# Gravitational Waves, Astrophysics and LIGO

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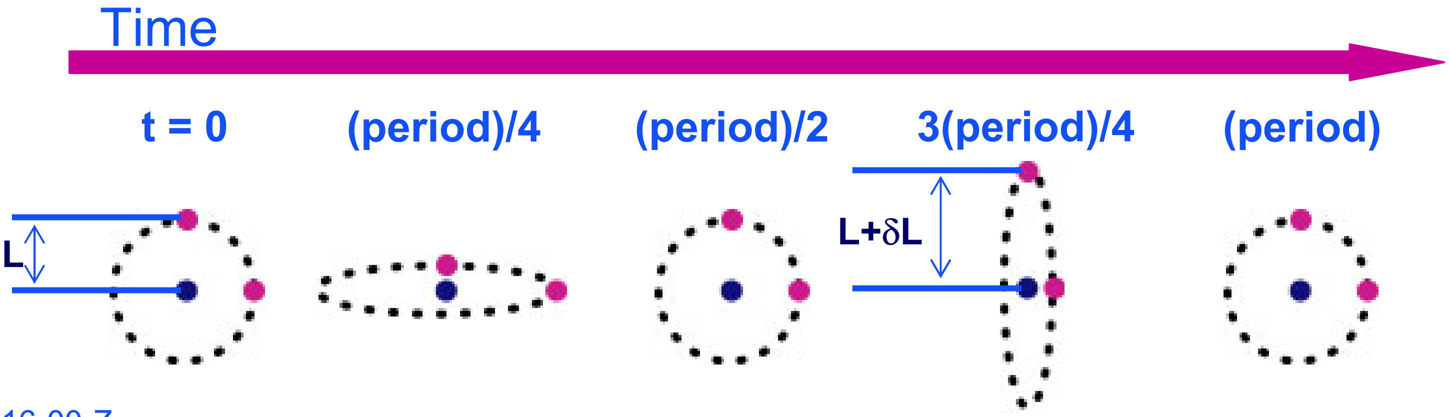
# Gravitational Waves

- Einstein's Equations:
  - » When matter moves, or changes its configuration, its gravitational field changes.
  - » This change propagates outward as a ripple in the curvature of spacetime: a gravitational wave.
- As gravitational waves pass, they change the distance between neighboring bodies
- Fractional change in distance is the strain given by $h = \delta L / L$

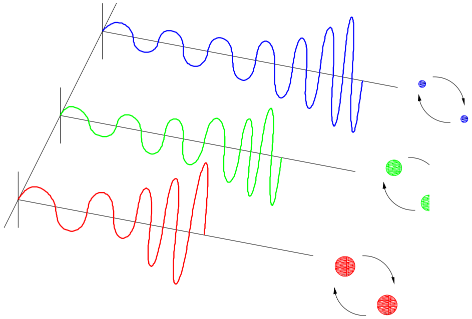


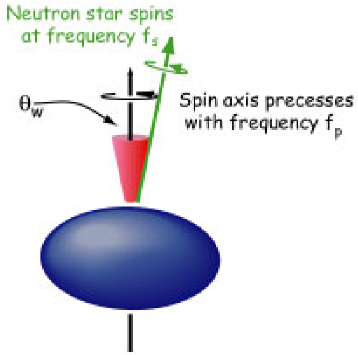
Time

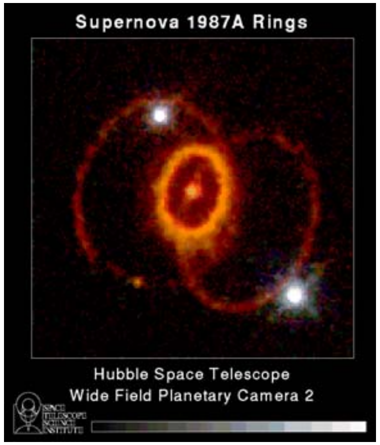
**t = 0** **(period)/4** **(period)/2** **3(period)/4** **(period)**

