Observing Gravitational Waves from Spinning Neutron Stars

Reinhard Prix (Albert-Einstein-Institut)

for the LIGO Scientific Collaboration

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Outline

Orders of Magnitude

Quadrupole formula (Einstein 1916).
GW luminosity (ϵ: deviation from axisymmetry):

$$L_{\rm GW} \sim \frac{G}{c^5}\,\epsilon^2\left(\frac{M\,V^3}{R}\right)^2$$

$$= \frac{c^5}{G}\,\epsilon^2\left(\frac{R_s}{R}\right)^2\left(\frac{V}{c}\right)^6$$

$\mathcal{O}(10^{-53})$ $\mathcal{O}(10^{59})\,\frac{\rm erg}{\rm s}$

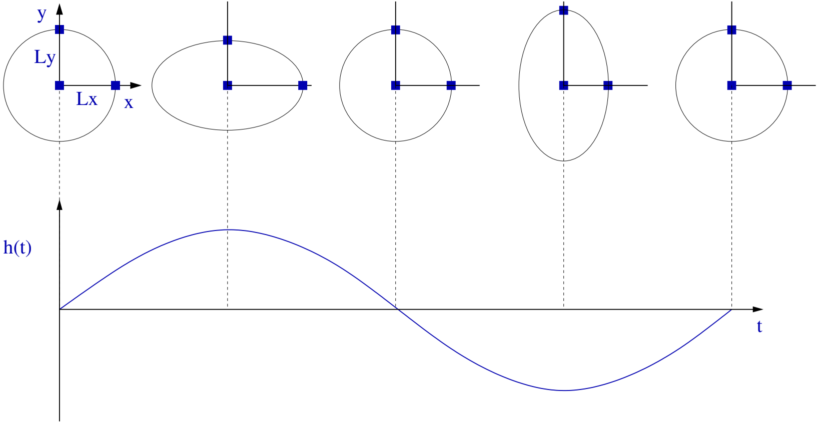
Schwarzschild radius $R_s = 2GM/c^2$

☞ Need compact objects in relativistic motion:
Black Holes, Neutron Stars, White Dwarfs

Gravitational Wave Strain $h(t)$

Plane gravitational wave $h^{+}_{\mu\nu}$ along z-direction:

Strain $h(t) \equiv \frac{L_x - L_y}{2L}$:

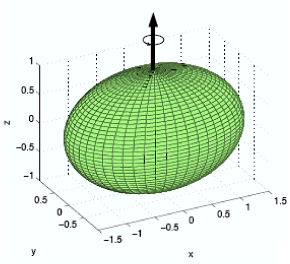


Triaxial Spinning Neutron Stars

Rotating neutron star:
- non-axisymmetric $\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$
- rotation rate ν

☞ GW with frequency $f = 2\,\nu$

Strain-amplitude h_0 on earth:



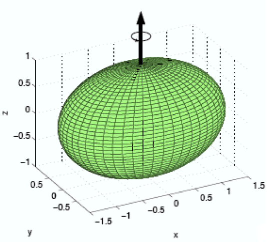
$$h_0 = \frac{16\pi^2\,G}{c^4}\,\frac{\epsilon\,I_{zz}\,\nu^2}{d}$$
$$= 4 \times 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm}^2}\right) \left(\frac{\nu}{100\ \mathrm{Hz}}\right)^2 \left(\frac{100\,\mathrm{pc}}{d}\right)$$

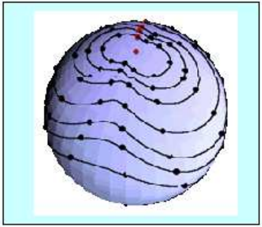
Current LIGO sensitivity (S5): $\sqrt{S_n} \sim 4 \times 10^{-23}\,\mathrm{Hz}^{-1/2}$

