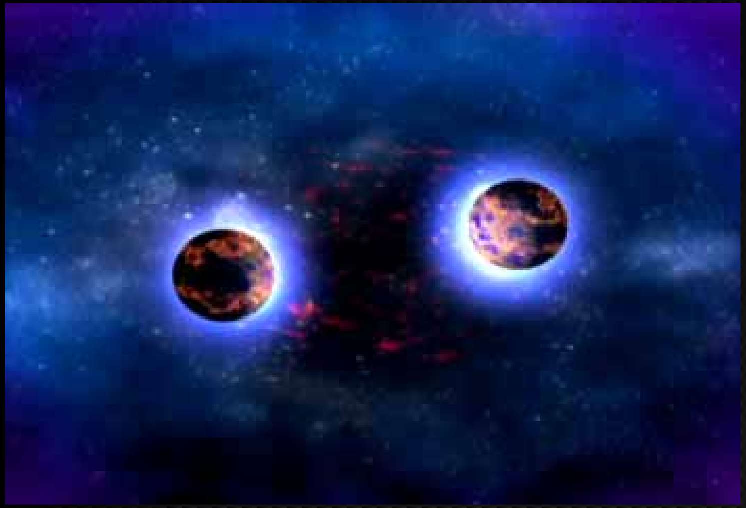
Gravitational Waves and Gamma-Ray Bursts in Multimessenger Astrophysics

LIGO-G0900996

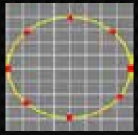
Szabolcs Márka
Columbia University in the City of New York

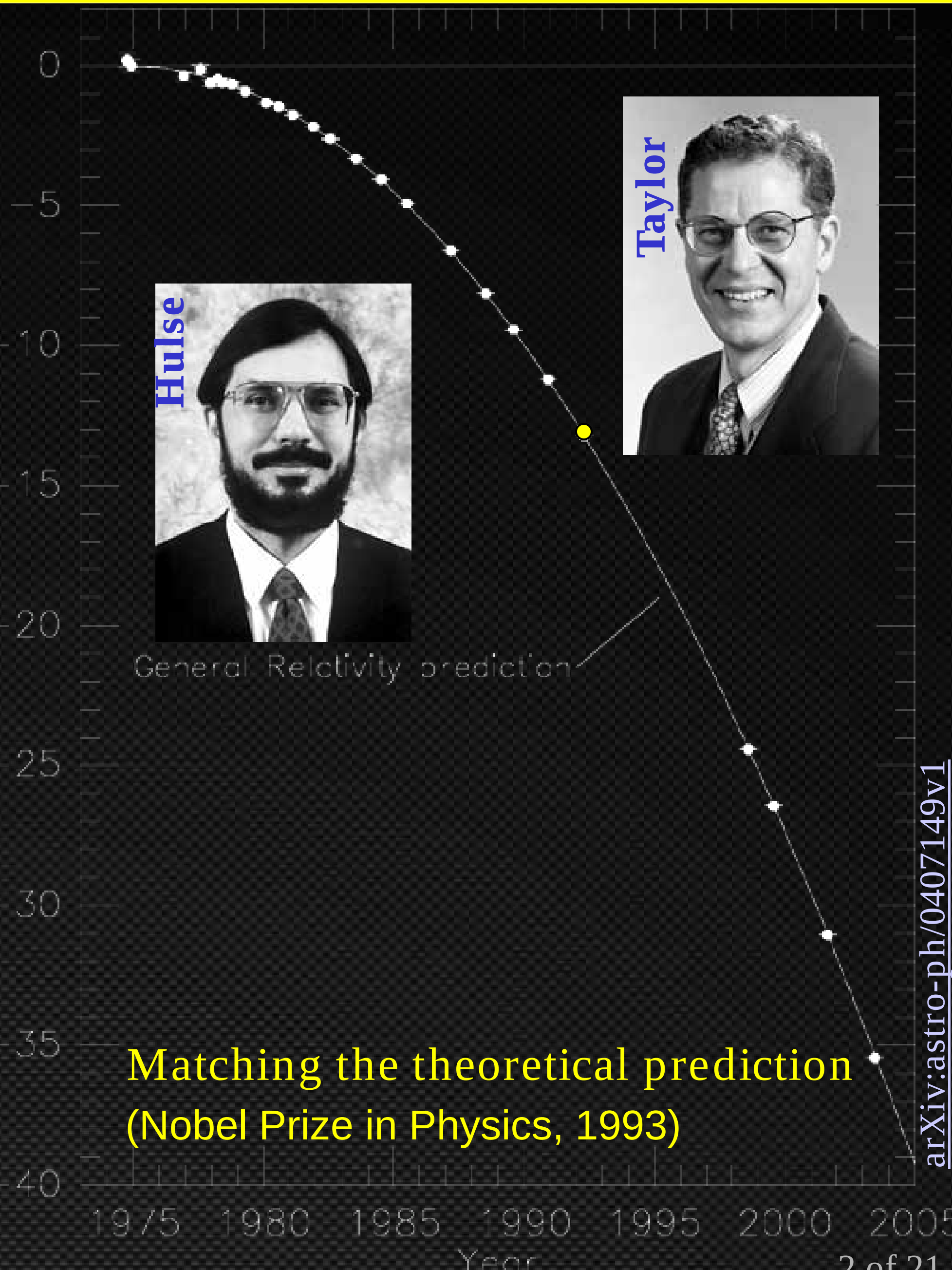
2009 Fermi Symposium, Washington DC, November, 2009

Indirect evidence of gravitational radiation



Video Credit: NASA



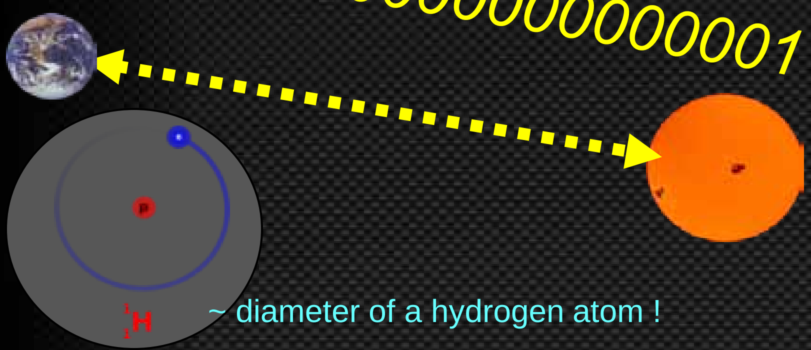


Matching the theoretical prediction

(Nobel Prize in Physics, 1993)

Typical strain at Earth: $h \sim 10^{-21}$!

0.000000000000000000001



~ diameter of a hydrogen atom !

Searches for Sources

- Transients
- Repeaters
- Continuous

e.g.

	Modeled	UnModeled	
Triggered	short GRB pulsar	SGR supernovae	Triggered
All-Sky/Time	circular inspiral eccentric encounter	stochastic bkg. BH-BH merger	All-Sky/Time

