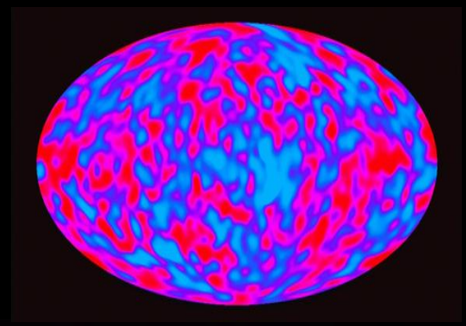


Credit: NASA/COBE

Past and Future in the Quest for Gravitational Wave Transients

Laura Cadonati - University of Massachusetts, Amherst
LIGO Scientific Collaboration and Virgo Collaboration

G1100602

TAUP 2011, Munich, Germany - September 8, 2011

Gravitational Waves: Einstein's Messengers

American Museum of Natural History GW project

- Gravitational waves are ripples in the fabric of space-time: perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.
- They travel at the speed of light, carrying information from the coherent, relativistic motion of large masses
- As they pass, they change the distance between neighboring bodies

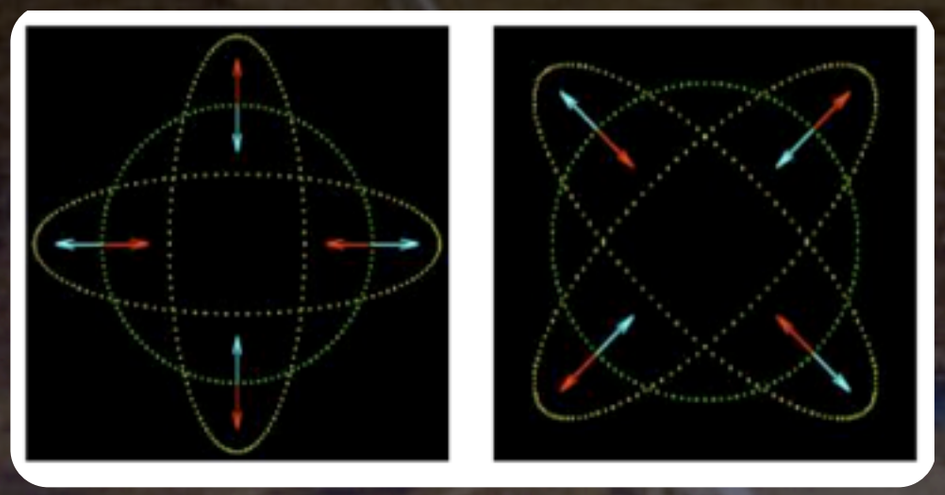
Dimensionless strain:

$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

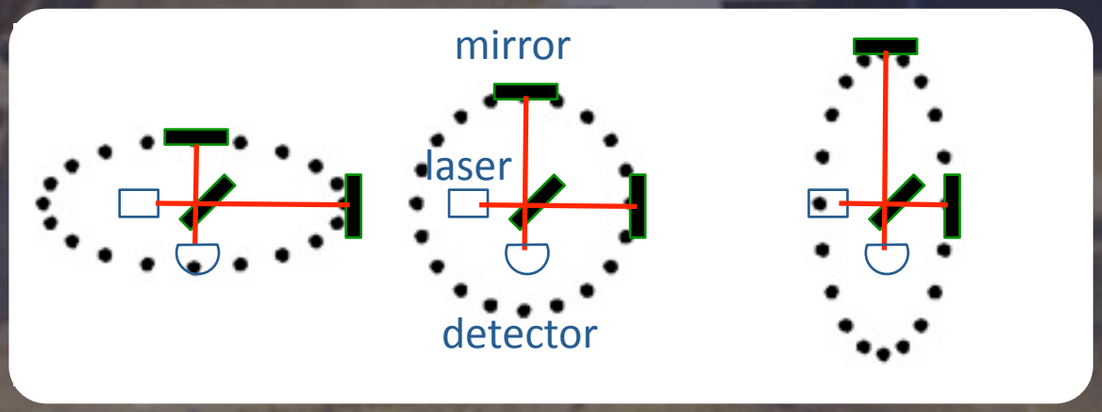
I = mass quadrupole moment of the source

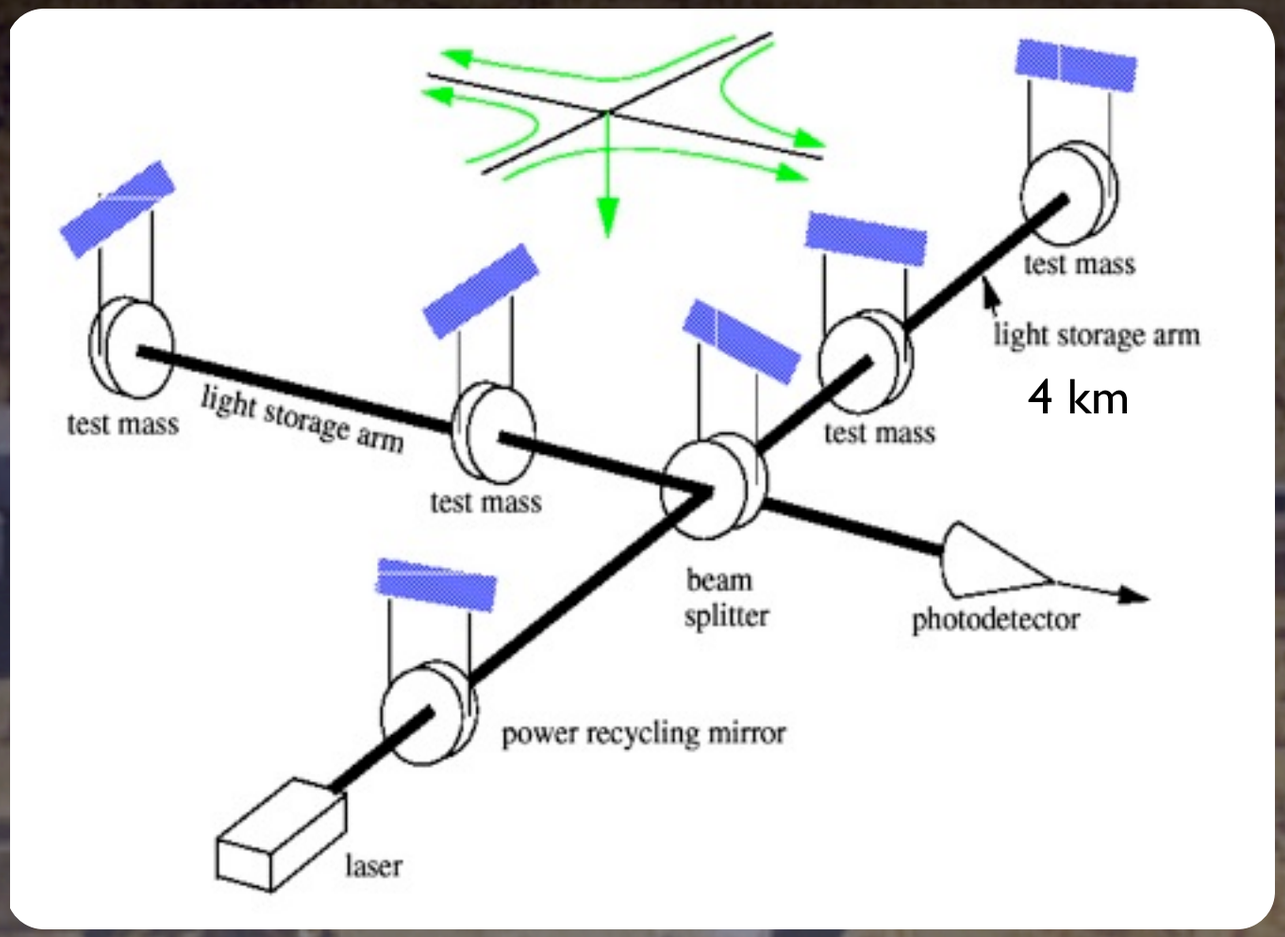
R = source distance

Interferometer: Suspended Mirrors as Test Masses



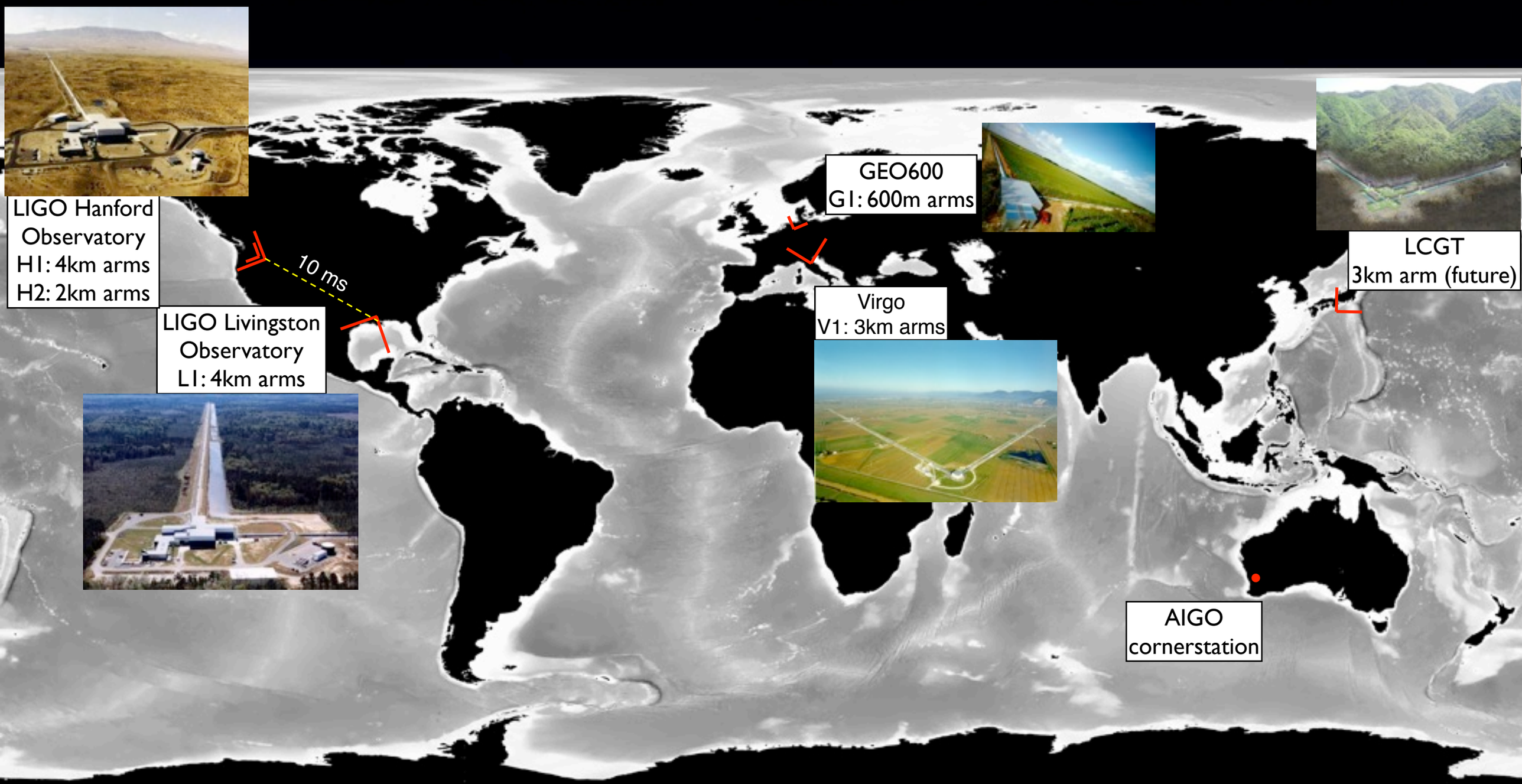
Deformation of a ring of particles due to the + and x polarization



