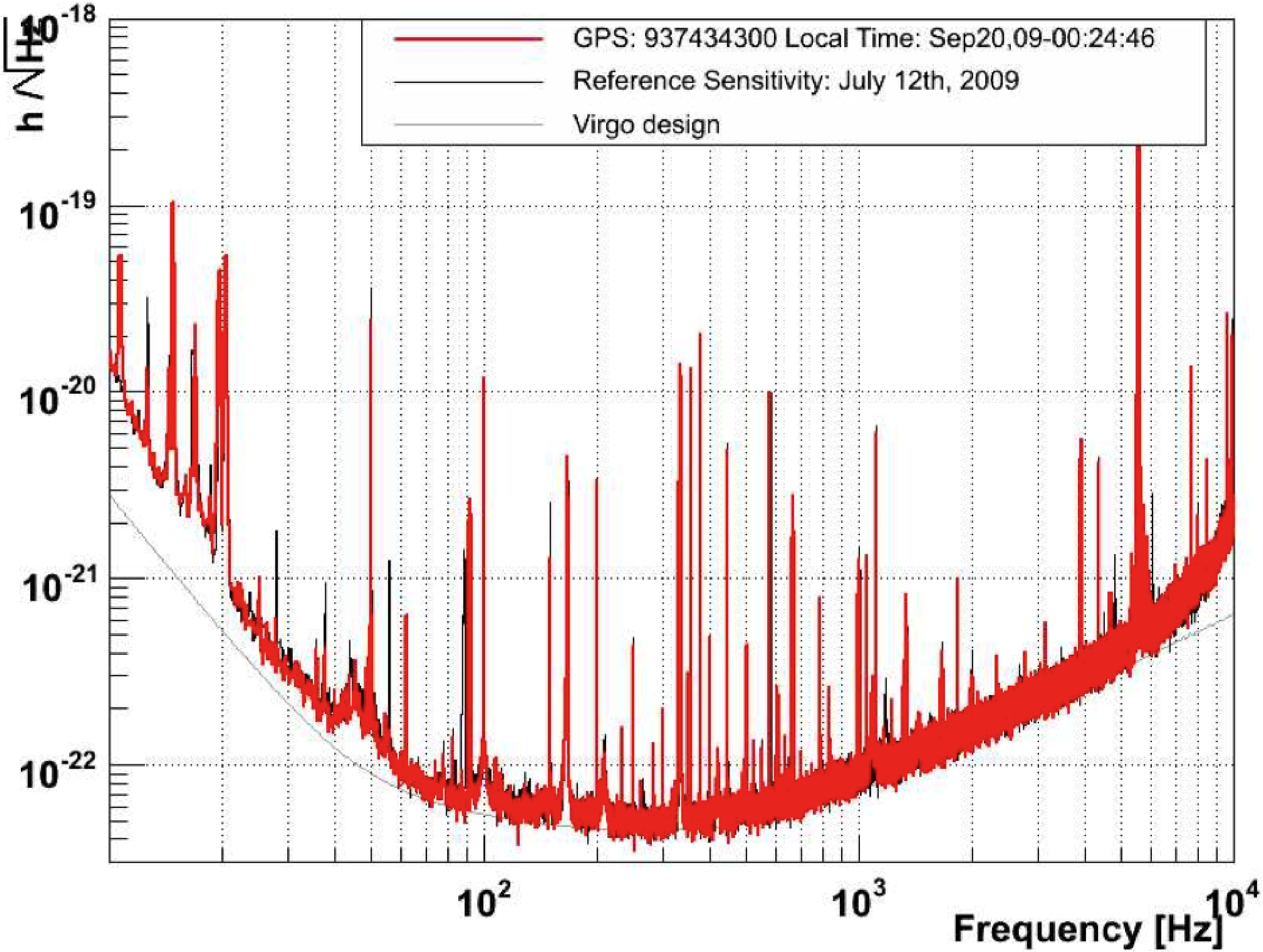
Science Runs: LIGO S1–S6 and VSR 1–3

Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-01-Z



Virgo Science Run-2



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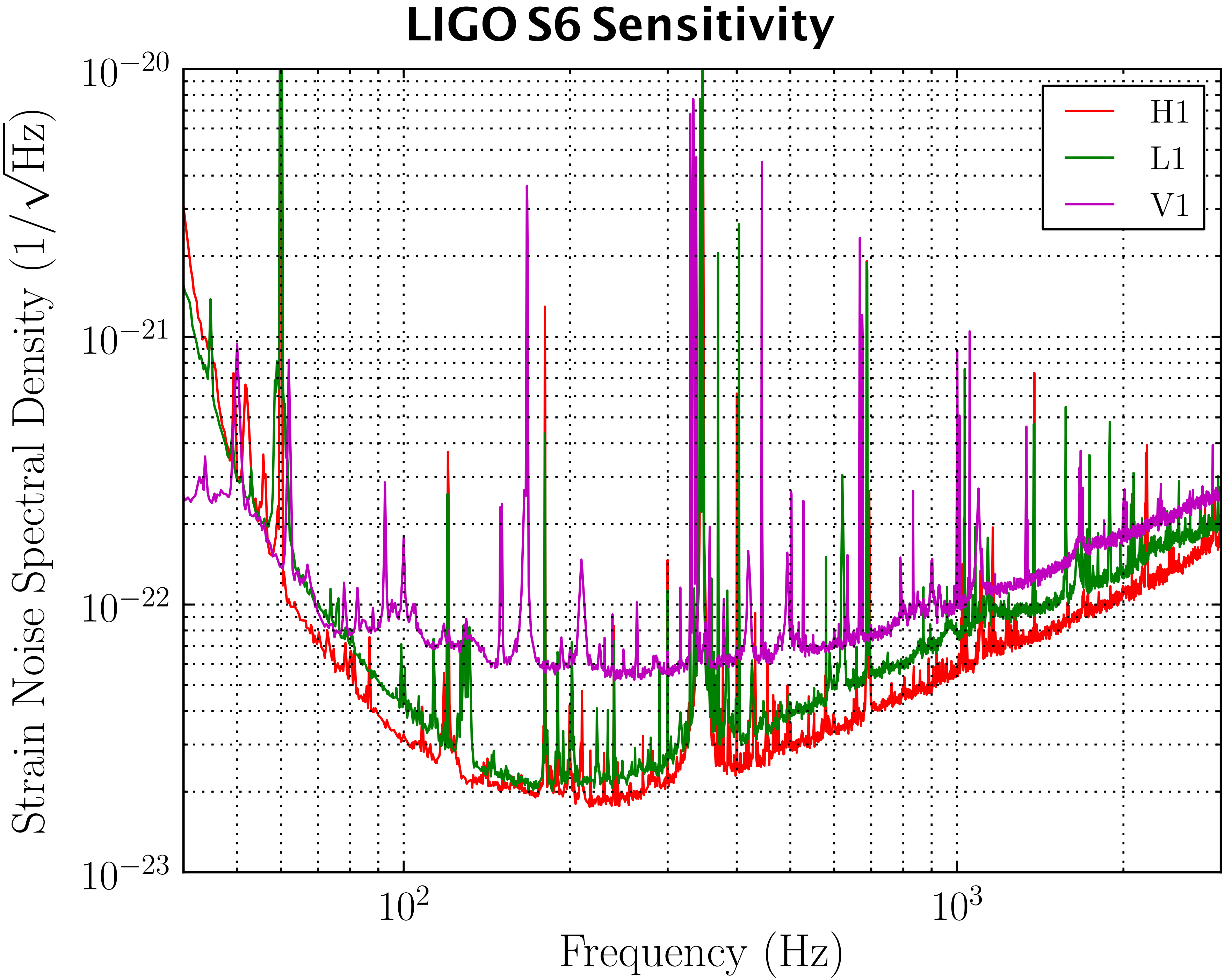

Wednesday, 26 June 2013

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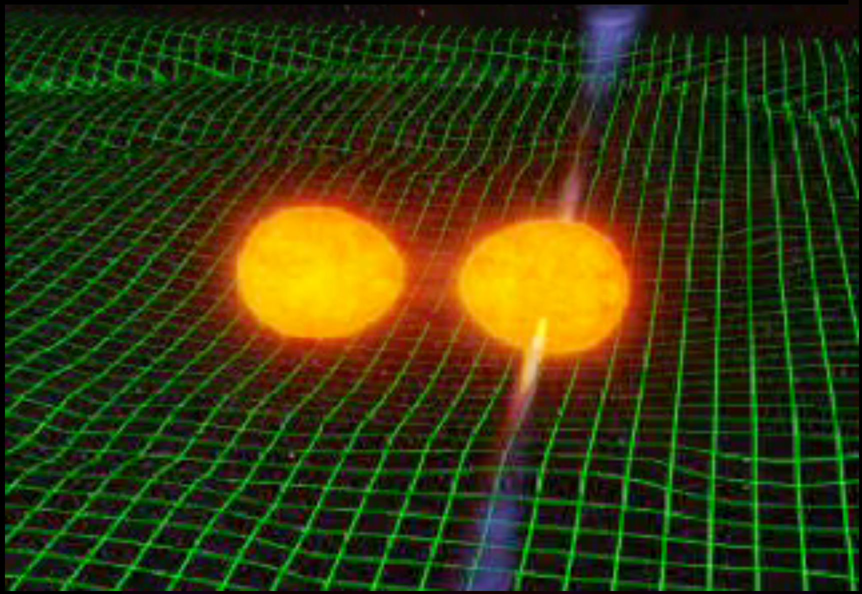
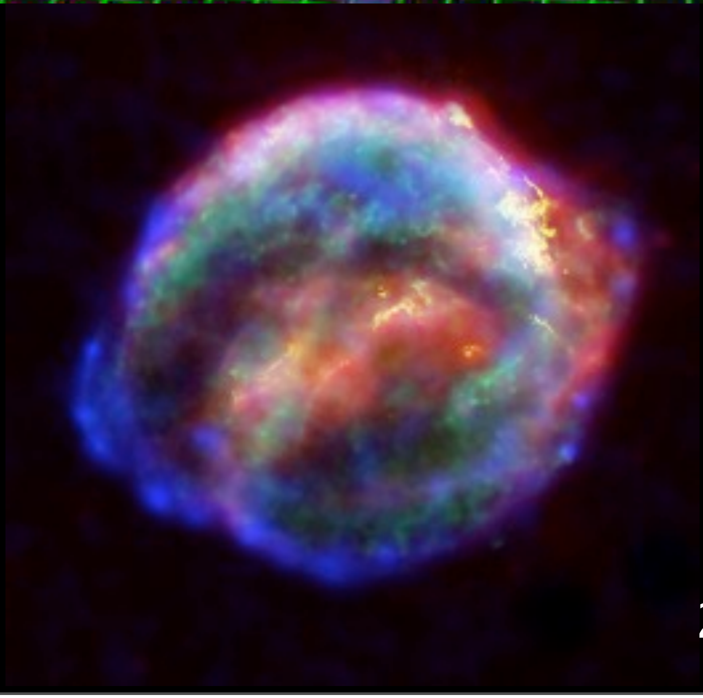
Gravitational wave searches





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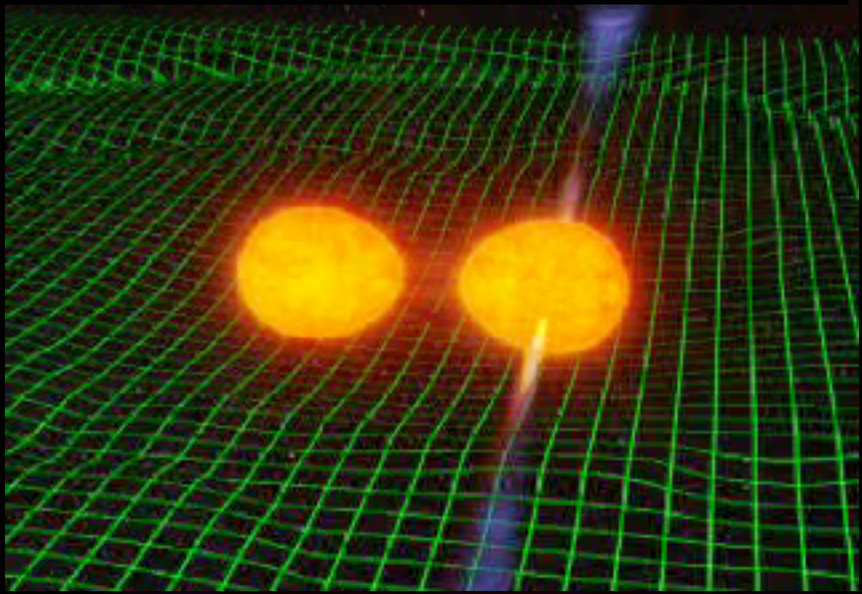