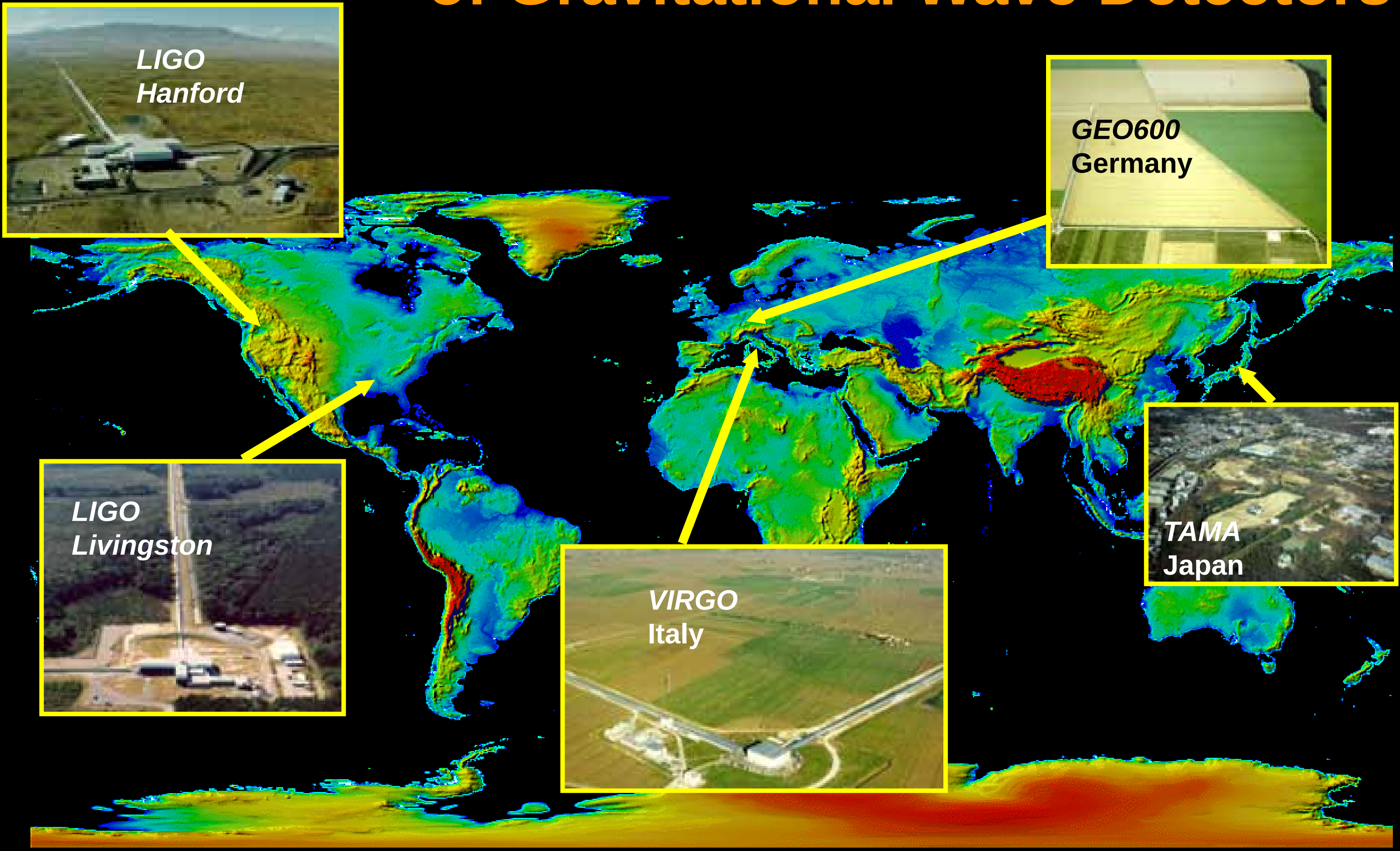
e.g., S5 publications:

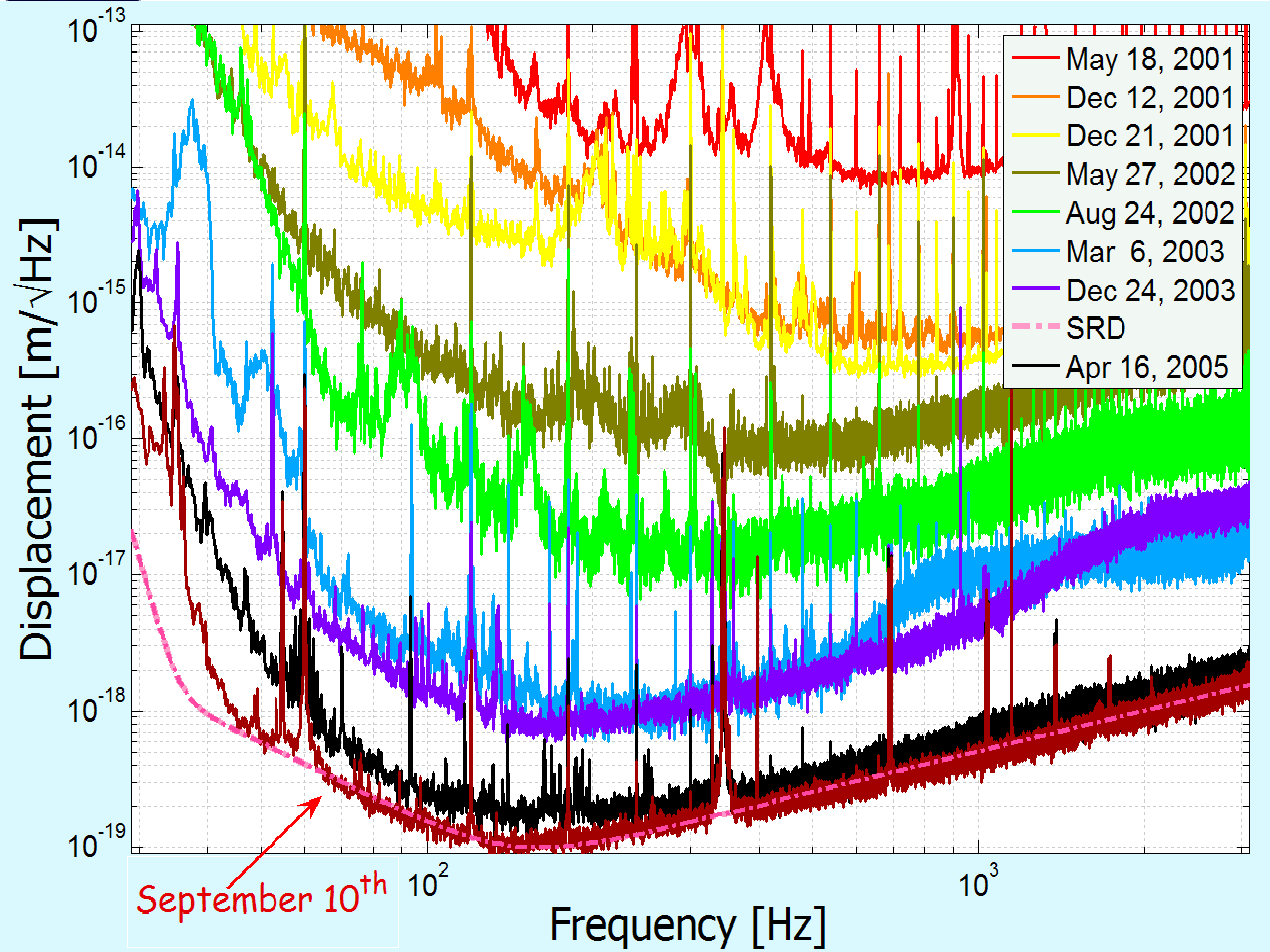
Abbott et al. (LIGO Scientific Collaboration). Implications for the Origin of GRB 070201 from LIGO Observations. ApJ, 681:1419–1430, July 2008.

LIGO Scientific Collaboration, S. Barthelmy, N. Gehrels, K. C. Hurley, and D. Palmer. Search for Gravitational Wave Bursts from Soft Gamma Repeaters. *arXiv:0808.2050*, 808, August 2008. **PRL**

Abbott et al. (LIGO Scientific Collaboration). Beating the Spin-Down Limit on Gravitational Wave Emission from the Crab Pulsar. ApJ, 683:L45–L49, August 2008.

The Global Network of Gravitational Wave Detectors





May 18, 2001
Dec 12, 2001
Dec 21, 2001
May 27, 2002
Aug 24, 2002
Mar 6, 2003
Dec 24, 2003
SRD
Apr 16, 2005
Displacement [m/√Hz]
Frequency [Hz]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{2}
10^{3}
September 10th

Multimessenger Astrophysics with GWs

» **Gamma-ray transients (GRBs, SGRs)**

» **Optical transients**

» **Neutrino events**

» **Radio transients**

» **X-ray transients**

»…

ø **Correlation in time**

ø **Correlation in direction**

ø **Information on the source properties, host galaxy, distance**

ø …

ü Confident detection of GWs.