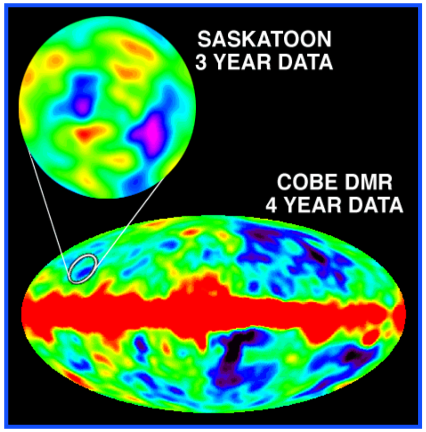
# Astrophysical Sources of Gravitational Waves

- Compact binary systems
  - Black holes and neutron stars
  - Inspiral and merger
  - Probe internal structure, populations, and spacetime geometry
- Spinning neutron stars
  - LMXBs, known & unknown pulsars
  - Probe internal structure and populations
- Neutron star birth
  - Tumbling and/or convection
  - Correlations with EM observations
- Stochastic background
  - Big bang & other early universe
  - Background of GW bursts



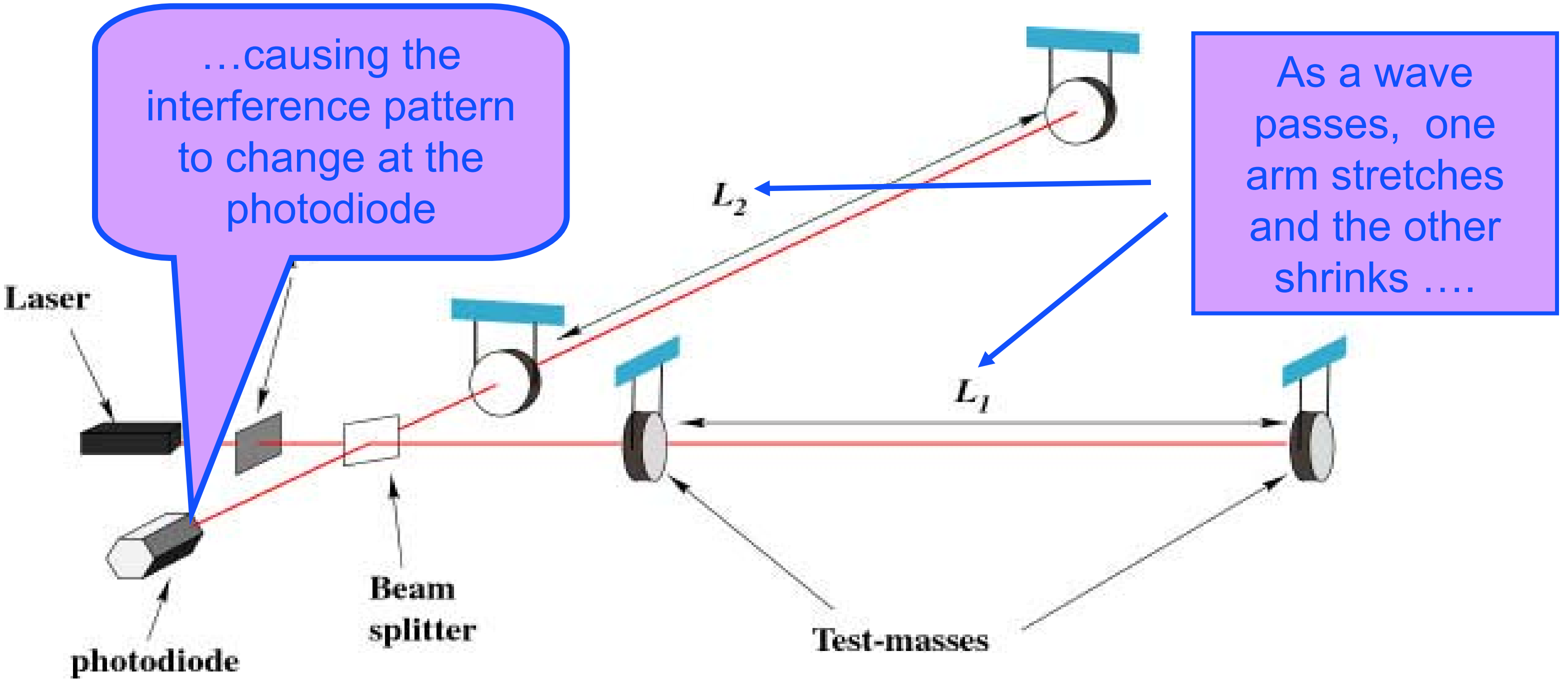






# How LIGO Works

- LIGO is an interferometric detector
  - » A laser is used to measure the relative lengths of two orthogonal cavities (or arms)
- LIGO design goal
  - » Arm length of 4km chosen so LIGO can measure $h = \delta L/L \sim 10^{-21}$ which is an astrophysically interesting target