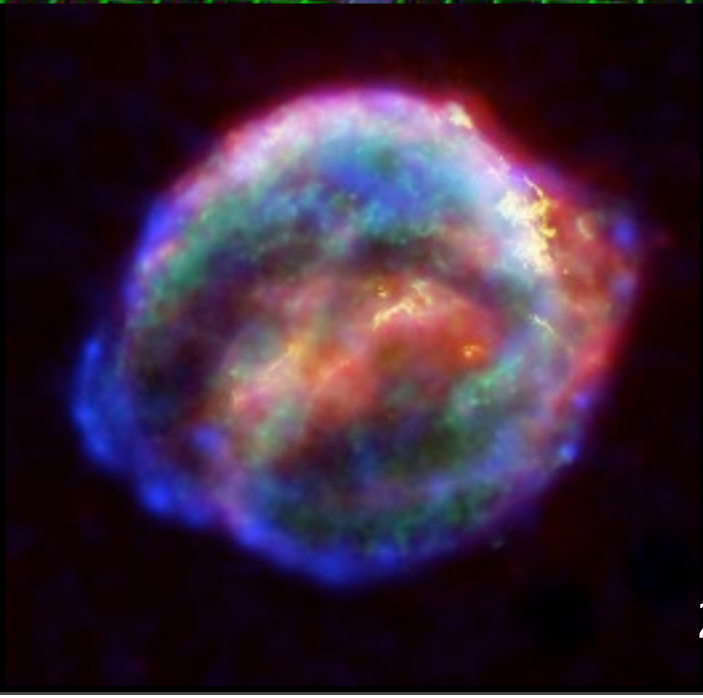

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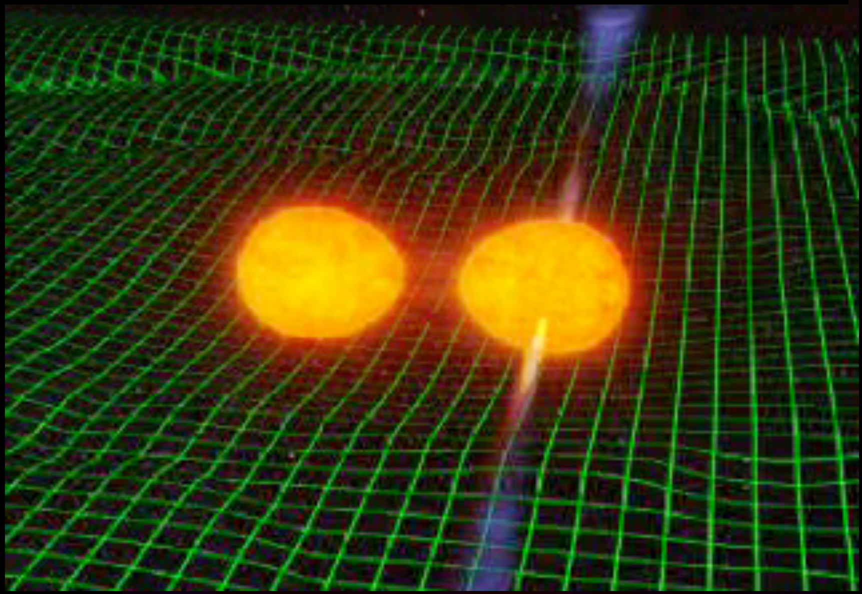

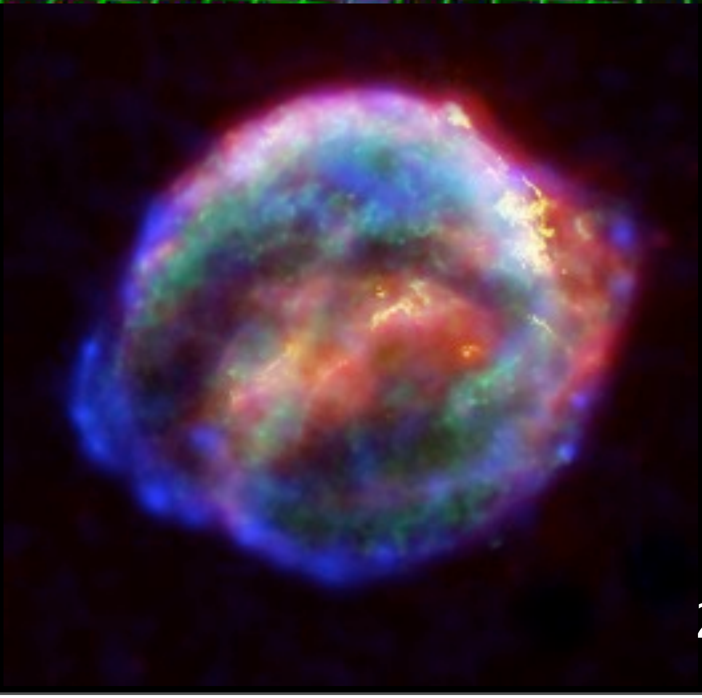

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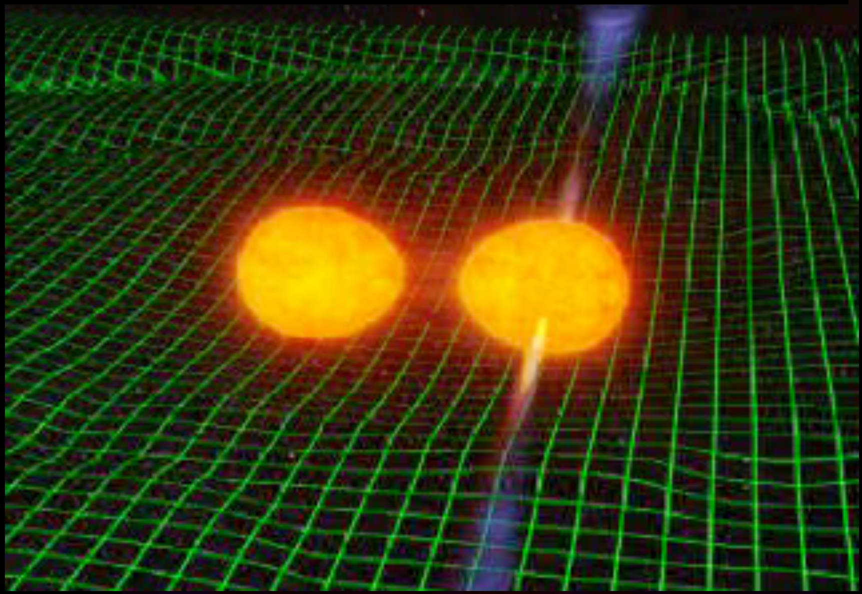

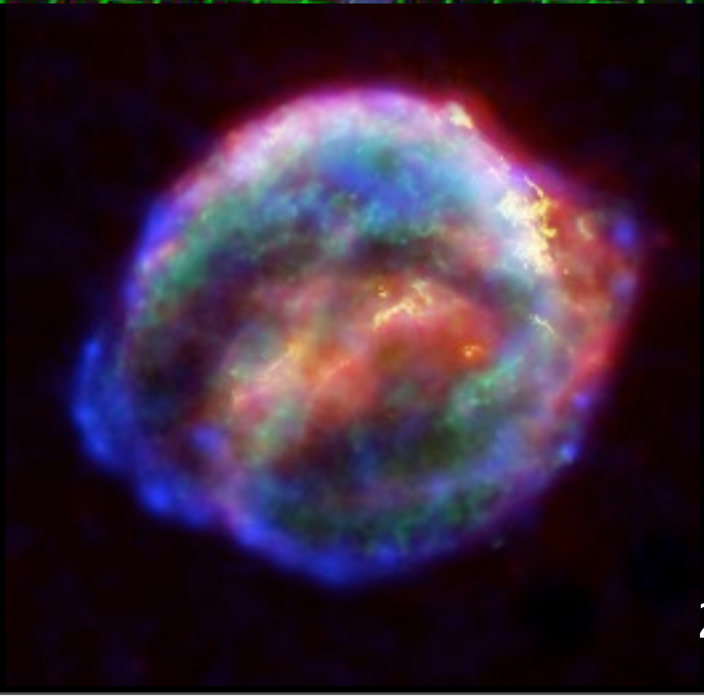

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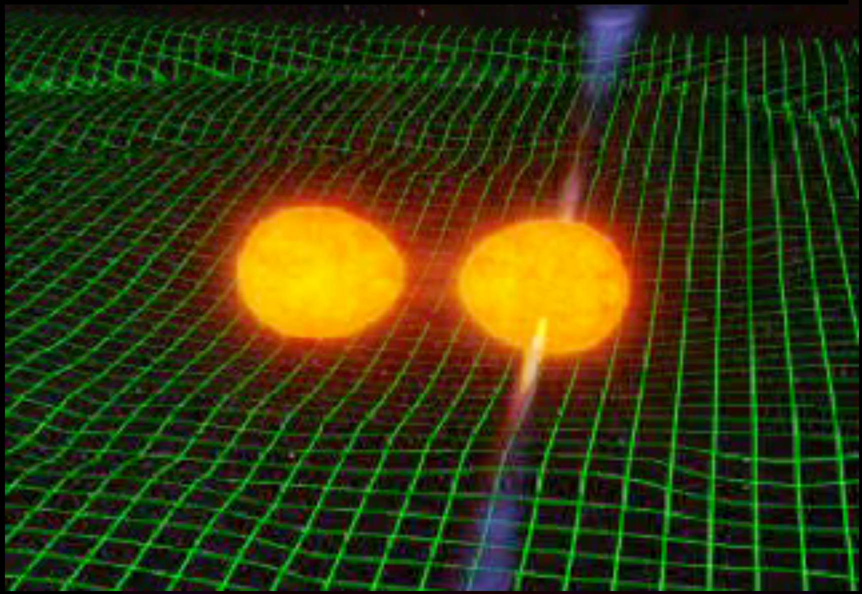

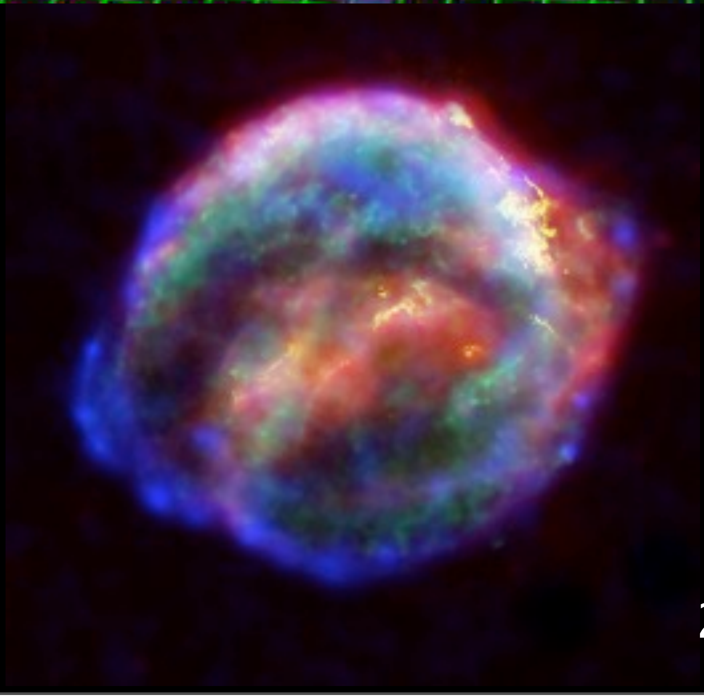

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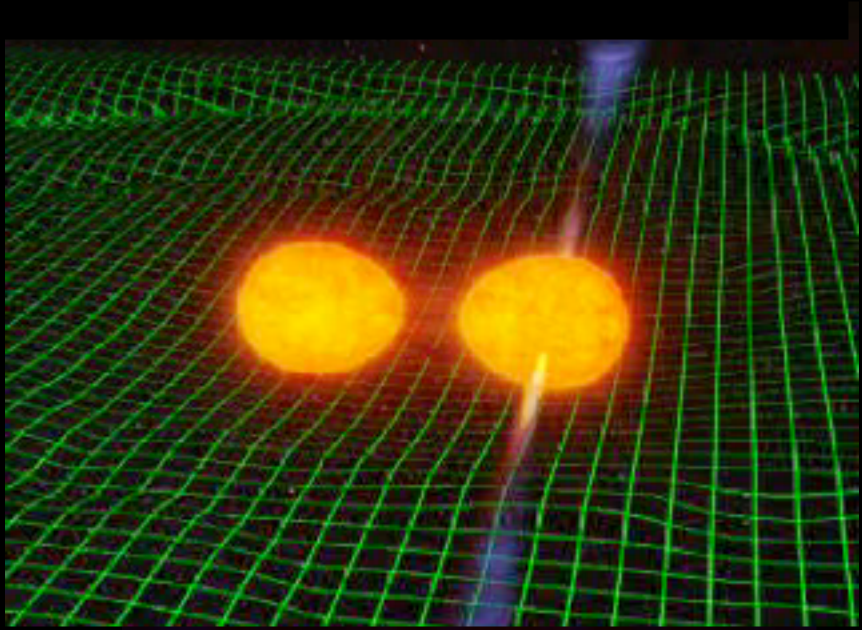

