VULCANO WORKSHOP 2012
FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

The past and future of direct search of GW from pulsars in the interferometric GW antennas era

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The effort to detect gravitational waves started humbly fifty years ago with Joe Weber's bar detectors They opened the way to the actual interferometric detectors: starting from a bandwidth of a maximum of 50 Hertz around 960 Hz(bar criogenic antennas) nowdays we realized antennas with useful bandwidth of thousandths of Hz, namely 10Hz-10 kHz (Virgo) 40Hz-10 kHz Ligo

BUT

Not yet detection of GW signal notwithstanding the target sensitivity was reached either for VIRGO or for LIGO

We have only Upper Limits!

Question: are GW real?

PSR 1913+16 NS – NS binary (Hulse-Taylor Binary)→Orbital decays as predictedby GR.
Indirect evidence for GWs. →Now **17** other such binaries known

Basic of GW emission from pulsars

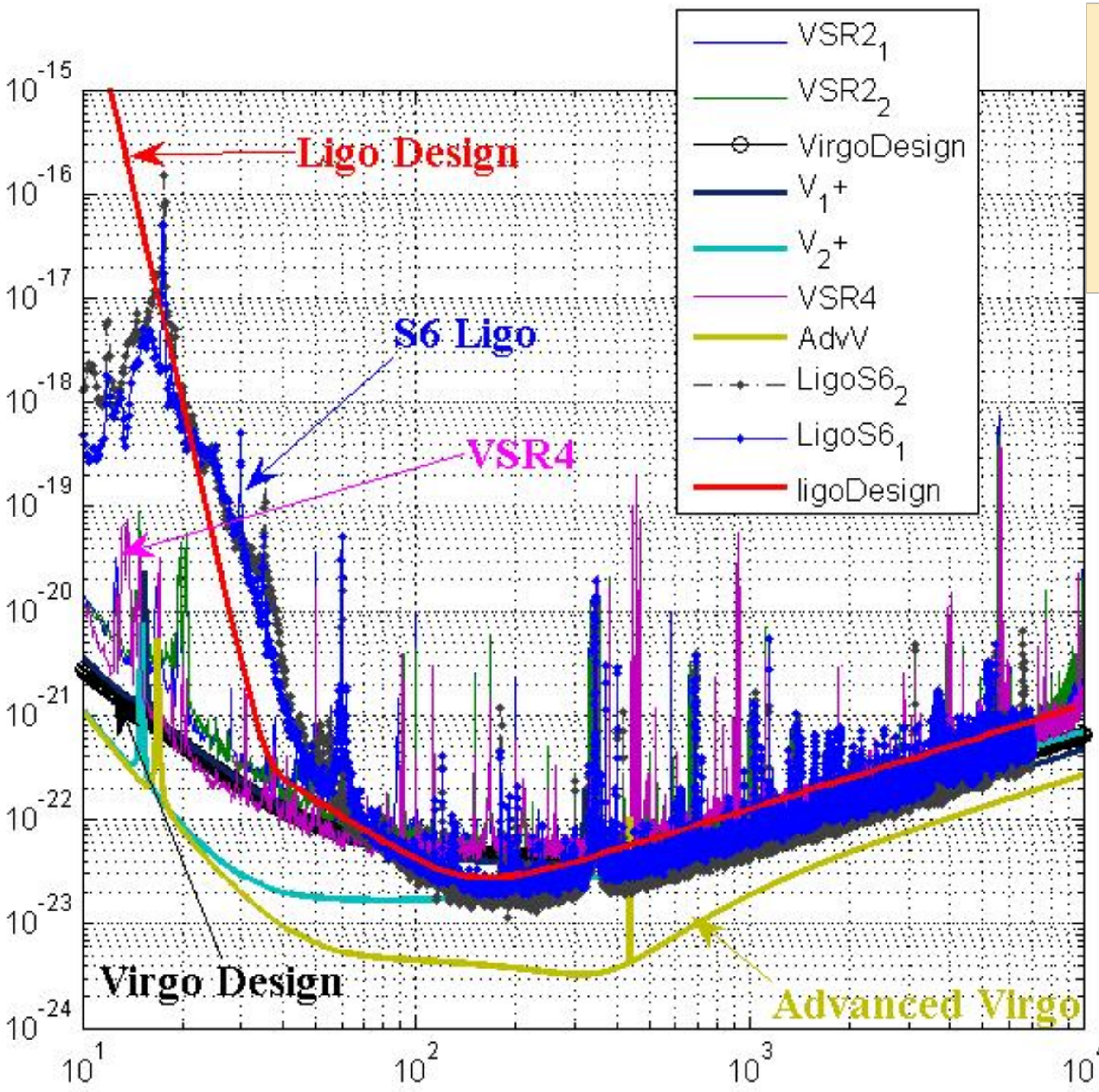
The GW from pulsars

→Results from the past up to now

→The future

Conclusions→Questions ☺

Sensitivity curves of Ligo and Virgo: Design sensitivity reached or also better then the target around 100 Hz (Ligo) . Run S5/S6→Ligo or VSR2/VSR4→ Virgo



Ligo Useful bandwidth from 40 Hz

Virgo Useful bandwidth from 10 Hz

Ligo

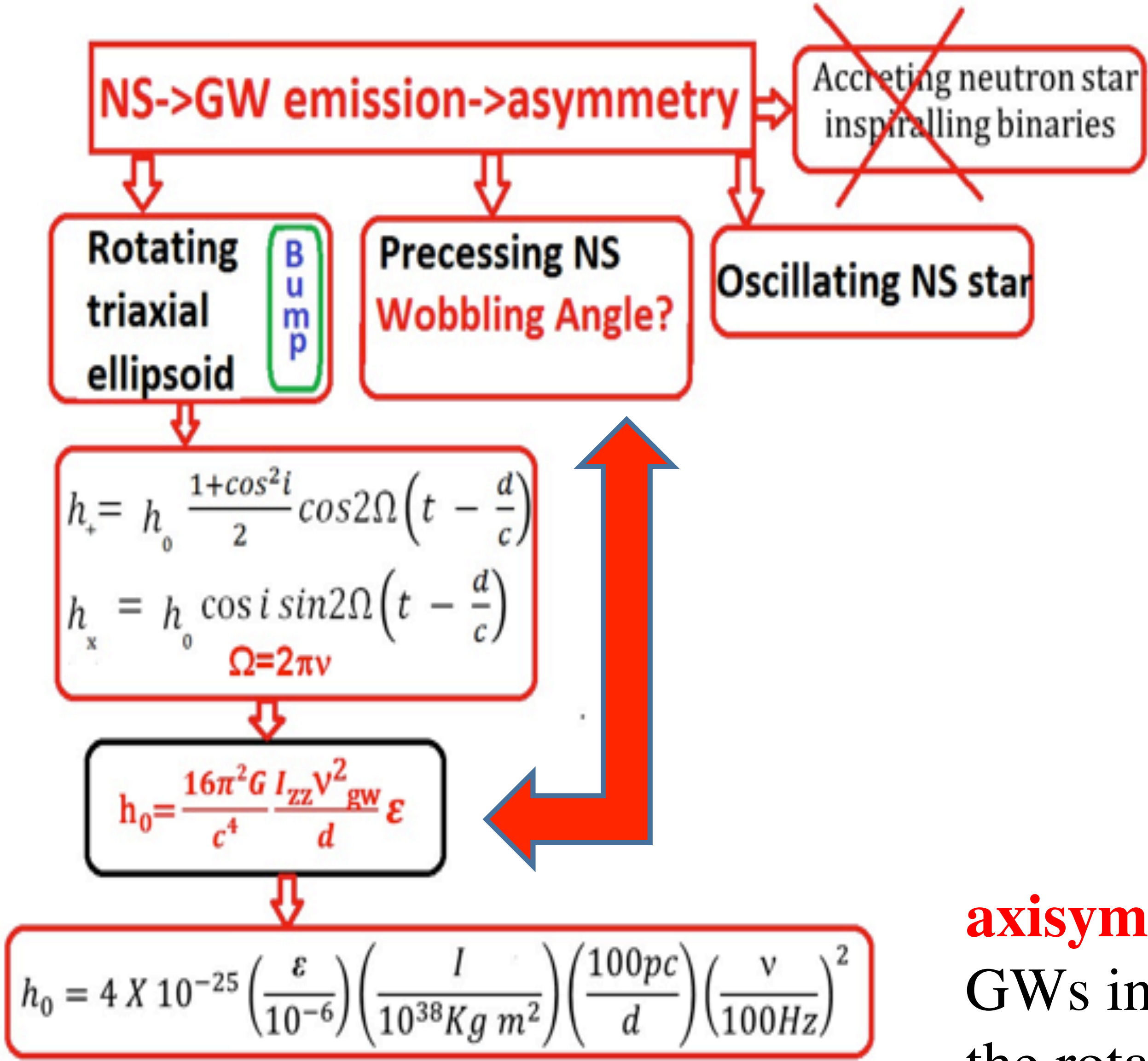
- **Fabry-Perot Cavity**: ~125 round trips

