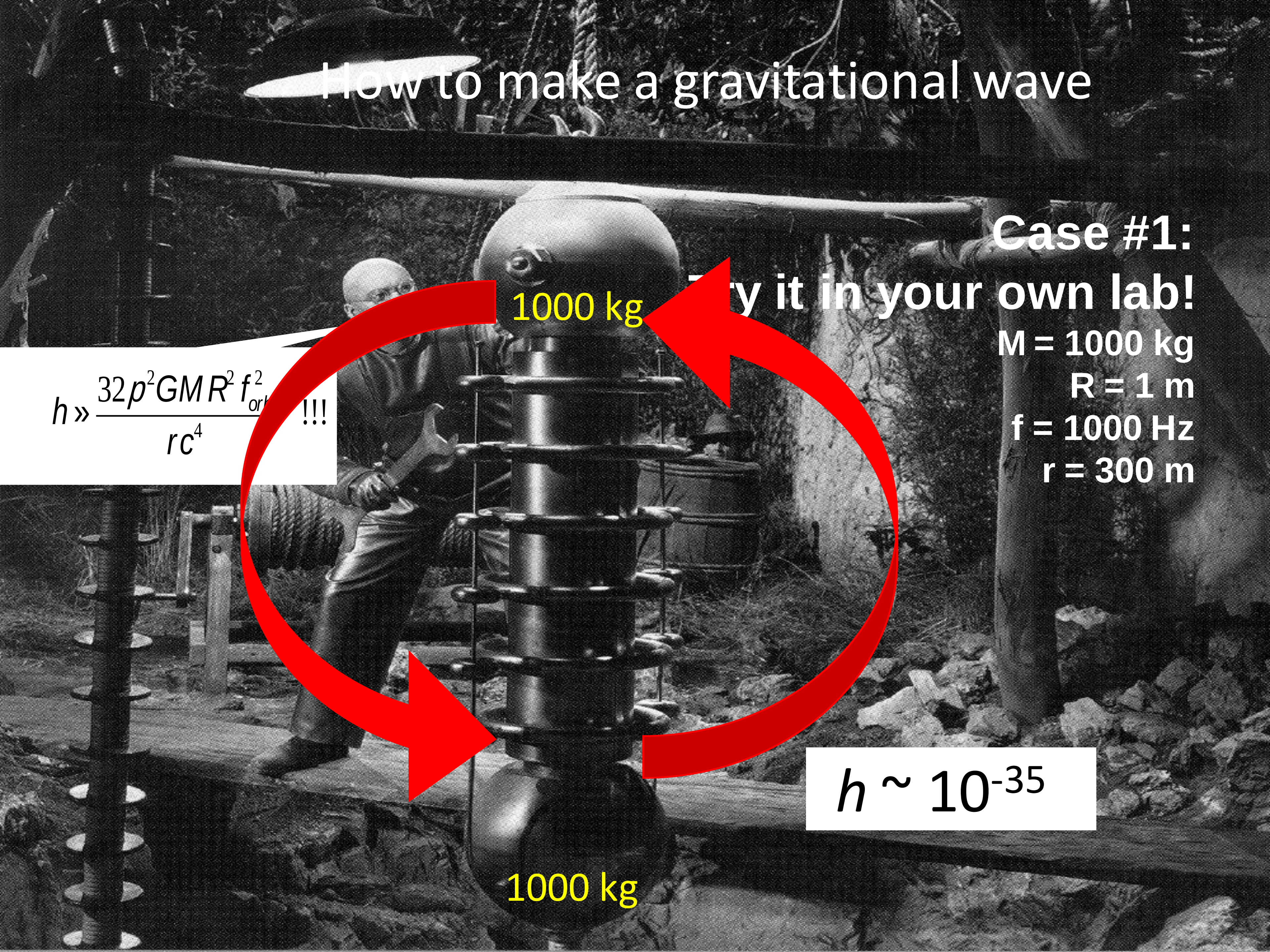
Advanced LIGO and Virgo projects

Andrzej Królak

on behalf of the Polish Consortium of the Virgo project

How to make a gravitational wave



Case #1:

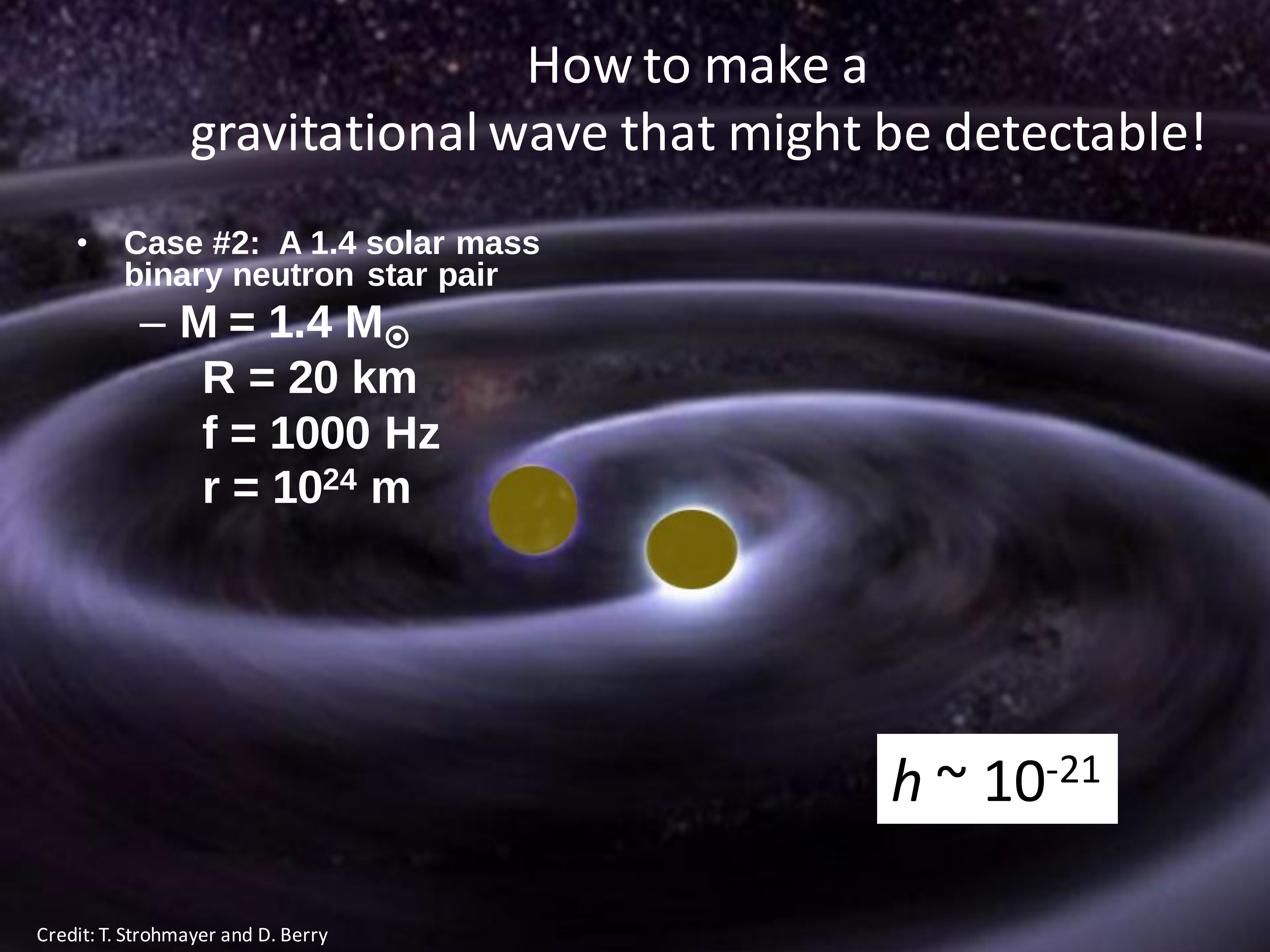
Try it in your own lab!

M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m

$$h \approx \frac{32\pi^2 G M R^2 f_{orb}^2}{r c^4} \quad !!!$$

$$h \sim 10^{-35}$$

How to make a gravitational wave that might be detectable!