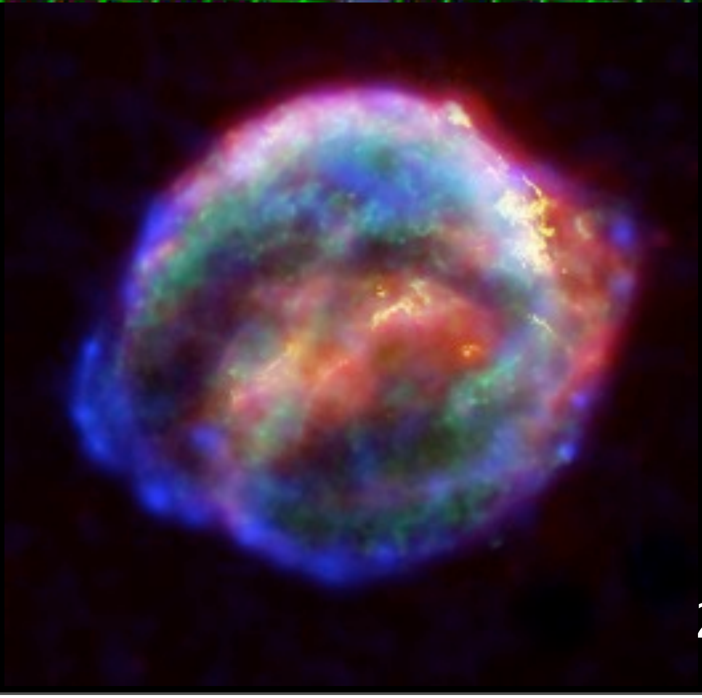

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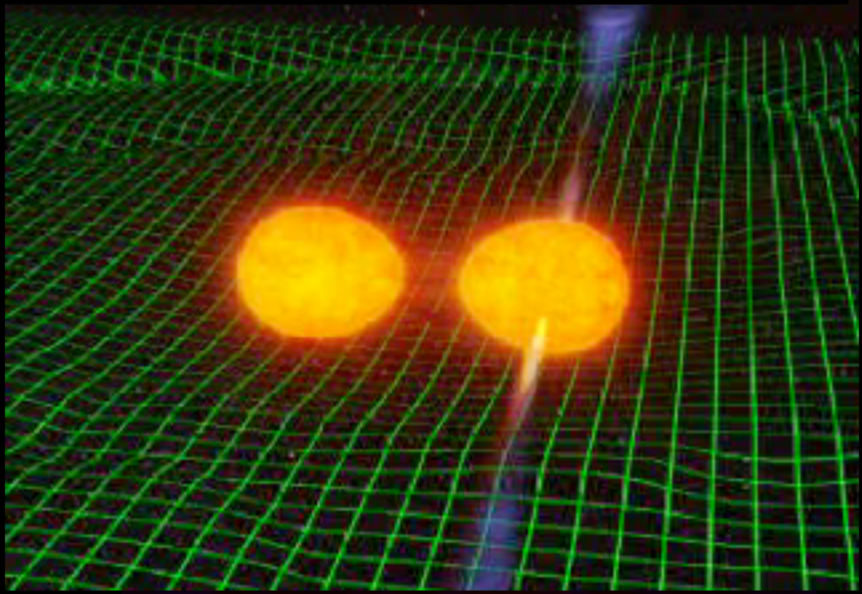

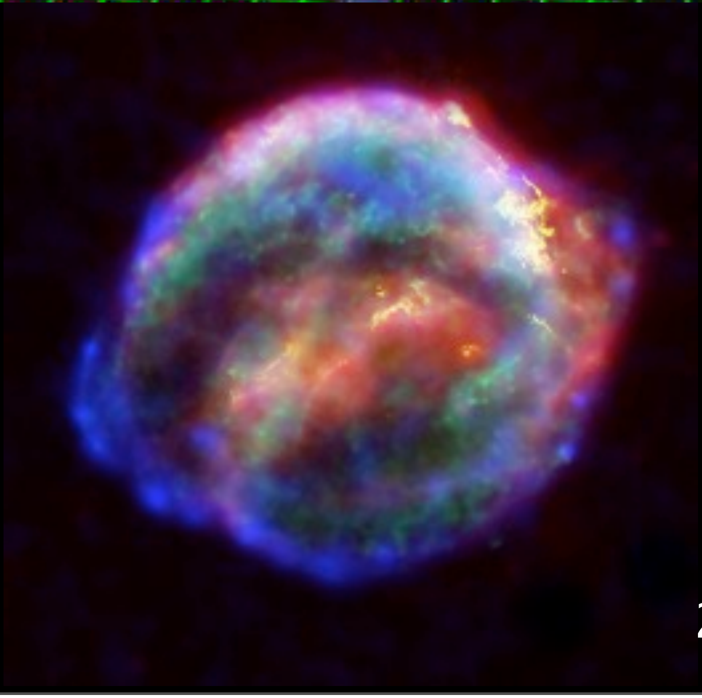

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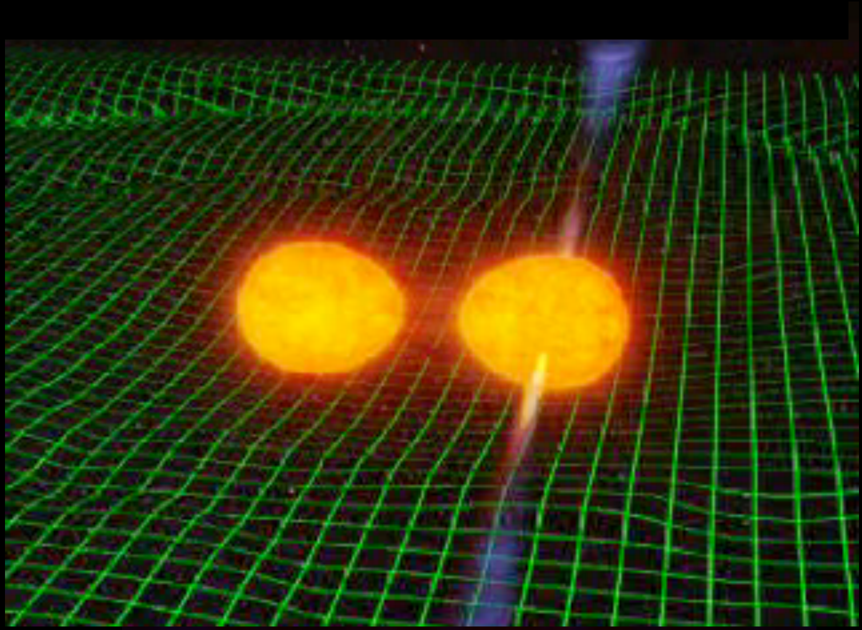

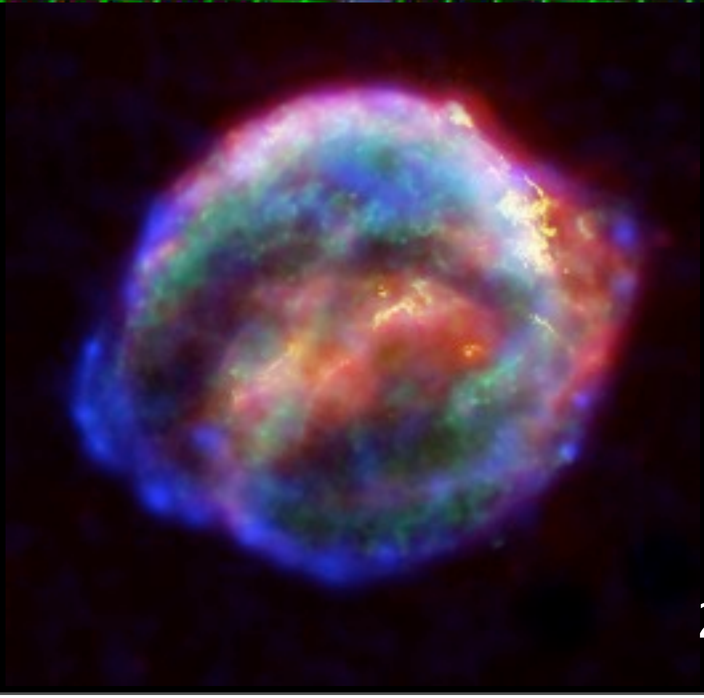

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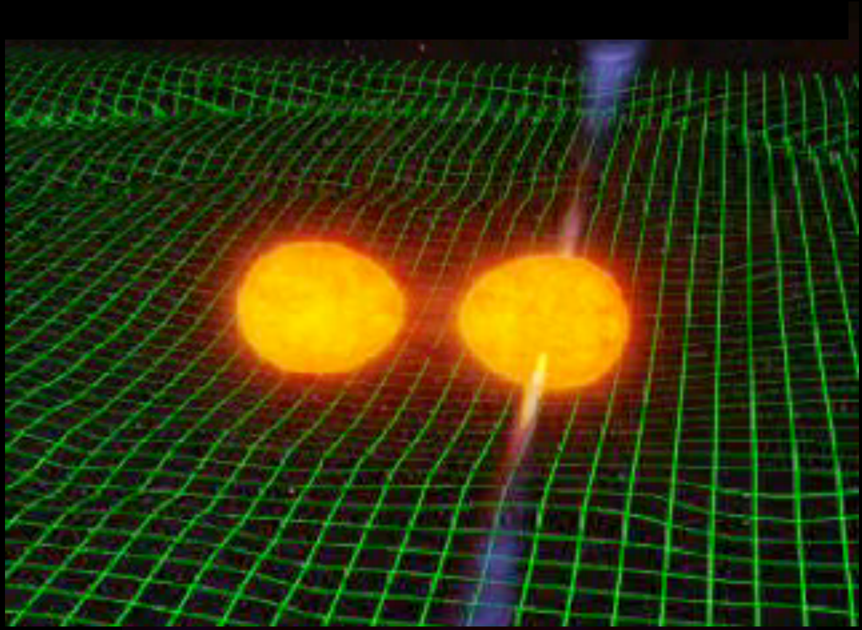

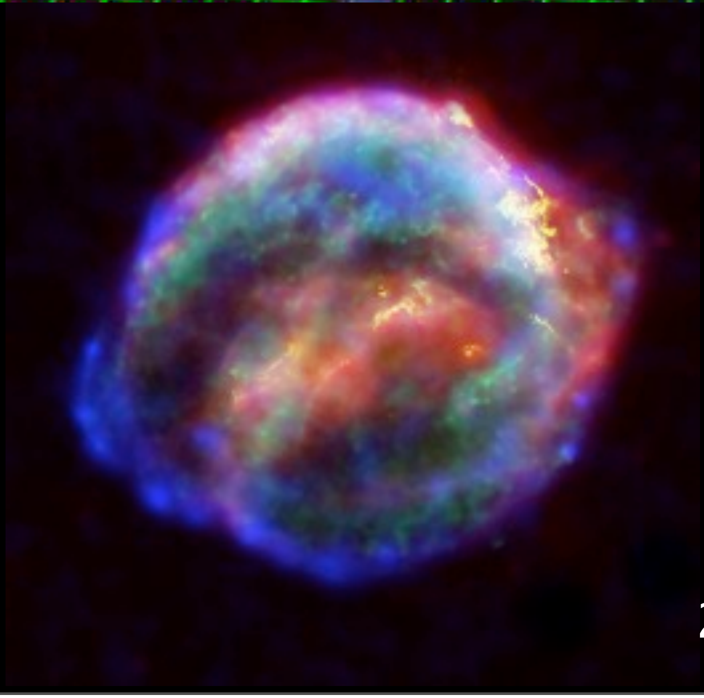

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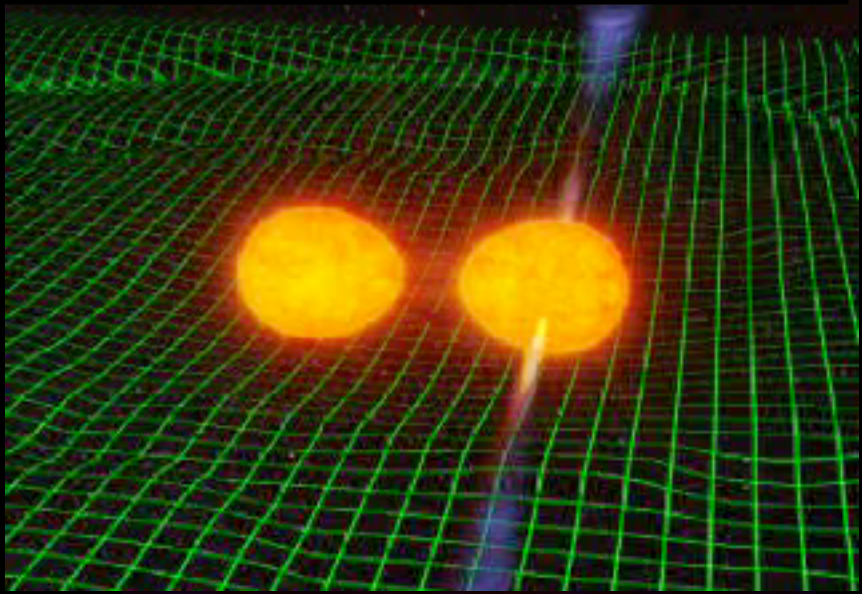