    ⇒ Effective optical path ~500km

Virgo

- **Fabry-Perot Cavity**: ~50 round trips

    ⇒ Effective optical path ~150km



On the Earth:d--> distance

I -->Moment of inertia with respect to the rotation axis

quadrupole ellipticity $\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$

Moment of inertia of NSs

From a large set of equations of state (EOS) describing NS matter at supra-nuclear densities, the result is:

$$I \approx [1–3] \times 10^{38}\ \mathrm{kg\ m^2}$$

depending on the EOS and on the rotation rate

axisymmetric shape: GWs in case of misalignement of the rotation and the symmetry axes of an angle α called wobble angle → values?

What about ellipticity?

The quadrupole ellipticity

The maximum quadrupole deformation ε sustainable by a NS (or a quark star) depends upon the **physics of the crust** and upon the **EOS of matter at supranuclear density**.

So we can put upper limit on ε looking for the maximal strain that the crust can sustain without breaking. Modelling of crustal strains indicates that $\varepsilon < k \left(\frac{u_{break}}{Br_{Lim}}\right)$

where u_{break} is the crustal breaking strain while **k** and Br_{Lim} *depend upon star model*. From molecular dynamics simulations

$$u_{break} \approx Br_{Lim} = 0.1 \text{ and } k = 2\times10^{-5},$$

(For terrestrial materials $u_{break} \cong 10^{-4} \div 10^{-2}$)

So the NS crust would break for deformation ≥ 20 cm.

According to different models of solid quark star we will have that $Br_{Lim} = 10^{-2}$ and $k = 6\times10^{-4 \div -3}$

For strong initial magnetic fields (10^{16} Gauss) the star could emit intense GW owing to deformation due to magnetic field

Conclusions: We have a lot of estimates on the ellipticity, but few certainties

Question:Could the gravitational data, we got, from Virgo and Ligo,be useful to constrain EOS model of a NS using the upper limit on ε and the moment of inertia I?

What we know from:

a) the astrophysical observations

b) the gravitational data

Astrophysical observations:

In the Galaxy there are ~ 10^8 neutron stars ,~ 2000 are radio pulsars. Knowing: d = distance ; ν_{rot} = rotation frequency (GW emiss. at $\nu_{gw} = 2\,\nu_{rot}$) $\dot{\nu} < 0$ →Pulsars lose energy and slow-down → mechanism is trough:

Magnetic dipole radiation Particle acceleration Gravitational radiation

Braking index n: **3** for pure magnetic dipole; **5** for pure GW radiat.

$$\dot{\nu} = k\nu^n \quad n = \frac{\nu\,\ddot{\nu}}{\dot{\nu}^2}$$

Pulsars with measurable braking indices (only 4 or 5 objects) have $n < 3$ → some combination processes?

Pulsar	n
Crab pulsar	2.51±0.01
B0540-69	2.28±0.02
B1509-58	2.837±0.001
Vela pulsar	1.4±0.2

from Palomba, *A&A*, **354**, 2000

Strong Hypothesis
spindown luminosity = gravitational wave luminosity

$$h_{\text{spindown}} \sim \left(\frac{5}{2}\frac{G\,I_{zz}|\dot{\nu}|}{c^3 d^2 \nu}\right)^{1/2}$$

spin-down rate

spin frequency

distance to pulsar

$$h_{spindown} \sim 2.5\times 10^{-25}\left(\frac{I_{zz}}{10^{38}\,kg\,m^2}\right)^{1/2}\left(\frac{|\dot{\nu}|}{10^{-11}\,Hz\,s^{-1}}\right)^{1/2}\left(\frac{100\;Hz}{\nu}\right)^{1/2}\left(\frac{1\;kpc}{d}\right)$$

- For most millisecond pulsars (with very small spin-downs) h_{spindown} is well below current sensitivities (but not for future GW antennas)
- **For several young pulsars we can approach, or beat this limit**

LIGO and Virgo have taken data for years and some periods of good data quality 'overlap

Science runs

- LIGO S5 (November 4, 2005 to October 1, 2007) **Published**

&

- VIRGO VSR1 (May 18, 2007 to October 1, 2007) }

- LIGO S6 (July7, 2009 to October 20, 2010.)

&

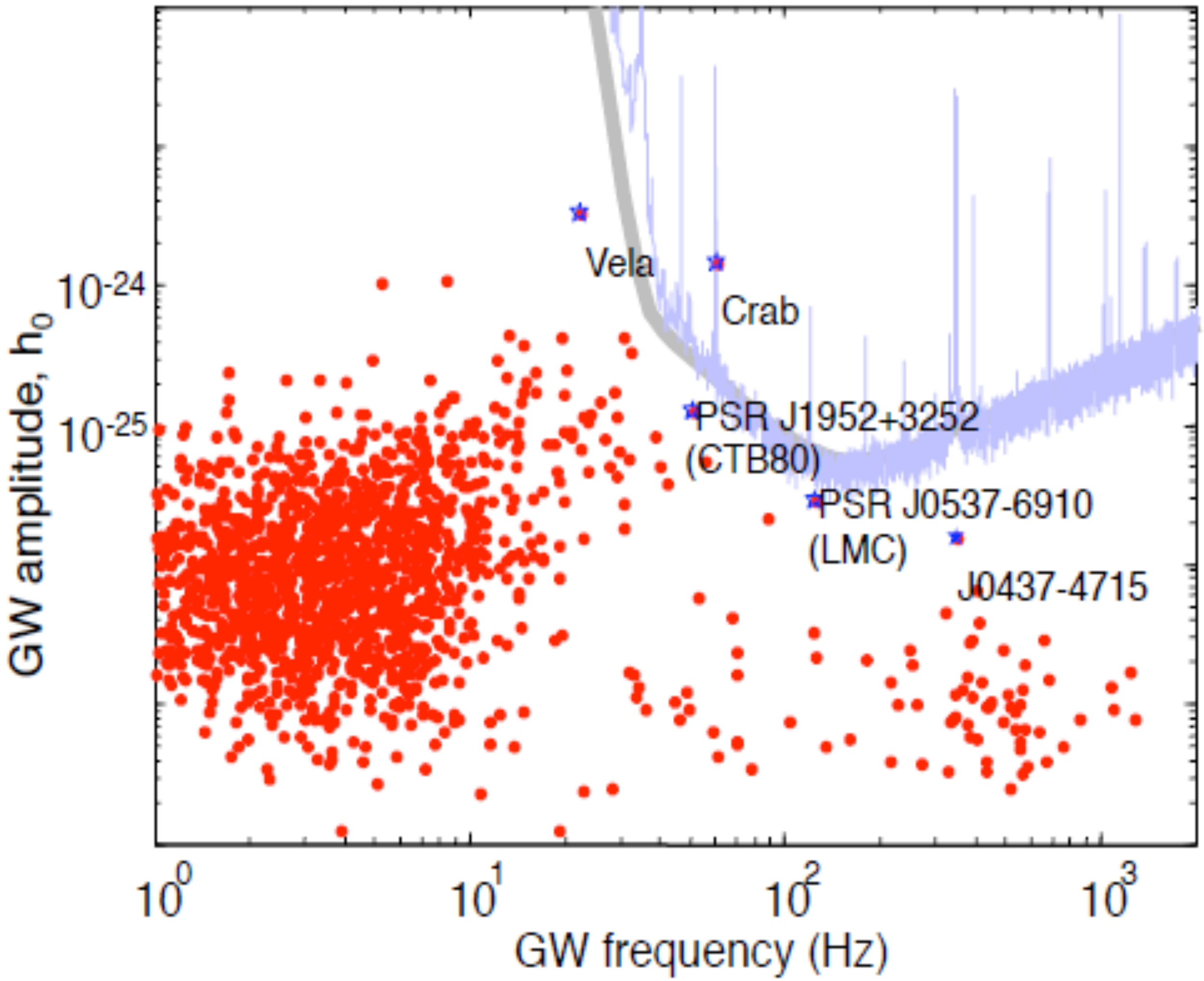
- VIRGO VSR2 (July 07, 2009 to January 08, 2010) }

+ VSR3 (August 11, 2010 to October 20, 2010)

+VSR4 (June 2011, to September 2011)

GW data analysis → Ligo & Virgo

The majority *of pulsars are out of the useful bandwidth and their* h_0 is < than the Ligo sensibility in S5/S6 or in Virgo VSR2/VSR4 (An integration time of one year is assumed)



Useful reference-
LIGO collab.
ApJ 713 (2010):
Targeted analysis
on 200 Known
pulsar ν > 20 Hz

The upper limits obtained with searches for periodic GW begin to be astrophysically interesting by imposing non-trivial constraints on the structure and evolution of the neutron stars.