- **Case #2: A 1.4 solar mass binary neutron star pair**
  - **$M = 1.4\ M_\odot$**
    $R = 20$ km
    $f = 1000$ Hz
    $r = 10^{24}$ m

$h \sim 10^{-21}$

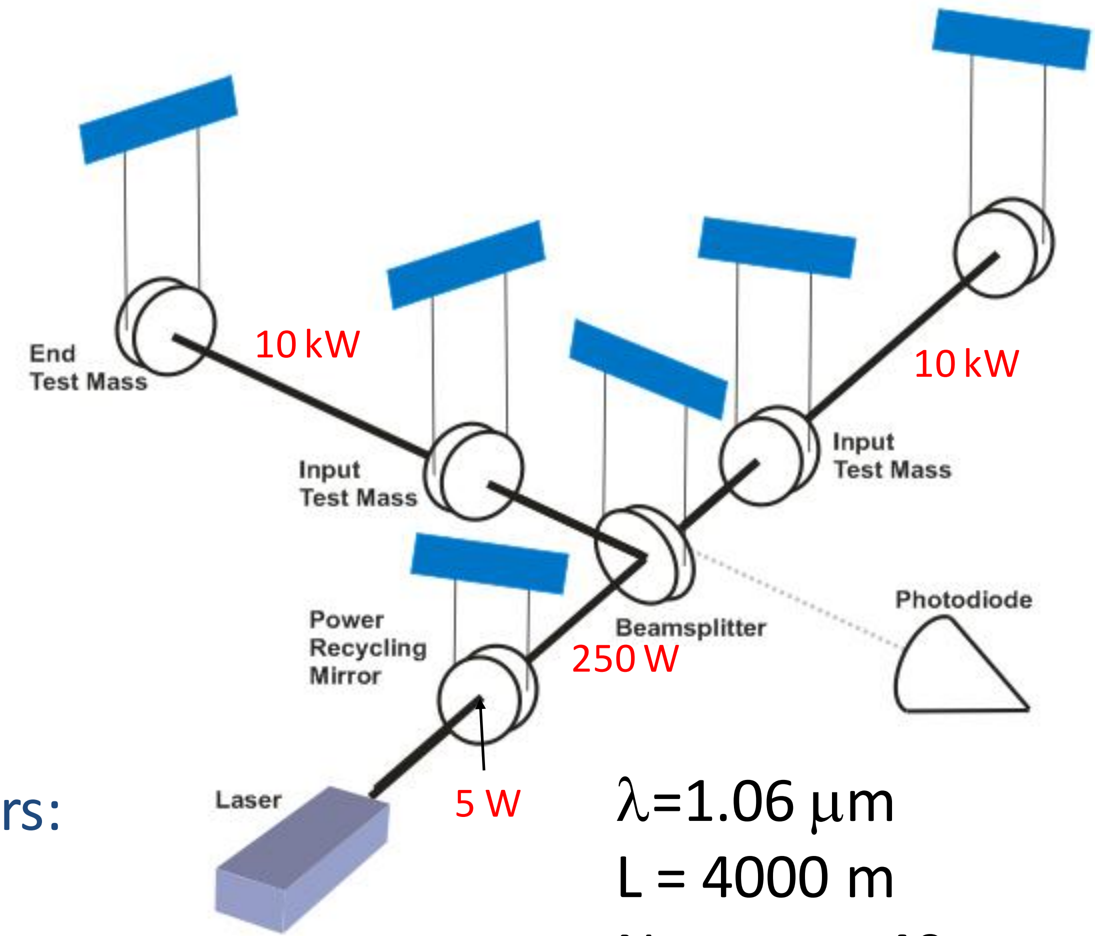
Credit: T. Strohmayer and D. Berry

Precision Interferometry a la LIGO and Virgo

$$h \sim \frac{\lambda}{L}$$

$$\times \frac{1}{N_{roundtrip}}$$

$$\times \sqrt{\frac{1}{\dot{N}_{photon}\tau_{storage}}}$$



λ=1.06 μm

L = 4000 m

$N_{roundtrip}$ = 40

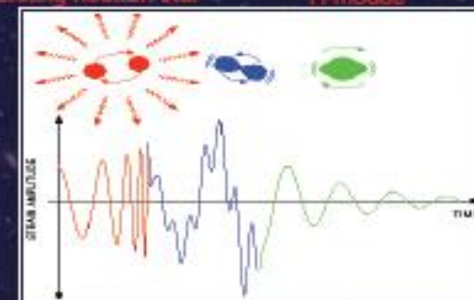
Putting in numbers:

$$h \sim 10^{-21}$$

Astrophysical sources of gravitational waves

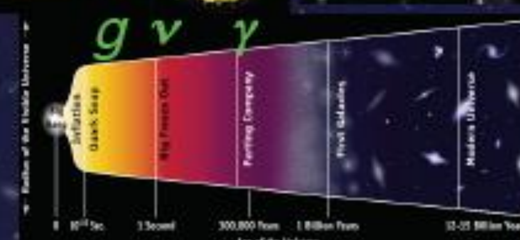
- Periodic sources
  - Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries

- Coalescing compact binaries
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW
  - waveforms



- Burst events
  - e.g. Supernovae with asymmetric collapse

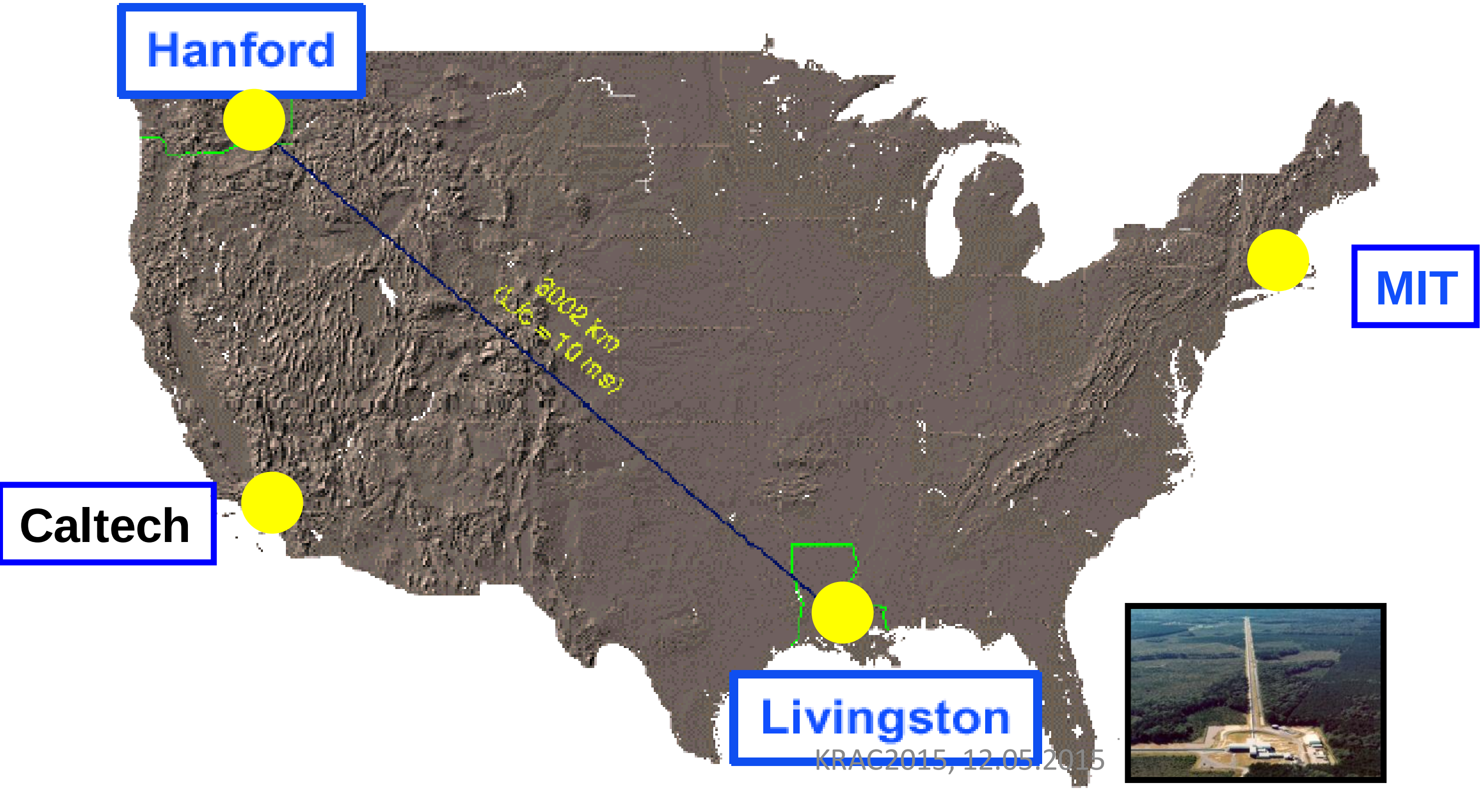
- Stochastic background
  - Primordial Big Bang ($t = 10^{-22}$ sec)
  - Continuum of sources
- *The Unexpected !*



LIGO - G070036-00-M

LIGO Laboratory

- Mission: Observe gravitational wave sources; operate the LIGO facilities; develop the instrument science and technology; scientific education and public outreach.
- NSF Major Research Facilities Construction LIGO grant in 1992 and in 2008; cooperative agreements since 1992, jointly managed by Caltech and MIT; develop the instrument science and technology; education and public outreach.
- ~200 scientists, engineer and staff; includes physicists working on instrument science and data analysis.