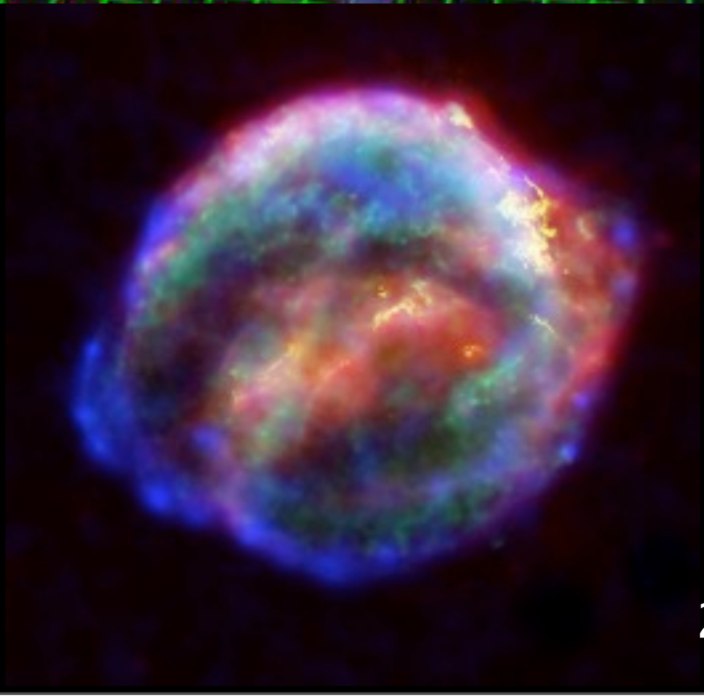

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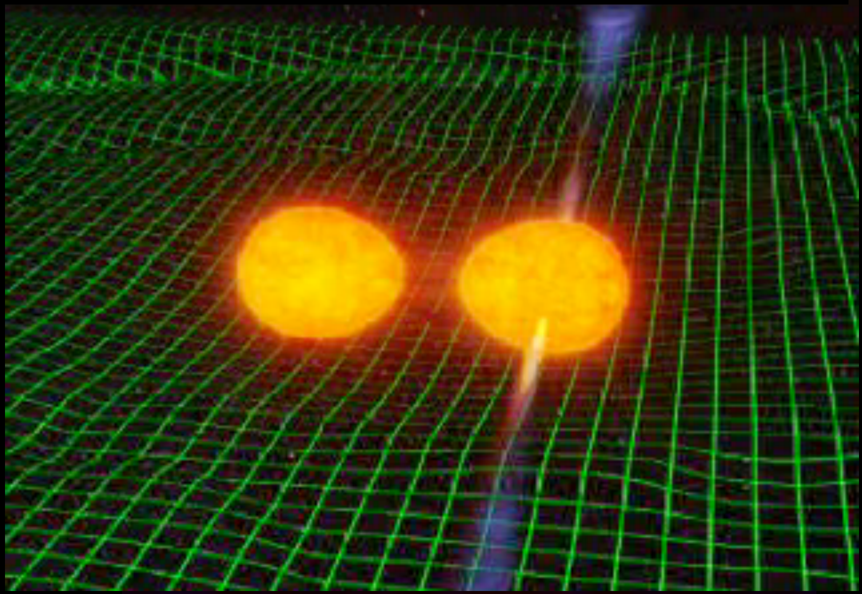

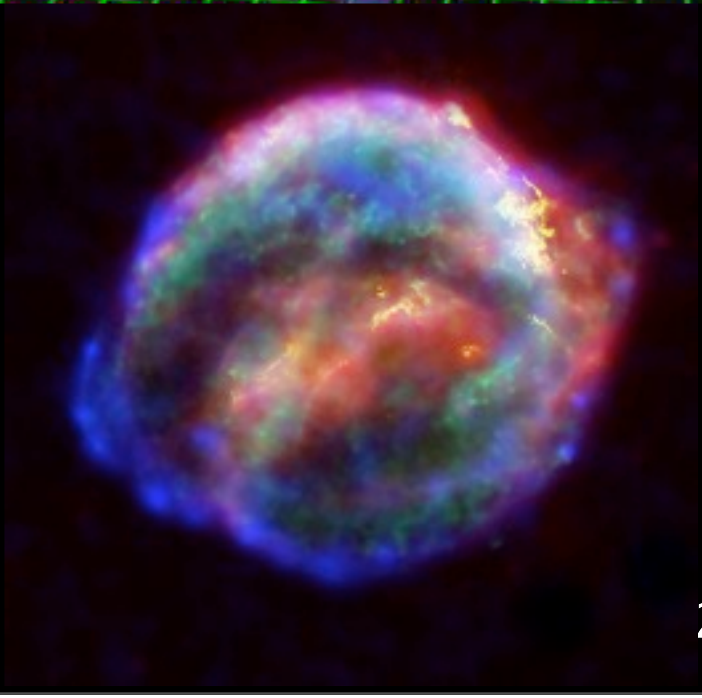

Gravitational wave searches

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  - Un–triggered searches
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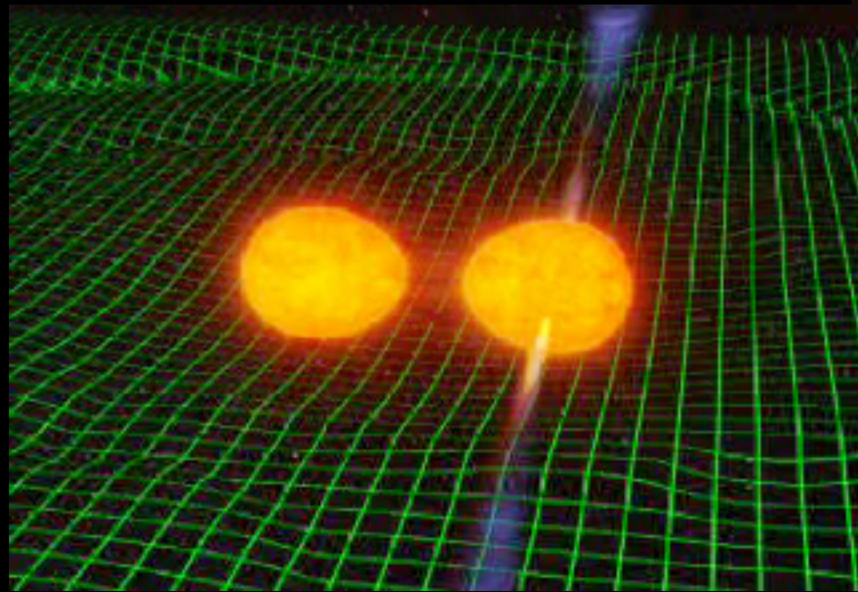

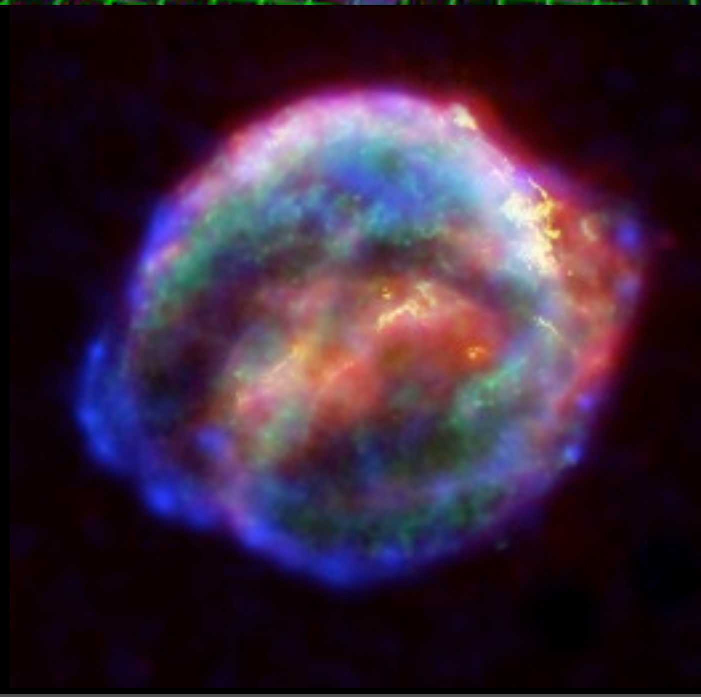

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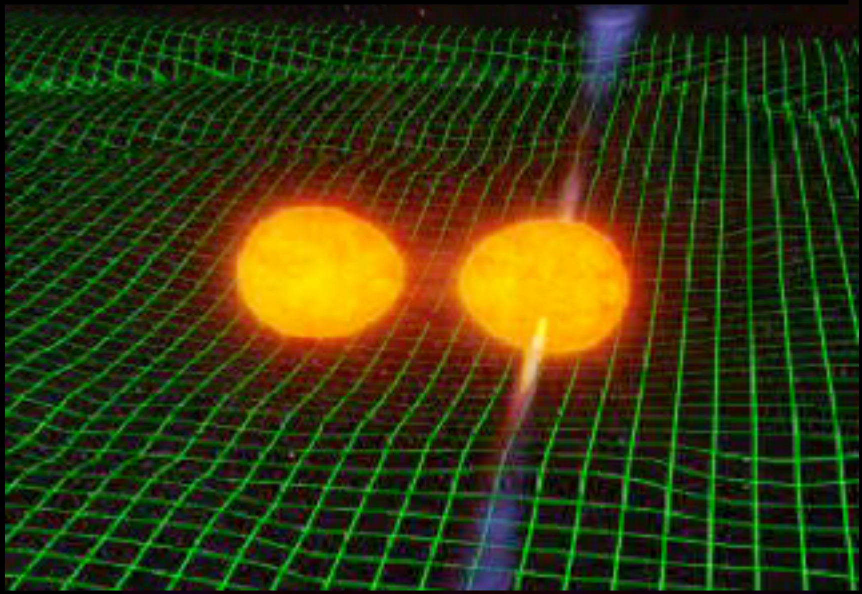