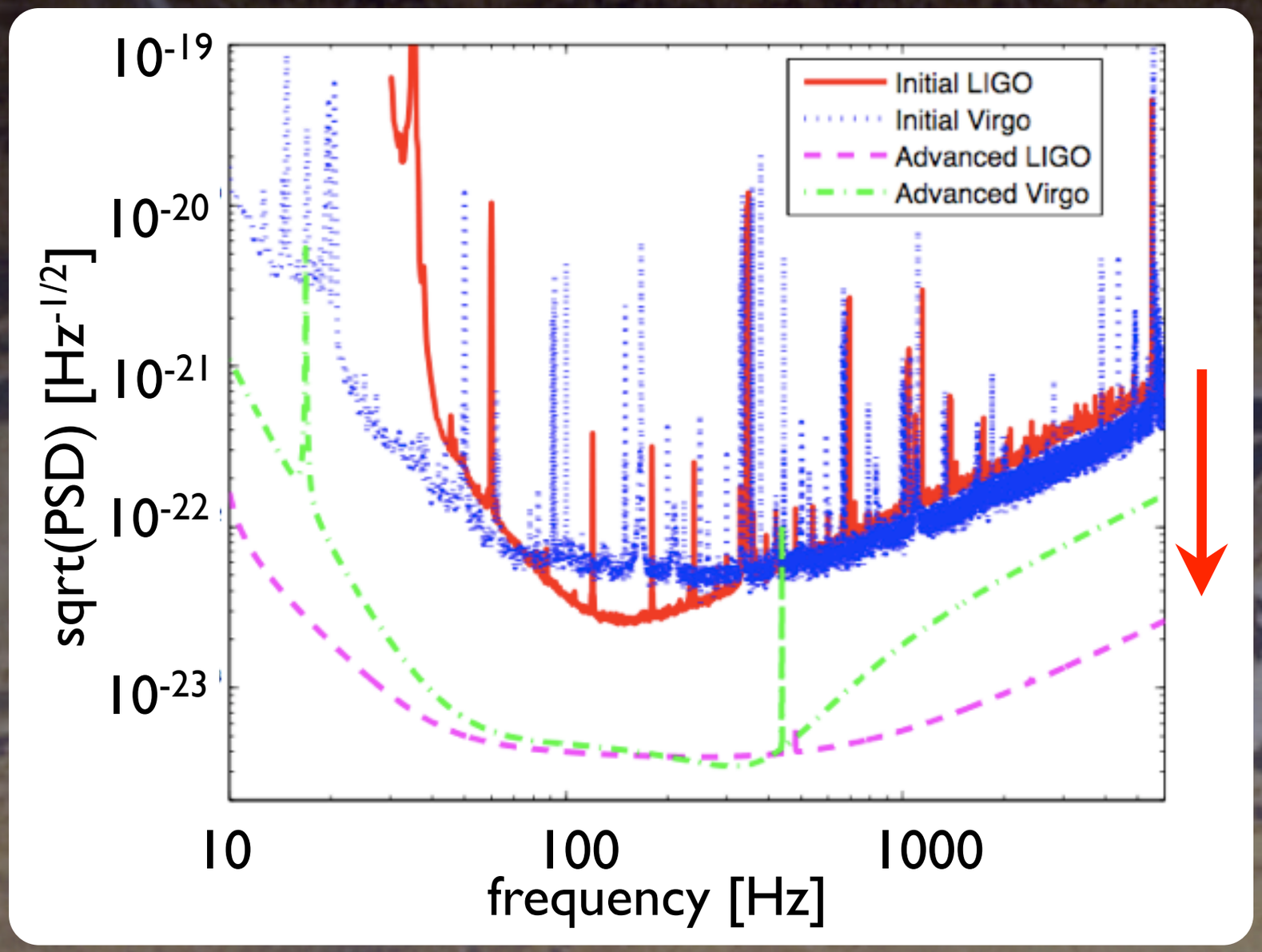


Goal: measure difference in length to one part in 10^{21}, or 10^{-18} meters

An International Network Of Ground-Based Interferometers



world map credit: NASA's Earth Observatory



~10 better amplitude sensitivity

~1000 more volume

Gravitational Wave Transients

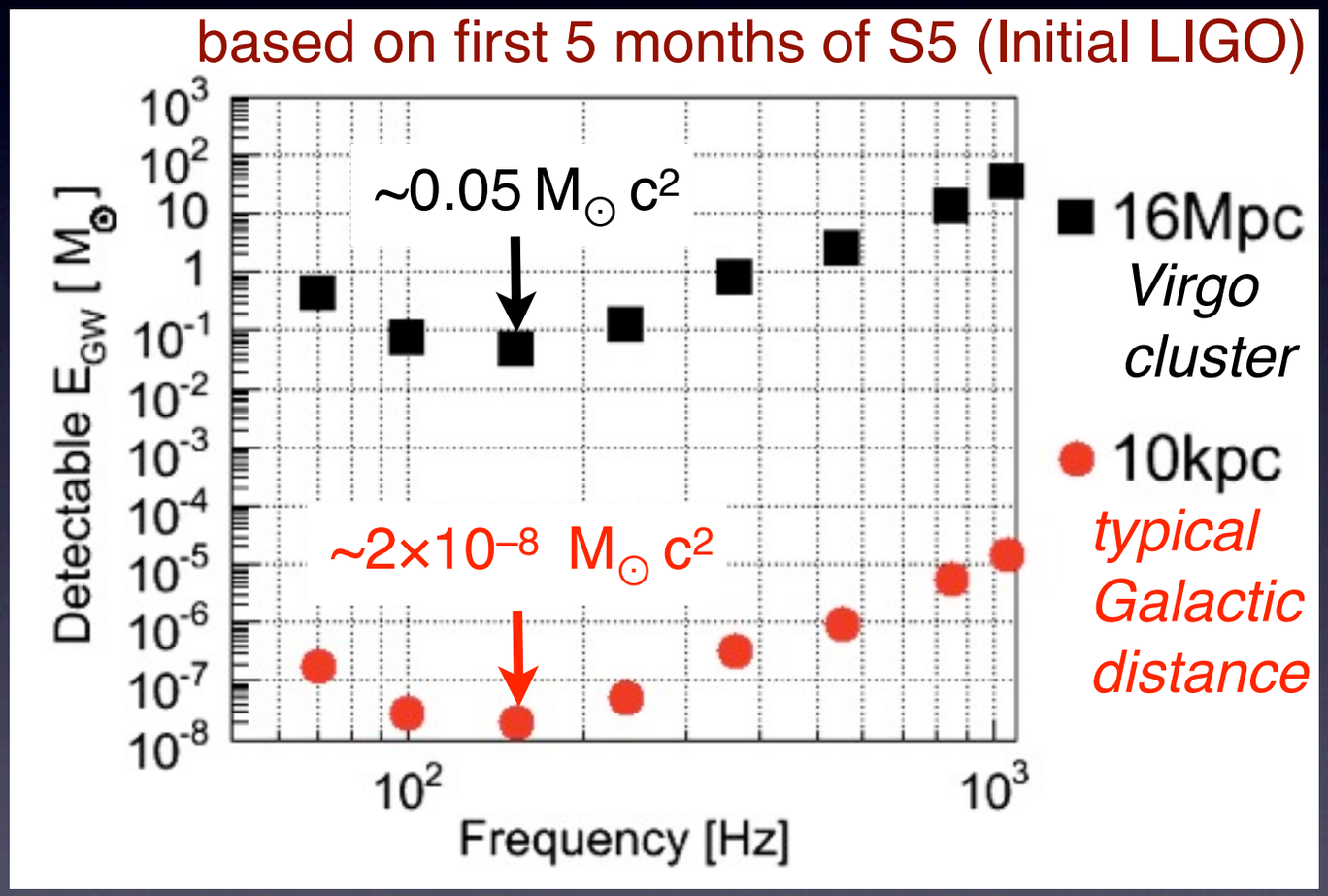
- short (fraction of second to minutes) bursts of gravitational waves from violent astrophysical events
- Plausible sources include mergers of compact binaries, supernova explosions, instabilities in nascent neutron stars, kinks and cusps in cosmic strings....