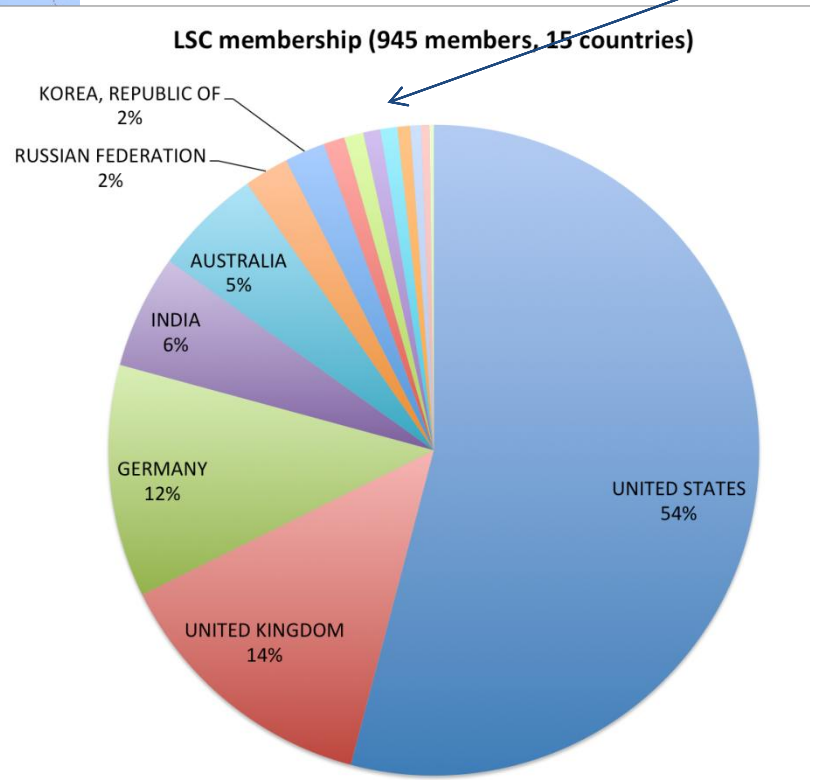


Advanced LIGO Fact Sheet

- **Funded by NSF in April 2008**
- **Cost of the upgrade: $205M (NSF) and $30M from partners in Germany (Max Planck Albert Einstein Institute), UK (STFC), and Australia (ARC)**
  - Cost comparison: 1 Advanced LIGO = 0.03 Large Hadron Colliders
- **Design goals:**
  - Complete upgrade of three LIGO interferometers
  - Sensitivity to binary neutron star inspirals to 200 MPc*
    - 10X the range of initial LIGO, 1000X the volume (and event rate)
- **Planned 7 year construction phase scheduled for completion in March 2015**
- **Current Status: Advanced LIGO Project FINISHED as of March 31!**
  - *LIGO Livingston interferometer*: completed installation in April 2014, first lock in May, currently being commissioned
  - *LIGO Hanford interferometer*: completed installation in September 2014, first lock in December, currently being commissioned
  - *Third interferometer*: components assembled and in storage for future installation in LIGO-India

*the 'average' distance to which an interferometer can detect a 1.4-1.4 $M_{\odot}$ BNS merger with an SNR of 8 (averaged over all sky positions and orbital inclinations)

LIGO Scientific Collaboration

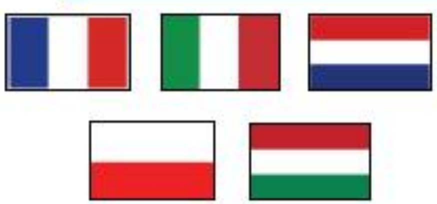


ITALY
HUNGARY
BRAZIL
SPAIN
CHINA
TAIWAN
CANADA
BELGIUM

www.ligo.org **Kraków 2010**

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

5 European countries
19 labs, ~200 authors



- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009
- Construction in progress. End of installation: fall 2015
- First science data in 2016

Polgraw-VIRGO

Institutions in Poland:

Białystok: UwB

Toruń: UMK

Warsaw: CAMK, IMPAN, NCBJ, OA UW

Wrocław: SI sp. z o.o. , UWr

Zielona Góra: WFiA UZ

Members:

7 scientists , 1 engineer, 1 PhD, 3 technicians

Main contribution:

Data analysis, electronic engineer , vacuum system

Main tasks:

Data analysis, astrophysics, organizations of meetings

Funding: 2010-2018 (grants from NCN, NCBiR and FNP)

Collaboration of LIGO Scientific Collaboration (LSC) and Virgo Collaboration

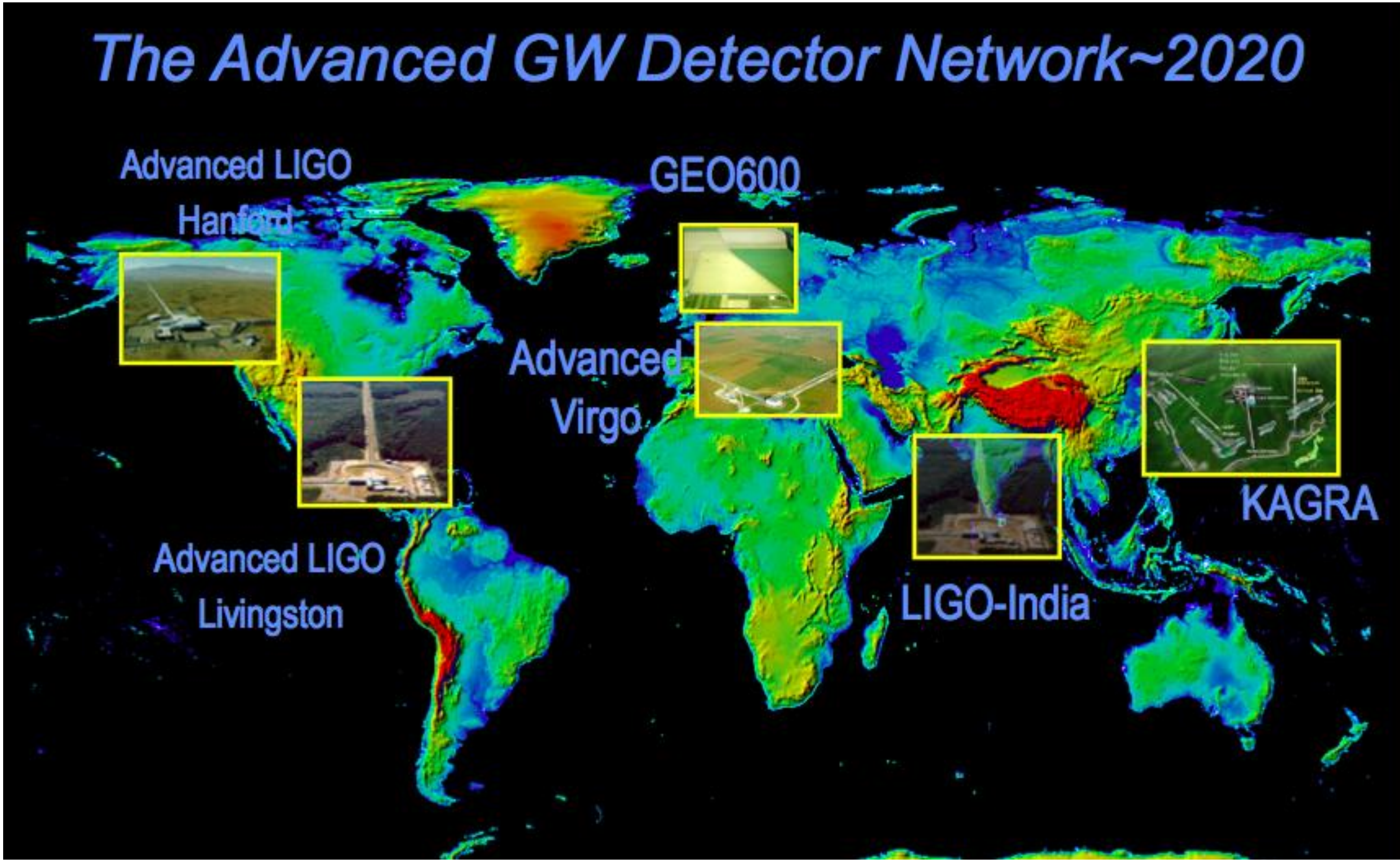
Virgo project collaborates closely with the American LIGO project.