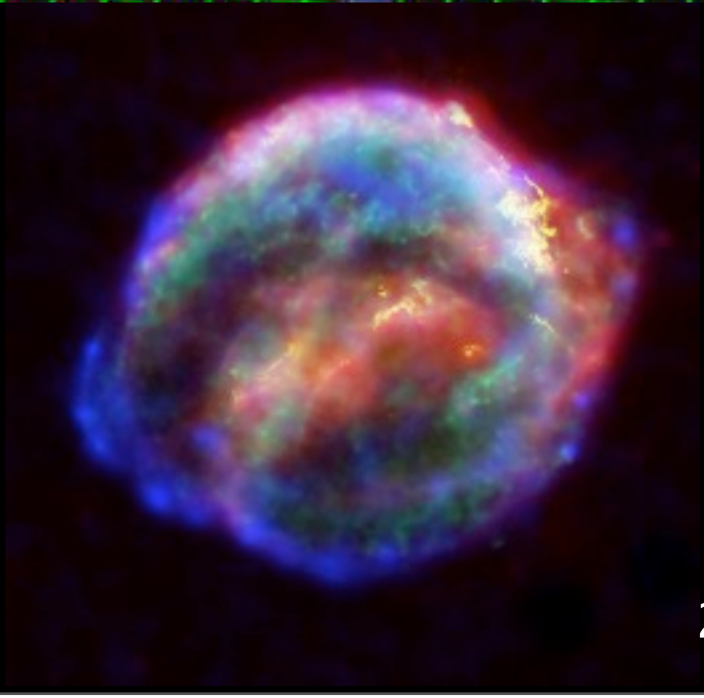

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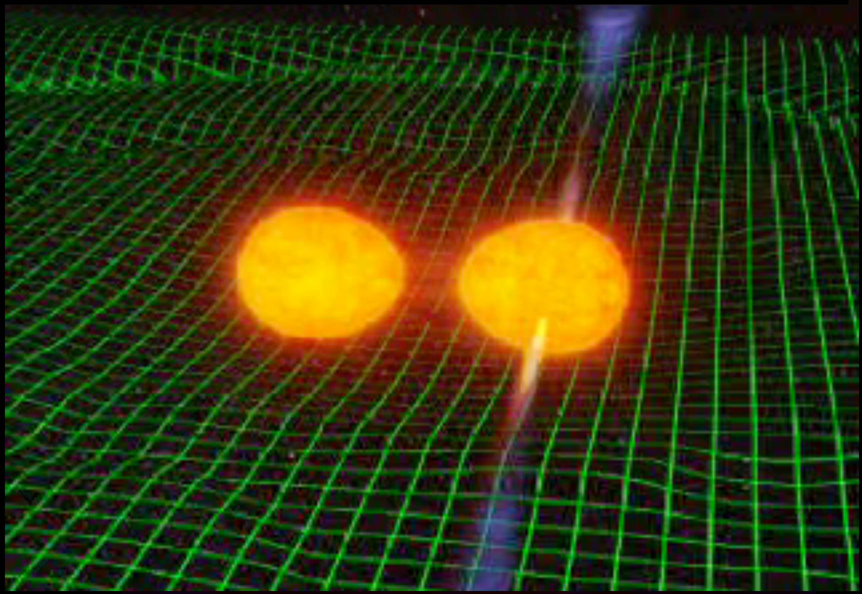
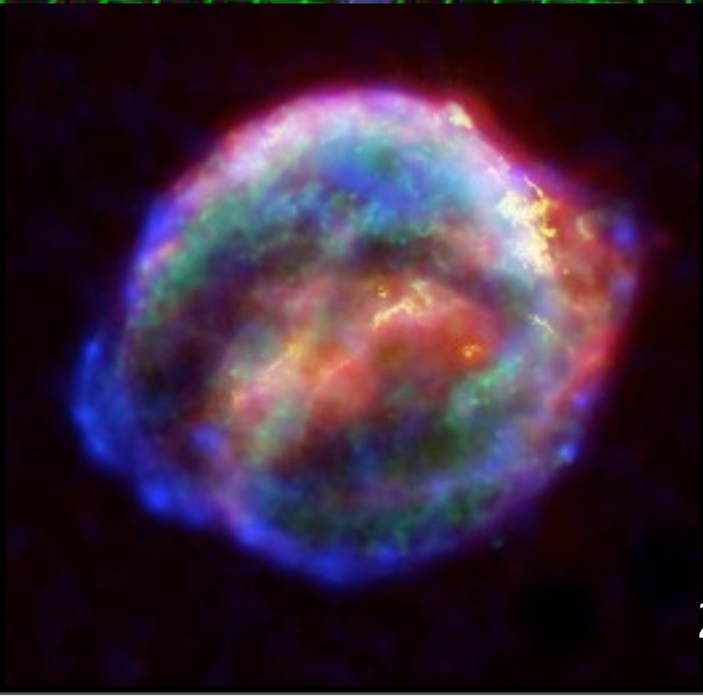
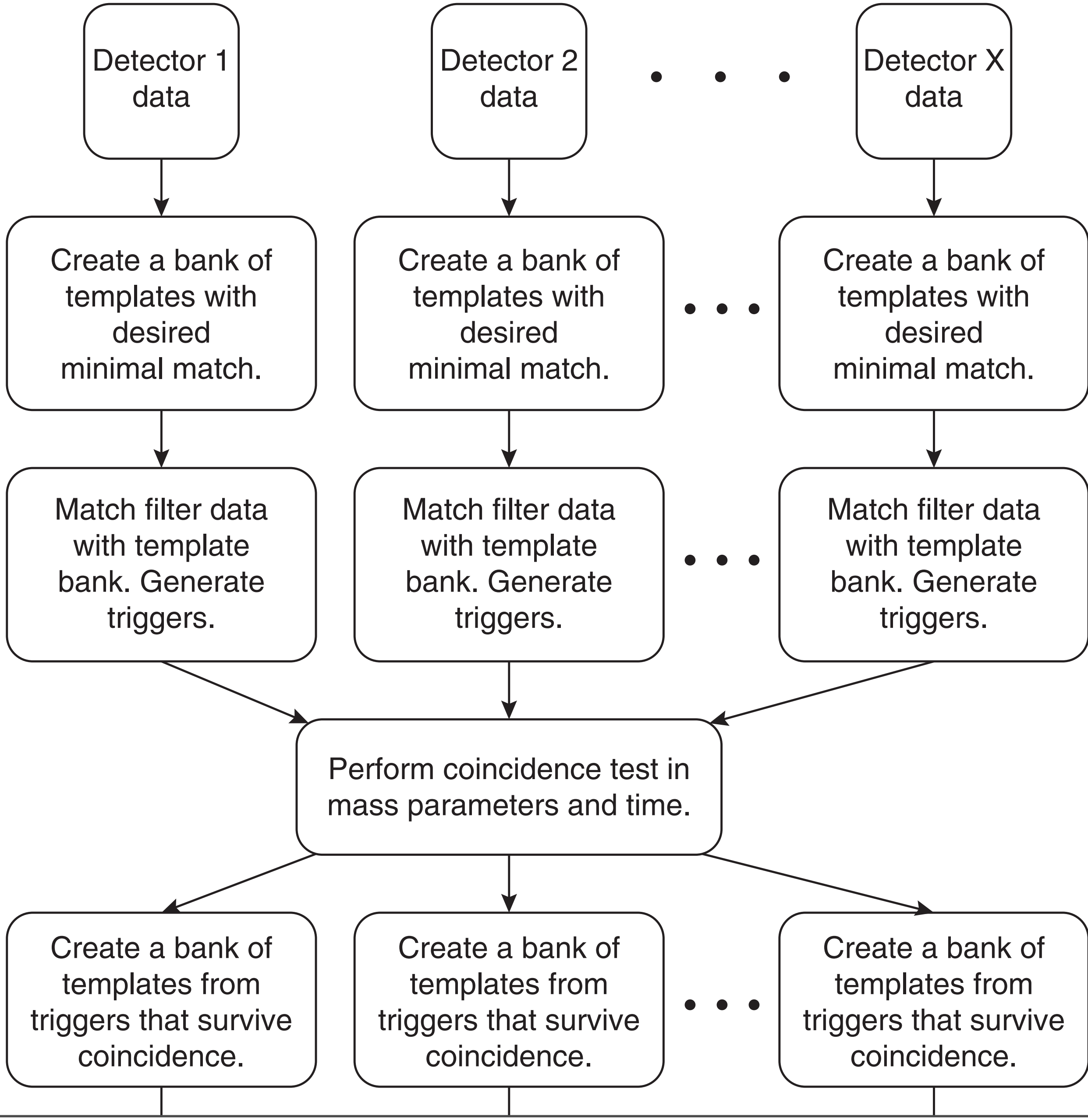




Inspiral Search Pipeline



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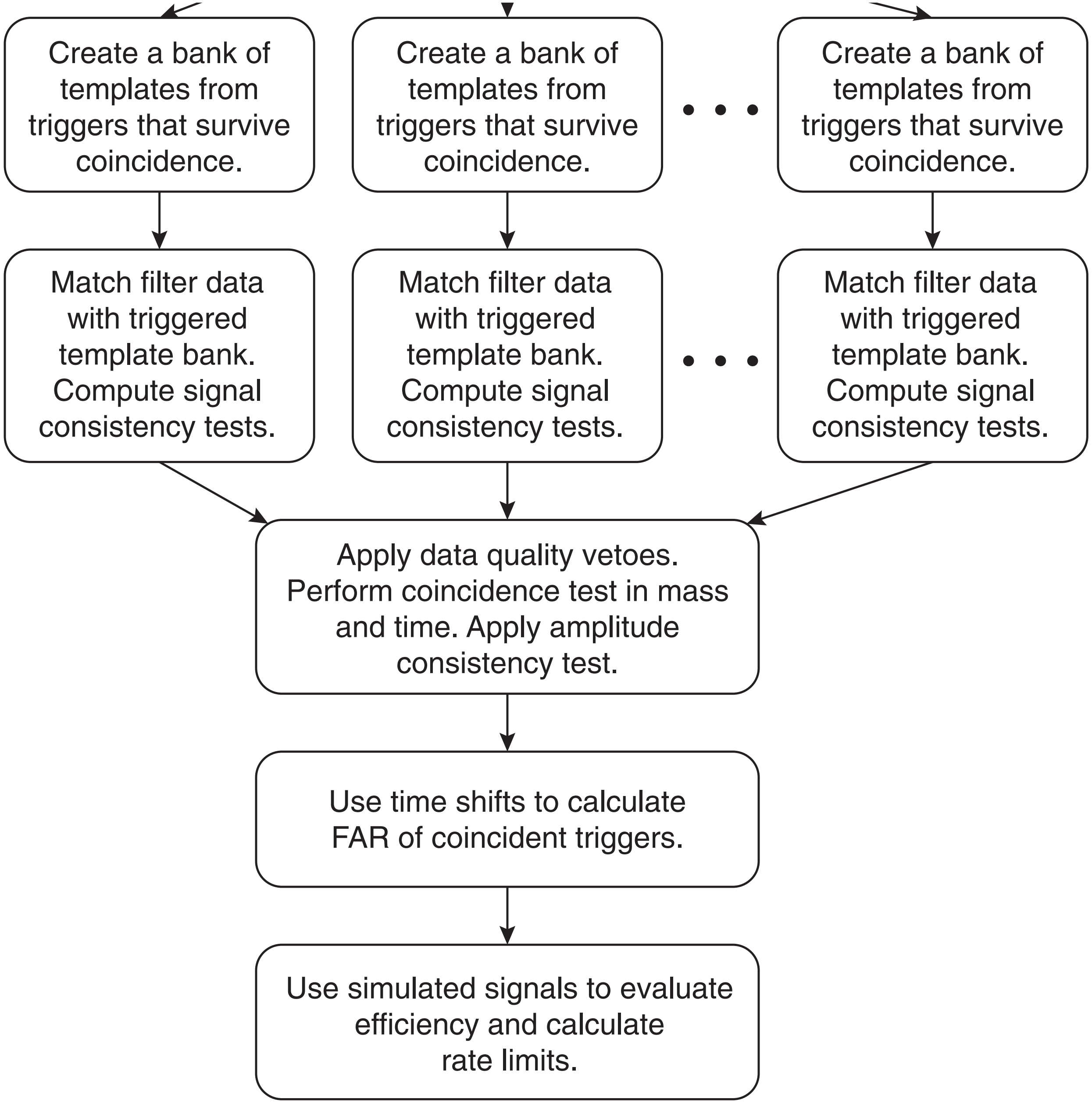