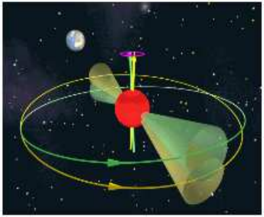
☞ NS signals buried in the noise $\Longrightarrow$ need "matched filtering"

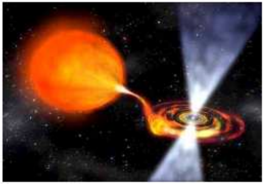
Possible Emission Mechanisms

- “Mountains”
- Oscillations
- Free precession
- Accretion (driver)





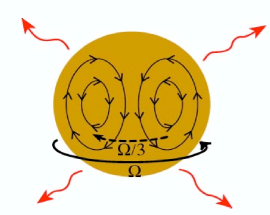




Neutron Star “Mountains”

- Conventional NS crustal shear mountains:
  ☞ $\epsilon_{\rm crust} \lesssim 10^{-7} - 10^{-6}$ (Ushomirsky, Cutler, Bildsten)
- Superfluid vortices: Magnus-strain deforming crust
  ☞ $\epsilon_{\rm Magnus} \sim 5 \times 10^{-7}$ (D.I. Jones; Ruderman)
- Exotic EOS: strange-quark solid cores
  ☞ $\epsilon_{\rm strange} \lesssim 10^{-5} - 10^{-4}$ (B. Owen)
- Magnetic mountains:
  - large toroidal field $B_t \sim 10^{15}\,\rm G \perp$ to rotation:
    ☞ $\epsilon_{\rm toroidal} \sim 10^{-6}$ (C. Cutler)
  - accretion along B-lines $\Longrightarrow$“bottled” mountains
    ☞ $\epsilon_{\rm bottle} \lesssim 10^{-6} - 10^{-5}$ (Melatos, Payne)

Oscillation Modes

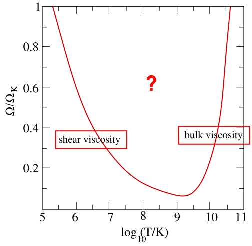


Chandrasekhar-Friedman-Schutz instability:

counter-rotating mode "dragged forward"
$\Longrightarrow$ negative energy and angular momentum

- ☞ emission of GW amplifies the mode
- ☞ counteracted by dissipation

r-mode instability window:

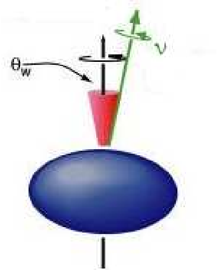


Open questions:

- Dissipation mechanisms: vortex friction, hyperons, crust-core coupling,...
- saturation amplitude, mode-mode coupling, evolution timescales

Free Precession

"Most general motion of a rigid body" (Landau&Lifshitz 1976)

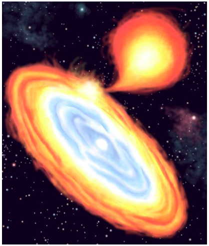


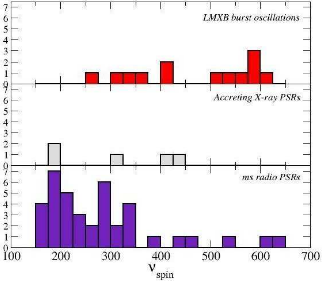
NS are not rigid: coupled crust - core (viscosity + superfluid vortex pinning)

- likely to be damped rapidly
- no obvious instability or "pumping mechanism"

$$h_0 \sim 10^{-26} \left(\frac{\theta_w}{0.1}\right) \left(\frac{100\,\mathrm{pc}}{d}\right) \left(\frac{\nu}{500\,\mathrm{Hz}}\right)^2$$

Accretion





Breakup-limit $\nu_K \sim 1.5$ kHz ☞ What limits the NS-spin?