ü Better background rejection Þ Higher sensitivity to GW signals.

ü More information about the source/engine.

ü Measurements made possible through coincident detection.

Graphics courtesy of Zsuzsa Marka

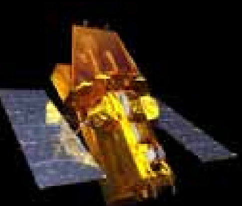
Basic Glossary: Multimessenger Approaches

"Multi-messenger astrophysics": connecting different kinds of observations of the same astrophysical event or system

"Looc-Up" strategy:

GW —— Flow of trigger information ——> **Telescopes, Satellites or other external entities**

"ExtTrig" strategy:



Telescopes, Satellites or other external entities —— Flow of trigger information ——> **GW**

Pulsars Spinning Down (5th Science Run)

- **The Crab Pulsar** *[see Abbott et al., ApJL 683, L45 for details]*
  - » Null search result implies that **< ~2%** of the spin-down energy is going into GW emission (beat spin-down amplitude limit by a factor of ~7)

- **Other known pulsars** *[see e.g., Abbott et al., PRD 76, 042001 for pulsar list]*
  - » PSR J1603–7202 : **$h_0 < 2.3 \quad 10^{-26}$**
  - » PSR J2124-3358 : **$\varepsilon < 7 \quad 10^{-8}$**

- **Theoretical context**
  - » Normal crystalline crust can have ε to be up to ~4 10^{-6} *[see e.g., Horowitz & Kadau, PRL 102, 191102]*
  - » Exotic forms of crystalline quark matter could sustain ε up to ~10^{-4} *[see e.g., Owen 2005; Lin 2007; Haskell et al 2007; Knippel & Sedrakian 2009]*

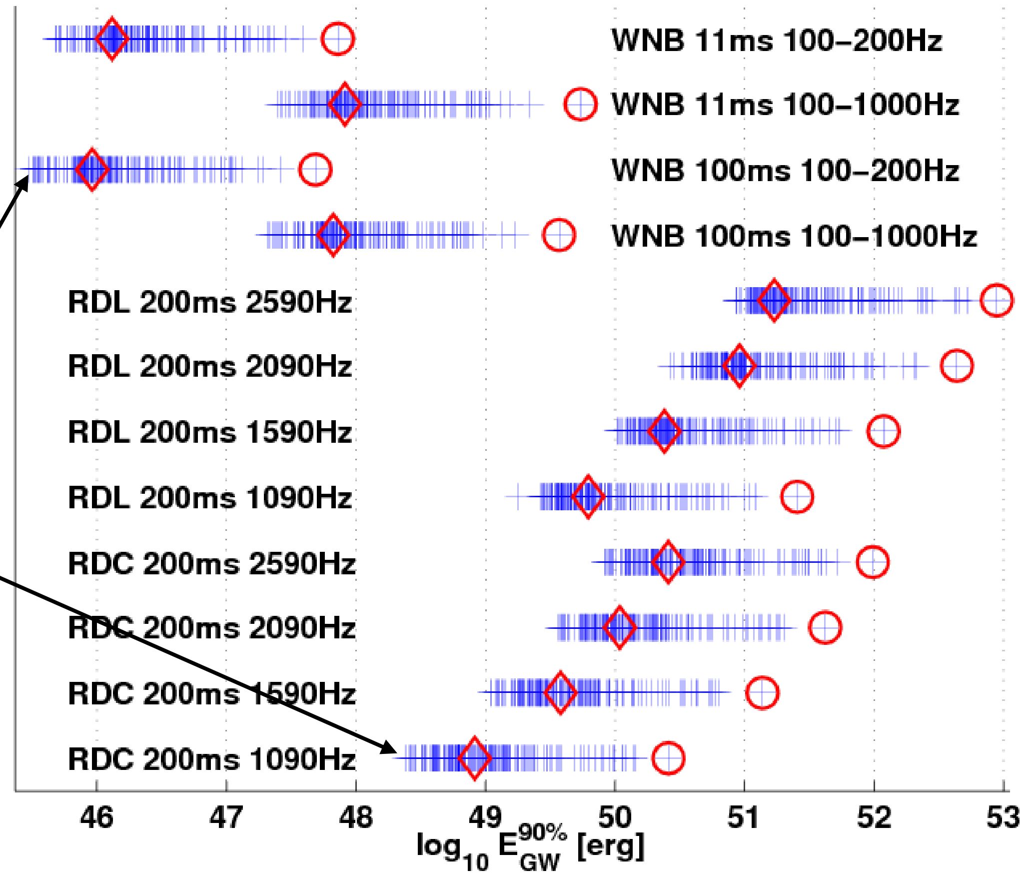
S5y1 Individual SGR Burst Search

- **PRL 101, 211102 (2008)** SUGGESTION
- **First search sensitive to NS f-modes**
- LIGO S5 + Astrowatch
- 191 SGR events including:
- largest giant flare (SGR 1806-20)
- SGR 1900+14 storm

2.9×10^{45} erg

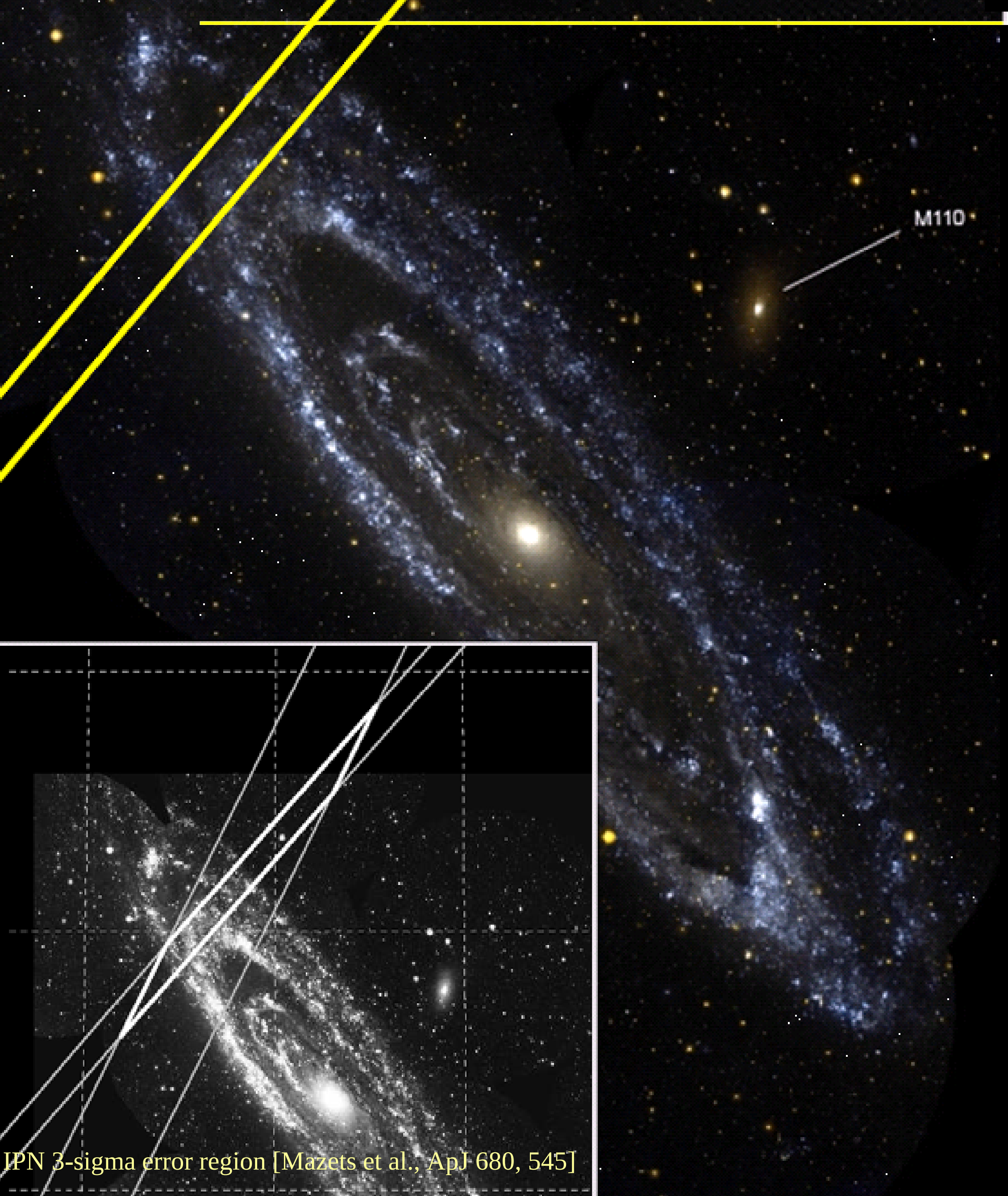
2.4×10^{48} erg

- Ioka MNRAS 327, 639 (2001)
- Most quantitative, detailed model
- E_{GW}=~10^{48} erg not unreasonable