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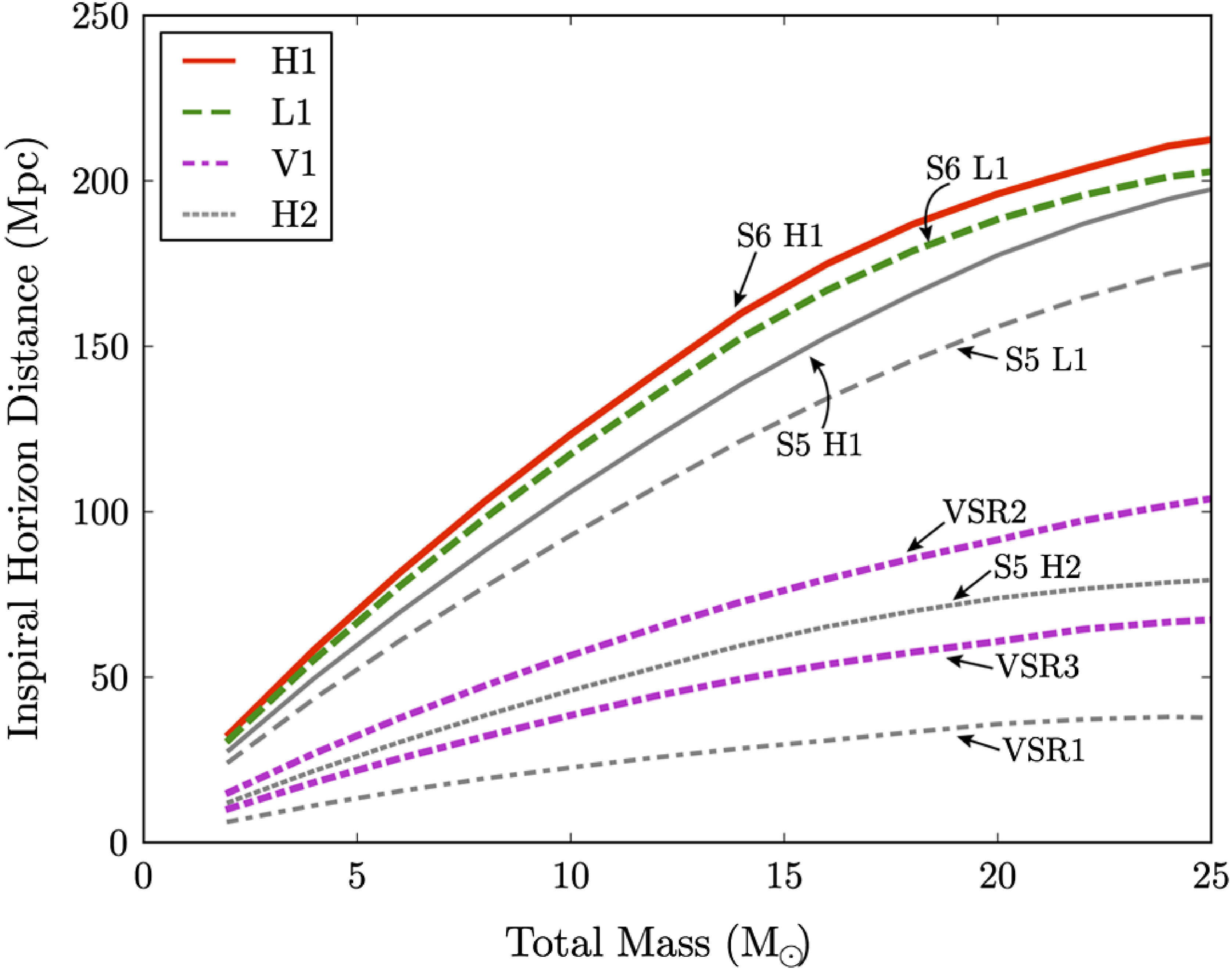
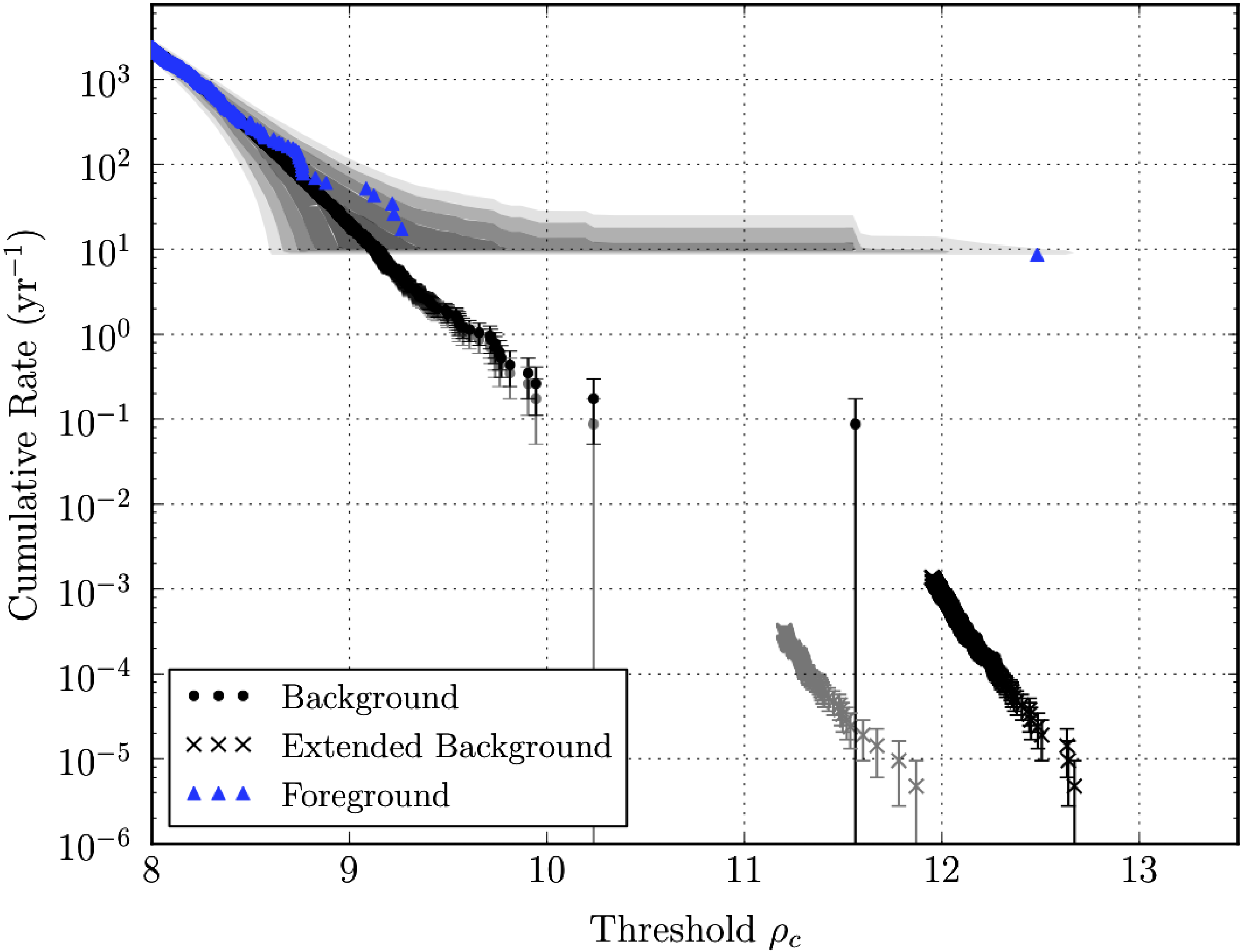
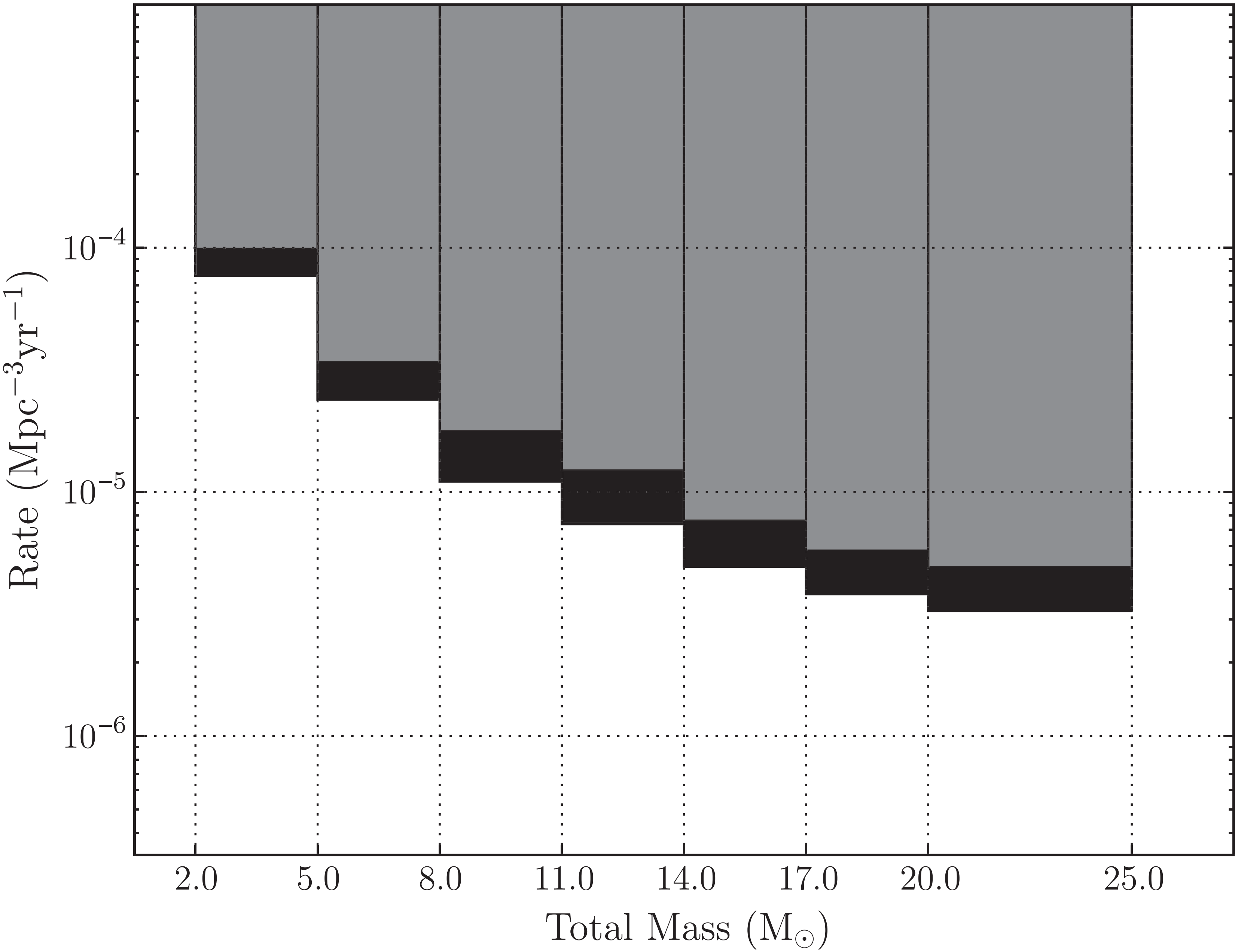
Distance Reach of the Various Detectors



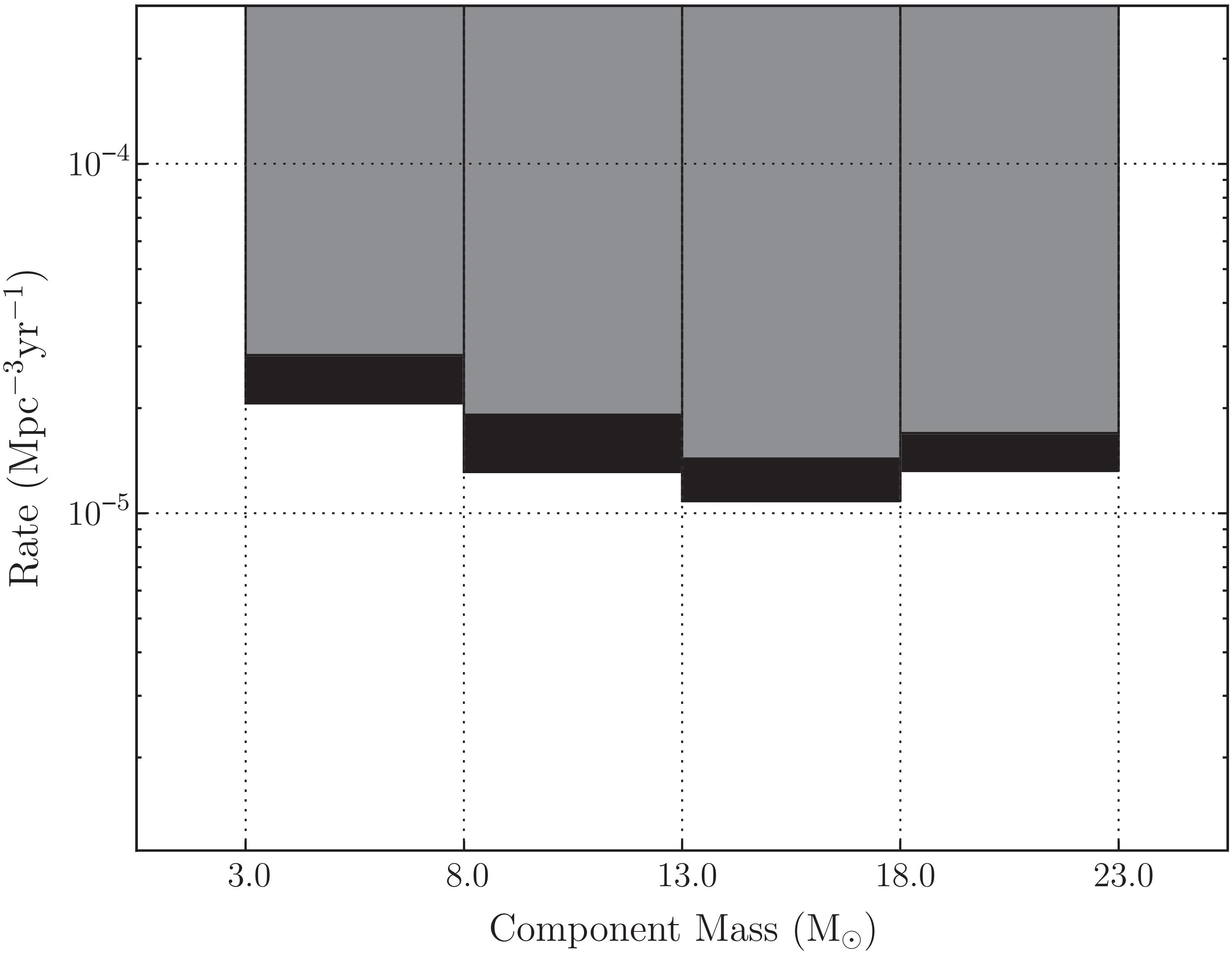
S6 / VSR3 Big Dog Event



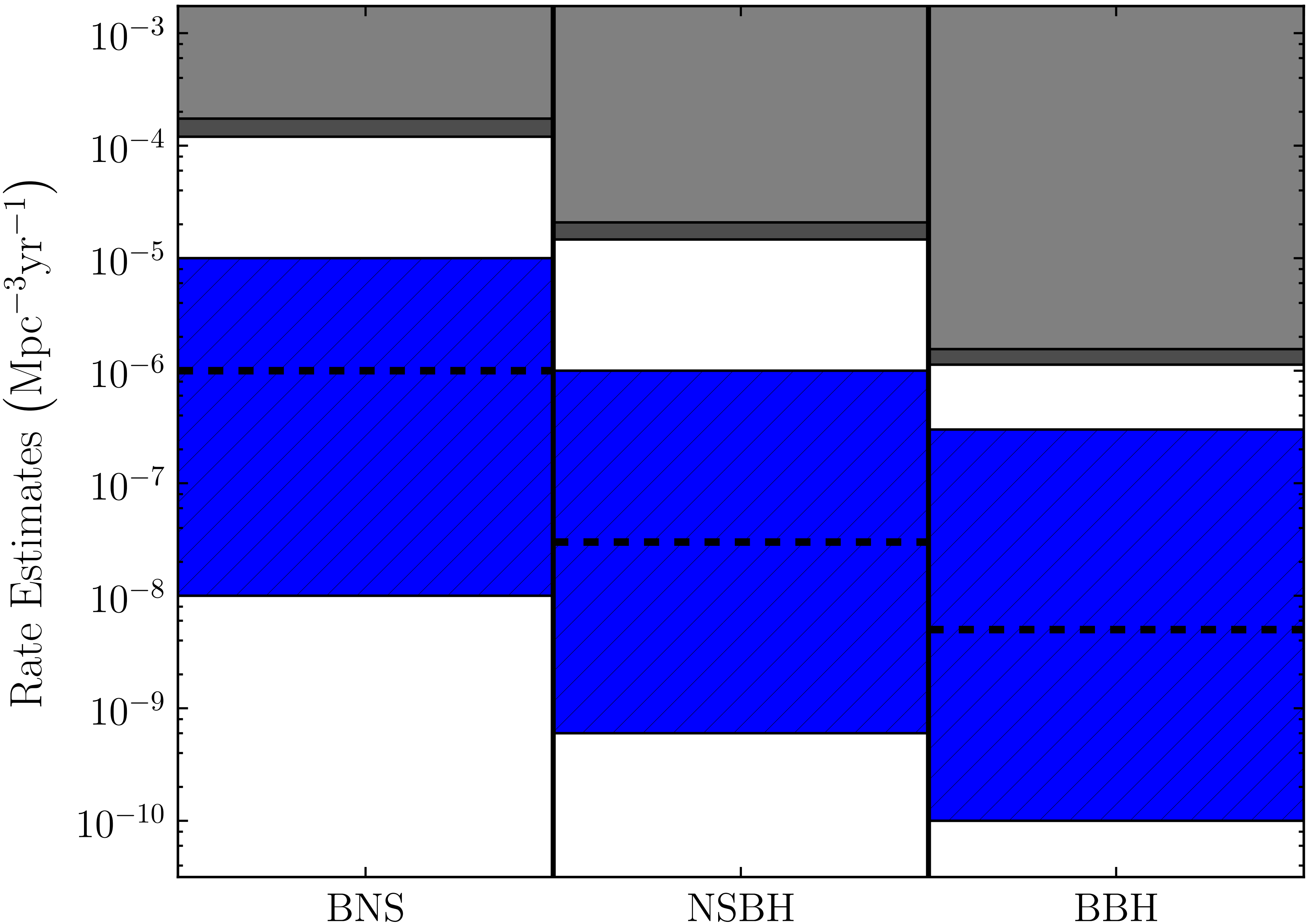
Binary Neutron Star Searches: Rate Upper Limits