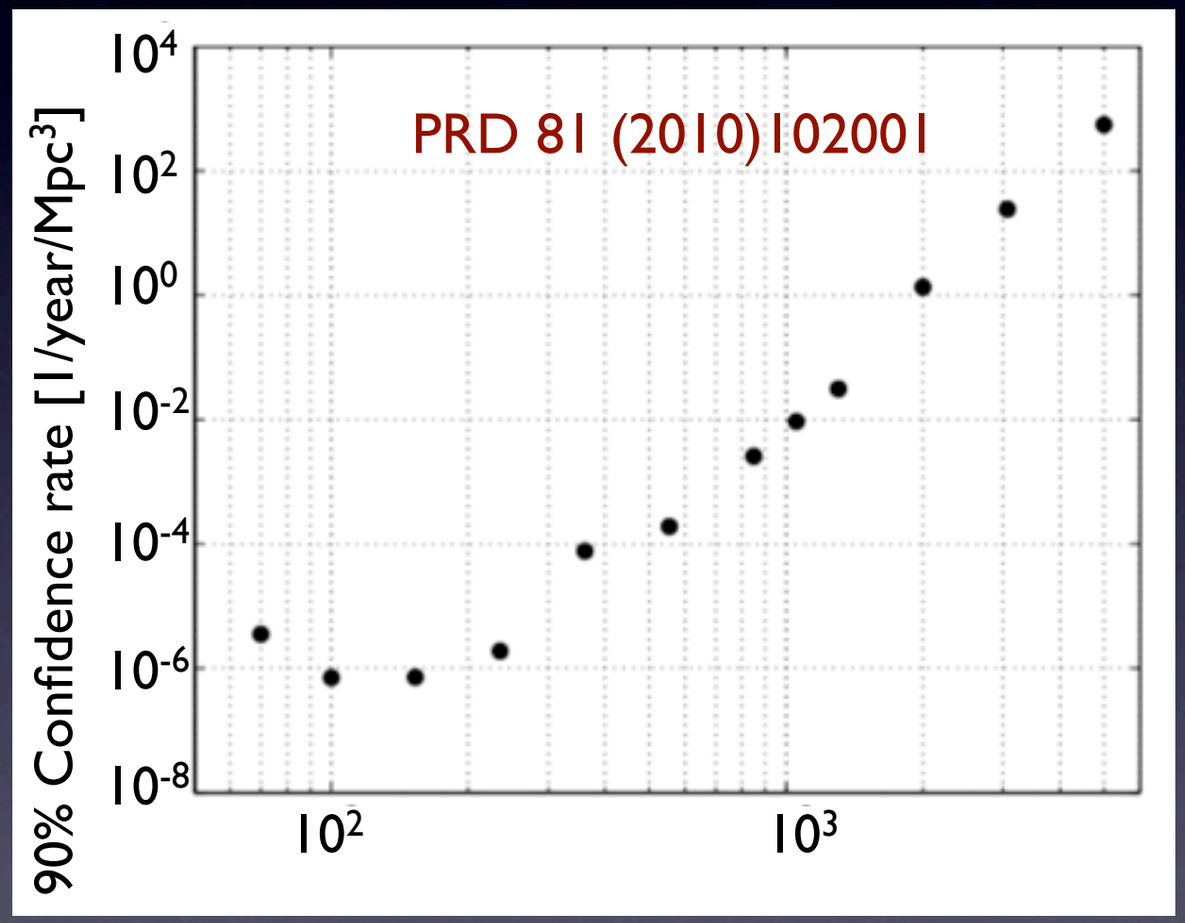
N63A Supernova Remnant - Hubble
Image Credit: NASA, ESA, HEIC, and the Hubble Heritage Team STScI/AURA.

"Ears Wide Open"

Excess power in time-frequency maps, coherent in multiple detectors
Don't require prior knowledge of the waveform.

Talk by Giovanni Prodi



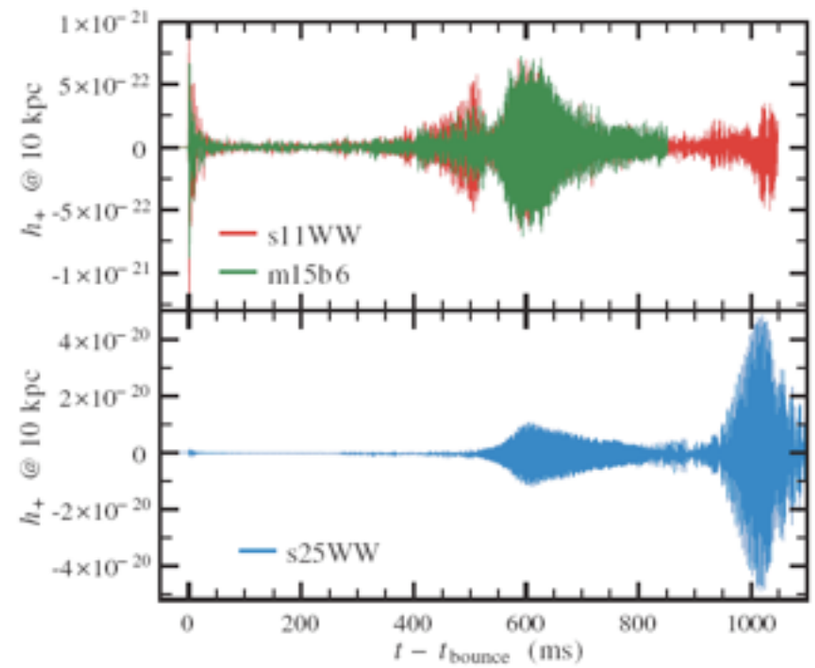


GW energy in short, monochromatic pulses detectable with 50% probability.
Function of frequency.

Rate limit per unit volume 90% CL linearly polarized sine-Gaussian with E_{GW}= 1 $M_\odot c^2$

Adding Models: Core-Collapse Supernovae

- Waveforms not well constrained: variety of morphologies, must use template-less analysis approach
- Core Collapse numerical simulations: E_{GW} up to $10^{-7}\ M_{\odot}c^2$
- Analytical calculations for extreme models: E_{GW} up to $10^{-2}\ M_{\odot}c^2$



EXAMPLE

Ott, et al,
PRL 96, 201102 (2006)

TABLE I. MODEL SUMMARY.

Model	Δt^a (ms)	$\lvert h_{+,max}\rvert^b$ (10^{-21})	$h_{char,max}{}^{b,c}$ (10^{-21})	$f(h_{char,max})$ (Hz)	$E_{GW}{}^d$ ($10^{-7} M_{\odot}c^2$)
s11WW	1045	1.3	22.8	654	0.16
s25WW	1110	50.0	2514.3	937	824.28
m15b6	927.2	1.2	19.3	660	0.14

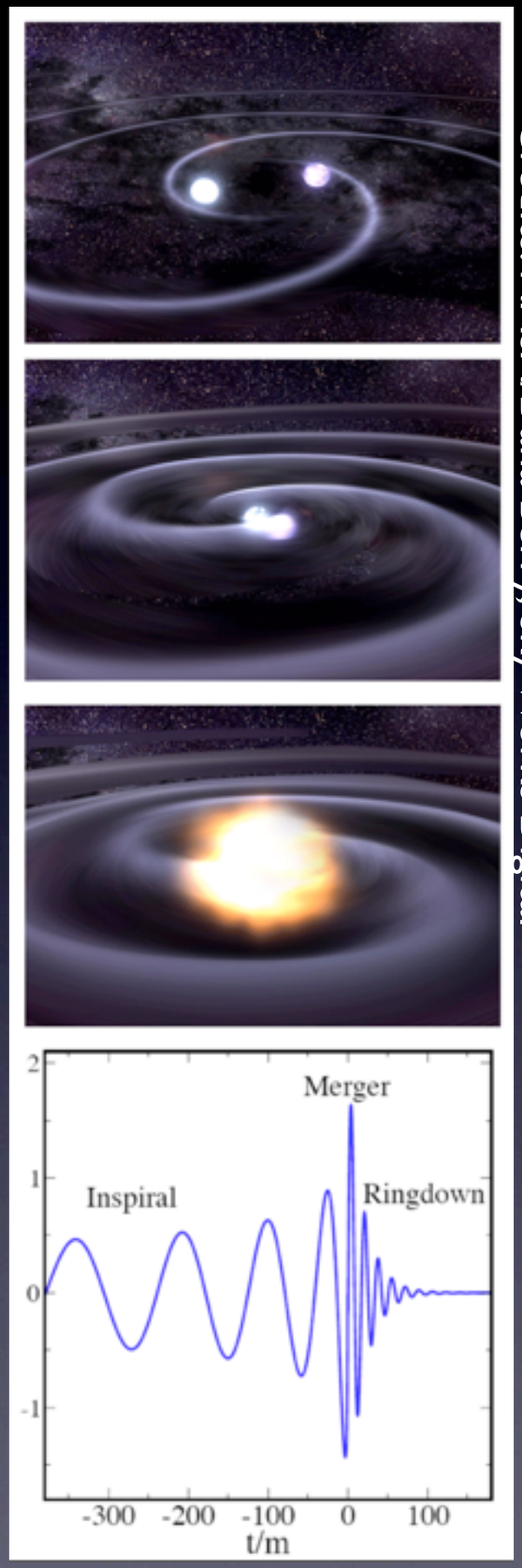
11 $M_{\odot}$ progenitor (s11WW model) $\Rightarrow$ ~ 0.4 kpc
25 $M_{\odot}$ progenitor (s25WW model) $\Rightarrow$ ~ 16 kpc

Adding Models: Compact Binary Coalescences

- Pairs of black holes, neutron stars, or a black hole and neutron star
- As they orbit one another, they emit gravitational waves causing the objects to get closer, and eventually merge
- Ground-based detectors are sensitive to the last few minutes of inspiral (mass dependent)