Isotropic GW emission upper limits at 10kpc
Circles: Giant Flare
Diamonds: GRB 060806

GRB 070201 – Sky Location



IPN 3-sigma error region [Mazets et al., ApJ 680, 545]

R.A. = 11.089 deg,
Dec = 42.308 deg

$D_{M31} \approx 770$ kpc

Possible progenitors for short GRBs:

- **NS/NS or NS/BH mergers**
  Emits strong gravitational waves

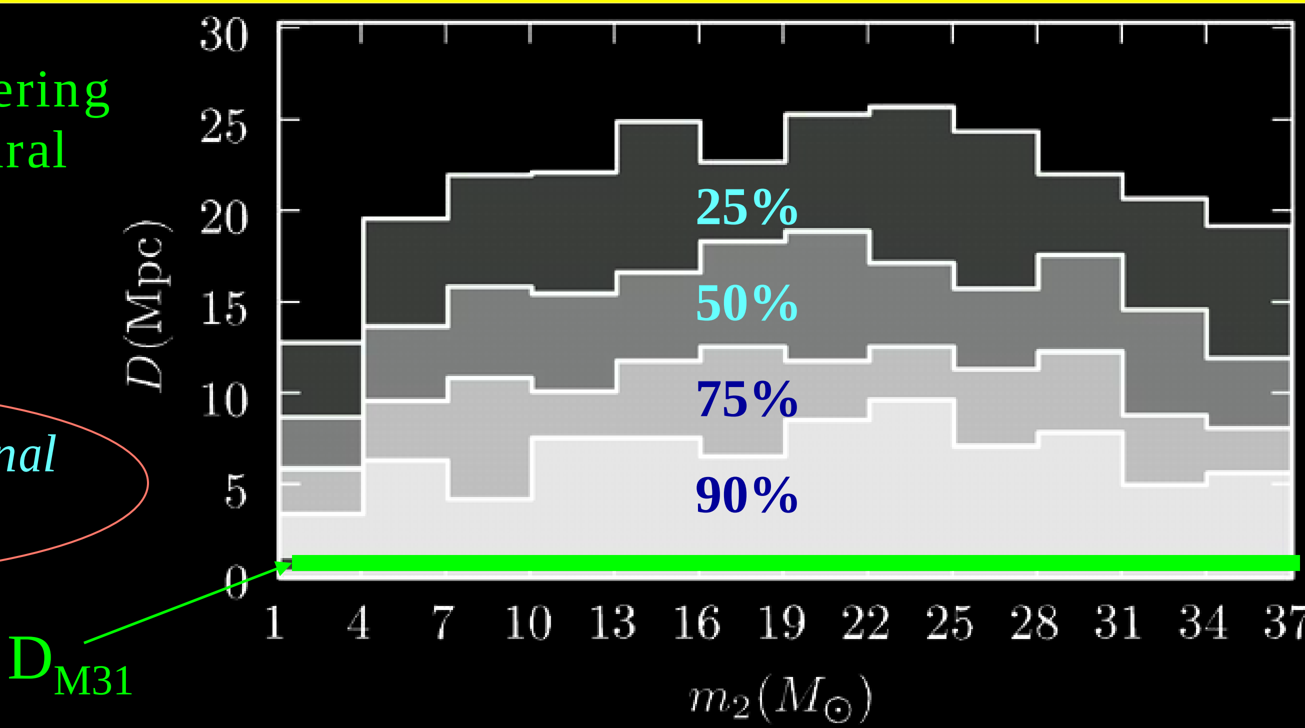
- **SGR**
  May emit GW but weaker

$E_{iso} \sim 10^{45}$ ergs
if at M31 distance
(more similar to SGR than GRB energy)

Example: Model Based Compact Binary Inspiral Search 070201

Exercise matched filtering techniques for inspiral waveform search

No plausible gravitational waves identified



Exclude compact binary progenitor with masses

$1\ M_\odot < m_1 < 3\ M_\odot$ and $1\ M_\odot < m_2 < 40\ M_\odot$ with D < 3.5 Mpc at 90% CL

Exclude any compact binary progenitor in our simulation space

at the distance of M31 at > 99% confidence level

Abbott et al. (LIGO Scientific Collaboration). Implications for the Origin of GRB 070201 from LIGO Observations. ApJ, 681:1419–1430, July 2008.

These do happen from time to time…

GRB 051103

Sky position error box overlaps with

M81 group

~3.6 Mpc

(Frederiks et al 2006)

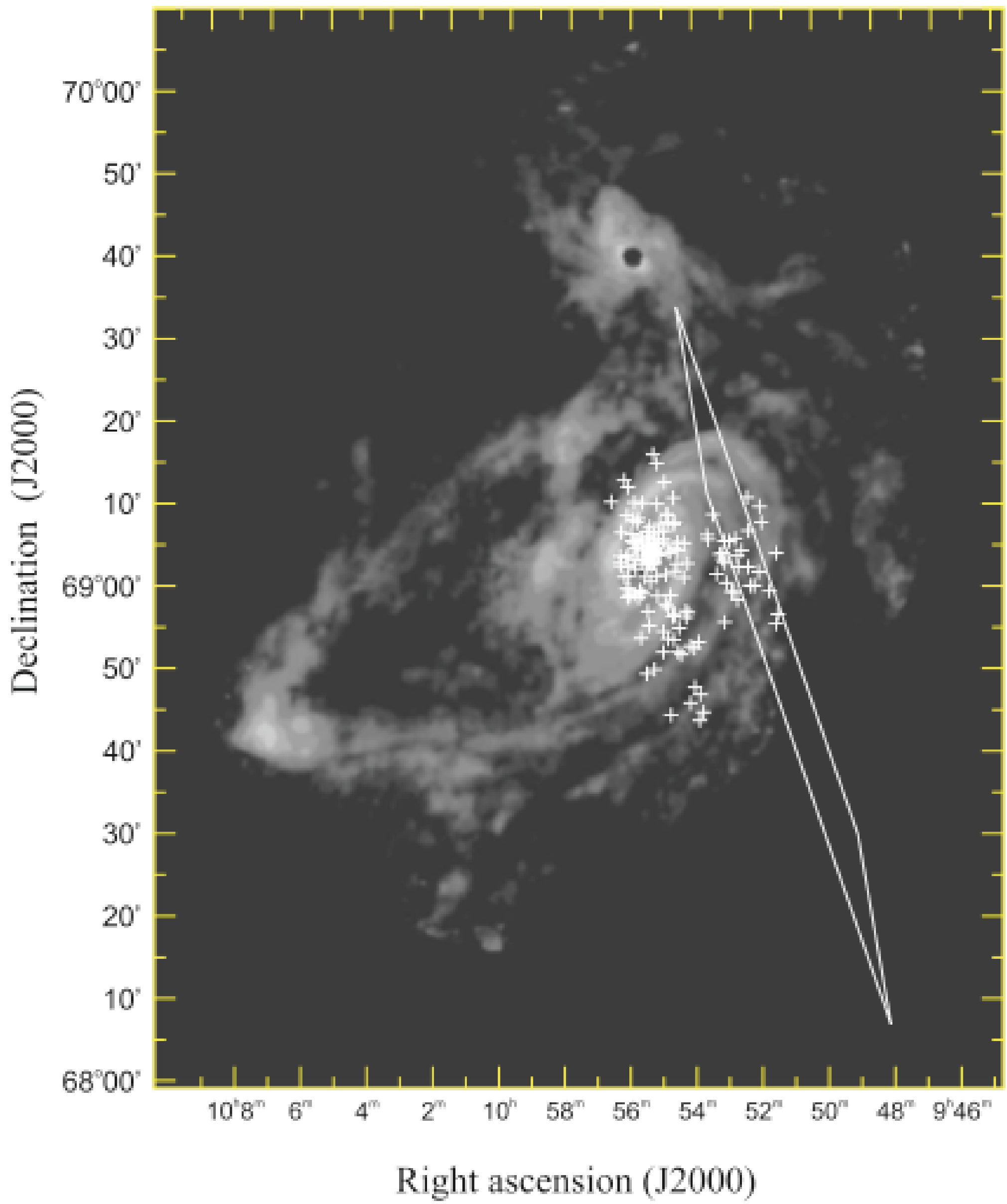
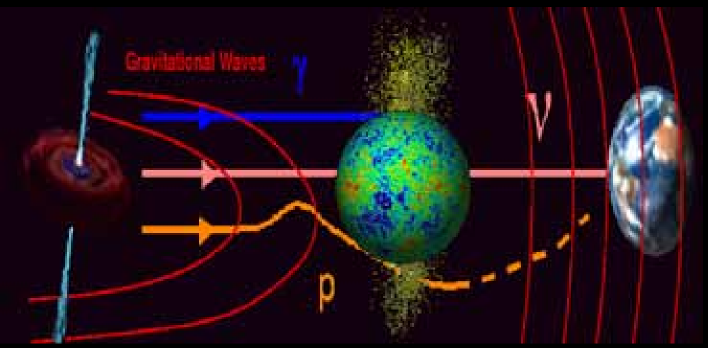