Neutron Star–Black Hole Searches: Rate Upper Limits



Upper Limits Compared to Predicted Rates



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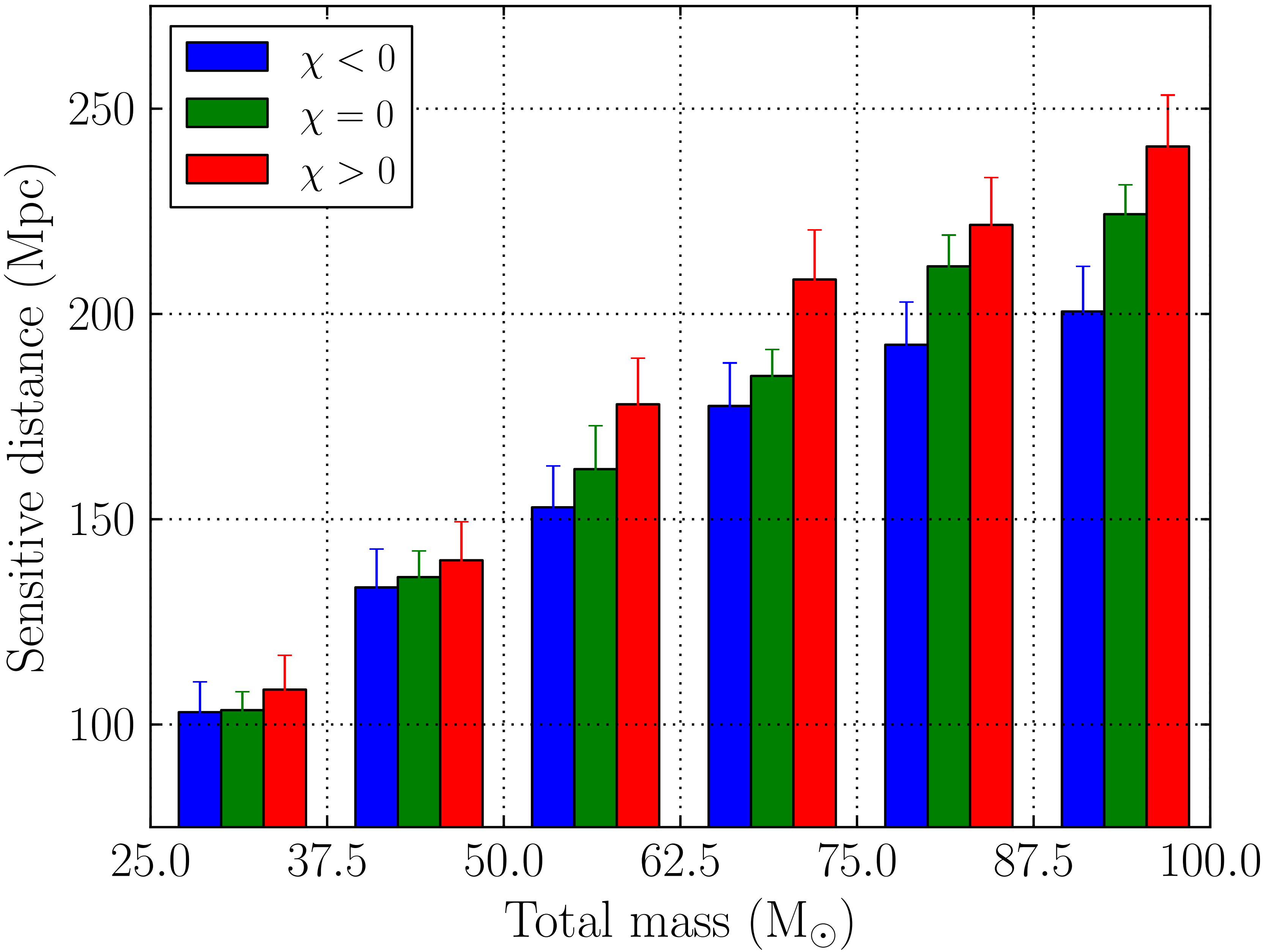
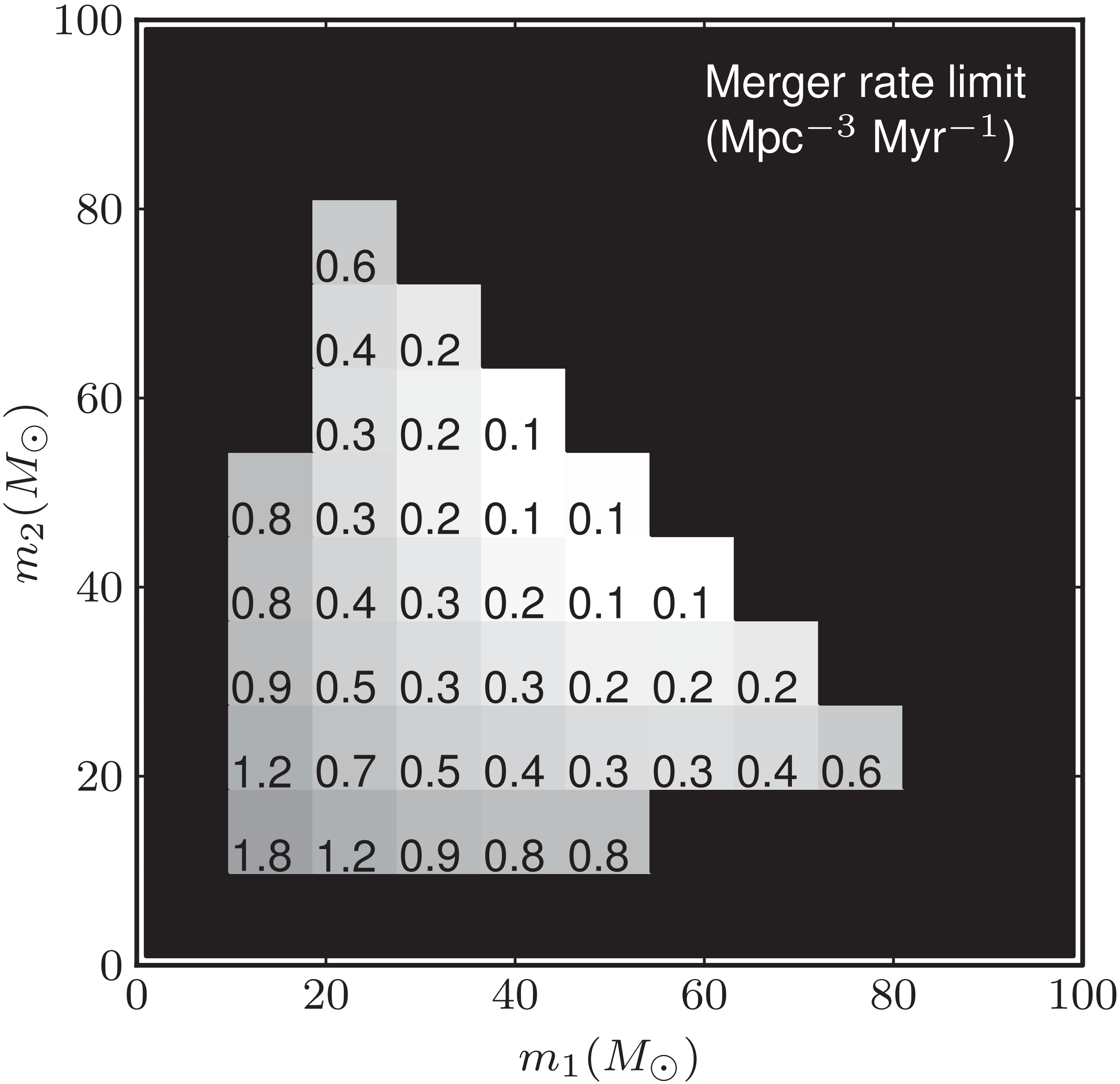


Rate upper limit: per Mpc^3 per Myr



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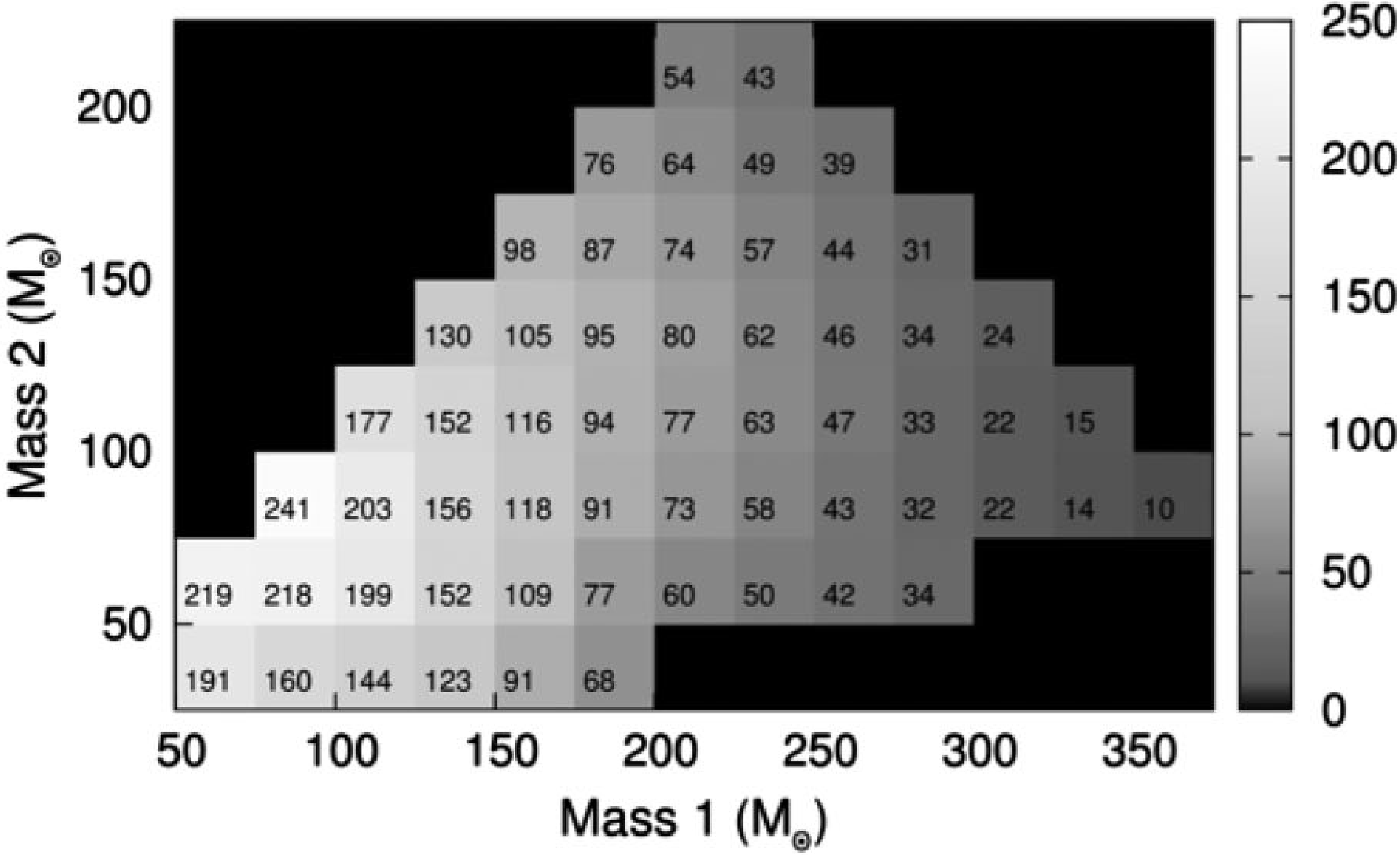