Match filter to templates

PRD 82 (2010)102001
PRD 83 (2011)122005

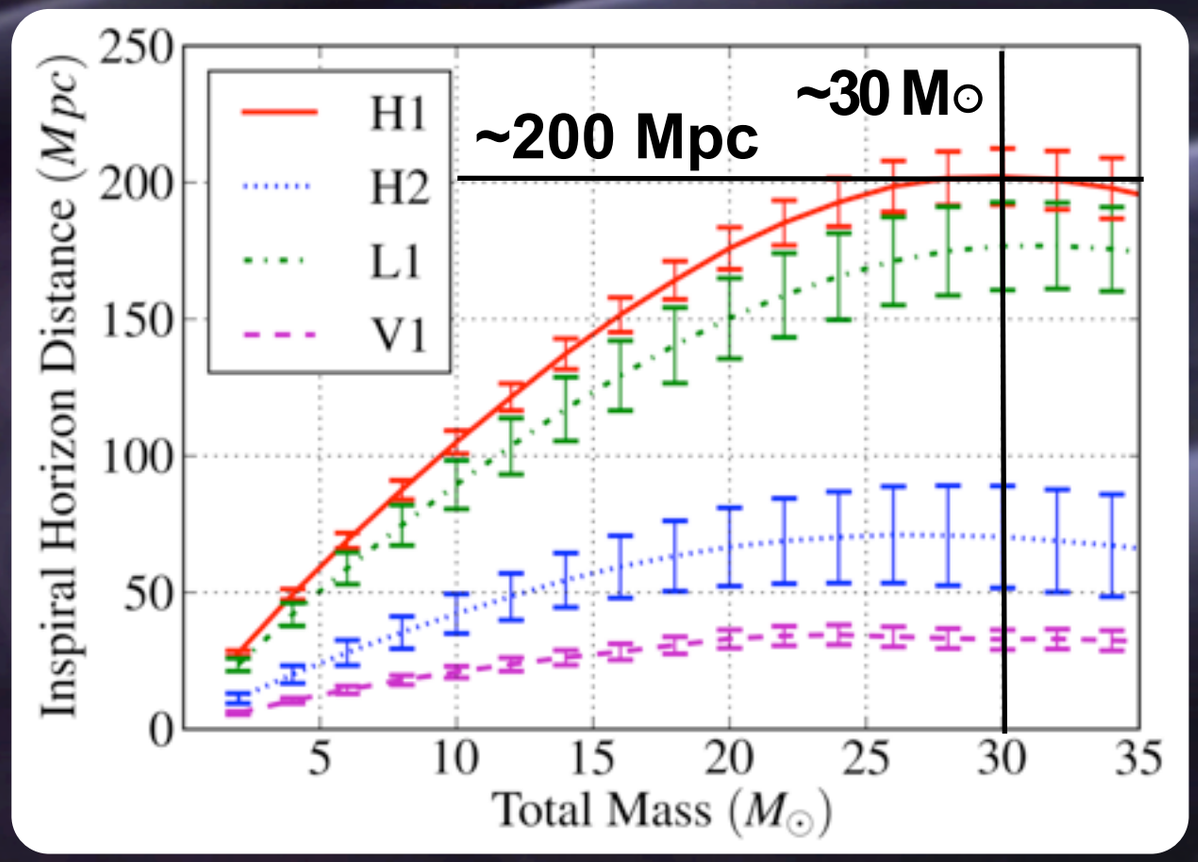


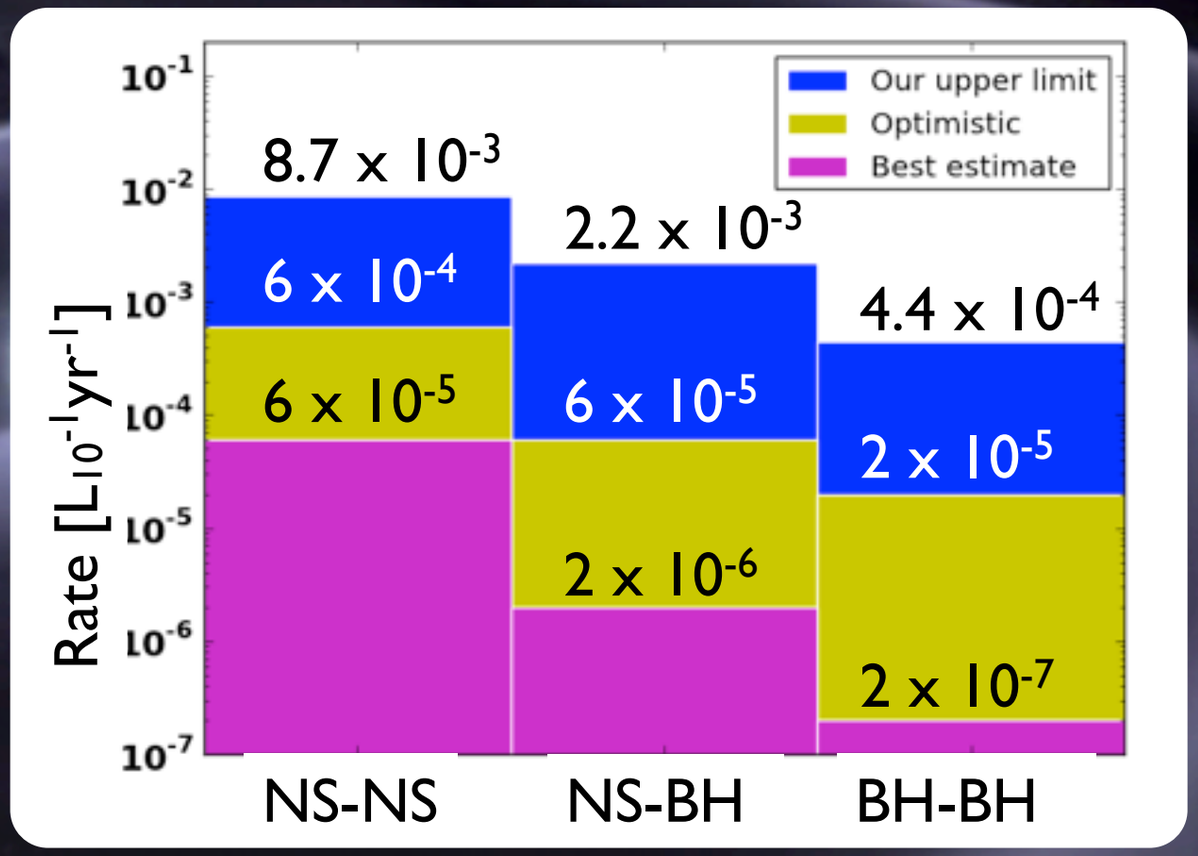
Credits: NASA/Dana Berry, Sky Works Digital

How Far? How Many?

"Horizon" = Distance at which an optimally oriented inspiral yields SNR=8

Binary coalescence rate in a galaxy follows approximately the star formation rate, or blue light luminosity. $L_{10} = 10^{10} L_{\odot,B}$ (Milky Way = 1.7 L_{10})



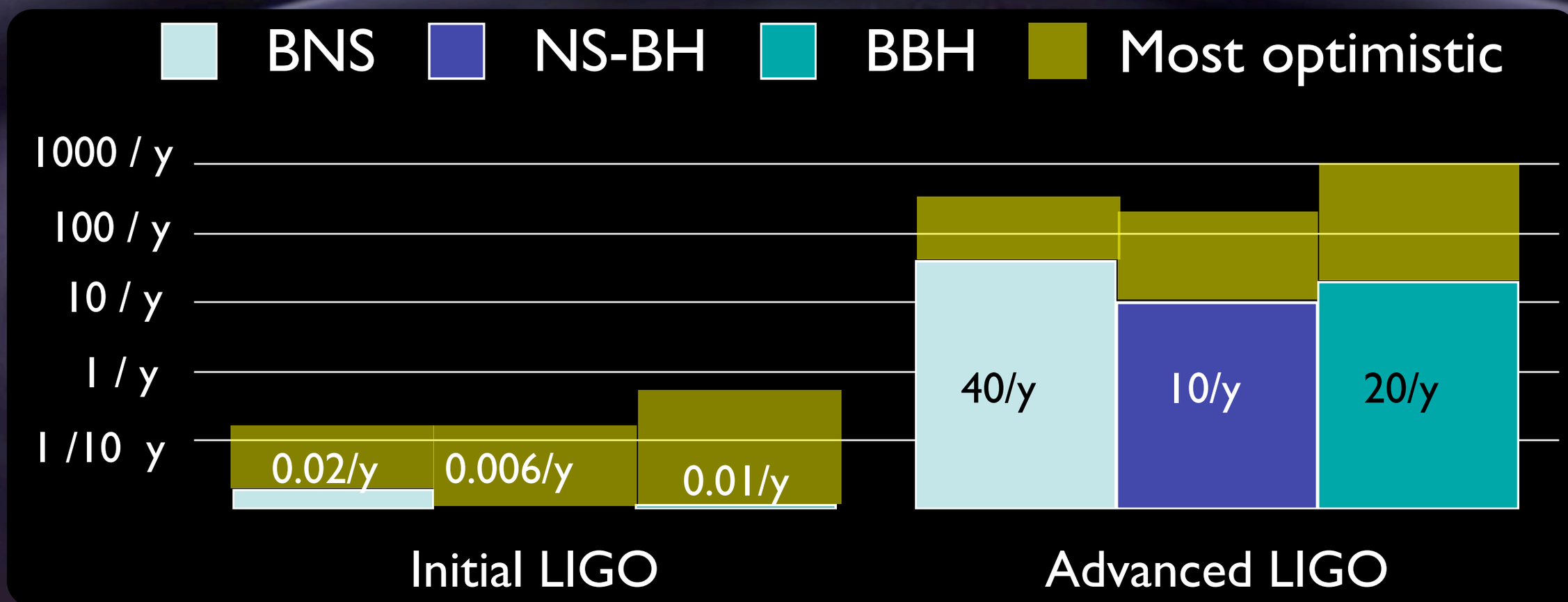


Search for Gravitational Waves from Compact Binary Coalescence in LIGO and Virgo Data from S5 and VSR1

PRD 82 (2010)102001

Advanced LIGO Expected Rate of Binaries

Class Quant Grav 27 (2010) 173001



Binary neutron star mergers: from ~30 Mpc to ~450 Mpc

Binary black hole mergers: from ~100 Mpc to z=2

Increasing importance as way to the future...

Multi-Messenger Astrophysics:

connecting different observations of the same astrophysical event or system

- Gamma-Ray transients (GRBs, SGRs)
- Optical transients
- Neutrino Events
- Radio transients
- X-ray transients
- ...

➡ Correlation in time and direction, targeted analysis
➡ Information on source properties
➡ Increased confidence in detection of gravitational waves

WR124 Wolf-Rayet star in the Saggitarius constellation

Image Credit: Grosdidier, Moffat, Joncas, Acker - NASA, ESA.