Highlight results of the pulsars data analysis

ApJ 713 (2010):Targeted analysis on 200 known pulsar ν>20 Hz

CRAB pulsar

$h_0 < 2.4 \times 10^{-25} < \sim 6 \times h_0^{spindown}$

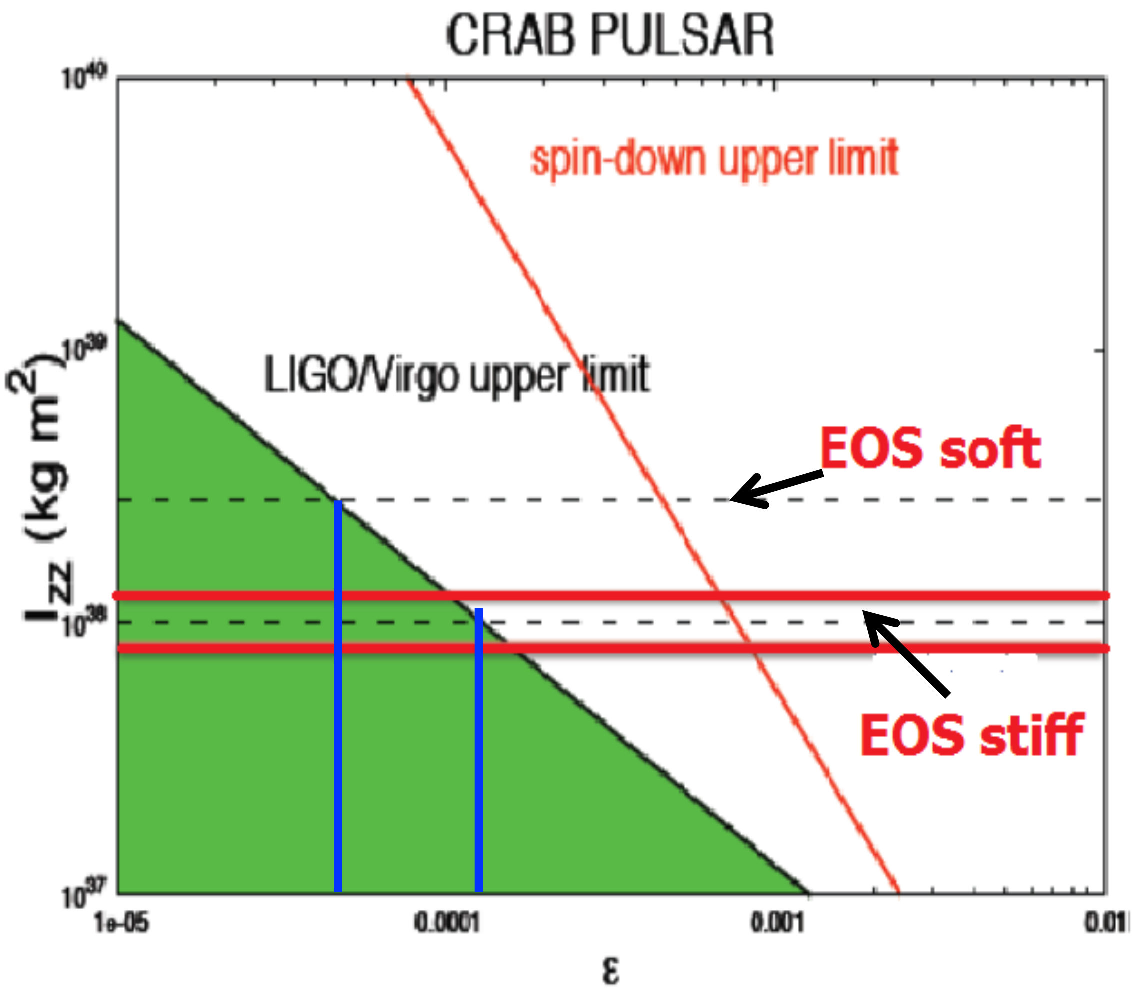
$h_0^{spindown} \equiv 1.4 \times 10^{-24}$

implies that <2% of rotational energy is lost in GW

A further interesting constraint was imposed on the ellipticity ε because we know that for a bumpy NS :

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz}\nu^2_{gw}}{d} \varepsilon$$

$\varepsilon < 1.3 \times 10^{-4}$



$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} \nu^2_{gw}}{d} \varepsilon$$

For a NS made of quarks

The permitted region for the moment of inertia and the ellipticity is the green zone

If we take account of studies on the equation of state of the NS, region allowed narrows between the two dashed lines
Benhar et al. Phys. Rev. D 72, 2005; Bejeret. Al.MNRAS 364 2005

Highlight results of the pulsars data analysis

Targeted analysis on Vela pulsar (Virgo VSR2 data only)

★ Vela pulsar $\nu_{rot} = 11.19$ Hz ; $\nu_{GW} = 22.38$ Hz ;

$\dot{\nu}_{rot} \cong -1.56 \times 10^{-11}$ Hz s^{-1}

Assuming that $I = 10^{38}$ kg m^2 and $\dot{E}_{rot} \cong \dot{E}_{GW}$

$h_0 < 2x\ 10^{-24} < h_0^{spindown}$
$h_0^{spindown} = 3.29 \times 10^{-24}$ and $\varepsilon_0^{spindown} = 1.8x10^{-3}$
implies that <35% of rotational energy is lost in GW

A further interesting constraint was imposed on the ellipticity ε obtaining

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} \nu^2_{gw}}{d} \varepsilon \quad \Rightarrow \quad \varepsilon < 1.1x10^{-3}$$

What are we doing?
Search underway using LIGO S6 and Virgo VSR2/3/4 for more pulsars

- Vela should get factor 1.5 improvement
- Search for GWs at rotation frequency and twice rotation frequency
- Perform narrow-band search for all pulsars (like S5 Crab analysis

Prospects for the future

- Advanced LIGO/Advanced Virgo (upgrade of most detector systems for 2015)
  - ~10 times increasing in sensitivity over initial LIGO/VirgO