Fig. 4.— The 21 cm HI emission map of the central region of the M81 group of interacting galaxies. M81 at the center; M82 ~ 35′ to the north; and NGC 3077 ~ 40′ to the east and ~ 20′ to the south. X-ray sources (crosses) observed by Chandra, and IPN box of GRB 051103 are superimposed.

Some GW+HEN source candidates



***Long GRBs*:** In the prompt and afterglow phases, high-energy neutrinos (10^5-10^{10} GeV) are expected to be produced by accelerated protons in relativistic shocks (e.g., *Waxman & Bahcall 1997; Vietri 1998; Waxman 2000*). Good prospects for detection in GW too.

***Short GRBs*:** HENs can also be emitted during binary mergers (*Nakar 2007; Bloom et al. 2007; Lee & Ramirez-Ruiz 2007*). The n flux is expected to be large enough for the current generation of detectors. Prospects for detection in GW too.

***Low-Luminosity GRBs*:** Associated with particularly energetic population of core-collapse supernovae. Might also be strong neutrino emitters (*Murase et al. 2006; Gupta & Zhang 2007; Wang et al. 2007*). Expected event rate in the local volume is more than an order of magnitude larger than that of conventional long GRBs (*Liang et al. 2007; Soderberg et al. 2006*).

"Failed" GRBs: Associated with plausible baryon-rich jets. Optically thick, can be hidden from conventional astronomy, <u>neutrinos and GWs might to be able to reveal their properties</u>. *Ando & Beacom (2005), Razzaque et al. 2004; Horiuchi & Ando 2008*.

Likelihood Function for Spatial Overlap: LIGO + Virgo

LIGO + Virgo:

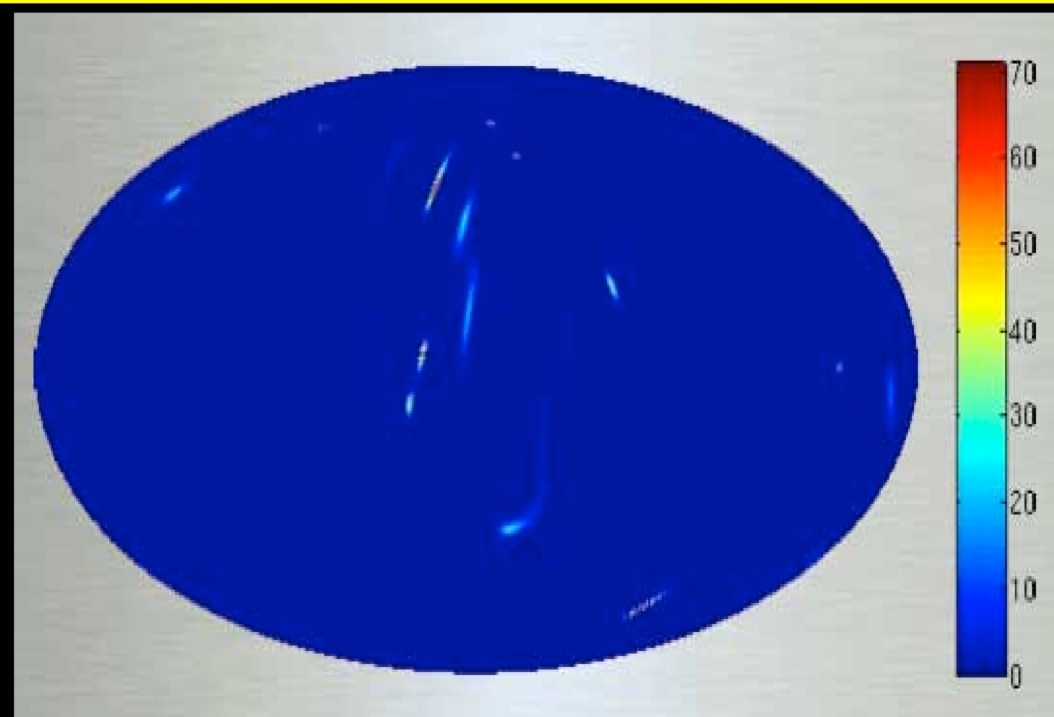
- Triple coincidence
- Improved "point" spread function
- Reduced coincident noise trigger rate

Y. Aso et al. APS'08 and
CQG 25, 114039, 2008

Pradier
arXiv:0807.2567v1 and

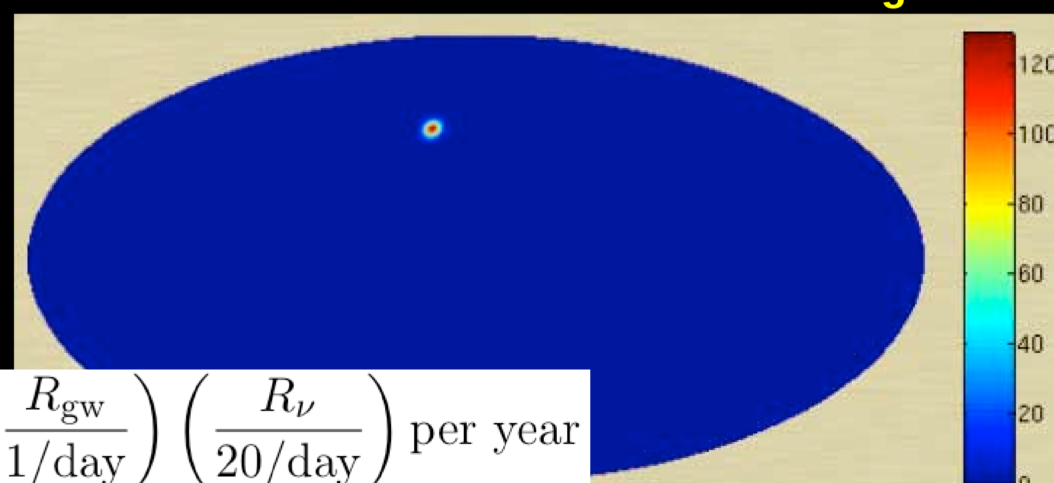
Coincidences between
Gravitational Wave Interferometers
& High Energy Neutrino Telescopes