Electromagnetic Followup of GW Transient Candidates

GW

Image courtesy ROTSE collaboration

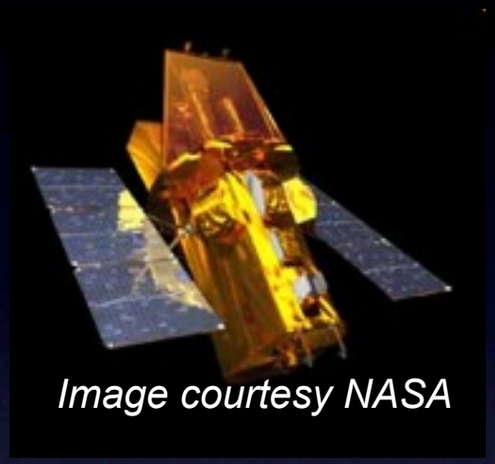
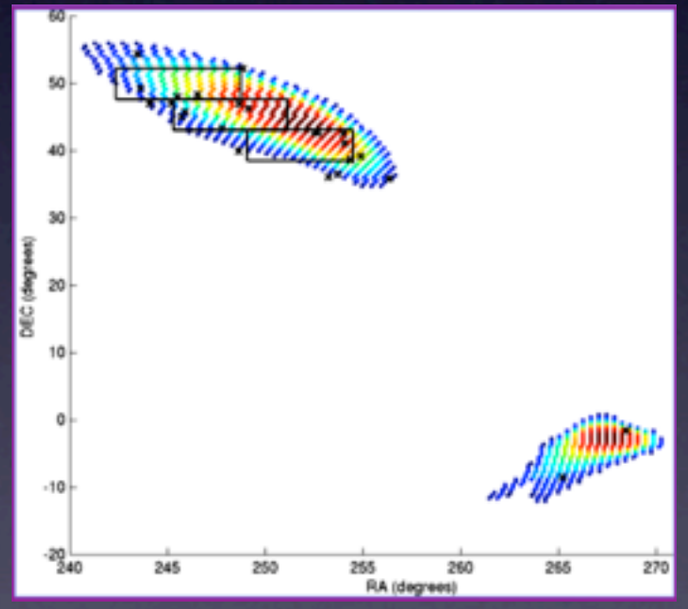
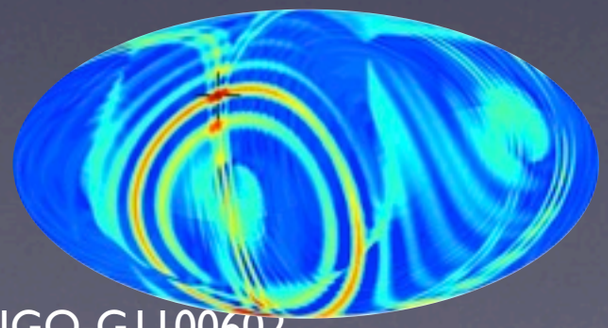


Image courtesy NASA

Telescopes, Satellites, particle detectors





A detectable GW source must be an extremely energetic event and/or be located relatively close. Expect radiation in EM channels too (optical, X)

Use GW information to point telescopes, SWIFT

Tested in the 2010 run

Talk by Marica Branchesi

See: Kanner et al. CQG 25 (2008)184034 [0803.0312]

The GRB-GW Connection

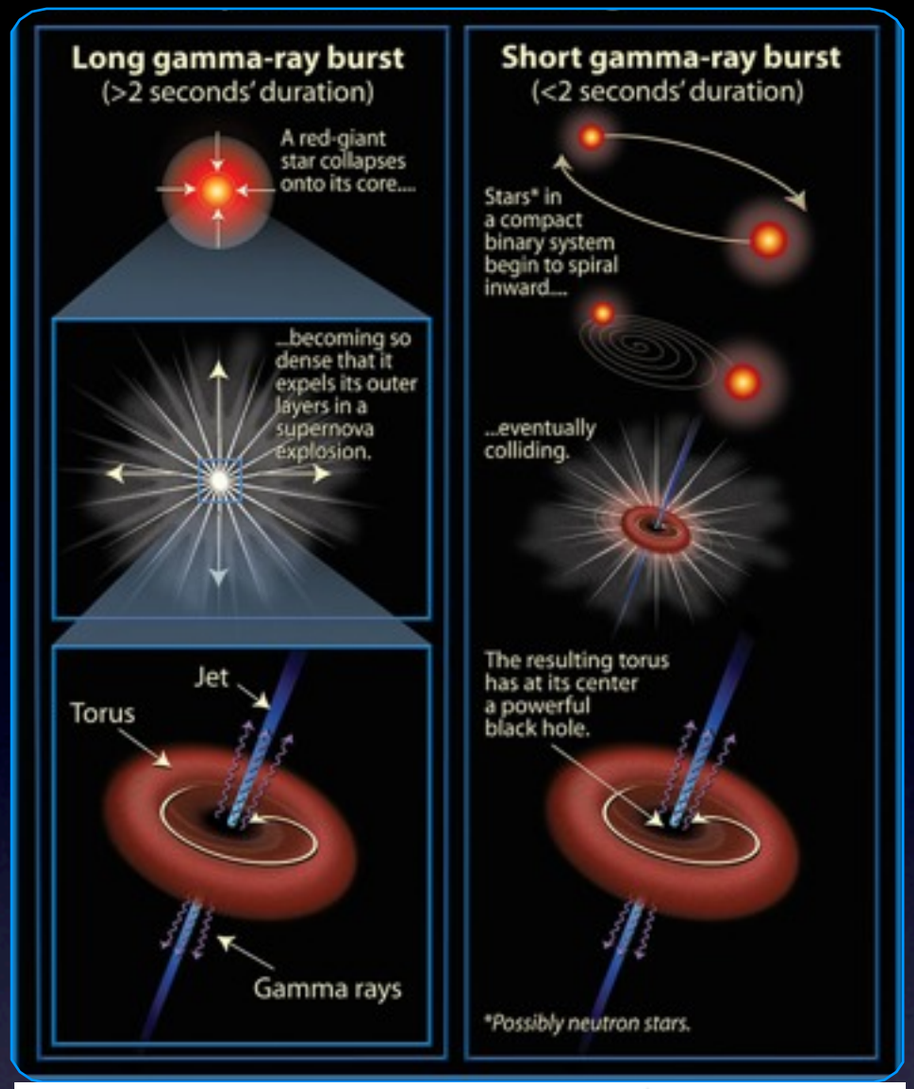
GRBs are the result of catastrophic events; expect gravitational wave emission from the immediate neighborhood of the GRB central engine.

GW-GRB Probe

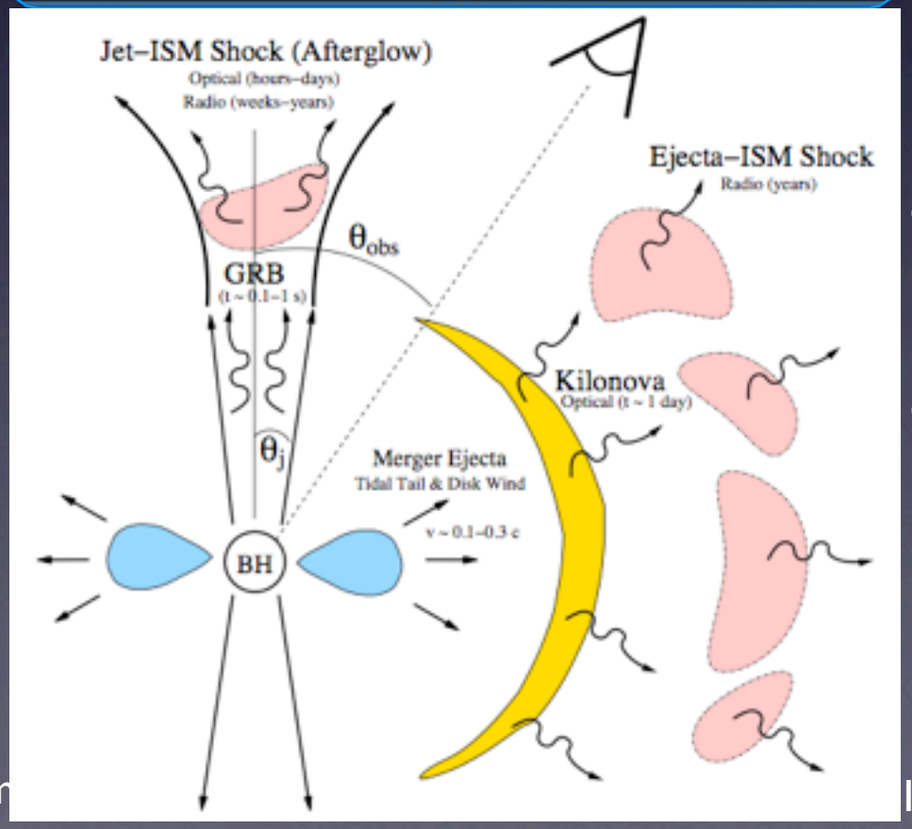
- Direct evidence of engine mechanism
- Measure component masses and spins in NS-NS/ NS-BH
- constrain NS equations of state
- test general relativity in the strong-field regime
- calibration-free luminosity distance (Hubble expansion, dark energy)

Questions

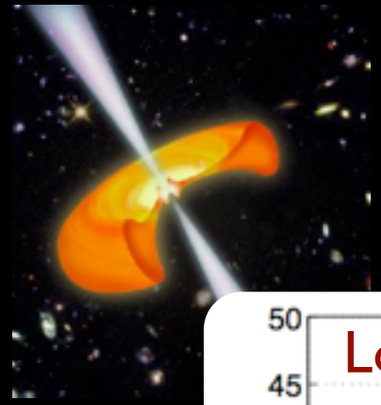
- Which GW waveform
- Timing of GW burst emission