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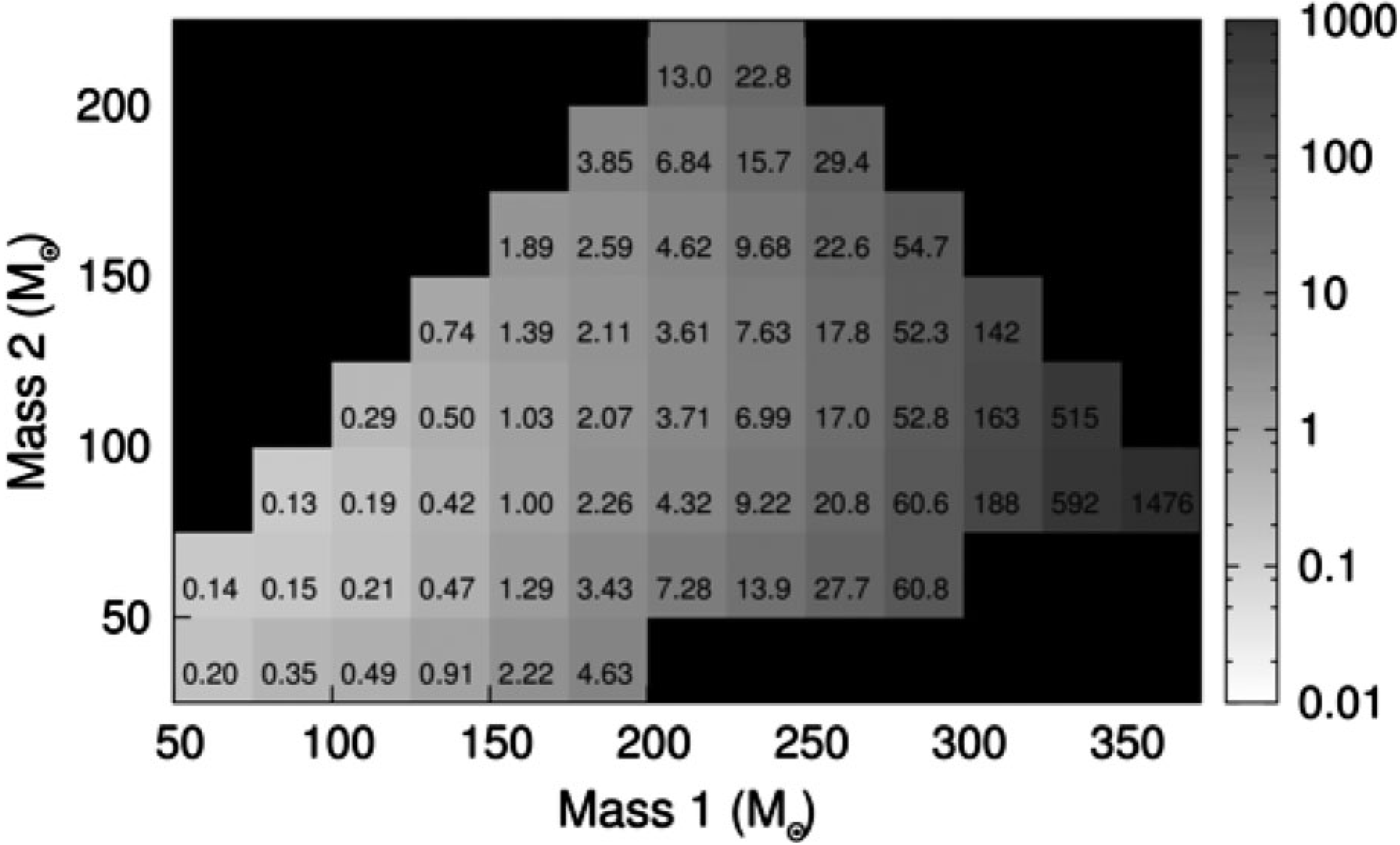

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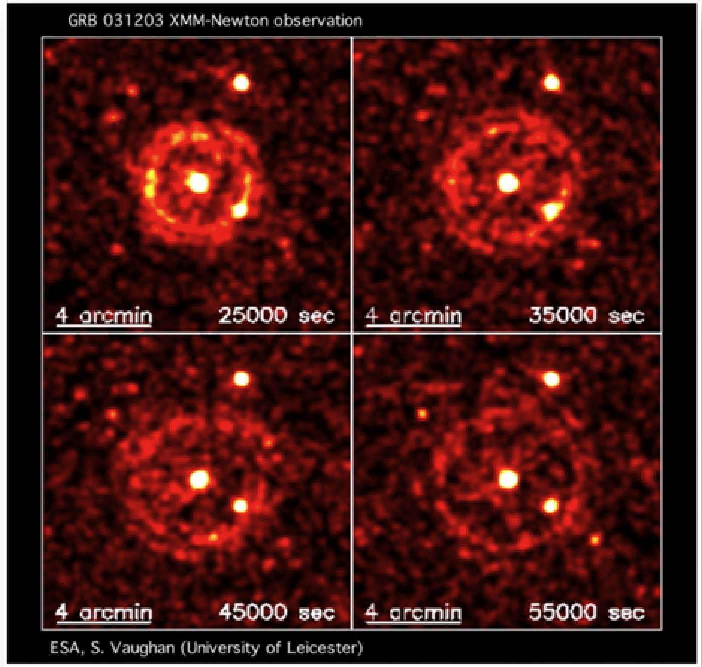
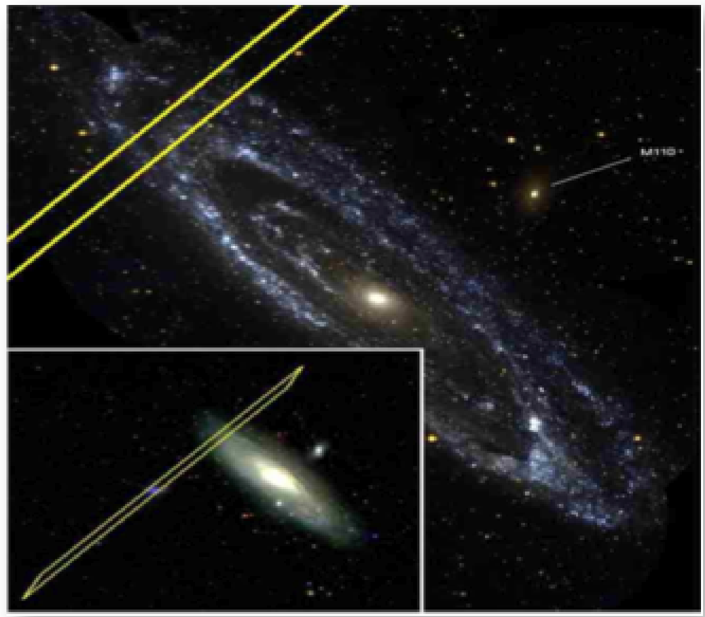
  - Inspiral searches can use fully coherent search algorithms to further improve upon sensitivity

Origin of GRB 070201 from LIGO Observations

- LSC searched for binary inspirals and did not find any events: results in ApJ **681** 1419 2008
- Null inspiral search result excludes binary progenitor in M31
- Soft Gamma-ray Repeater (SGR) models predict energy release <= 10^{46} ergs.
- SGR not excluded by GW limits





nature | Vol 460 | 20 August 2009 | doi:10.1038/nature08278

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

Stochastic background

- Metric fluctuations carry energy:

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\, \dot{h}^{ab} >$$

- Characterize by frequency dependence:

$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d\ln f}$$

- Describe in terms of strain power spectrum

$$S(f) = \frac{3H_0^2}{10\pi^2} \frac{\Omega_{GW}(f)}{f^3}$$

- Strain scale:

$$h(f) = 6.3 \times 10^{-22} \sqrt{\Omega_{GW}(f)} \left(\frac{100\ \mathrm{Hz}}{f}\right)^{3/2} \mathrm{Hz}^{-1/2}$$

Searching for a Stochastic Background

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm gw}}{d\ln f}$$

- Nucleosynthesis upper_limit

$$\int \frac{df}{f} \Omega_{\rm gw}(f) \lesssim 1.5 \times 10^{-5}.$$

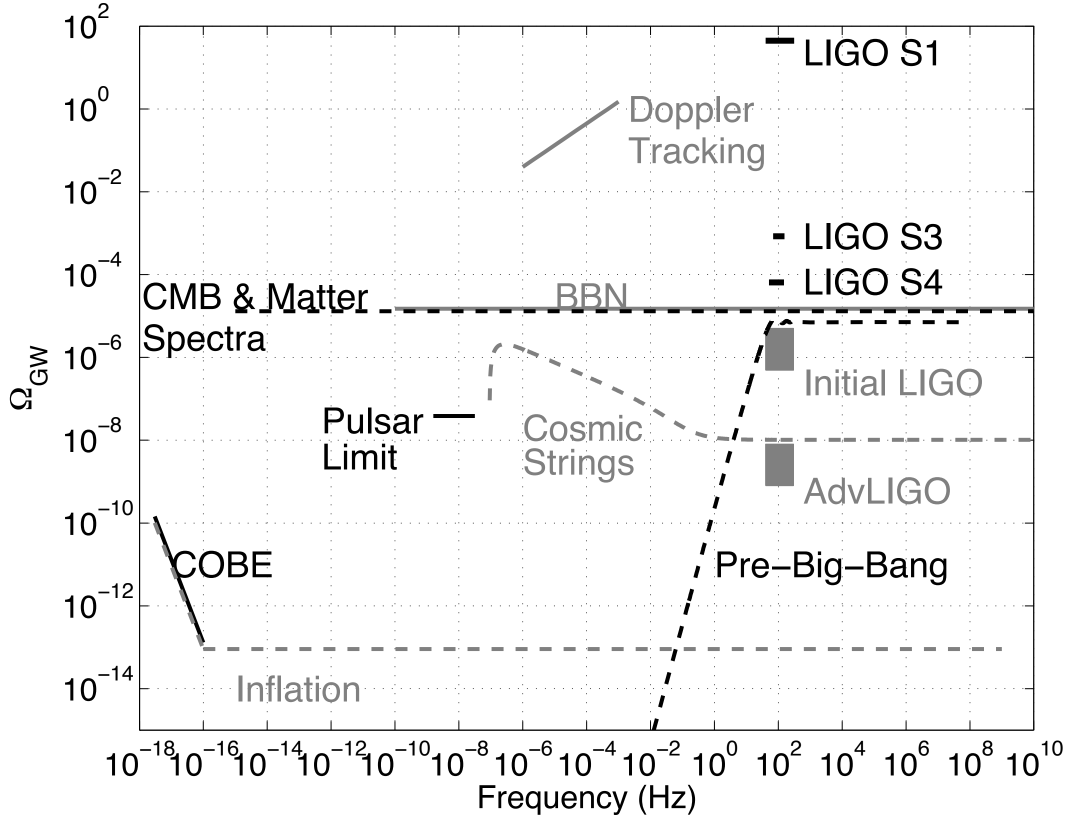
- Upper limit from LIGO data from the 4th Science run

$$\Omega_{\rm gw}(f) < 6.5 \times 10^{-5}$$

- Data from the 5th science run has improved this better than the nucleosynthesis limit

$$\Omega_{\rm GW} < 6.9 \times 10^{-6}$$

LSC, Astrophys. J. 659 (2007) 918



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  - Einstein@HOME one of the most successful project that uses public volunteered computational resources to get in excess of 100's of TFLOPS for GW searches

Spin–down limit on the Crab pulsar

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin–down

LSC, ApJ Lett., **683**, (2008) 45

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

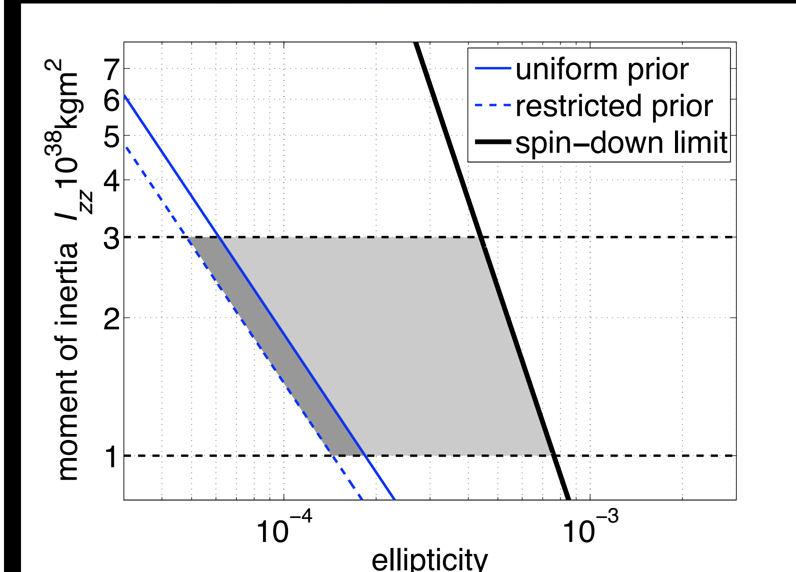
spin-down rate, $\dot{\nu} \approx -3.7\times 10^{-10}\,\mathrm{Hz\,s^{-1}}$

$$\dot{E} = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4\times 10^{31}\ \mathrm{W}$$

$$h_0^{\mathrm{sd}} = 8.06\times 10^{-19}\, I_{38} r_{\mathrm{kpc}}^{-1} (|\dot{\nu}|/\nu)^{1/2}$$

- We have searched for gravitational waves in data from the fifth science run of LIGO detectors
- The search did not find any gravitational waves
- Lack of GW at S5 sensitivity means a limit on ellipticity a factor 4 better than spin-down upper limit - less than 4% of energy in GW

$$h_0^{95\%} = 3.4\times 10^{-25}. \qquad \varepsilon = 1.8\times 10^{-4}$$



Challenges of Gravitational Astronomy

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  - What are the expected mass and spin distributions of binary mergers and how do they differ from one model to another
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  - What is the mechanism behind core-collapse supernovae, especially core bounce and shock revival when a black hole forms?
- Measuring the neutron star equation of state from binary neutron star mergers
- How well can we measure cosmological parameters with GW observations?
- Following-up GW events with astronomical telescopes
  - The EM transient background