Thierry Pradier
IPHC/DRS & University Louis-Pasteur Strasbourg-I



LIGO+Virgo PSF

IceCube 22 string PSF



$$\text{FalseAlarmRate} = \frac{1}{600}\left(\frac{p}{1\%}\right)\left(\frac{T_{\rm w}}{1\text{sec}}\right)\left(\frac{R_{\rm gw}}{1/\text{day}}\right)\left(\frac{R_\nu}{20/\text{day}}\right)\text{ per year}$$

Circular Inspirals: **~20** / year (Kalogera et al. 2006)

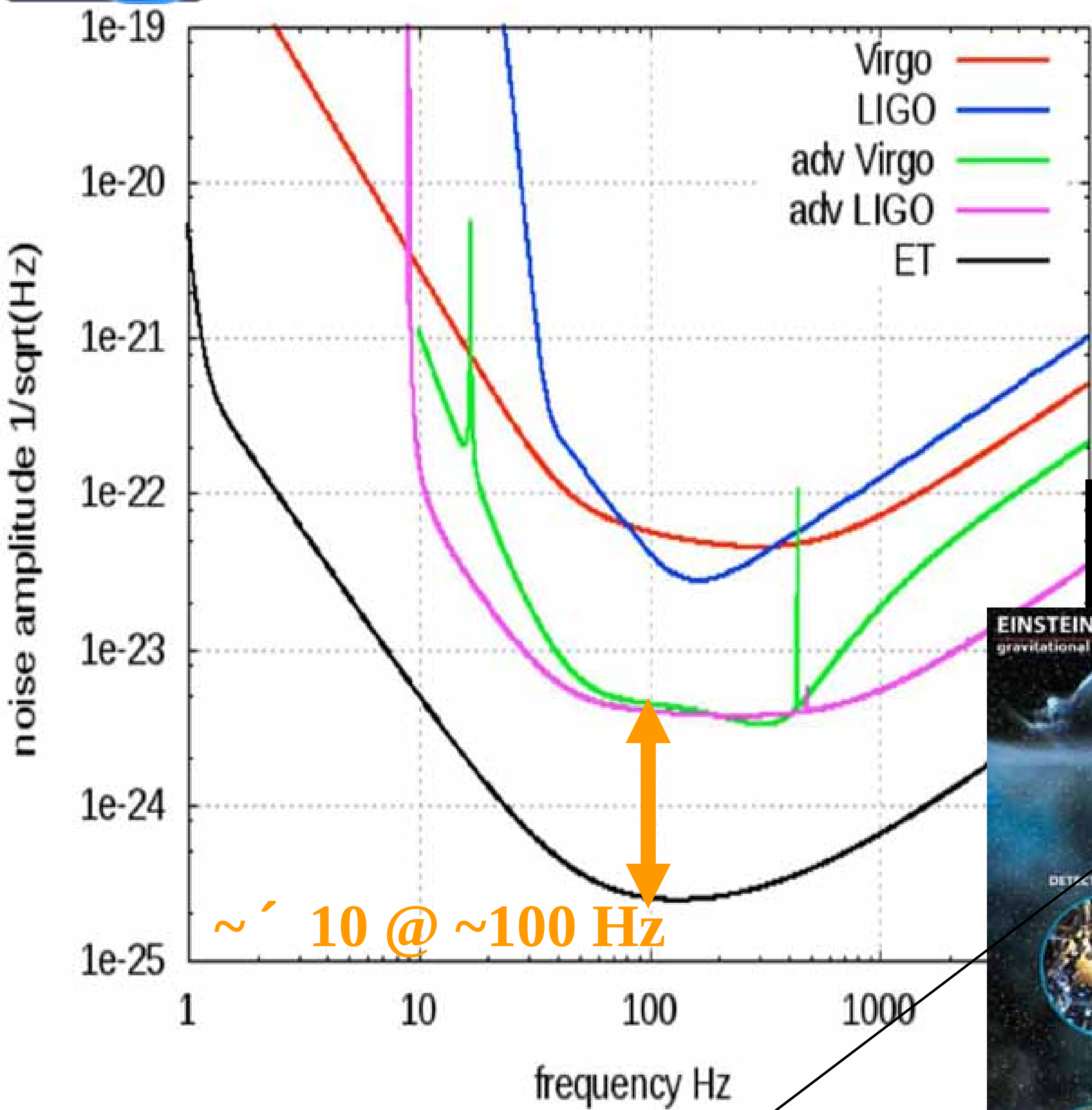
Eccentric Encounters:~ **several** / year (O'Leary, Kocsis, Loeb 2008)

x10 better amplitude sensitivity

Þ x1000 rate=(reach)^3

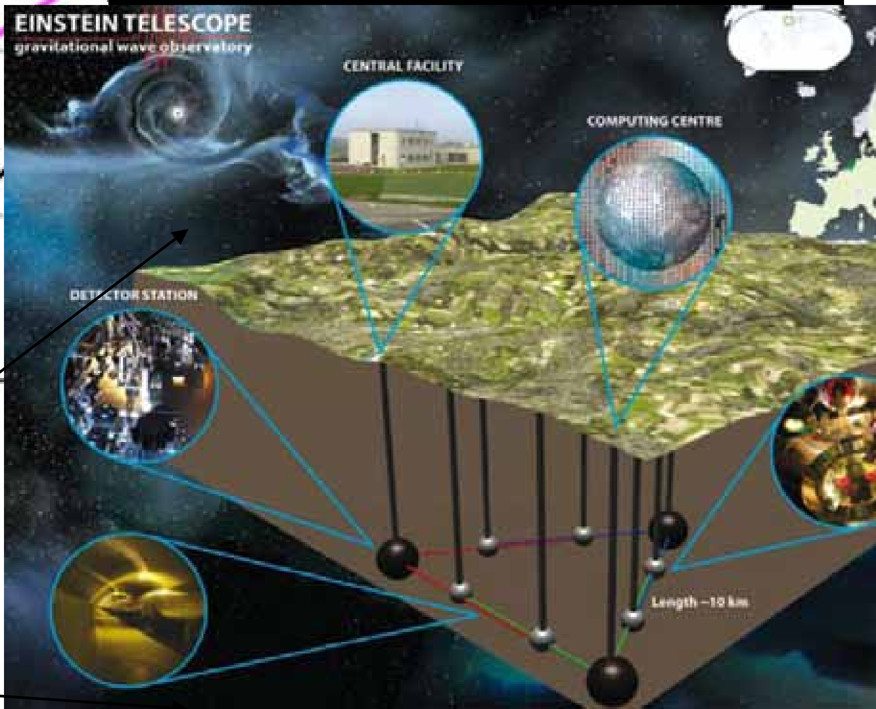
Þ 1 year of Initial LIGO < 1 day of Advanced LIGO !