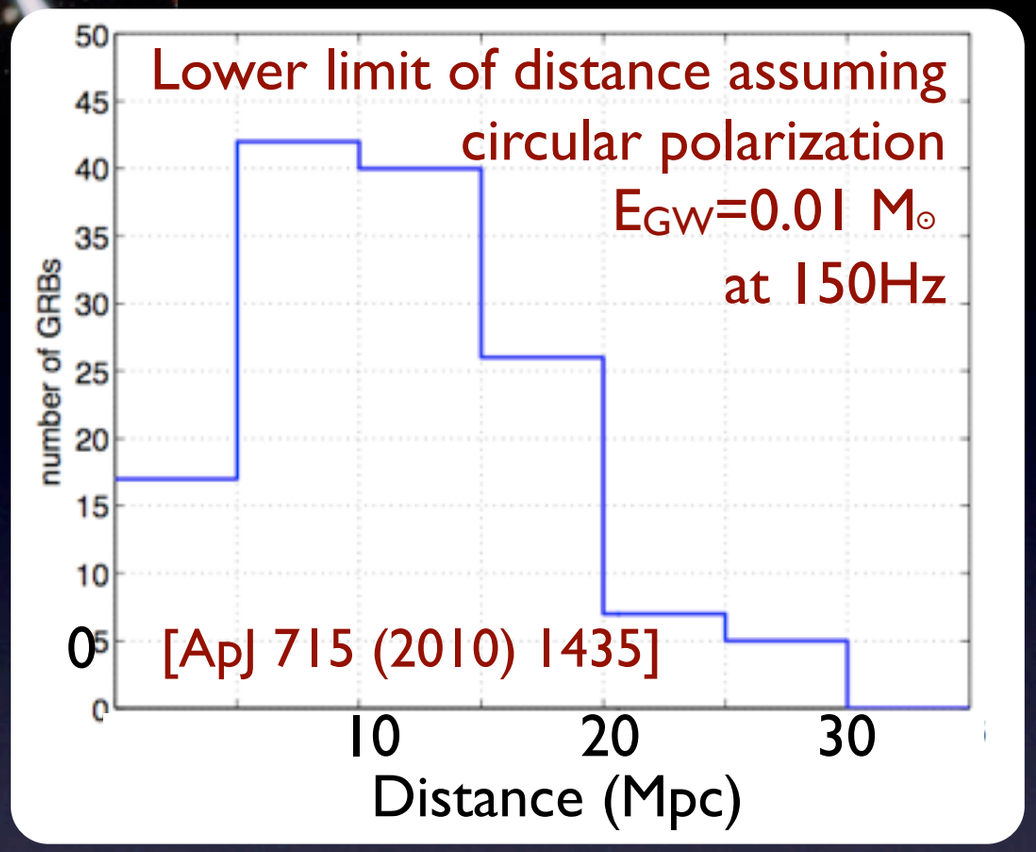
Credits: Ute Kraus

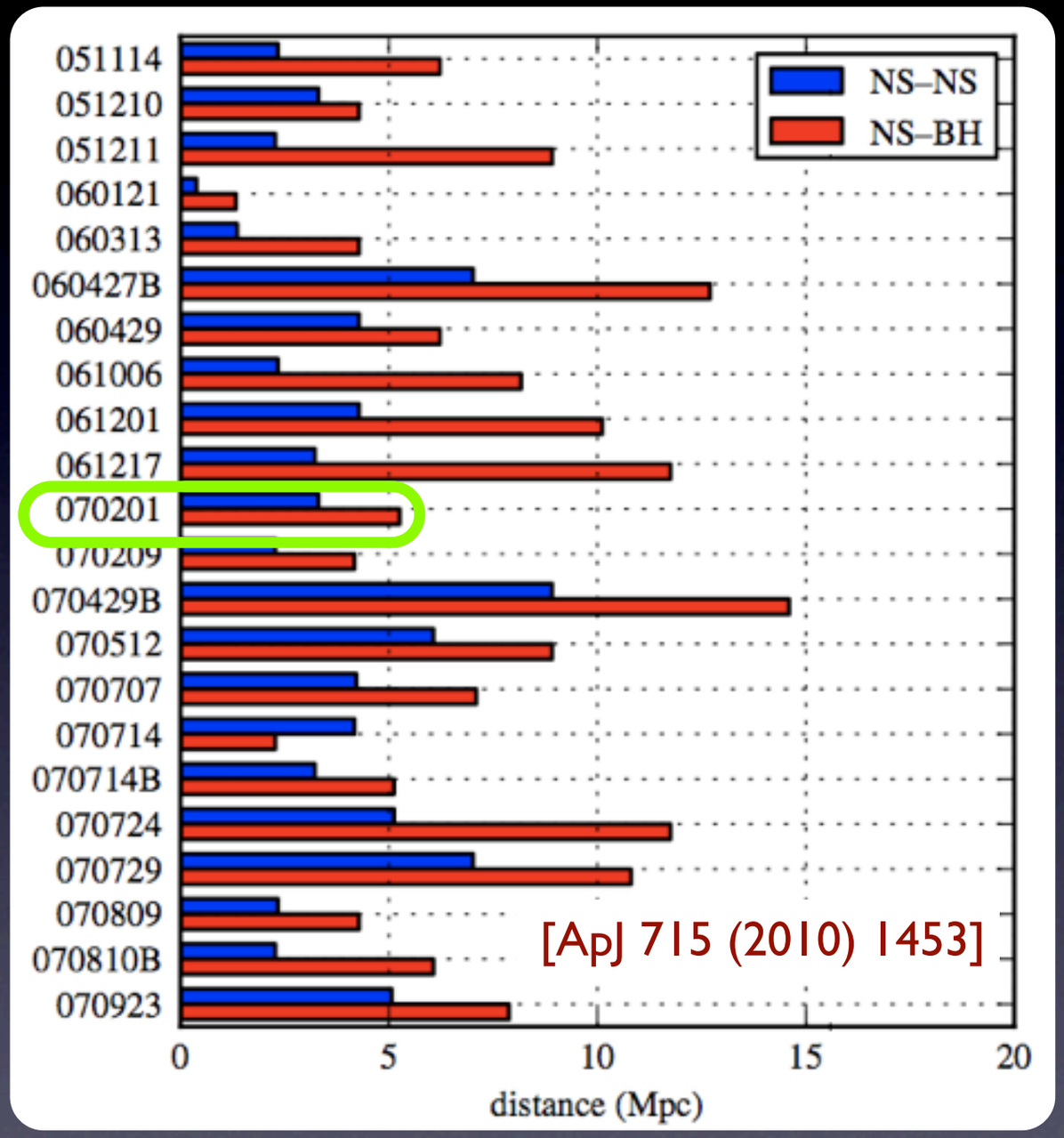


Metzger & Berger 2011



GRB-GW Connection





If: Fermi sky coverage and Enhanced LIGO sensitivity E_{GW} = 0.01 $M_\odot$, f_0 = 150 Hz

$\langle N_{short} \rangle \simeq 1 \times 10^{-4}$ /year

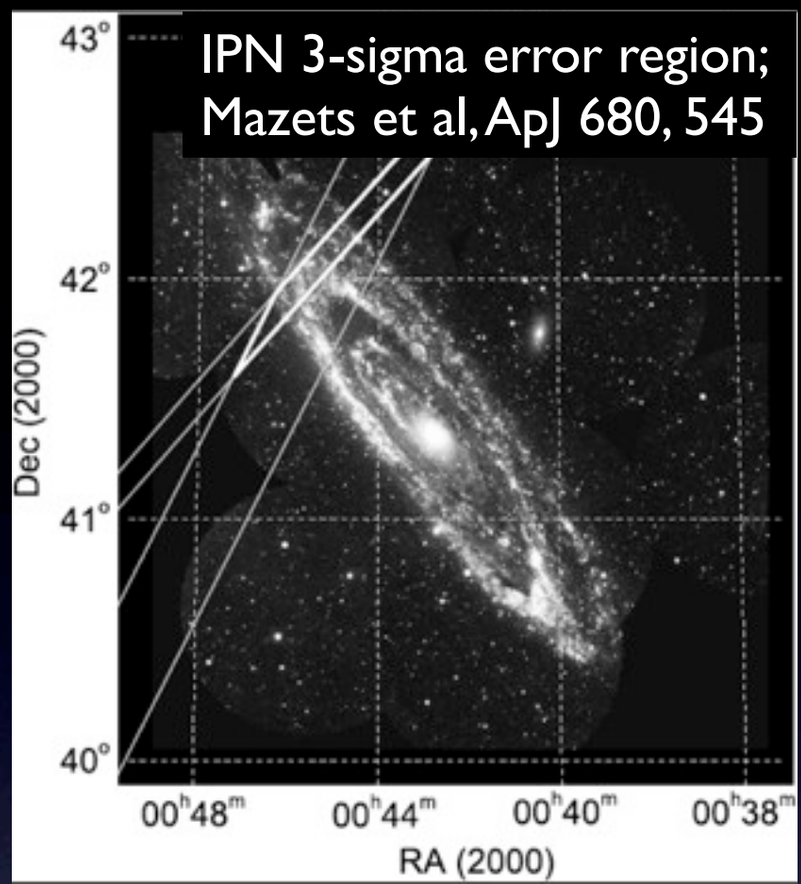
$\langle N_{long} \rangle \simeq 7 \times 10^{-6}$ /year