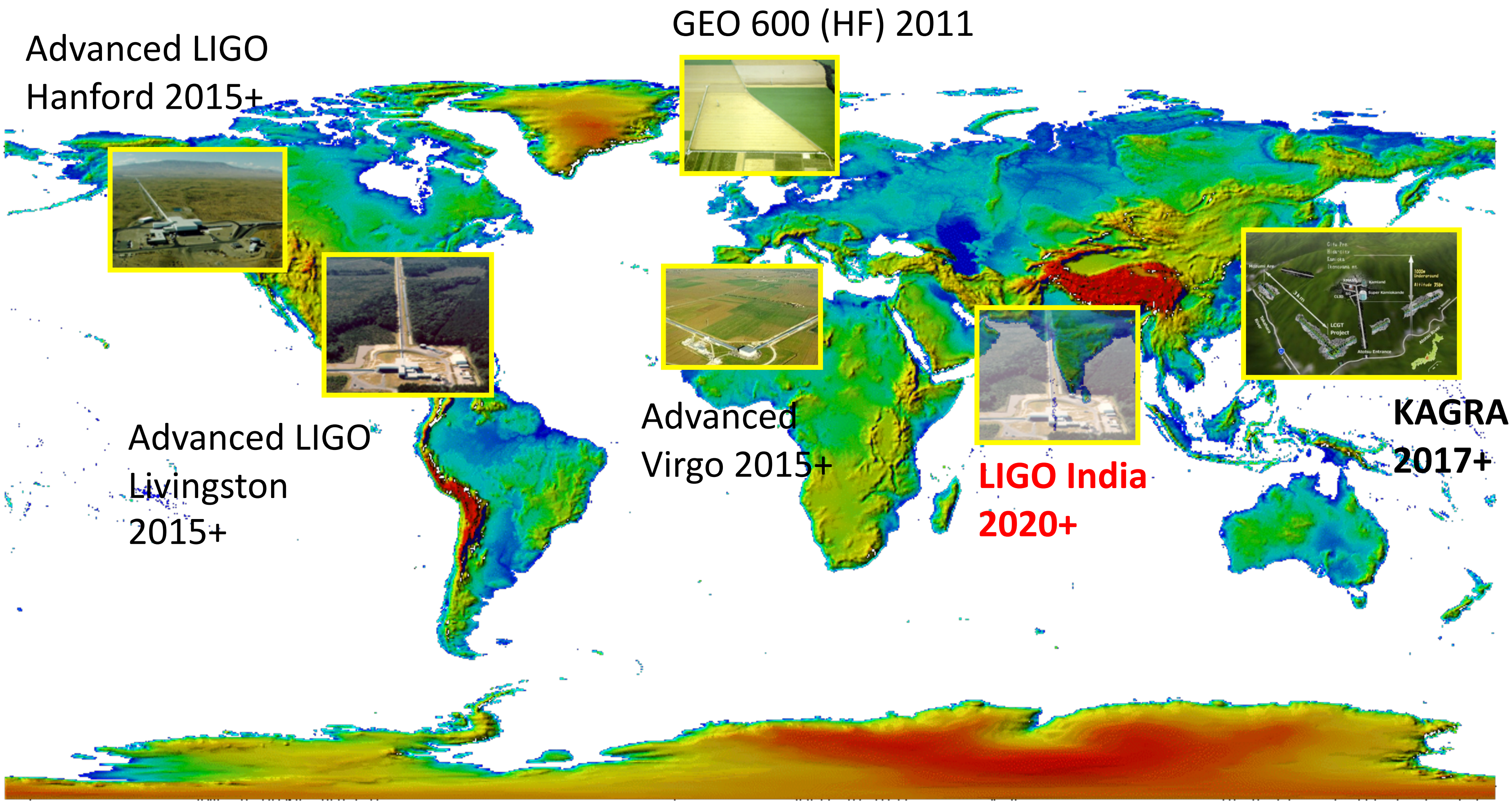
- Einstein Telescope (ET)

proposed European 3rd generation GW telescope another 10 times more sensitive than AdvLIGO

built in the underground (not yet known where): 4 interferometers Optimally Oriented and spaced→sources angle from time of flight differences

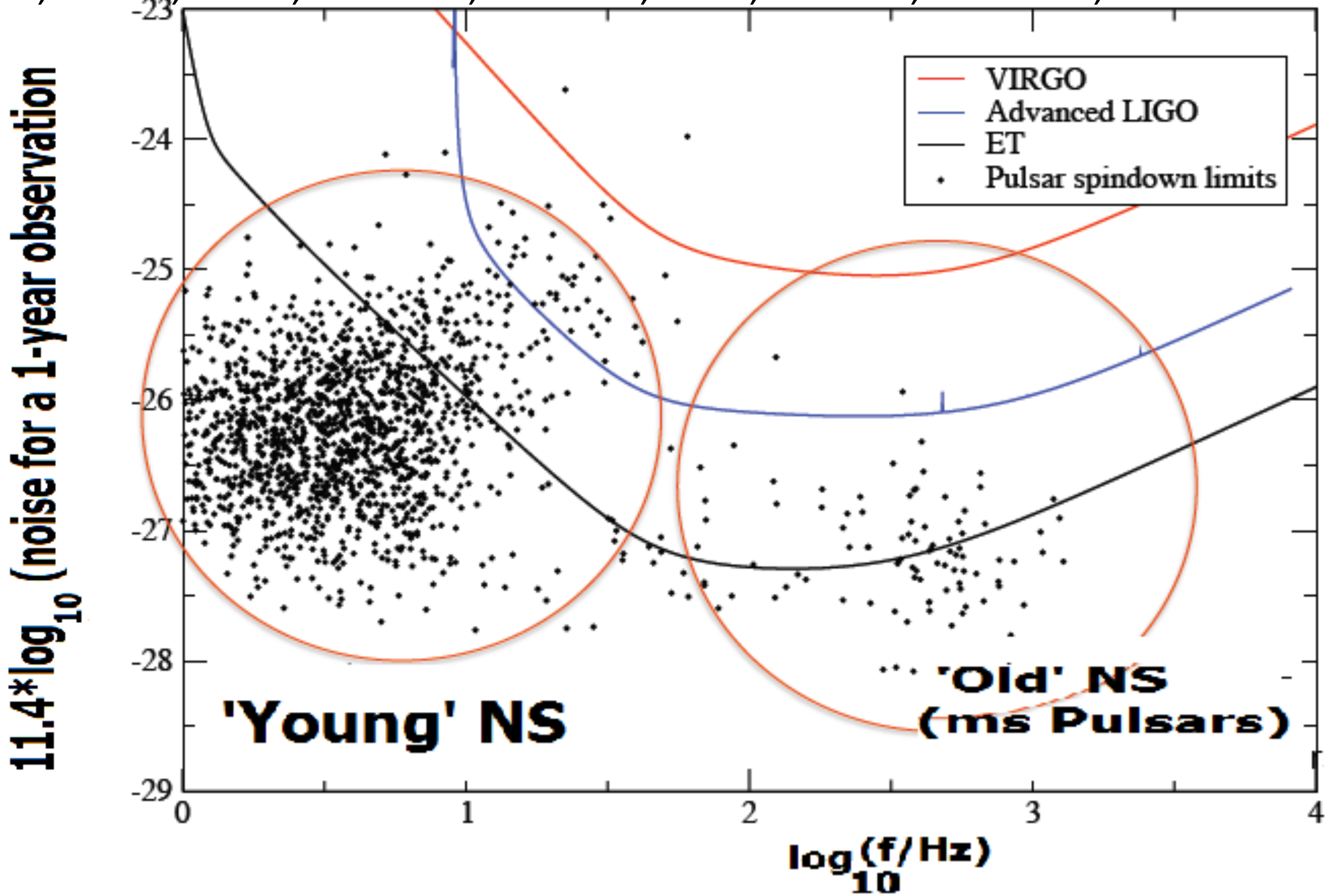
- **cryogenic**
- **how to go beyond gravity-gradient noise**
- **and many other technological challenges: Diffused light, E.m. fields Ground loops, Unforeseen noises, Etc…→Last but not the least the necessary budget: A large international collaboration is needed with suitable funding agencies**

The Advanced GW Detector Network: 2020+



Upper bounds on GW amplitude from known pulsars assuming 100% conversion of spindown energy into GWs. An integration time of one year is assumed.

Andersson, Ferrari, Jones, Kokkotas, Krishnan, Read, Rezzolla, Zink GRG, 43 2011



Conclusion → open questions ☺

- Upper limits for pulsars: when a direct detection?

Some questions related to pulsars:

- What fraction of a pulsar energy is really emitted in the form of gravitational waves?
- Can we have direct inferences on the pulsars parameters from gravitational waves to constrain EOS of a NS?
- What model of NS or quark star?