Far-Future Detectors – Rule of Thumb?



$$D_{\rm L} \simeq \sqrt{\frac{3G\,(1+z)\,E_{\rm GW}}{\pi^2 c^3\,S(f)}\,\frac{F_{\rm rms}}{\rho_{\rm det}\,f}}$$

Einstein Telescope Gravitational Wave observatory (planned)

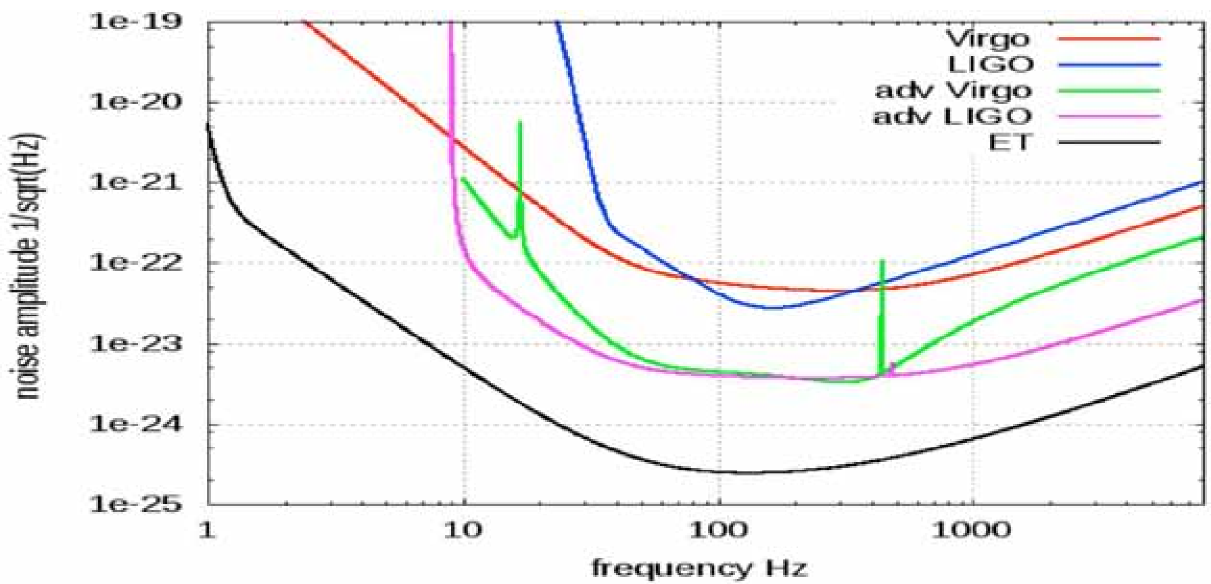


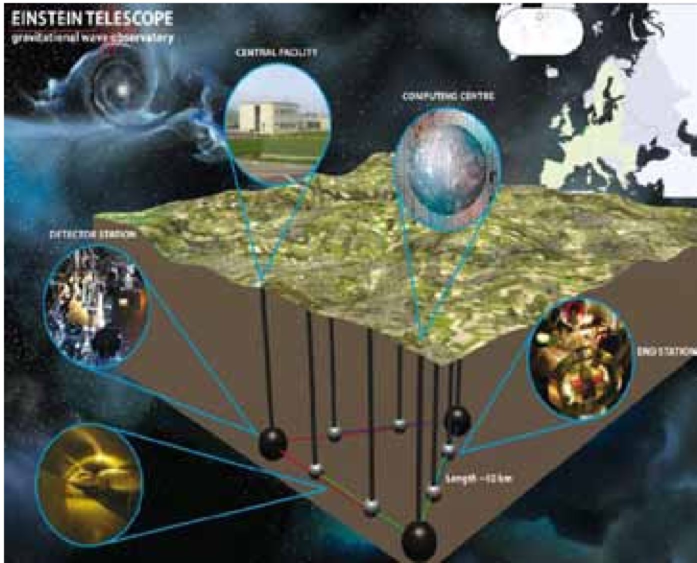
Data is courtesy of VIRGO and the LIGO Scientific Collaboration.

Far-Future Detectors – Rule of Thumb?

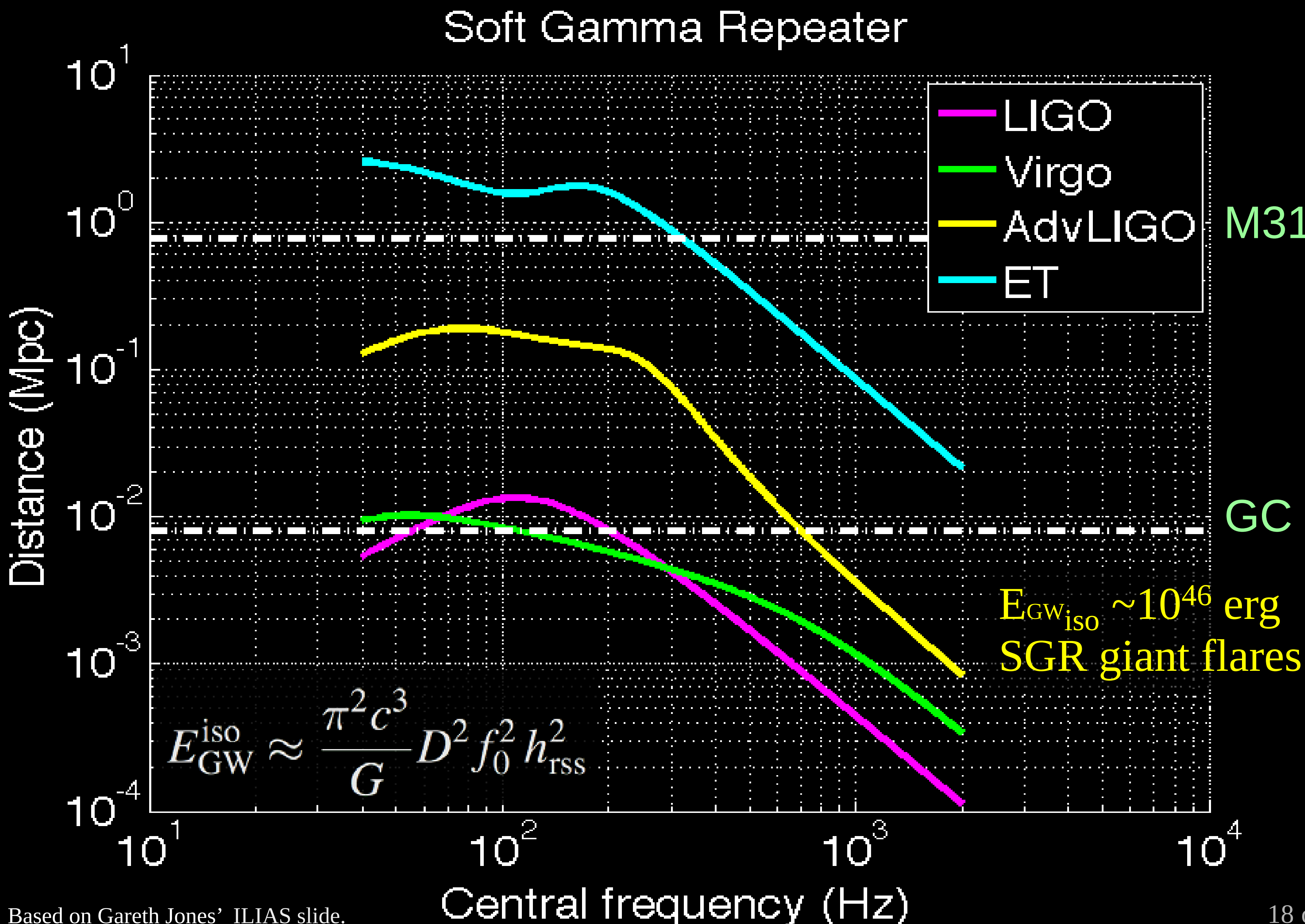
$$D_{\rm L} \simeq \sqrt{\frac{3G\,(1+z)\,E_{\rm GW}}{\pi^2 c^3\, S(f)}}\;\frac{F_{\rm rms}}{\rho_{\rm det}\, f}$$

y 5Gpc $(1+z)^{1/2}\,\frac{10}{\rho_{\rm det}}\,\frac{100\,{\rm Hz}}{f}\left(\frac{E_{\rm GW}}{10^{-2} M_\odot c^2}\right)^{1/2}\frac{2.5\times10^{-25}/\sqrt{\rm Hz}}{S(f)^{1/2}}\,F_{\rm rms}$