By memorandum of understanding between the two projects all analysis of data from the Virgo and LIGO detectors is performed jointly by common data analysis groups.

All publications concerning searches of gravitational wave signals in data of the detectors are signed by all members of the collaborations.

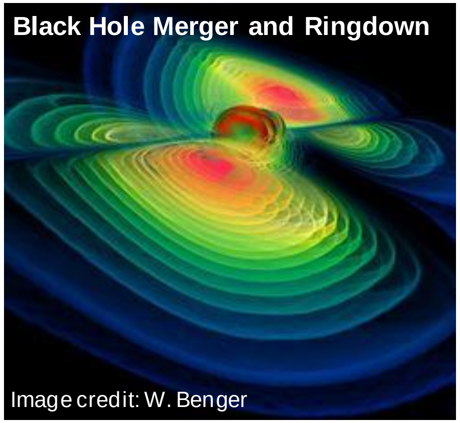
FUNCTIONS:

A.K. – Member of Virgo Steering Committee and LSC-Virgo Data Analysis Committee
A.K. - Virgo co-chair of LSC-Virgo Continuous Waves Group
Tomek Bulik – Virgo co-chair of LSC-Virgo Burst Group review committee

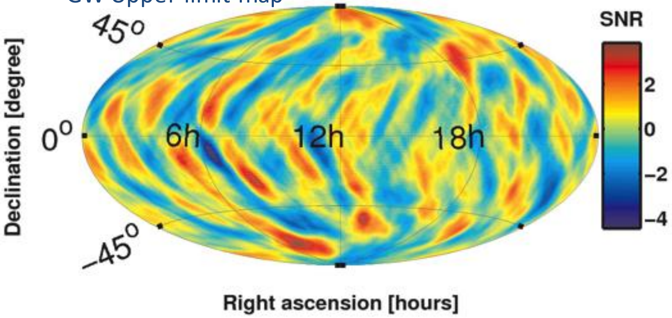

The Advanced GW Detector Network~2020
Advanced LIGO
Hanford
GEO600
Advanced
Virgo
KAGRA
Advanced LIGO
Livingston
LIGO-India

Some Questions Gravitational Waves May Be Able to Answer

- **Fundamental Physics**
  - *Is General Relativity the correct theory of gravity?*
  - *How does matter behave under extreme conditions?*
  - *What equation of state describes a neutron star?*
  - *Are black holes truly bald?*
- **Astrophysics, Astronomy, Cosmology**
  - *Do compact binary mergers cause GRBs?*
  - *What is the supernova mechanism in core-collapse of massive stars?*
  - *How many low mass black holes are there in the universe?*
  - *Do intermediate mass black holes exist?*
  - *How bumpy are neutron stars?*
  - *Is there a primordial gravitational-wave residue?*
  - *Can we observe populations of weak gravitational wave sources?*
  - *Can binary inspirals be used as “standard sirens” to measure the local Hubble parameter?*