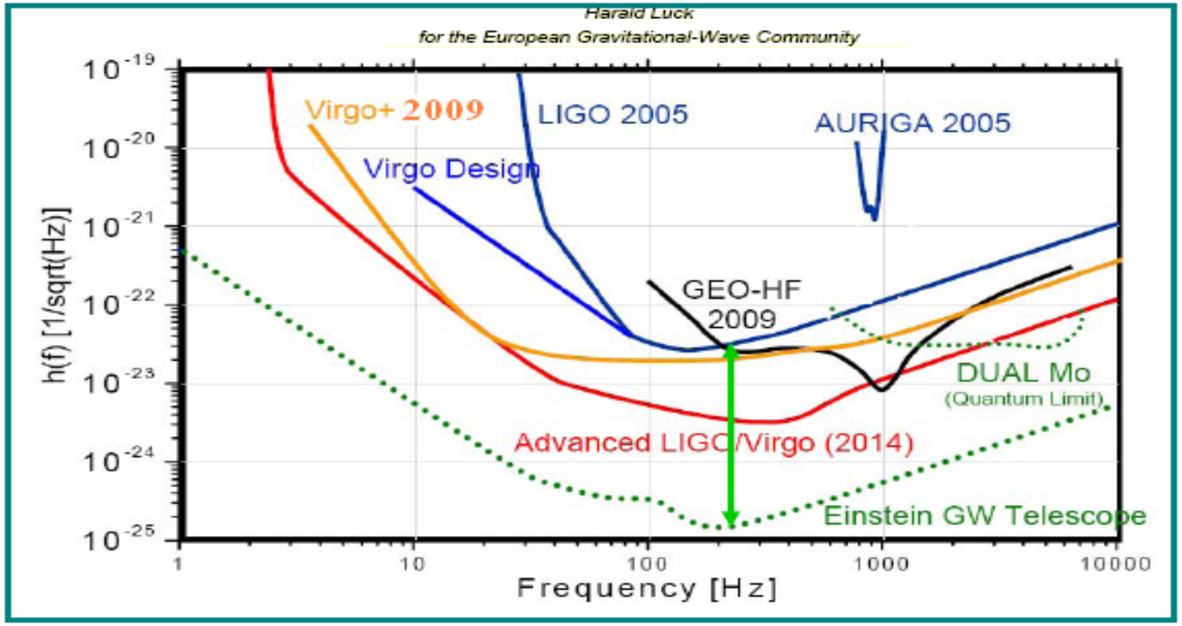
Some of these questions begin finally to have an answer!

Thanks for your attention

EXTRA SLIDE

Expected Sensitivity for 3rd generation of ground-based ITFs
ET, the Einstein Telescope

Detection of GWs events on earth should become routine!



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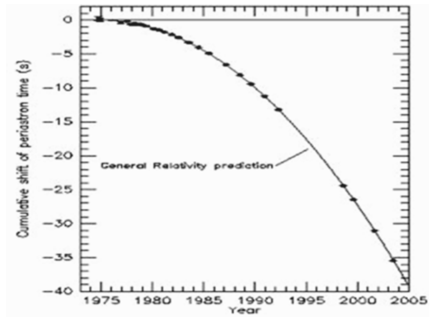
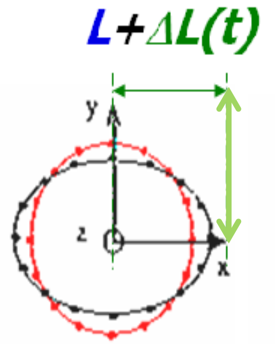
Grav. Waves

- Einstein's theory of General Relativity (1916) – Geometrical
- Theory of Gravity.
- Gravitational interaction mediated by a deformation of space-time.
- Moving masses produce *Gravitational Waves (GW)* as a ripple in the curvature of space-time.

  - Hulse-Taylor binary pulsar system (PSR B1913+16) - loosing the energy with radiating GW. (1974, Nobel prize 1993)
  - *Gravitational Waves should exist!*
  - **NO direct detection yet.**
  - Direct detection of GW will help understanding Gravity, GR, BH etc.





- **GW** - **Transverse waves** travelling at the speed of light.
- **Quadrupolar Distortions of Space** between freely falling masses:

GW as Dimensionless Strain: $h(t) = \Delta L(t) / L$

GW→ $\Delta L(t) = h(t)\, L$

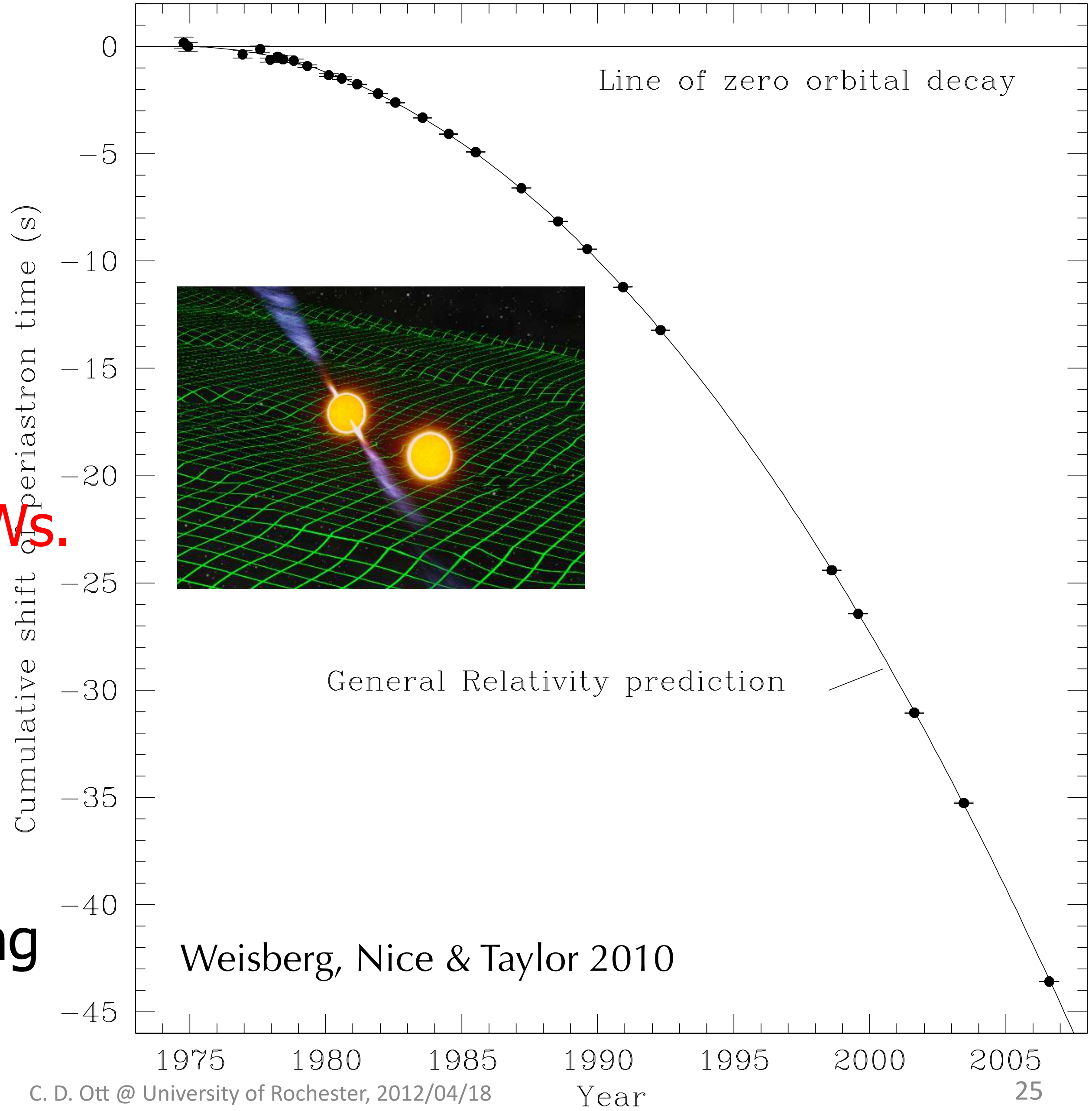
Are Gravitational Waves real?