Bildsten, Wagoner: Accretion-torque = GW torque ($\propto \nu^5$)

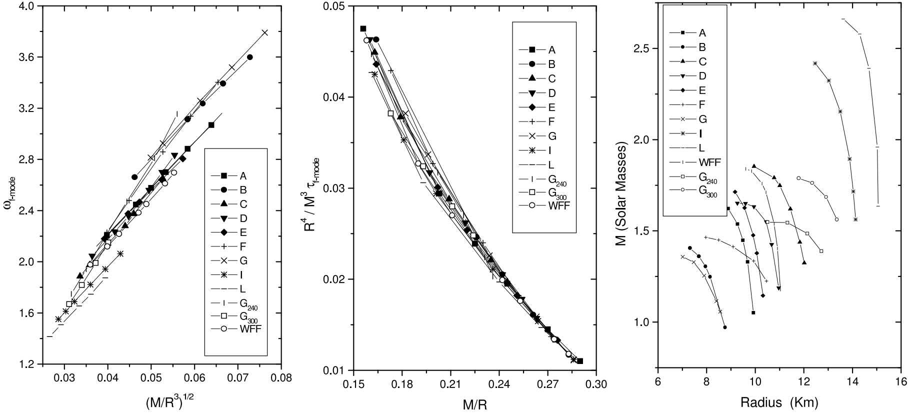
Observed X-ray flux ☞ Sco X-1: $h_0 \sim 3 \times 10^{-26} \, (270 \, \mathrm{Hz}/\nu)^{1/2}$

Astrophysics Summary

- NS are plausible sources for GW detection with LIGO I or II
- Whether or not they are detectable depends on many poorly-understood aspects of NS physics
- ☞ Any GW-detection from rotating NS will be extremely valuable for NS physics
- ☞ Even the absence of detection can yield astrophysically interesting information (crust deformation, B_t, instabilities)
- NS physics producing GWs is very different and complementary to electromagnetic emission (bulk-mass motion vs magnetosphere-electron motion)

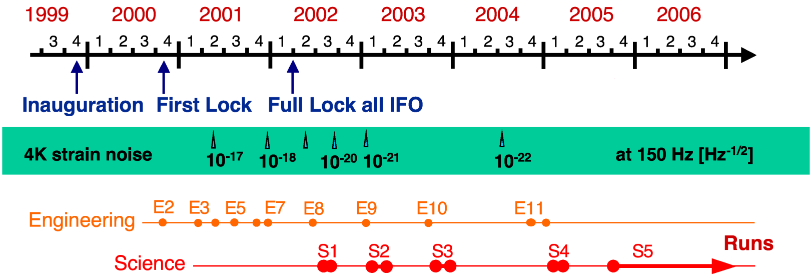
Gravitational Wave Astronomy

"Astero-Seismology" (Andersson, Kokkotas 1998): f-mode

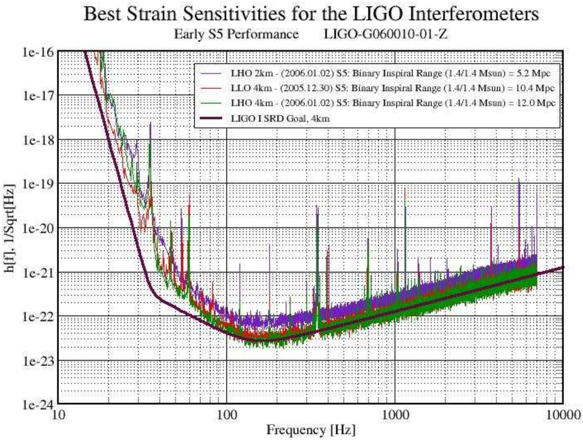


☞ Measurement of $(\omega_f, \tau_f) \Longrightarrow$ deduce $(M, R) \Longrightarrow$ EOS

LSC detectors: LIGO + GEO600



Current LIGO noise performance



$$h_0 = \frac{\Delta L}{L} \sim 3 \times 10^{-23} \Longrightarrow \Delta L \sim 10^{-19}\ m = 10^{-4}\ fm!!$$