$\langle N_{local} \rangle \simeq 7 \times 10^{-3}$ /year

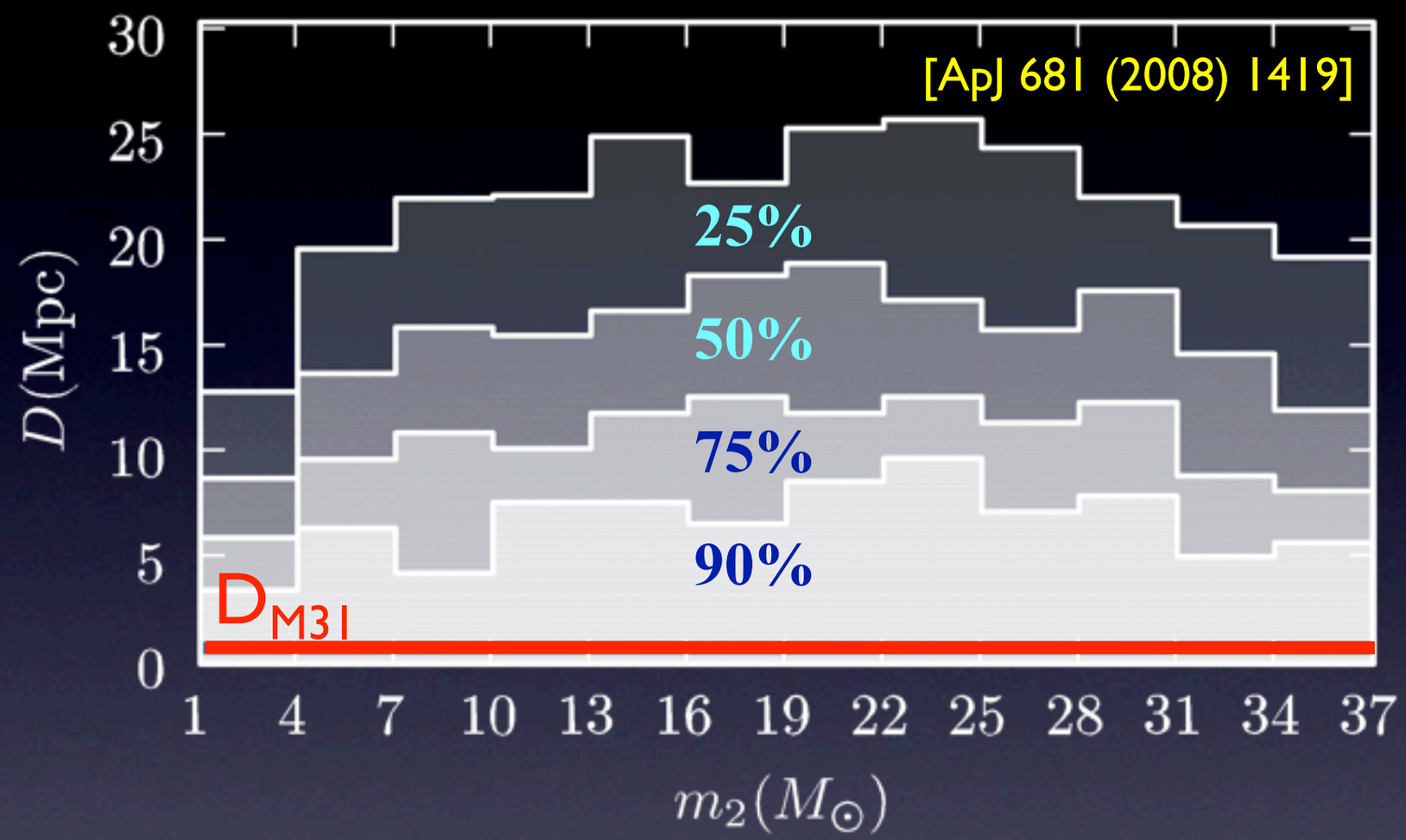
Advanced Detectors will be 10 times more sensitive, probe 1000 times larger volume: good probability to observe GRB-GW coincidence.

GRB 070201

"intense, short, hard GRB" (GCN 6088)



Error box Consistent with Andromeda (M31) ~770 kpc

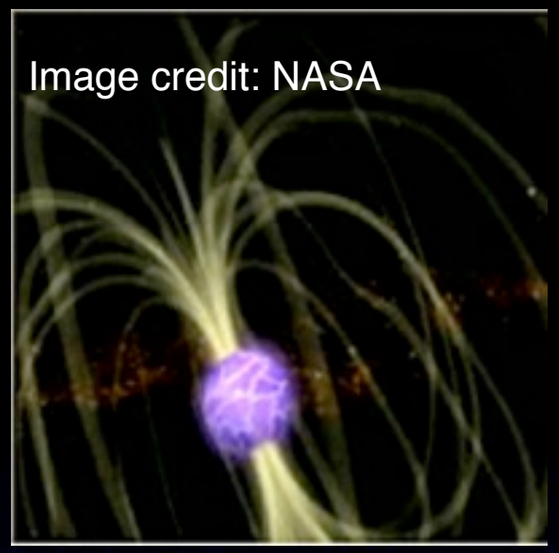


Absence of a GW signal in LIGO: exclude compact binary coalescence progenitor in M31 with more than 99%CL

Most likely an SGR giant flare in Andromeda

Mazets et al., ApJ 680, 545
Ofek et al., ApJ 681, 1464

Neutron Star Physics



Soft gamma repeater (SGR) flares

[PRL 101 (2008) 211102 ; ApJL 701 (2009) L68] ; Ap. J. 734 (2011) L35

Crustal cracking in neutron stars may excite quasi-normal modes which can emit gravitational waves

SGR 1806-20, SGR 1900+14: for certain assumed waveforms, gravitational wave energy limits are as low as few × 10^{45} erg, comparable to EM energy in giant flares

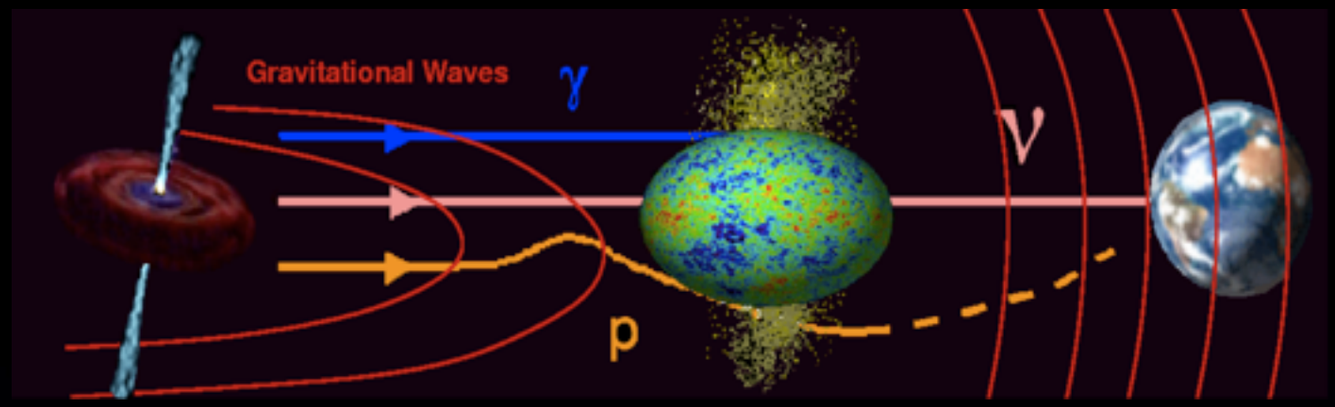
Long-lived quasiperiodic GWs after giant flare ? [PRD 76 (2007) 062003]

SGR 1806-20 hyperflare of December 27, 2004: GW energy limits are comparable to total EM energy emission

Mechanism for pulsar time glitches? [PRD 83 (2011) 042001]

Search for ringdown around the August 2006 timing glitch of the Vela pulsar for model selection, limits a few × 10^{45} erg

High Energy Neutrinos (10^5-10^{10} GeV)



Ongoing collaboration with Antares, IceCube

No absorption/diffusion: travel cosmological distances

(as opposed to photons - dust, gas, microwave or IR background)

No deflection by magnetic fields: trace back

(as opposed to charged cosmic rays)

weakly interacting: escape from dense objects

CQG 25, 114039, 2008
arXiv:0807.2567
arXiv:0908.2454
arXiv:1101.4669

Long GRBs, Short GRBs, "Failed GRBs"

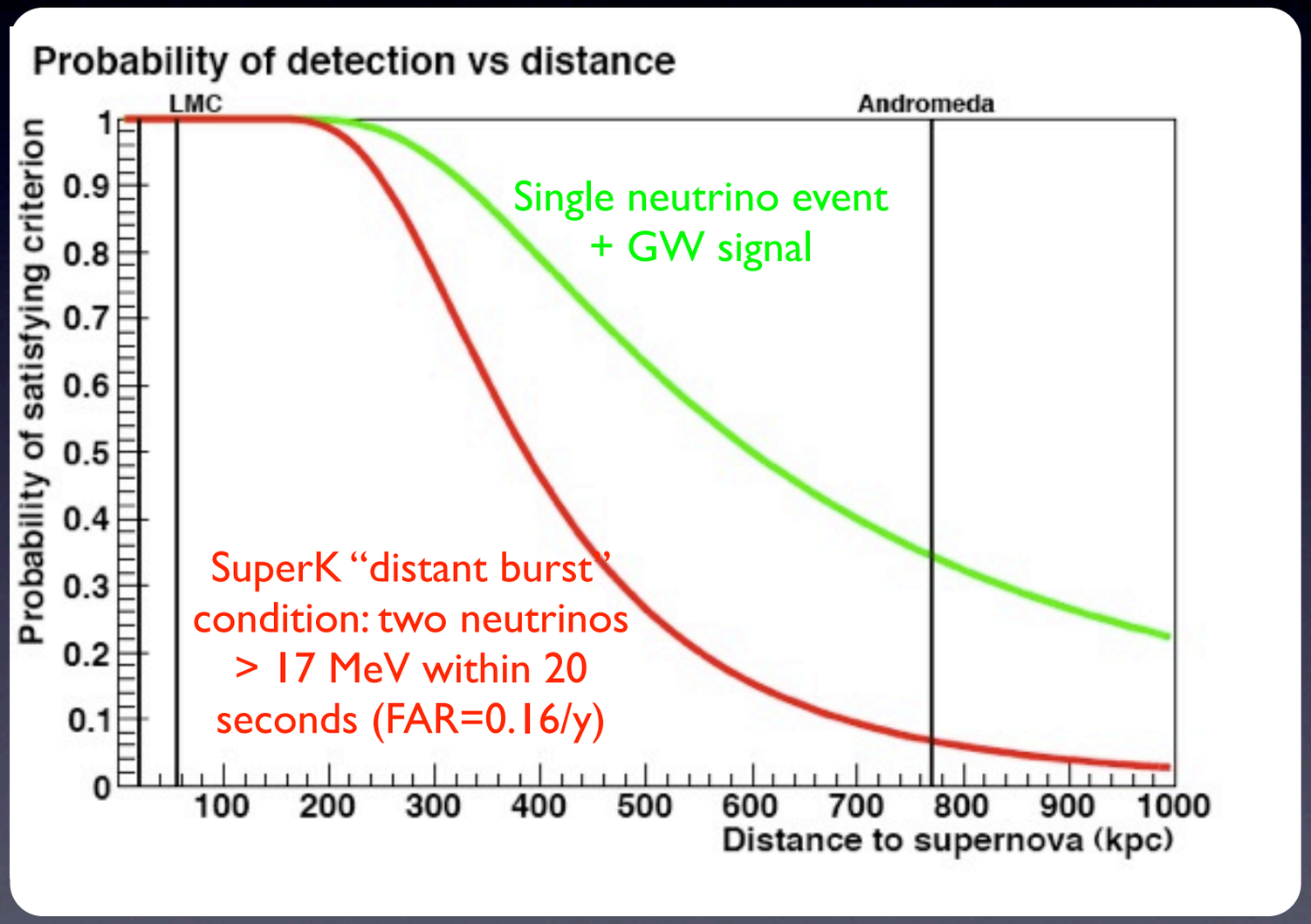
Talk by Irene di Palma

Low Energy Neutrinos (1-100 MeV)

Core-collapse supenovae

Joint search would bring greater detection confidence and improved sensitivity

Advanced detectors: could constrain models in galactic neighborhood, most extreme models to Andromeda.