PSR 1913+16
Neutron-Star –
Neutron-Star binary
(Hulse-Taylor Binary)

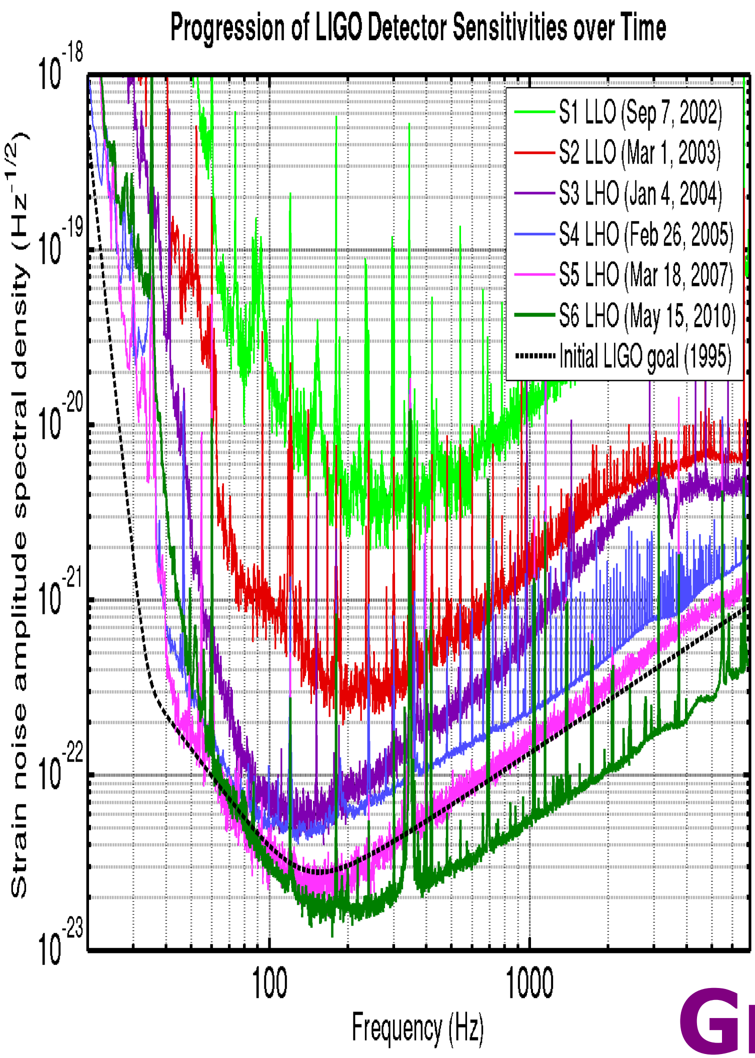
Orbital decays as
predicted
by General Relativity.
Indirect evidence for GWs.

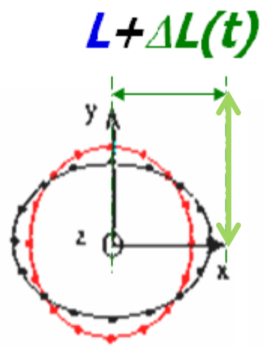
Nobel Prize in Physics
1993

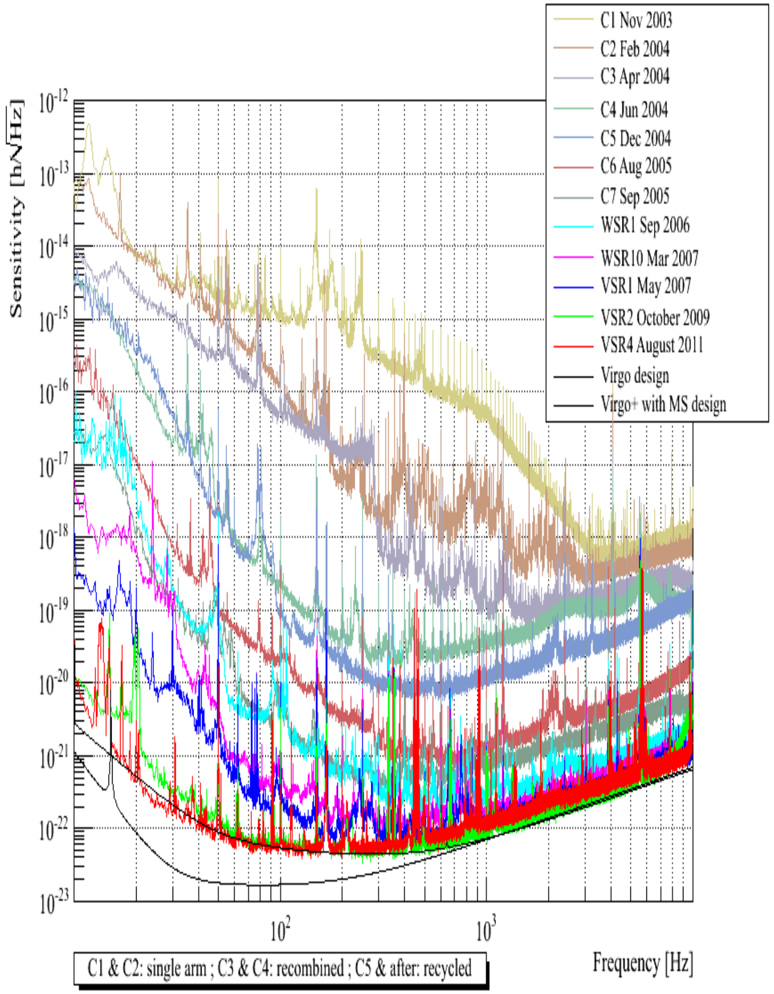
Now 17 other such
binaries known, including
double pulsar
PSR J0737-3039



LIGO & Virgo Interferometers milestones







Grav. Waves

- **GW** - **Transverse waves** travelling at the speed of light.
- **Quadrupolar Distortions of Space** between freely falling masses: ***GW as Dimensionless Strain: h(t) = ΔL(t) / L***

Experimental GW Detection Strategies

Two approaches: 1)Resonant bar 2) Interferometry

1) Measurements of the amplitude of oscillations of a resonant bar originated by gravitational wave impinging on the bar

2)Interferometric detection of GWs

measures spacetime geometry variations detected by free falling masses moving on geodesics using interferometry.

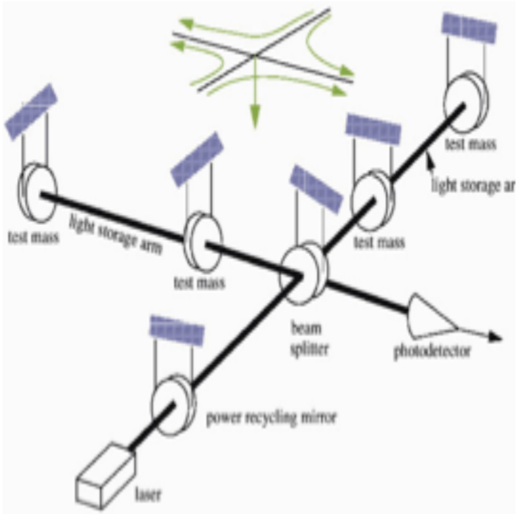
Displacement sensitivity can reach ~10^{-19}-10^{-20} m, then, to measure $\Delta L/L \sim 10^{-22}$ arms should be km long.

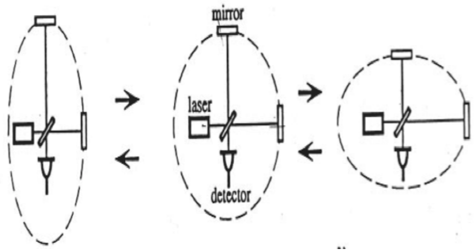
So for fixed ability to measure ΔL, make L as big as possible!