LSC Data Analysis

LIGO (H1, H2, L1) and GEO600 data analyzed within the LIGO Scientific Collaboration (LSC):

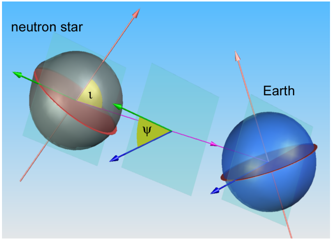
$\sim$ 40 institutions, $\sim$ 320 authors (S3)

4 major search groups (different targets and methods):

- Binary inspirals: short inspiral signals (*modeled*)
- Bursts: short *unmodeled* signals (supernovae, merger)
- Stochastic background: cosmological background GWs
- "Continuous waves": spinning NS signals (long-lived)

Nature of GW from Rotating Neutron Stars

- NS frame: monochromatic wave, slowly varying frequency
  - Phase $\Phi(\tau) = \phi_0 + 2\pi \left(f\,\tau + \frac{1}{2}\dot{f}\,\tau^2 + \ldots \right)$
    GW frequency for triaxial NS: $f = 2\,\nu$, r-modes: $f = 4/3\,\nu$, precession: $f \approx \nu$
  - Amplitudes (2 polarizations)
    $A_+ = h_0 \cos\iota$
    $A_\times = \frac{1}{2} h_0 (1 + \cos^2\iota)$
  - $\Longrightarrow$ Wave-components in NS frame:
    $h_\times(\tau) = A_+ \cos\Phi(\tau)$
    $h_+(\tau) = A_\times \sin\Phi(\tau)$



- Detector frame t: sky-position (α, δ) dependent *modulations*:
  - Phase: Doppler-effect due to earth's motion $\tau = \tau(t; \alpha, \delta)$
  - Amplitude: rotating Antenna-pattern $F_{+,\times}(t, \psi; \alpha, \delta)$

Signal Received at the Detector

GW strain at the detector:
$h(t) = F_+(t)\, h_+(t) + F_\times(t)\, h_\times(t)$

Signal dependencies

$$h(t) = F_+(t, \psi; \alpha, \delta)\; A_+\; \cos\Phi(t, \phi_0; \alpha, \delta, f, \dot{f}, ..) + F_\times(t, \psi; \alpha, \delta)\; A_\times\; \sin\Phi(t, \phi_0; \alpha, \delta, f, \dot{f}, ..)$$

Signal parameters:

- *"Amplitude parameters":* $\mathcal{A} = \{h_0, \iota, \psi, \phi_0\}$
- *"Doppler parameters":* $\lambda = \{\alpha, \delta, f, \dot{f}, \ldots$ (+ orbital parameters) $\}$

Matched filtering

Measured strain: $x(t) = \underbrace{n(t)}_{\text{noise}} + \underbrace{h(t)}_{\text{signal}}$ noise power $S_n(f)$

Optimal detection statistic:

"matched filtering" = correlate $x(t)$ with signal-model $h(t; \mathcal{A}, \lambda)$

$\Longrightarrow$ find maximum "match" $M = M(x; \mathcal{A}, \lambda)$

Signal-to-noise ratio @ perfect match

$$\mathrm{SNR}^2 = \int_0^T \frac{h^2(t; \mathcal{A}, \lambda)}{S_n(f)}\, dt \quad \Longrightarrow \quad \mathrm{SNR} \propto \frac{h_0}{\sqrt{S_n}} \sqrt{T \mathcal{N}}$$

$h_0/\sqrt{S_n} \ll 1$ ☞ want long T (and many detectors $\mathcal{N}$)