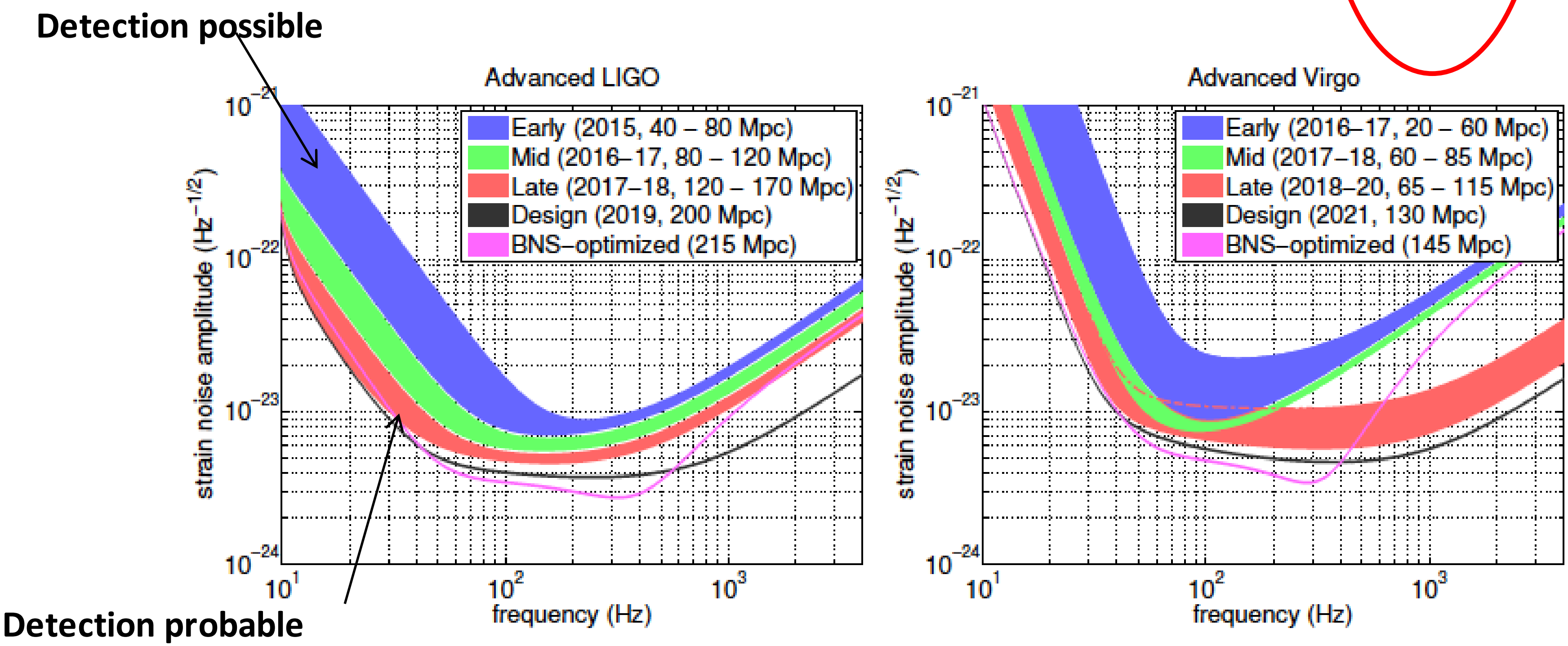


GW Upper limit map

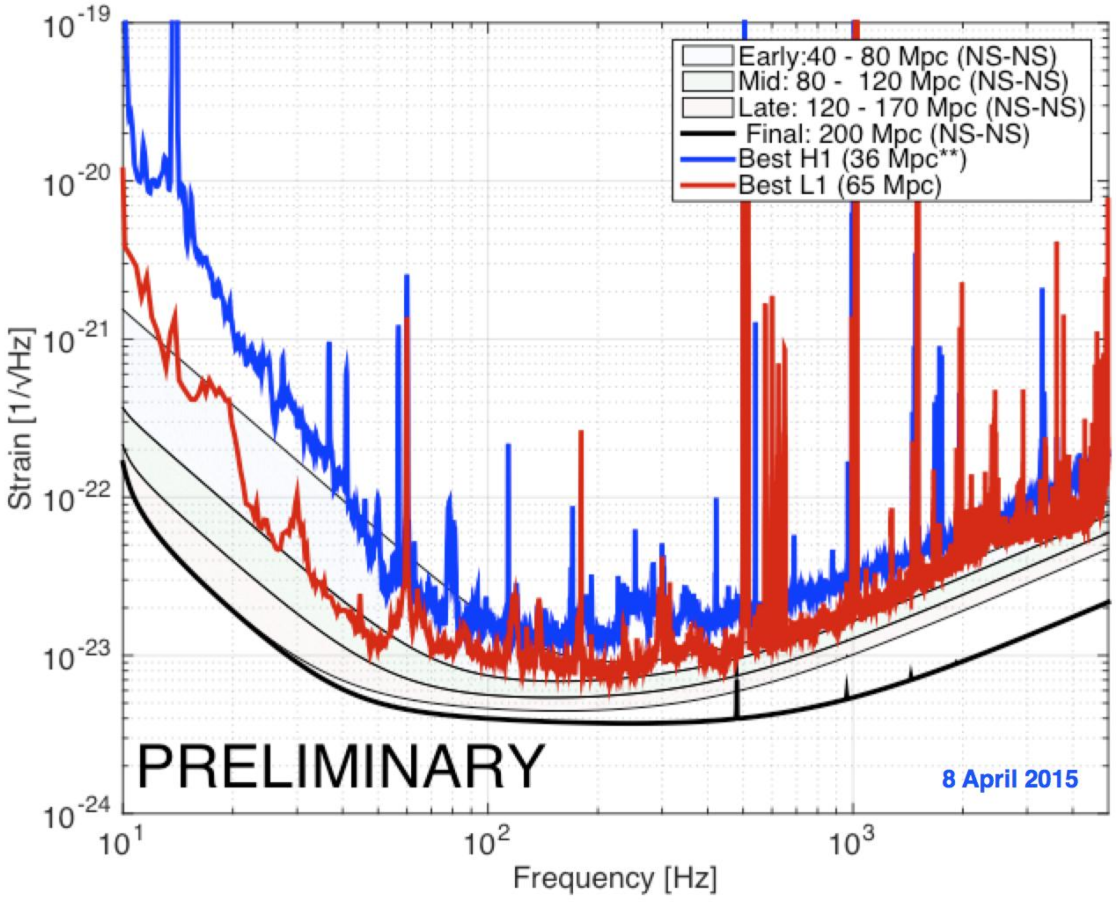


Expected sensitivity

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100

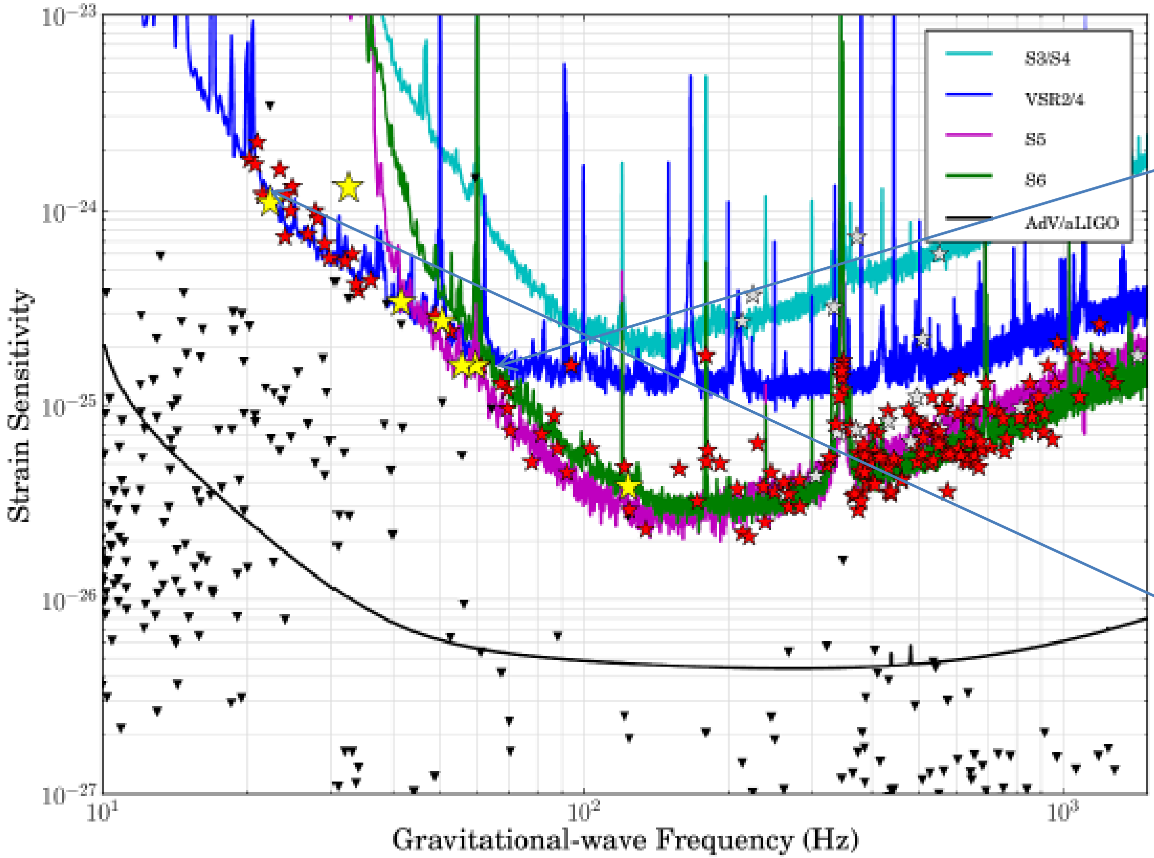


Expected sensitivity for O1 achieved!



Some astrophysical results obtained form initial LIGO and Virgo detectors so far with contribution from Polgraw-Virgo team

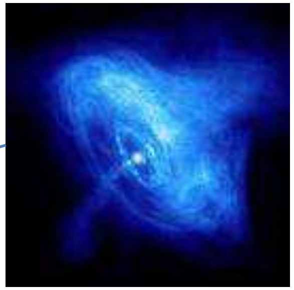
Search for GWs from known pulsars



Upper limits on the gravitational wave strain amplitude for 195 pulsars using data from the LIGO S3-S6, and Virgo VSR2 and VSR4 runs (**stars**). The **triangles** show the spin-down limits for a selection of these stars.

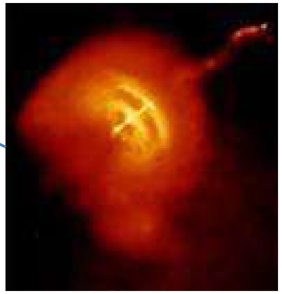
Polgraw-Virgo group participated in this analysis