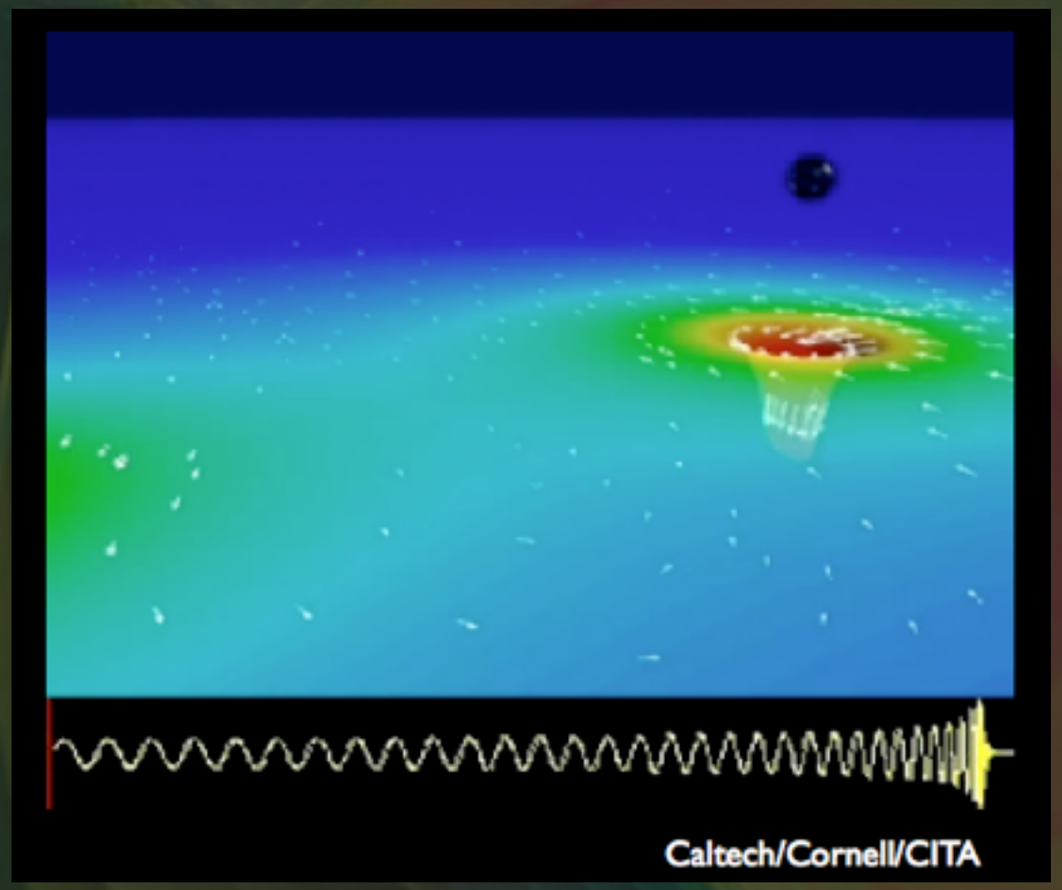
At proposal stage arXiv:1002.1511

Incorporating Models in the Analysis

1. Can numerical relativity help improve how we search for gravitational waves?
2. Once we have a detection, what can we say about the source?

Most progress incorporating models in the analysis so far: Binary Black Hole Coalescences, vacuum solutions - ongoing collaboration with Numerical Relativity community

CQG 26 (2009) 165008

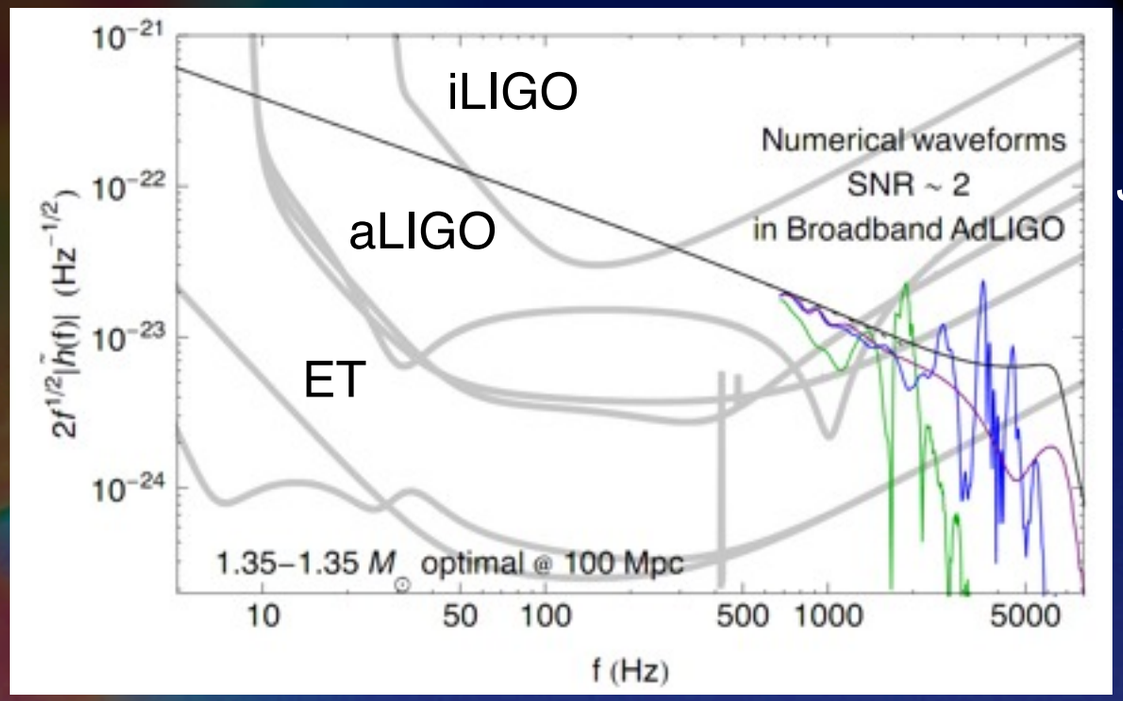


Background Image Credit: Werner Berger/AEI

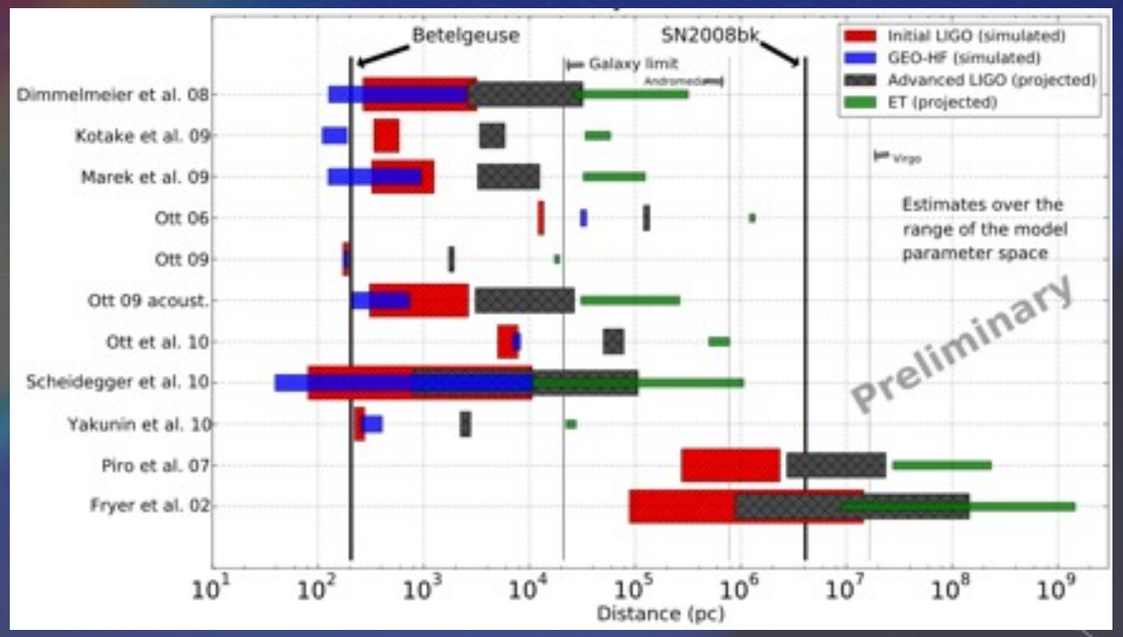
Matter Effects

Circularity of the problem: relativistic astrophysics needs observations to constrain models. Some examples:

- Wide set of phenomena: (NS-NS, NS-BH, SNe, single NS, GRB engine, etc.). Examples of current interests:
  - post-merger oscillation from neutron star coalescences (NS equation of state, tidal disruption effects)
  - EM counterparts to black hole binaries
  - core-collapse supernovae (mechanism, 3D models, numerical vs analytical)



Source: J. Read, GWPAW 2011



Talk by Alan Weinstein

Background Image Credit: Marek & Janka (2009)

Conclusions

1. Initial Detector Era: GW transient searches have placed meaningful constraints on individual objects and events, source populations, total energy density in gravitational waves.

2. Preparing for detection: increasing confidence, increased interaction with modeling and astrophysics community, to maximize science output.

The Advanced Detector era is around the corner!