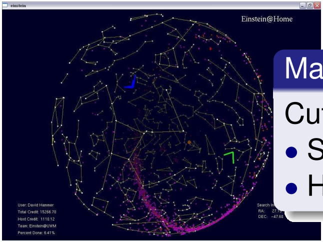
Search Strategies

- Wide-parameter searches for unknown NS:
  Need to scan space of Doppler-parameters λ (but not $\mathcal{A}$)
  e.g. isolated NS ($\alpha, \delta, f, \dot{f}$): number of templates $N_p \propto T^5$

  1. Fully coherent: $\mathcal{F}$-statistic (Einstein@Home $T \lesssim 30$ hours)
     ☞ optimal sensitivity @ *infinite* computing power
  2. Semi-coherent: Hough, StackSlide, PowerFlux ($T \sim$ data)
     ☞ sub-optimal but fast
  3. Hierarchical search: combine 1 + 2, will run on E@H
     ☞ optimal sensitivity @ *finite* computing power

- Targeted searches for known pulsars ($f = 2\nu$)
  ☞ only *one* template $\lambda_0 = \{\alpha, \delta, f, \dot{f}, ..\}$ from radio/X-ray
  Fully coherent, not computationally limited ($T \sim$ data),
  $\Longrightarrow$ most sensitive search!

Einstein@Home: Search for Unknown NS



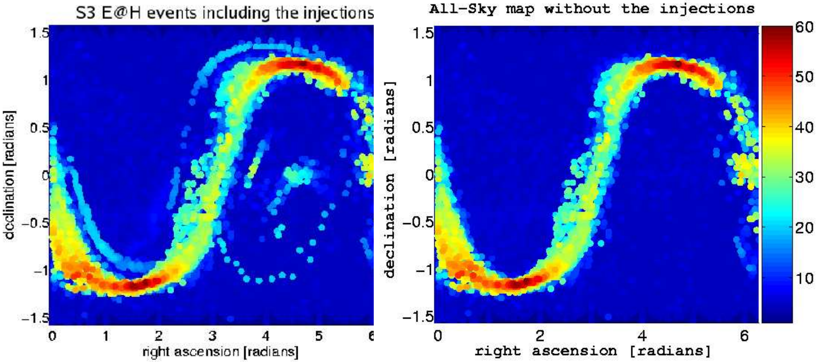
Maximize available computing power

Cut parameter-space λ in small pieces $\Delta\lambda$

- Send workunits $\Delta\lambda$ to participating hosts
- Hosts return finished work and request next

- Public distributed computing project, launched Feb. 2005
- Currently $\sim$120,000 active participants, $\sim$50Tflops
- runs on GNU/Linux, Mac OSX, Windows,..
- Search for isolated neutron stars $f \in [50, 1500]$ Hz
- Aiming for detection, not upper limits
- Analyzed data from S3, S4, next: S5

Einstein@Home S3 results



- correctly identified injections ($h_0 \sim 10^{-23}$)
- all "outliers" either on $\boldsymbol{r}(t) \cdot \boldsymbol{n} = 0$ circles (☞ stationary lines), or ruled out by follow-up studies (S4)

Wide-Parameter Searches: (Best) Upper Limits

- Fully coherent ($\mathcal{F}$-statistic) searches `[gr-qc/0605028]`:

S2 Sco X-1 (unknown $f, a_p, \bar{T}$), using $T = 6\ h$ of S2
☞ $h_0^{95\%} \sim 2 \times 10^{-22}$

S2 All-sky, isolated NS, ($f \in [160, 728]$ Hz), using $T = 10\ h$ of S2
☞ $h_0^{95\%} \sim 7 \times 10^{-23}$

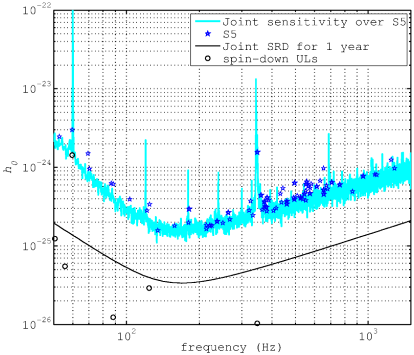
- Semi-coherent searches:

S2 Hough-transform: all-sky, isolated NS ($f \in [200, 400]$ Hz)
☞ $h_0^{95\%} \sim 4.5 \times 10^{-23}$

S4 StackSlide: all-sky, isolated NS ($f \in [50, 225]$ Hz)
☞ $h_0^{95\%} \sim 4.5 \times 10^{-24}$ *(preliminary)*

Early S5 PowerFlux: all-sky, isolated NS ($f \in [40, 700]$Hz)
☞ $h_0^{95\%} \sim 2 \times 10^{-24}$ *(preliminary)*

Targeted Pulsar Search: Early S5 (*preliminary*)



- Targeted 73 pulsars ($f = 2\nu$):
  32 isolated, 41 binary (29 in GCs)
- first 2 months of S5
- all 3 detectors: H1, H2, L1
- Best 95% upper limits:
  $h_0 \lesssim 2 \times 10^{-25}$ (PSR J1603-7202)
  $\epsilon \lesssim 4 \times 10^{-7}$ (PSR J2124-3358)

Upper-limits well above *spindown-limit* (except in GCs)

But: Crab-pulsar is only a factor 2.1 away from spindown-limit

☞ will (most likely) be able to beat spindown-limit during S5!

Published results

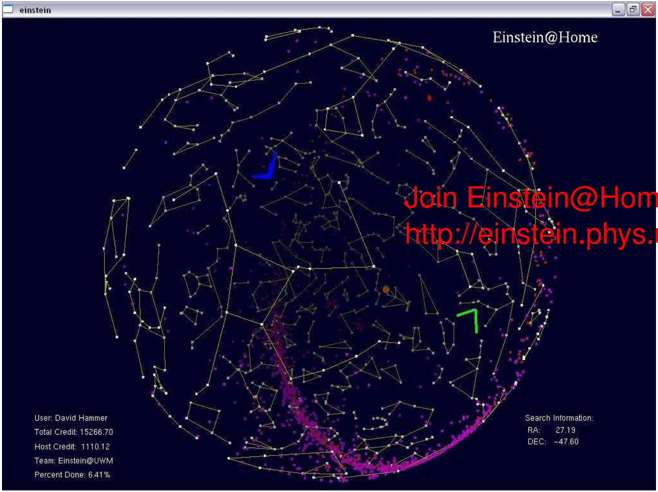
Published LSC results of neutron-star searches:

- S1 Setting upper limits on the strength of periodic gravitational waves from PSR J1939 + 2134 using the first science data from the GEO 600 and LIGO detectors, B. Abbott et al. (LSC), Phys. Rev. D 69, 082004 (2004)
- S2 Limits on gravitational wave emission from selected pulsars using LIGO data, B. Abbott et al. (LSC), Phys. Rev. Lett. 94, 181103 (2005)
- S2 First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform, B. Abbott et al. (LSC), Phys. Rev. D 72, 102004 (2005)
- S2 Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run, to be submitted, `[gr-qc/0605028]`
- S3 Online report on Einstein@Home results for S3 search: `http://einstein.phys.uwm.edu/PartialS3Results/`

Summary and outlook

- No GW detection so far, but none expected
  ☞ setting upper limits on h_0 and ϵ
- S5 upper-limits are approaching astrophysically relevant regimes (☞ Crab, EOS-limits on ϵ)
- LIGO S5 operating at design-sensitivity, will collect one year's worth of data (duration $\sim$1.5 years)
- Einstein@Home: Currently analyzing S4, S5. Developing a fully hierarchical search ☞ most sensitive possible search for unknown NS
- NS detection with LIGO-I not very likely, but not impossible ("Expect the unexpected!")
- The future is bright: S6, VIRGO, LIGO-II, GEO-HF, ...

You can help us find Gravitational Waves!



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