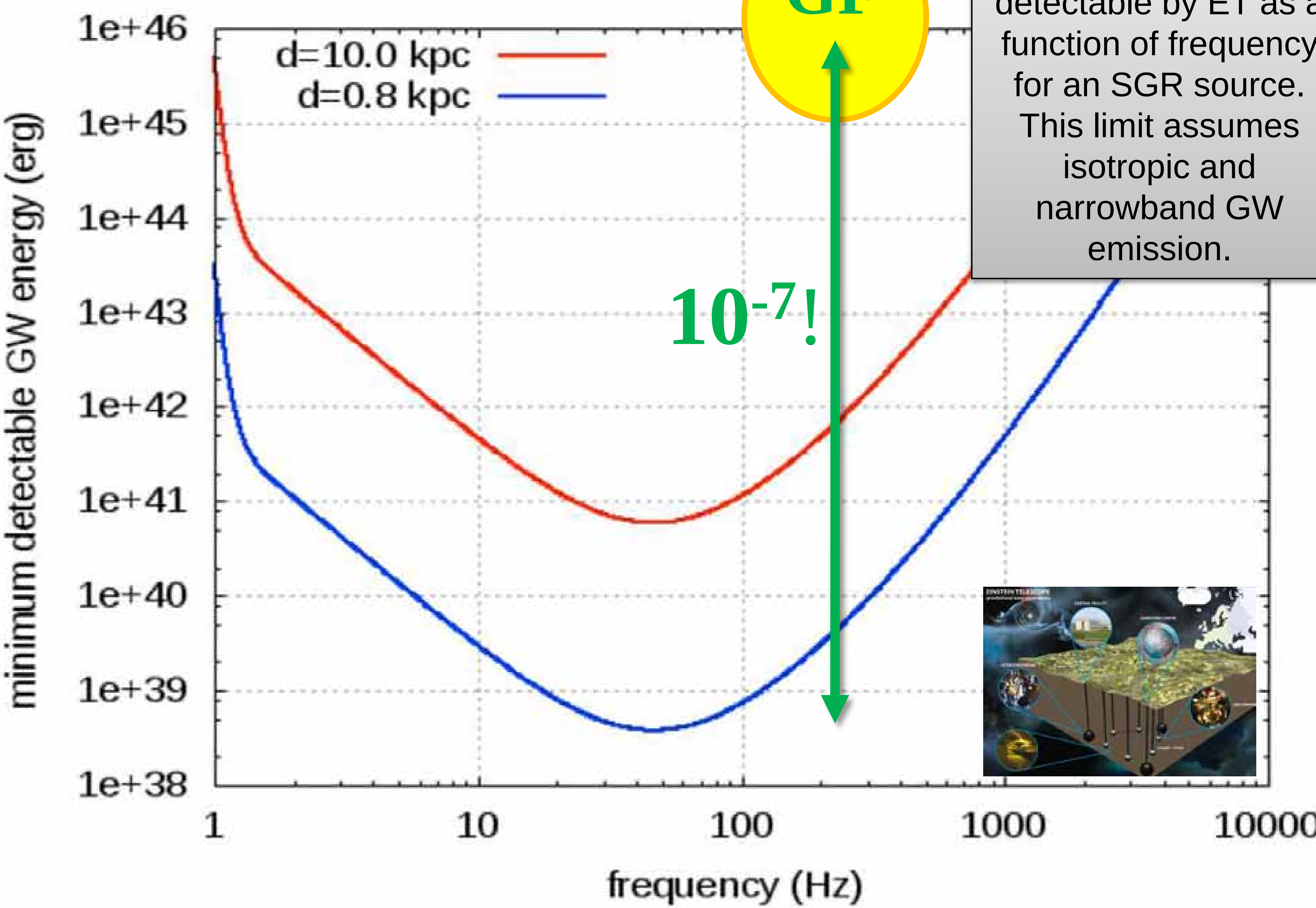
Unmodelled GW burst (rough) examples



Astrophys. J. 681 (2008) 1419 and arXiv:0808.2050

Based on Gareth Jones' ILIAS slide.

ET Reach for SGRs



Minimum energy in gravitational waves detectable by ET as a function of frequency for an SGR source. This limit assumes isotropic and narrowband GW emission.

Unmodelled GW burst (rough) examples

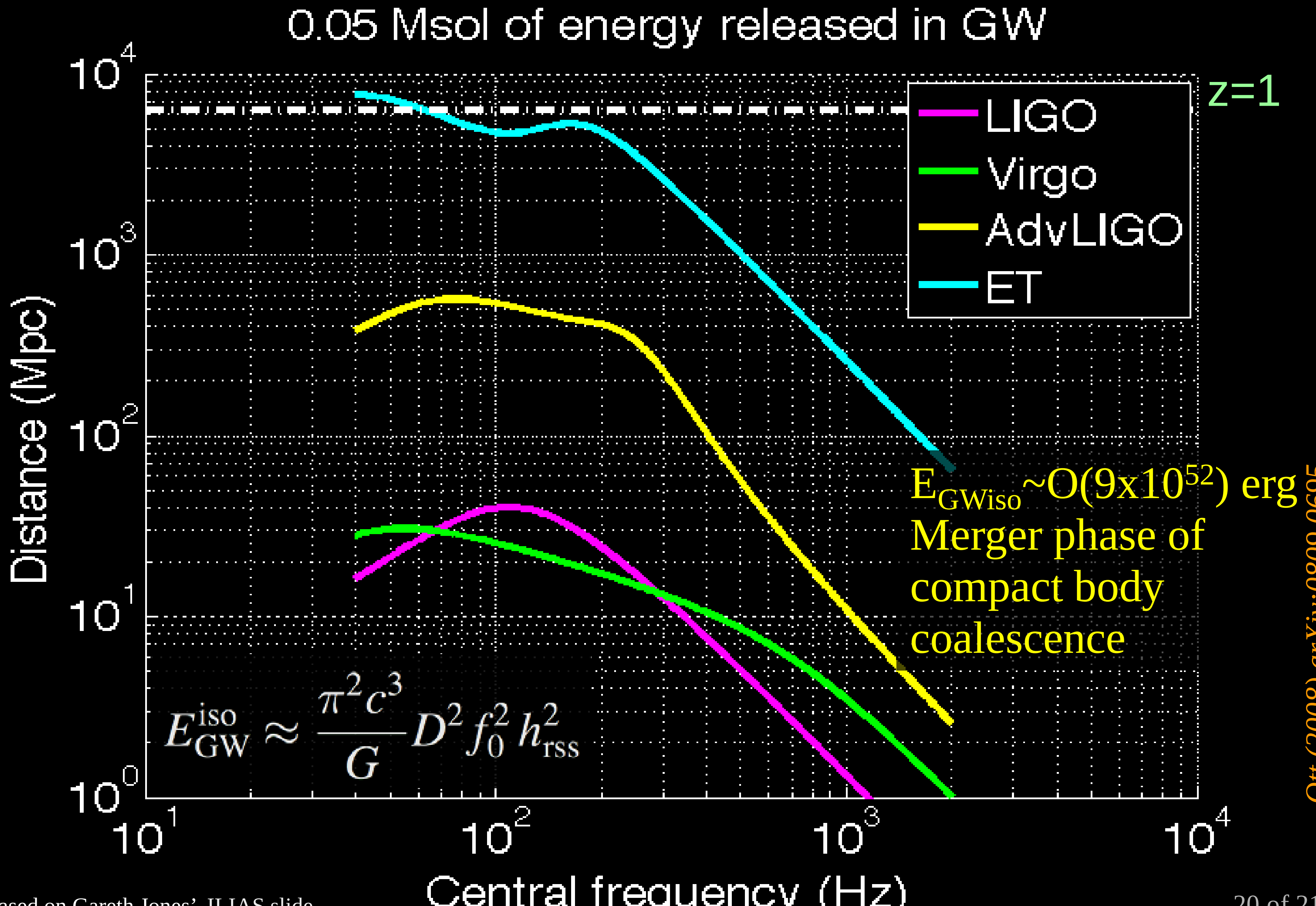


Image courtesy of U. of Florida, LIGO, LSC

This is great exploratory science !

- There is a bold effort underway to get a new view of the universe

- Initial LIGO has reached its design sensitivity
  - Several astrophysically interesting results are out from S5
    - SGR1806-20
    - GRB070201
    - Crab-spindown
    - and others to come…
- Active data sharing collaboration with VIRGO

- Enhanced LIGO is here
- Advanced LIGO is around the corner… the excitement is high!



LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- CSU Fullerton
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Tsinghua University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington