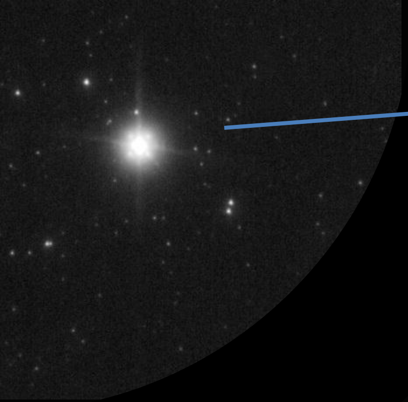


Supernova 2008bk

Credit: ESO/S. Mattila, S. Smartt, M. Crockett, J. Eldridge, J. Maund and J. Danziger

Prospects for Detecting Gravitational Waves from Supernovae

Peter Shawhan

University of Maryland

Gravitational Wave Physics & Astronomy Workshop

Milwaukee, 27 January 2011

LIGO-G1100026

An Attractive Target

Supernovae occur frequently and liberate up to

~10^{53} erg

~1% as EM radiation

- Optical
- Radio
- X-ray
- Gamma ray

~99% as neutrinos

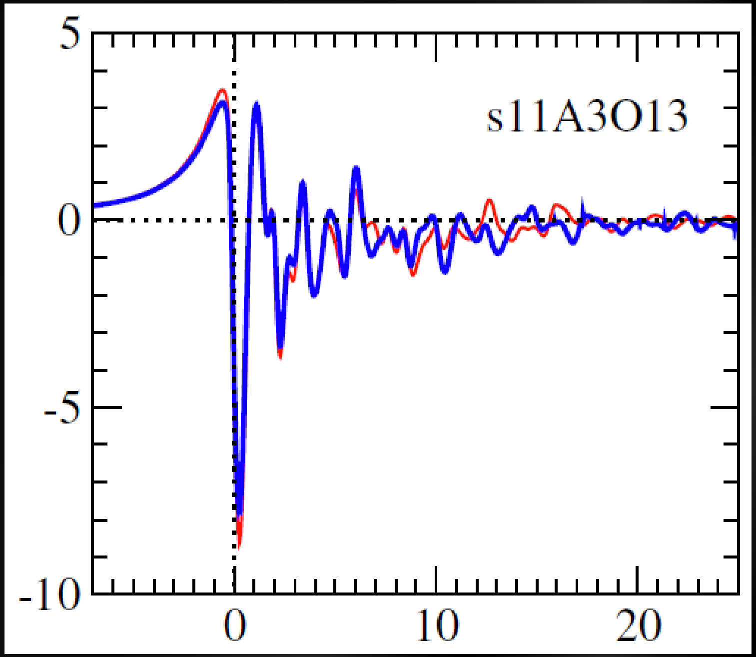
- Low-energy
- High-energy

??? as gravitational waves

SN GW Emission Mechanisms

(See Ott 2009 [CQG 26, 063001] and Fryer & New 2011 [LRR-2011-1] and refs therein)

- Collapse and bounce
- Rotational instabilities
- Convection
- Standing accretion shock instability (SASI)
- Proto-neutron star oscillations (*g*-modes)



Dimmelmeier et al. 2008 [PRD 78, 064056]

SN GW Emission Mechanisms (2)

Anisotropic matter outflow

Anisotropic neutrino emission

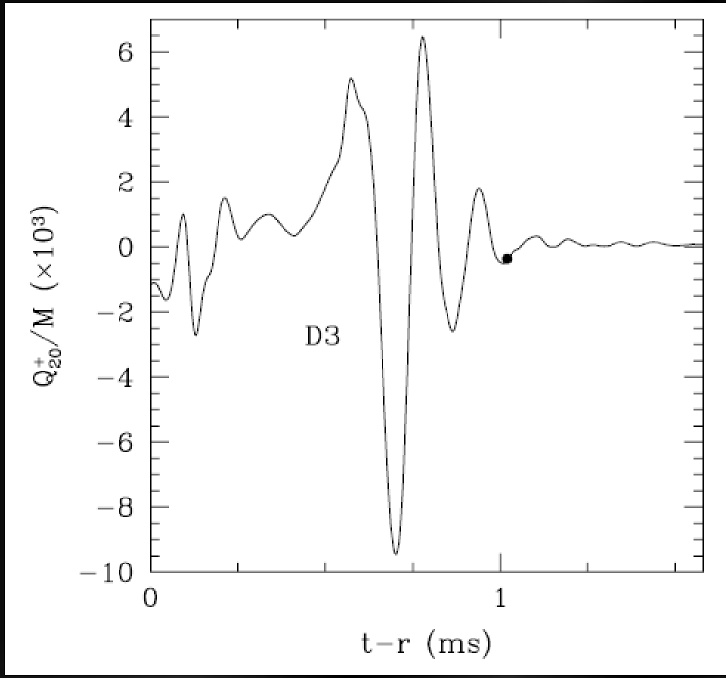
Postbounce *r*-modes

Black hole formation →

Fallback onto black hole

- Possibly fragmented disk

… and more !



Baiotti et al. 2007 [CQG 24, S187]

What Waveforms Can We Expect?

Waveform	Waveform	Polarization
Collapse and bounce	spike	linear
Rotational instabilities	quasiperiodic	circular
Convection	broadband	mixed
SASI	broadband	mixed
PNS *g*-modes	quasiperiodic	linear
Anisotropic matter outflow or ν emission	slow growth with memory	linear
r-modes	quasiperiodic	circular
Black hole formation	QNM ringing	lin/circ
Fallback onto black hole	driven QNMs	”

Summary of Plausible Waveforms

Wide variety of morphologies !

Not amenable to exact waveform modeling

Short duration

- From a few milliseconds up to a few seconds

In frequency band of ground-based detectors

GW Burst Search Methods

Primary tools used so far by LSC+Virgo :
generic burst search algorithms

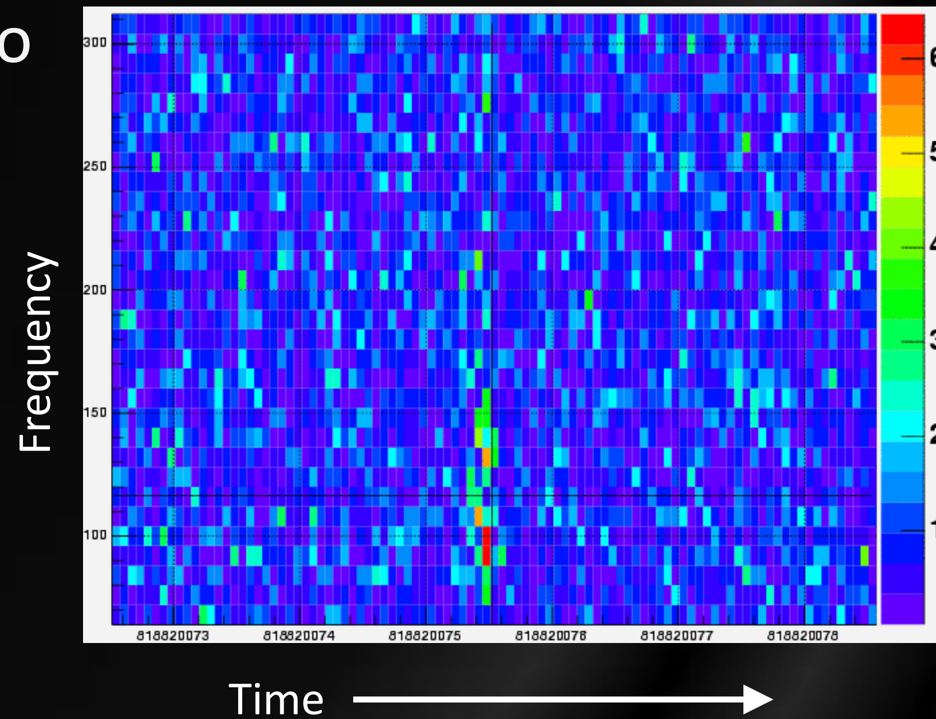
Goal: be able to detect *any* signal

- … if it has sufficient power within the sensitive frequency band of the detectors
- … and is "short"

“Excess Power” Search Methods

Decompose data stream into time-frequency pixels

- Fourier components, wavelets, Q transform, etc.
- Several implementations of this type of search



Normalize relative to noise as a function of frequency

Look for “hot” pixels or clusters of pixels

Can use multiple ($\Delta t, \Delta f$) pixel resolutions

…

Signal Consistency Tests

Crucial since there is no morphological distinction between a GW burst and an instrumental glitch !

Coincidence

- Require signals found in individual detectors to have compatible times, frequencies, amplitudes

Cross-correlation

- Look for same signal buried in two data streams
- Checks for consistent morphology, regardless of relative amplitude

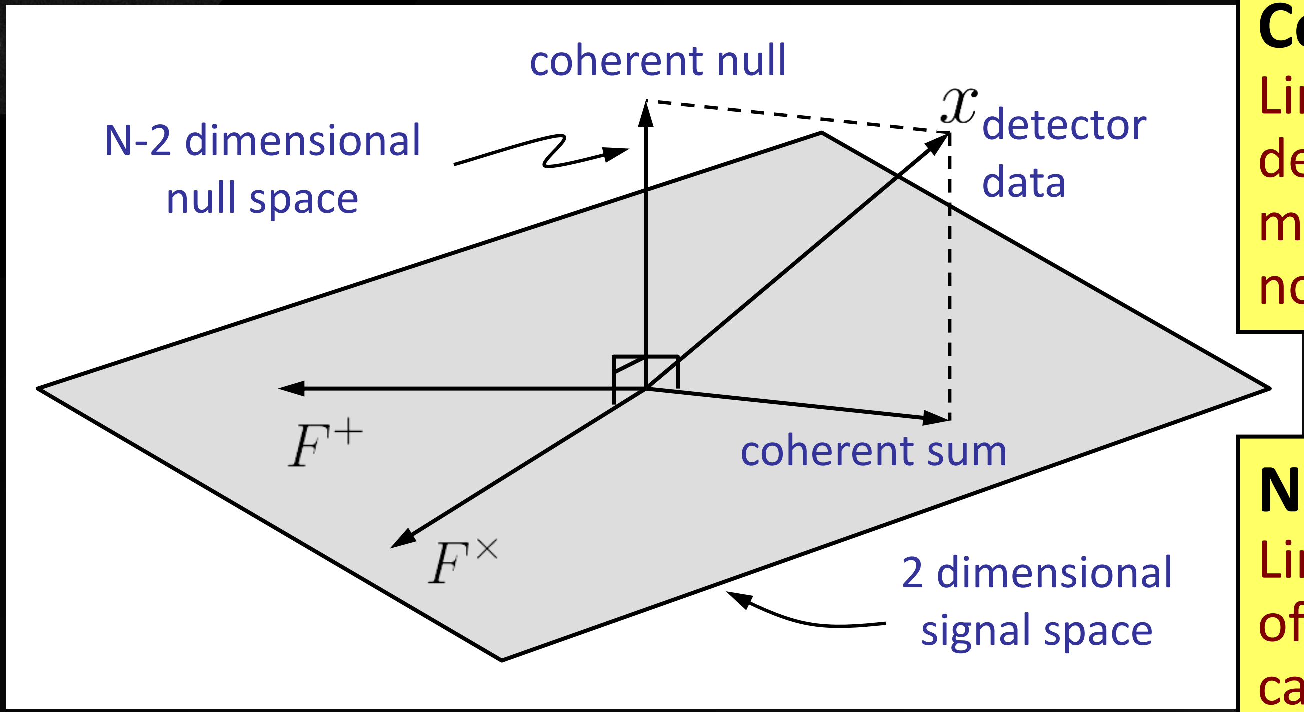
Coherent Analysis

Each detector measures a linear combination of $h_+(t)$ and $h_\times(t)$ (assuming that GR is correct)

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

- 2 sites can uniquely determine $h_+(t)$ and $h_\times(t)$ for an arbitrary signal, *in the absence of noise and if the arrival direction is known*
- 3 or more sites *over-determine* $h_+(t)$ and $h_\times(t)$ if the arrival direction is known

Coherent Analysis (2)



Coherent sum:
Linear combination of detector data that maximizes signal to noise ratio

Null sum:
Linear combination(s) of detector data that cancel the signal provide useful consistency tests

A maximum likelihood problem

- Maximize over arrival directions
- Can penalize physically unlikely signal hypotheses

Benefits of an EM/Neutrino Signal

Know the sky position of the event

- Only do coherent analysis for that direction
- Can do decent search with as few as 2 GW detectors

Know the event time

- Avoids vast majority of glitches during science run
- Hopefully avoids gaps in data

Could also limit search to certain waveform types

Benefits of an EM/Neutrino Signal (2)

Limiting the search reduces the background, allowing the search threshold to be lowered

- By a factor of ~2, judging from LSC-Virgo GRB-triggered GW burst search
  LSC+Virgo 2010 [ApJ 715, 1438]

MASIL Imaging Team

Knowing host galaxy solidifies interpretation of any GW search

- Detection: get estimate of emitted energy, relative timing and polarization with respect to EM/ν signal
- Non-detection: yields a limit on emitted energy

Value of Guidance from Modeling

Time window in which GW signal is expected

- Seconds or less from low-energy neutrinos
- Seconds to minutes (?) from high-energy neutrinos and gamma rays
- Hours to days (?) from optical light curve
  - Can place best limits if 2 or more detectors were operating during entire window

Waveform models to guide detection algorithms

- Even just characteristic frequency, bandwidth, and/or duration could help

Modeling Range of Plausible Sources

Estimate distance to which a GW signal could plausibly be detected from various sources:

- Ordinary core-collapse supernovae
- Accretion-induced collapse of white dwarf to NS
- Dim low-mass (electron-capture) supernovae
- Dim supernovae from high-mass stars
- Supermassive stars

Lack of detection could constrain models

What Can GWs Say About SN Astrophysics?

Provide direct information about the core dynamics that power the supernova

e.g. distinguish among shock revival mechanisms to drive explosion *(Ott 2009 [CQG 26, 063001])*

- MHD with rapid rotation
  - Expect strong bounce, likely rotational instabilities
- Acoustic (PNS *g*-mode) mechanism
  - Expect strong GW emission from PNS oscillations
- Neutrino heating
  - Weak convection/SASI would be main GW signal

How Far Can GW Search Reach?

Maximum distance to detect a given signal, if relatively narrowband:

$$\text{distance} \approx \sqrt{\frac{G_N}{\pi^2 c^3}} \frac{\sqrt{E_{GW}}}{f\, h_{rss}^{50\%}}$$

Central frequency (f)

Search sensitivity ($h_{rss}^{50\%}$)

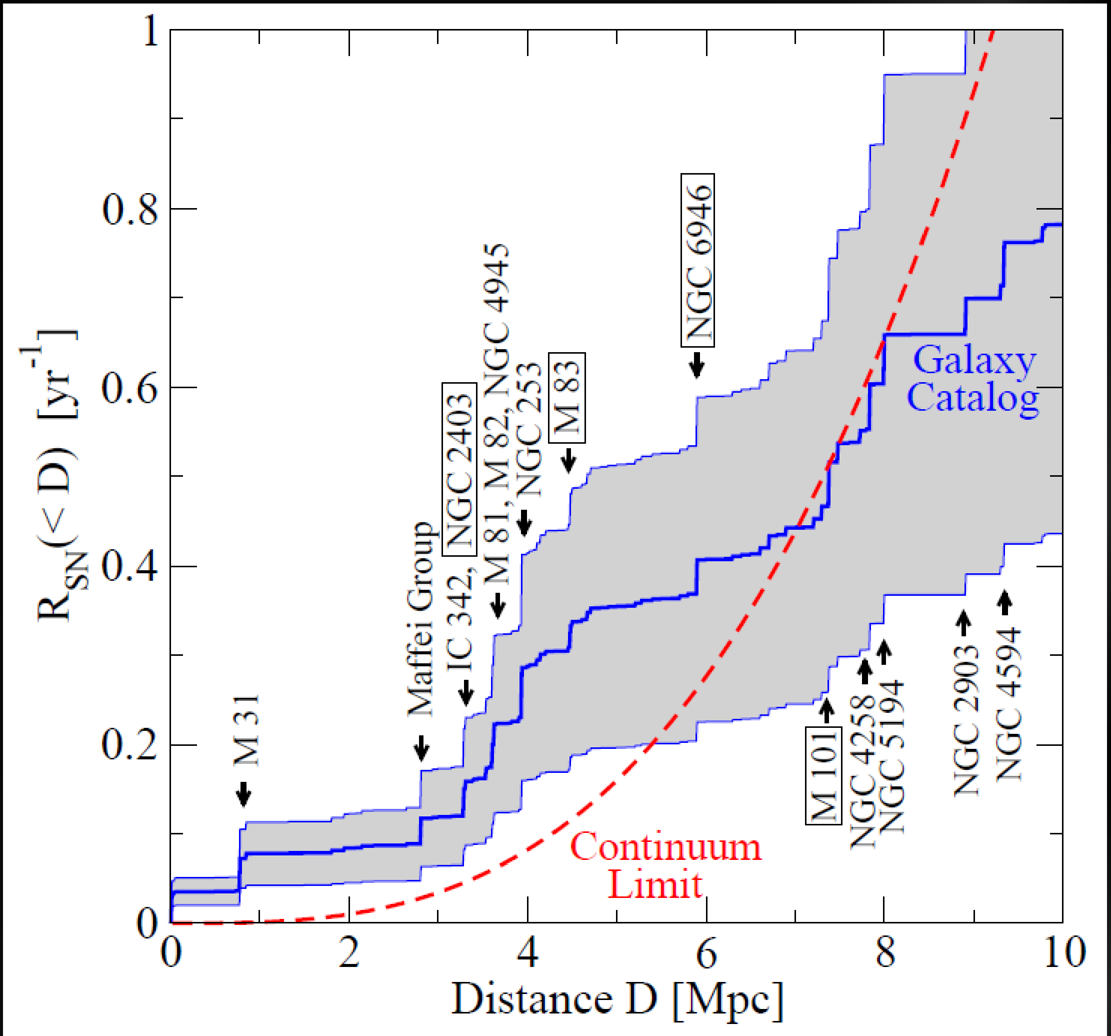
Note: for a given E_{GW}, high-frequency signals are harder to detect

How Far Do We Need to Reach?

Galactic rate ~1 per 30–50 years

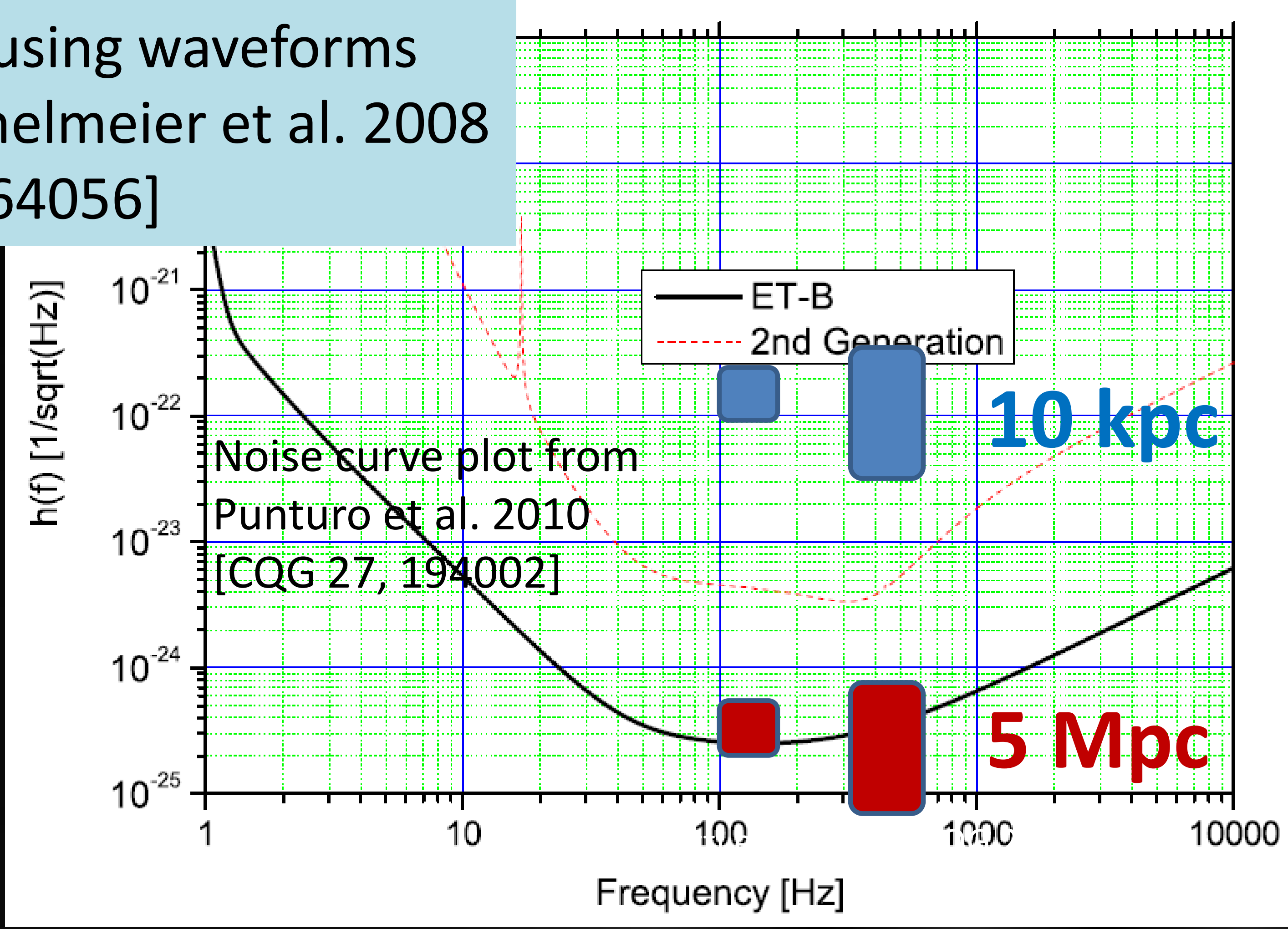
Expect one core-collapse SN within 5 Mpc every 2–5 years

Ando et al. 2005 [PRL 95, 171101]



Detectability Example: Bounce

Estimated using waveforms from Dimmelmeier et al. 2008 [PRD 78, 064056]



Noise curve plot from Punturo et al. 2010 [CQG 27, 194002]

What if GR is Wrong?

Alternative theories of gravity permit additional modes

besides the tensor modes of GR

e.g. scalar-tensor theories

- Brans-Dicke is one
- Actual coupling depends on the specific theory
- Could allow SNe to be detected from farther away?

See talk by K. Hayama

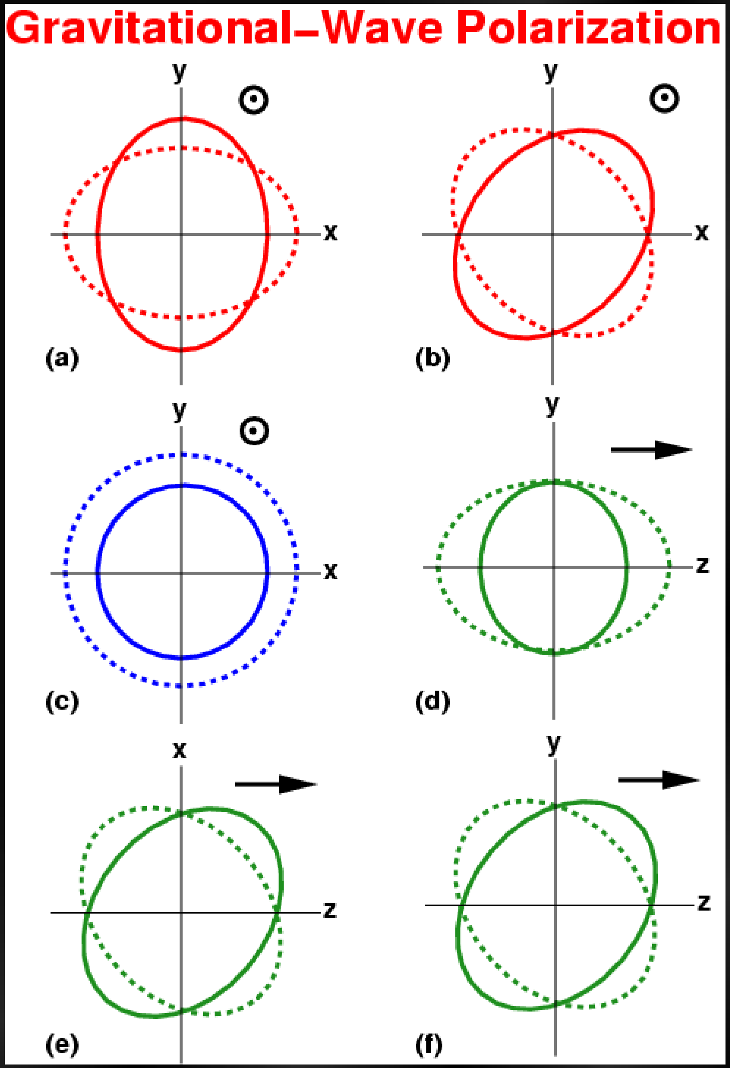


Figure from Will 2006 [LRR-2006-3]

Could We Be Missing Nearby SNe?

Some SNe can be obscured & unseen optically

- In optically thick environments, or behind the Galactic center / disk
- Historical examples: Cas A; 2008 SN in M82

Any Galactic SN will have a extremely strong low-energy neutrino signal

- But current neutrino detectors don't reach beyond the Local Group

Infrared & radio could see optically obscured SNe

- Are currently planned surveys sufficient?

Summary and Top Questions

Supernovae are important GW search targets

- Many plausible astrophysical processes
- But detecting the (probably) weak GWs is hard

Questions:

- What more can modeling tell us about time windows and expected signatures?
- What can observations and modeling tell us about particularly promising SN classes?
- Is a special effort needed to be sure of knowing about all nearby supernovae?
- Would there be value in a GW-triggered SN search using IR and/or radio?