CRAB



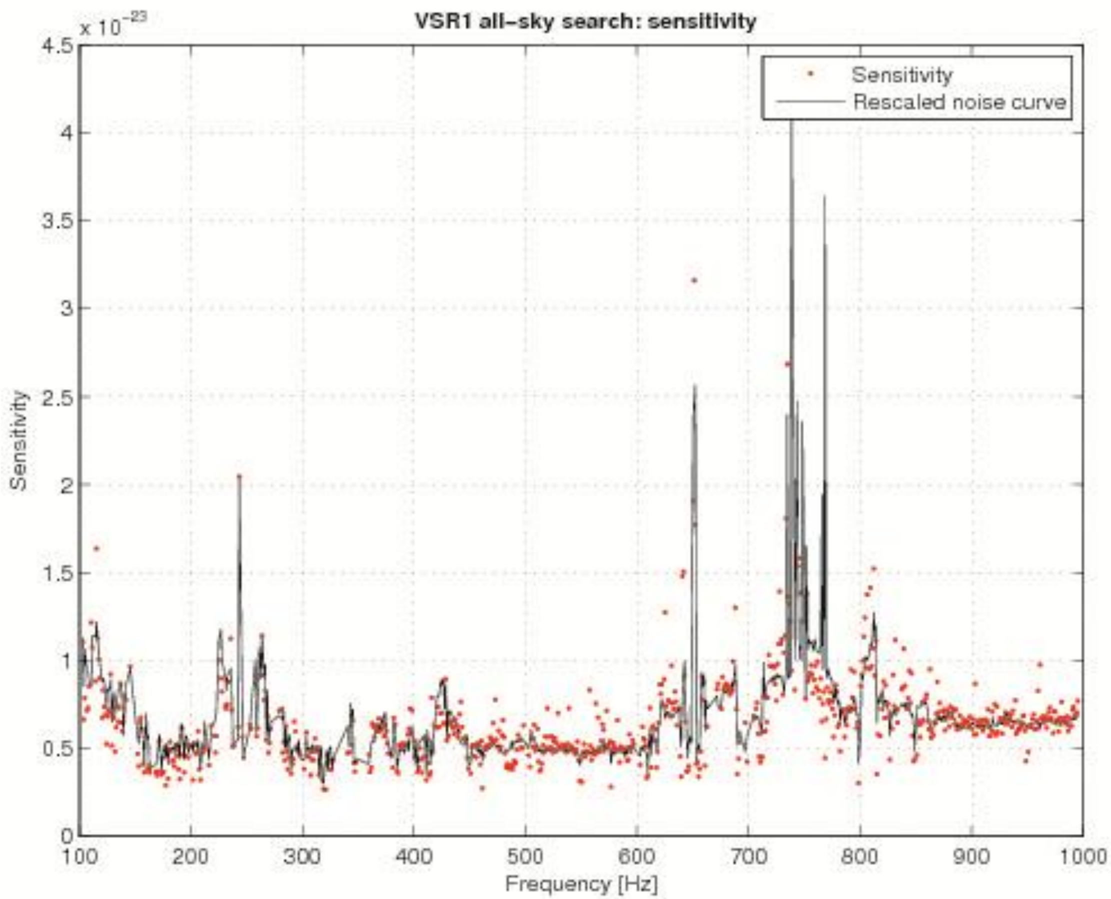
<1% of energy loss due to GW emission

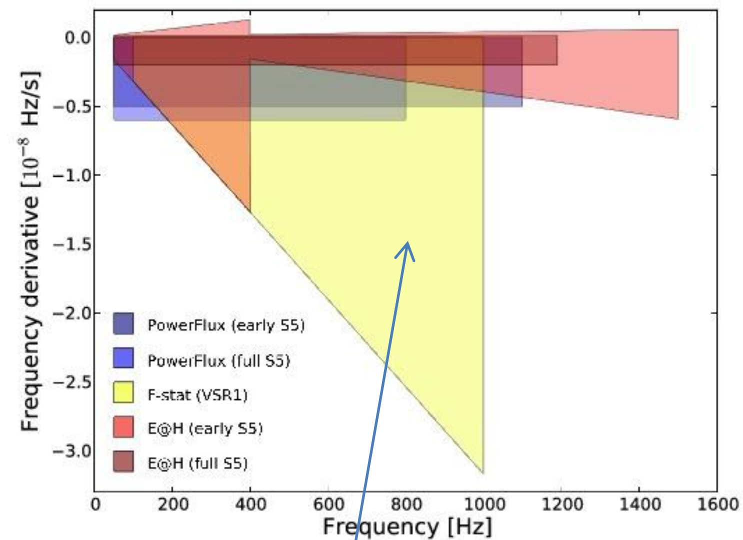
VELA



<10% of energy loss due to GW emission

All sky search of Virgo data for GWs form rotating neutron stars

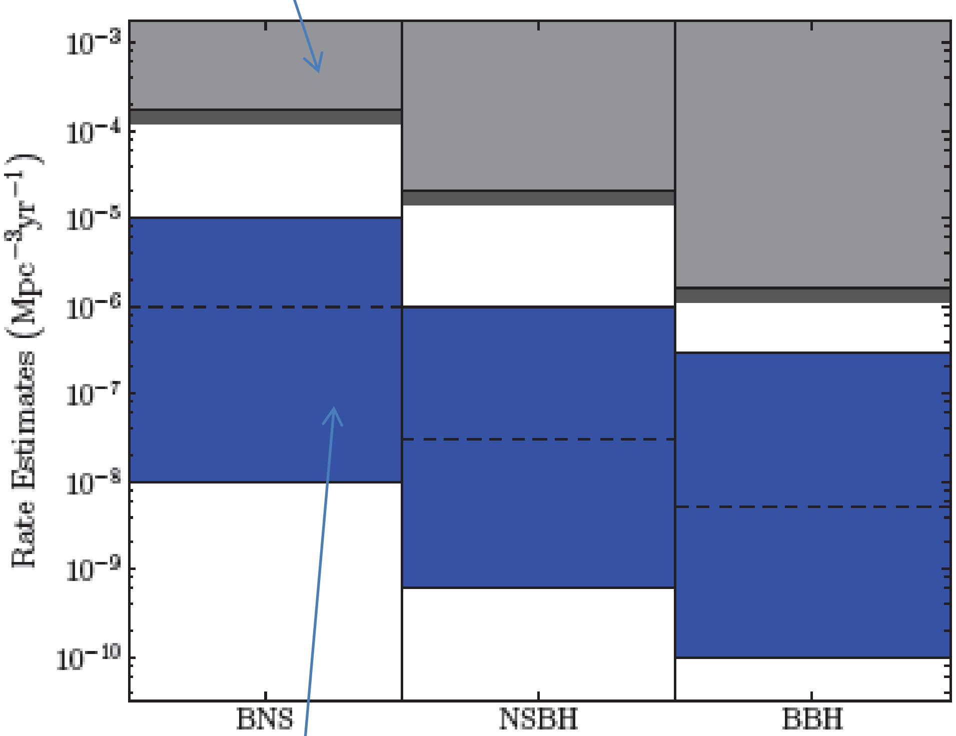




Search by members of Polgraw-Virgo group. Parameter space analyzed larger than ever before

Compact binaries upper limits (2-100 $M_\odot$ total mass search)

Observations



Predictions

$M_c = 5M_\odot$

Search of LIGO and Virgo data (2012):

$$R_O = 5.9 \times 10^{-7}\ Mpc^{-3}\ yr^{-1}$$

Bulik, Belczynski and Prestwich (2010):

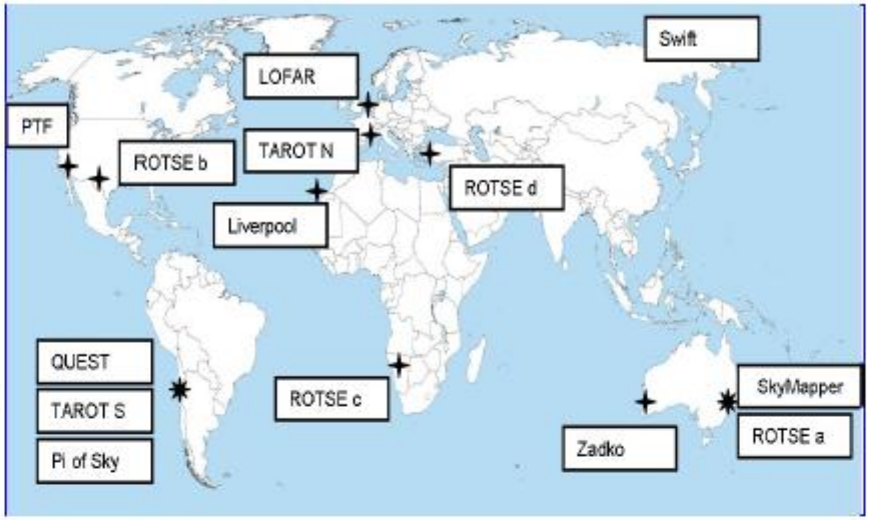
$$R_T = 3.6 \times 10^{-7}\ Mpc^{-3}\ yr^{-1}$$

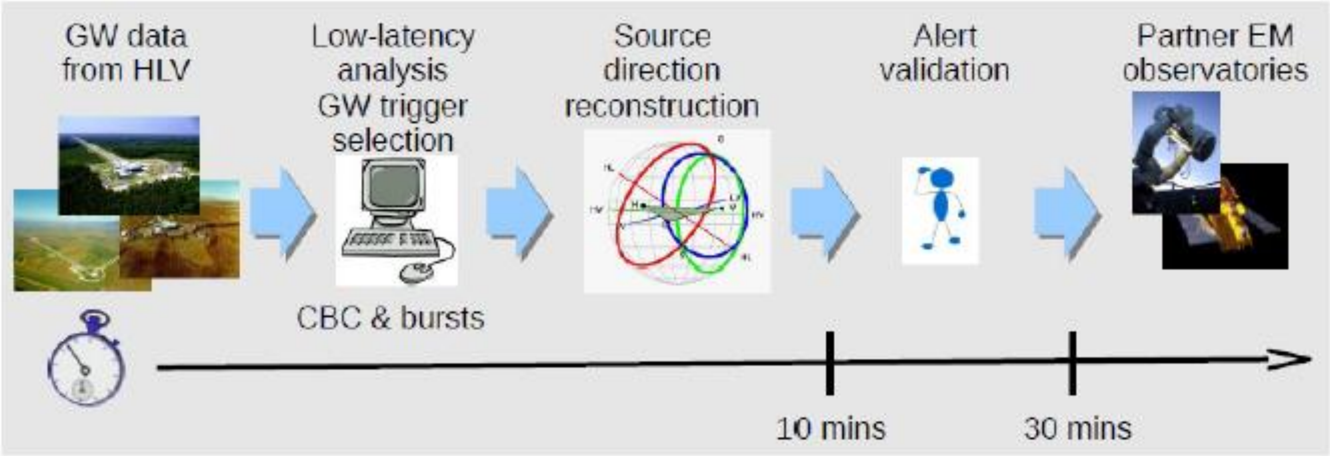
Based on evolution studies of two systems IC10 and NBC300 that should evolve to BBH of M_t :25.5 - 59 $M_\odot$

Series of papers led by Belczynski, Bulik , Dominik and PhD by Dominik point to high rate of BBH based on population synthesis

Looc-Up search

- LIGO/Virgo & rapid-pointing telescopes partnership (MOUs)
- 14 triggers sent out (FAR < ¼ d), 9 triggers followed up.
- Also Swift (one event) and LOFAR radio array (commissioning during run).
- Goal: test pipelines and gain experience





Teleskop Pi-of-the-Sky took part in the observations
Polgraw – Virgo team contributed to data analysis (PhD)

Talk by Adam Zadrożny

Searching data from advanced detectors for GW signals

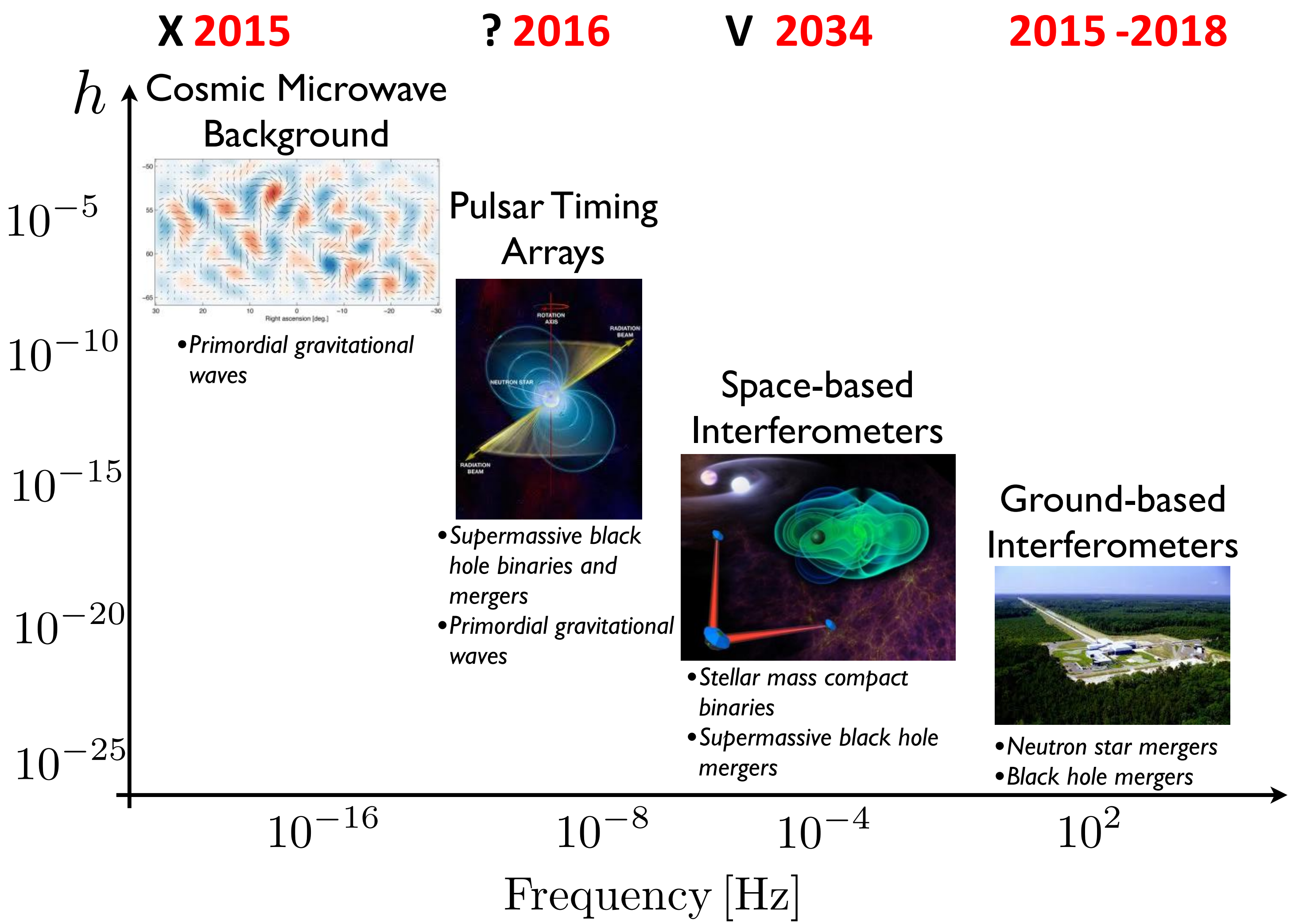
- LIGO detectors will start collecting science data 14th of September 2015 and Virgo detector in 2016.
- Data will be analyzed jointly by the members of both collaborations.
- Well defined and motivated search plans exist (https://dcc.ligo.org/LIGO-T1400054/public).
- Data analysis pipelines tested, optimized, reviewed and ready to analyzed data from day 1.
- MoAs with dozens of astronomical projects concerning joint observations signed.
- Publication templates prepared.

Concluding remarks

- Initial ground based detectors have not discovered gravitational waves. Astrophysically interesting upper bounds were imposed.
- Large experience in analysing data has been gained.
- Number of astronomical projects got involved in joint observations.
- Detection of gravitational waves by advanced detectors very probable.
- Team of scientists and engineers from Poland takes part in all aspects of the gravitational wave searches.

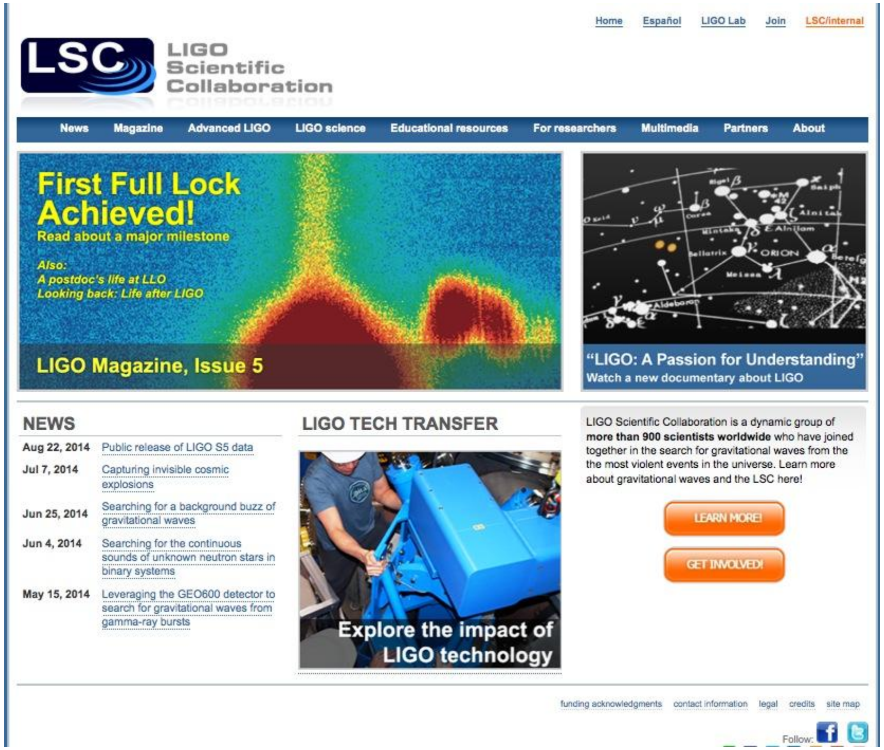
Extra slides

Metody detekcji fal grawitacyjnych



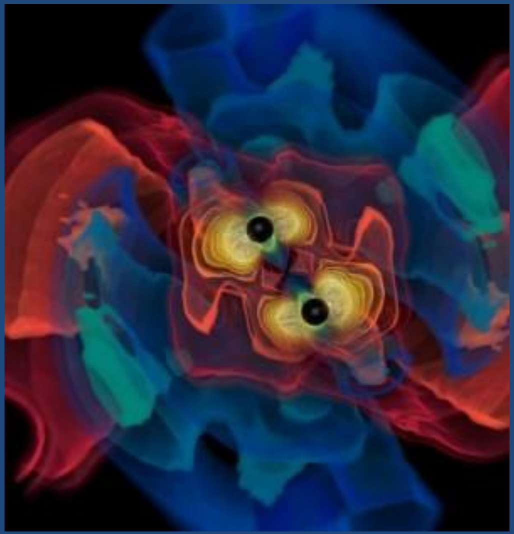
LIGO and LSC

- **The LSC and the LIGO Laboratory together make up "LIGO".**
- LSC Mission: The LIGO Scientific Collaboration (LSC) is a **self-governing collaboration** seeking to detect gravitational waves, use them to explore the fundamental physics of gravity, and develop gravitational wave observations as a tool of astronomical discovery.
- LSC Responsibilities:
  - data analysis strategy, goals, and timeline, and carry out the data analysis program;
  - identify priorities for research and development, and carry out the R&D program;
  - carry out a public outreach, and provide educational opportunities for young people;
  - disseminate the results of the data analysis program and the R&D program;
  - participate in the scientific operations of the LIGO detectors;
  - perform internal evaluation of progress in data analysis and R&D.



www.ligo.org

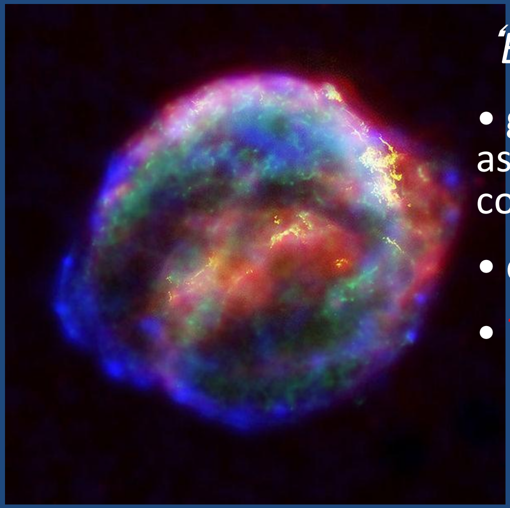
Astrophysical targets for ground-based detectors



Credit: AEI, CCT, LSU

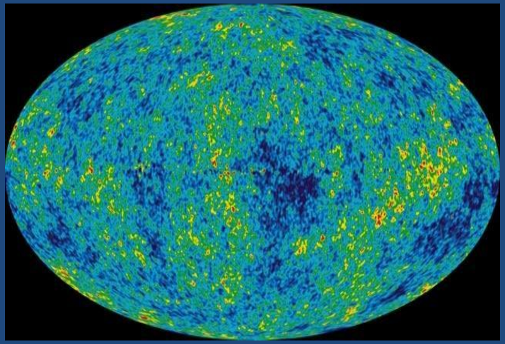
Coalescing Binary Systems

- Neutron stars, low mass black holes, and NS/BS systems



'Bursts'

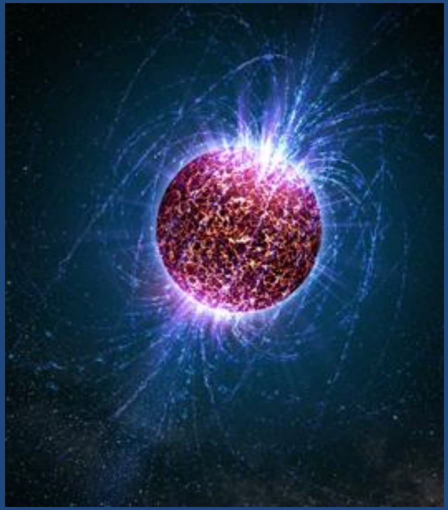
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Stochastic GWs

- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range



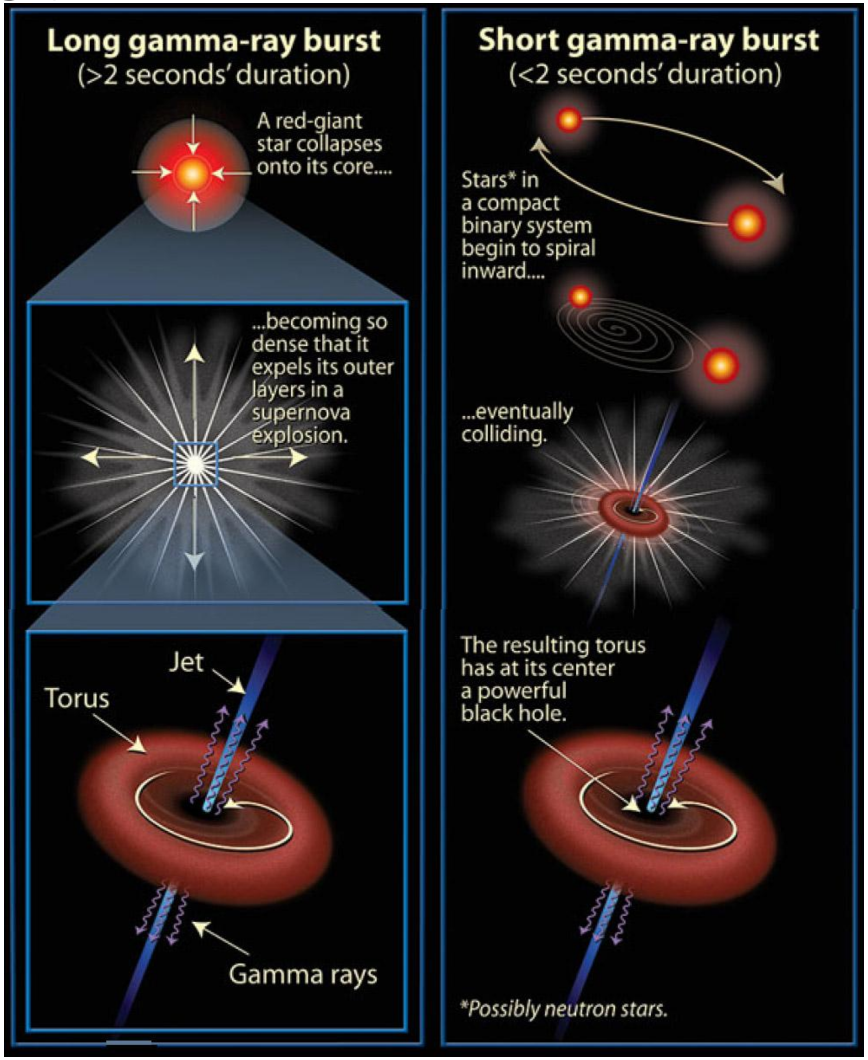
Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- probe crustal deformations, 'EOS, quarki-ness'

Do compact binary mergers produce GRBs?

- **GRBs: the *brightest electromagnetic events in the universe***
  - Tremendous energy release (> 10^{50} ergs) associated with cataclysmic events involving compact objects
- **GRB progenitor models:**
  - Long GRBs → Core-collapse supernova of a massive spinning star
  - Short GRBs → *coalescence of a binary compact (NS-NS, NS-BH) object?*
- **Long and *in particular* short GRB progenitors should radiate GWs…**
- ***… but we won't know until we simultaneously detect GRBs in EM and GW channels***



Nakar, E. 2007, Phys. Rep., 442, 166,