$$h = \frac{\Delta L}{L}$$

Each arm a FP Cavity

Interferometer as GW Detector





Ligo Useful bandwidth from 40 Hz

Virgo Useful bandwidth from 10 Hz

Ligo

- **Fabry-Perot Cavity**: ~125 round trips

  ⇒ Effective optical path ~500km

Virgo

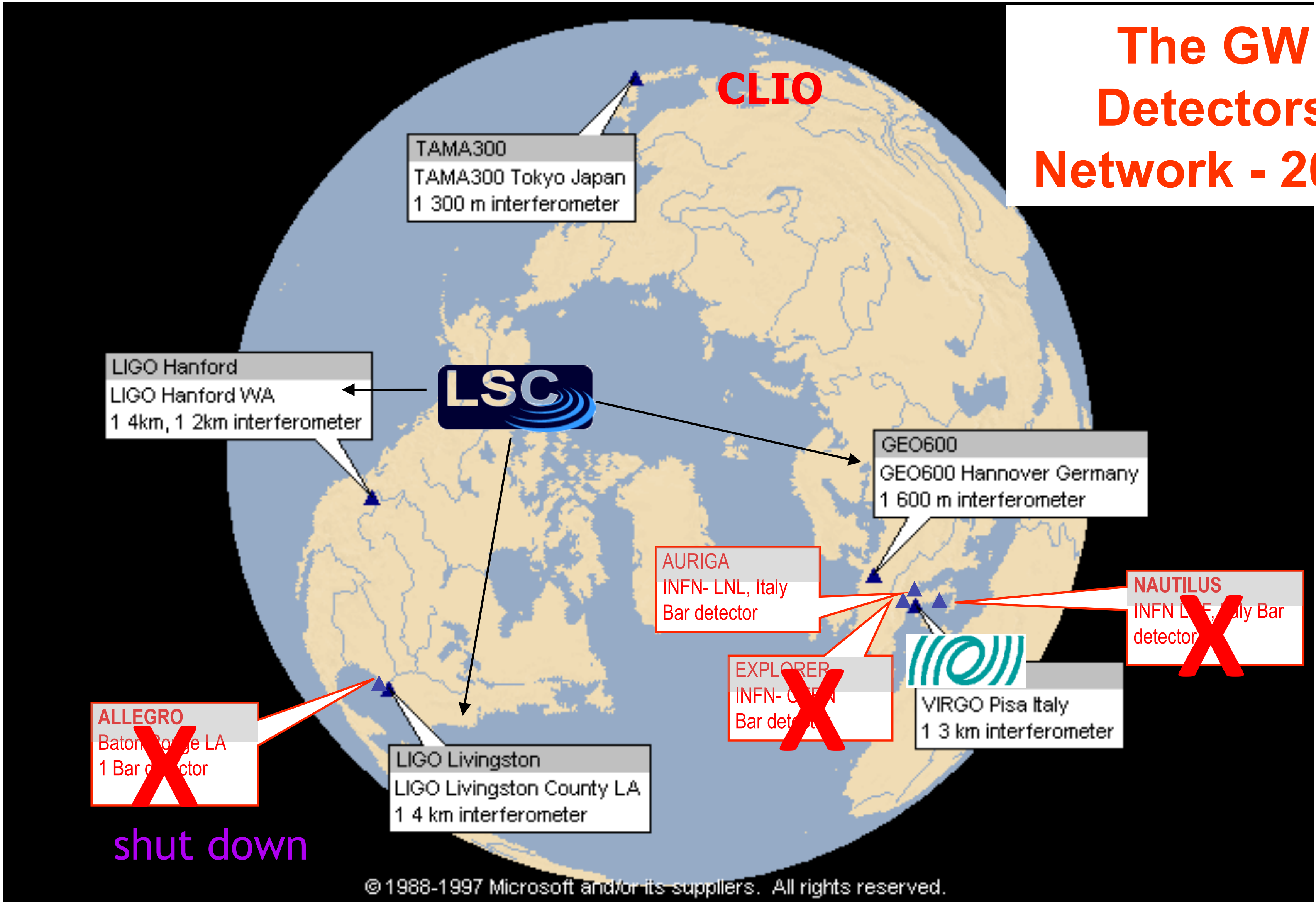
- **Fabry-Perot Cavity**: ~50 round trips

  ⇒ Effective optical path ~150km

- Interferometer for broadband antenna for gravitational waves - *R. Weiss* [1972].
- Using interferometer to detect GWs - Gedanken experiment by P.A.E. Pirani (1956)
- Became Feasible with Advent of Lasers

LIGO/VIRGO Detectors: Power-Recycled Fabry-Perot Michelson Interferometer

Over the years, techniques and sensitivities varied greatly, but since the start it has been clear that to detect GW we need an interacting GW-EM NETWORK



What level of asymmetry can we expect in a NS?

Effect of the crust

Detailed models of the maximum stress that can sustain the crust give:

$$\epsilon \lesssim 2 \times 10^{-5} \left(\frac{u_{break}}{10^{-1}} \right) \quad \textit{(Haskell, Jones, Andersson, MNRAS 2006)}$$

Recent molecular dynamics studies indicate $u_{break} \cong 0.1$
(Horowitz, Kadau PRL 2009)

(For terrestrial materials $u_{break} \cong 10^{-4} \div 10^{-2}$)

consequence

the crust of a neutron star breaks if the deformations are > **20 cm**

Effect of the Equation of State (EOS) in the core

At density higher than that of nuclear matter, matter could occur in the solid state and be more deformable

Based on a model of solid quark star, Owen estimated:

$$\epsilon \leq 6 \times 10^{-4} \left(\frac{u_{break}}{10^{-2}} \right) \quad (Owen,\ PRL\ 2005)$$

If instead the quarks are in a superconducting phase of color

$$\epsilon \leq 10^{-3} \left(\frac{u_{break}}{10^{-2}} \right) \quad (Haskell\ et\ al,\ PRL\ 2007)$$

Effect of the magnetic field

The internal magnetic field induces deformation in the star.
If the core is composed of a fluid

$$\epsilon \sim 10^{-12} \left(\frac{B}{10^{12} G} \right)^2$$

(Haskell et al, MNRAS 2008)
(Colaiuda, Ferrari, Gualtieri, MNRAS 2008)
(Lander,Jones, MNRAS 2009)

A superconducting core (II) would produce higher asymmetries

$$\epsilon \sim 10^{-9} \left(\frac{B}{10^{12} G} \right) \left(\frac{H_{crit}}{10^{15} G} \right)$$

(Cutler, PRD 2002, Akgun, Wasserman, MNRAS 2008)

Effect of the magnetic field

In the early stages of the star the internal magnetic field could be much more intense than that observed today, and have strong toroidal components, confined in a toroidal region (twisted torus configurations)

$$\epsilon \lesssim k \left(\frac{B[G]}{10^{16}} \right)^2 \cdot 10^{-4}$$

Ciolfi, Ferrari, Gualtieri, MNRAS (2009)

Ciolfi, Ferrari, Gualtieri, (2010)

K ~ (5-10) depending on the compactness of the star.

For magnetic initial fields strong enough the star could be a source of intense gravitational waves

axisymmetric shape: GWs in case of misalignement of the rotation and the symmetry axes of an angle α called wobble angle. Hyp. rotation axis directed along x_3 (i.e. ≈ the angular momentum **J**) → star motion with the superposition of two rotations at frequency *Ω* (along ≈ **J** **inertial precession frequency**) and one about the symmetry axis, with angular velocity $\boldsymbol{\omega_{prec} = (I_{33} - I_{22})/I_{33}\, \Omega \cos \alpha}$

free precession frequency. Being $(I_{33} - I_{22})/I_{33} \approx 1$ → $\omega_{prec} << \Omega$. In this case the gravitational wave signal is (Zimmermann & Szedenits 1979 *PR*D **20** 351[2]) :

$$h_+ = h_0 \sin\alpha \left[\frac{1}{2}\cos\alpha \sin i \cos i \,\mathbf{\cos \Omega}\left(t - \frac{r}{c}\right) - \sin\alpha \,\frac{1+\cos^2 i}{2}\,\mathbf{\cos 2\Omega}\left(t - \frac{r}{c}\right)\right]$$

$$h_\times = h_0 \sin\alpha \left[\frac{1}{2}\cos\alpha \sin i \cos i \,\mathbf{\sin \Omega}\left(t - \frac{r}{c}\right) - \sin\alpha \cos i \,\mathbf{\cos 2\Omega}\left(t - \frac{r}{c}\right)\right]$$

Thus, for an axisymmetric freely precessing body GW emission has two harmonic components: one at the rotation angular frequency *Ω* and one at **twice** the rotation angular frequency.

Thus, the wave amplitude depends on the moment of inertia, *I*, with respect to the rotation axis and on the ***quadrupole ellipticity*** ε_Q, which is a measure of the entire stellar bulk deformation.

Provided that the star distortion is small in the weak field limit ε_Q can be written in terms of the inertia tensor

$$\varepsilon_Q = (I_{11} - I_{22})/I_{33}.$$

Theoretical studies on the moment of inertia of NSs have been performed in several papers [Bejger et al. 2005 *MNRAS* **364** 635 4, Benhar et al 2005 *PR*D **72** 044028 5]; these studies use a large set of equations of state (EOS) proposed to describe NS matter at supranuclear densities, and show that

$$I \approx [1\text{–}3] \times 10^{38} \text{ kg m}^2$$

depending on the EOS and on the rotation rate.

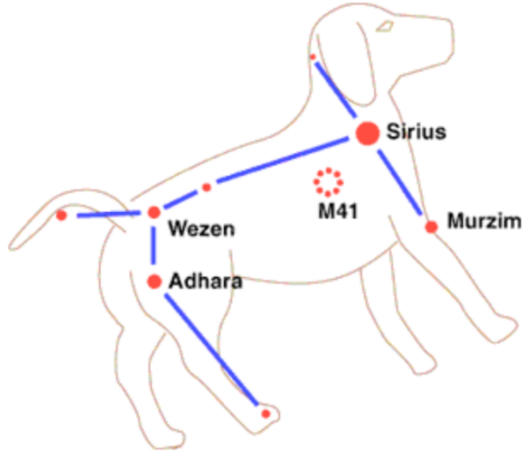
The most recently completed analysis involved a search of 840 hours of data from 66 days of the S5 LIGO run. The estimated sensitivity shows that in **the 125 Hz to 225 Hz band, more than 90% of sources with dimensionless gravitational wave strain tensor amplitude greater than $3x10^{-24}$ would have been detected.**

Power Flux search. A search of the whole S5 data set using the PowerFlux method has recently been completed An all sky search was performed with this method in the frequency band from 50Hz to 800Hz **The 95% confidence upper limits on h_o for the most favorable circular polarization ranged from**

$4x10^{-25}$ to $0.2x10^{-23}$

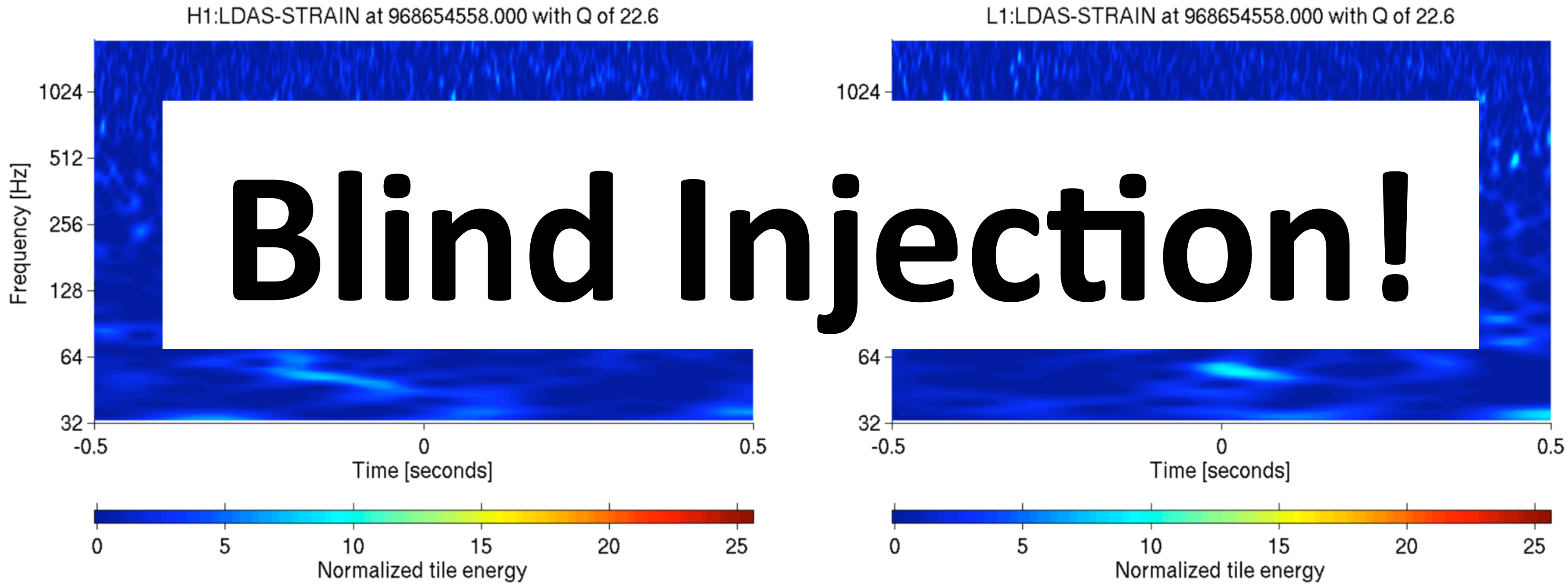
The upper limits obtained with searches for periodic GW begin to be astrophysically interesting by imposing non-trivial constraints on the structure and evolution of the neutron stars.

The Big Dog Event:



- September 16, 2010, close to midnight PDT.
- Strong H1-L1-V1 coincidence event. Source located.
- Triggered external observatories including Swift, ROTSE and the Palomar transient factory.
- Parameter estimation: low-mass BH-BH or BH-NS binary.
- Prepared paper draft, checked all instrumental issues, carefully evaluated false alarm probability to 1/7000 years.

H1 **http://ligo.org/science/GW100916/** L1



Blind Injection!

Targeted searches

Targeted search using LIGO S5 data. The search involved 116 known millisecond and young pulsars The pulsars included the Crab pulsar for which a sensitivity was reached below the spin down limit. The **spin down limit** was also reached for **the X-ray pulsar J0537-6910** under the assumption that any gravitational wave signal from it stayed phase locked to the X-ray pulses over timing glitches.

Targeted search ***only*** *using VIRGO VSR2 data for the* ***Vela pulsar***. The spin down limit was beaten This was possible because of the better sensitivity of the Virgo detector at low frequencies.

Directed searches

A search was performed for continuous gravitational radiation from the neutron star in the supernova remnant **Cassiopeia A** The search coherently analyzed 12 days of S5 data Confidence limits (95%) **of 0.7-1.2x10^{-24}** on amplitude h_o were imposed . Also, limits were imposed on the amplitude of the r-modes of the neutron stars.

Wide-parameter searches

Einstein@Home search. The Einstein@Home project carries out wide-parameter searches for periodic gravitational signals but not useful signal detected.

Known pulsar GW search history

- The 90s:
  - 1993 – Niebauer et al [*PRD*, **47**, 1993] searched for GWs from a possible NS remnant of SN1987A using Garching 30m interferometer (100 hrs of data from 1989; searching around 2 and 4kHz): $\boldsymbol{h_0 < 9 \times 10^{-21}}$
  - 1986-1995 – Tokyo group Crab pulsar search using torsion-type antenna Owa *et al* [1986mgm..conf..571O, 1988egp..conf..397O] using cooled (4.2K) 74 kg antenna, Suzuki [1995gwe..conf..115S] using cooled (4.2K) 1200kg antenna: $\boldsymbol{h_0 < 2 \times 10^{-22}}$ **(~140 times > spin-down limit)**
  - 2008 – CLIO search for GWs from Vela [Akutsu *et al*, *CQG*, **25**, 2008]: $h_0 < 5.3 \times 10^{-20}$ at 99.4% CL
  - 2010 – Tokyo proto-type low-frequency mag-lev torsional bar antenna search for slowest pulsar (PSR J2144-3933 at $f_{\rm rot} \sim 0.1$ Hz) [Ishidoshiro, *PhD thesis*, University of Tokyo]: $h_0 < 8.4 \times 10^{-10}$ (Bayesian 95% UL with 10% calibration errors)
  - Various narrow-band all-sky, and galactic centre, *blind* searches have been performed using **EXPLORER and AURIGA** bar detectors

[PRD 65 (2002) 022001, CQ 20 (2003) S665-S676]

The 2000s
Tama, CLIO,Auriga,S1-S2-S3-S4 , WSR1,WSR10,VSR1.

Recent results of searches in the LIGO and Virgo data:

- ***targeted searches*** - searches for GW from known pulsars,
- ***directed searches*** - position in the sky is known
- ***wide-parameter* searches** - unknown sky position, frequency, distance, and polarization.

Known pulsar GW search history

- Searches for GWs from pulsars did not begin with LIGO and VIRGO:
  - Looking for GWs from the **Crab pulsar** (optical pulsations at ~30Hz discovered in 1969 [Cocke et al, Nature, 221, Feb 1969]):
    - 1972 – Levine and Stebbins (PRD, **6**, 1972) [National Bureau of Standards and JILA] used a 30m laser interferometer (single arm Fabry-Perot cavity)
    - 1978 – Hirakawa *et al* (PRD, **17**, 1978 and PRD, **20**, 1979) [Tokyo] searched for the Crab - specially designed ~1000kg aluminium quadrupole antenna with resonant frequency at 60.2 Hz
    - 1983 – Hereld [PhD thesis] at Caltech using 40 m interferometer
    - 1983 – Hough *et al* [Nature, **303**, 1983] at Glasgow using split bar detector