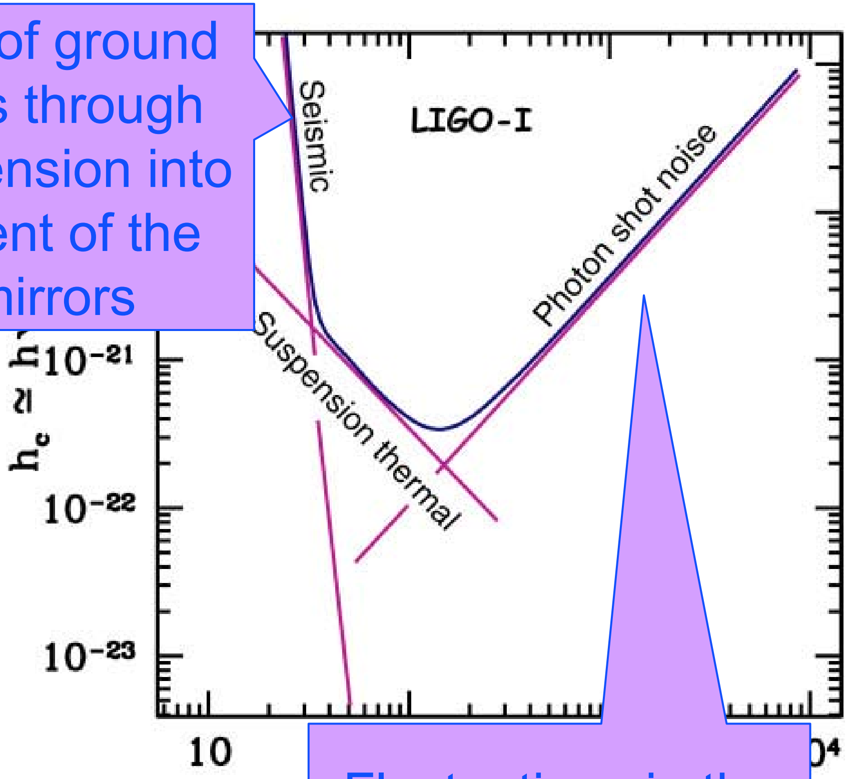
…causing the interference pattern to change at the photodiode

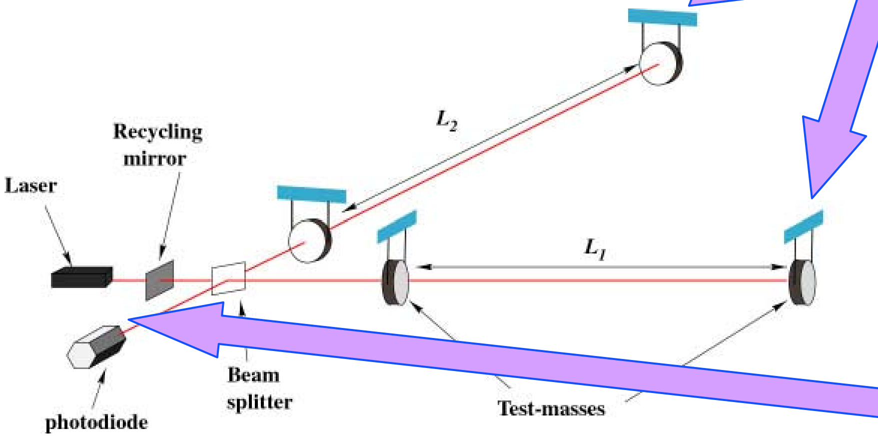
As a wave passes, one arm stretches and the other shrinks ….

# LIGO Sensitivity

- The noise in the LIGO interferometers is dominated by three different processes depending on the frequency band

Shaking of ground transfers through the suspension into movement of the test mirrors





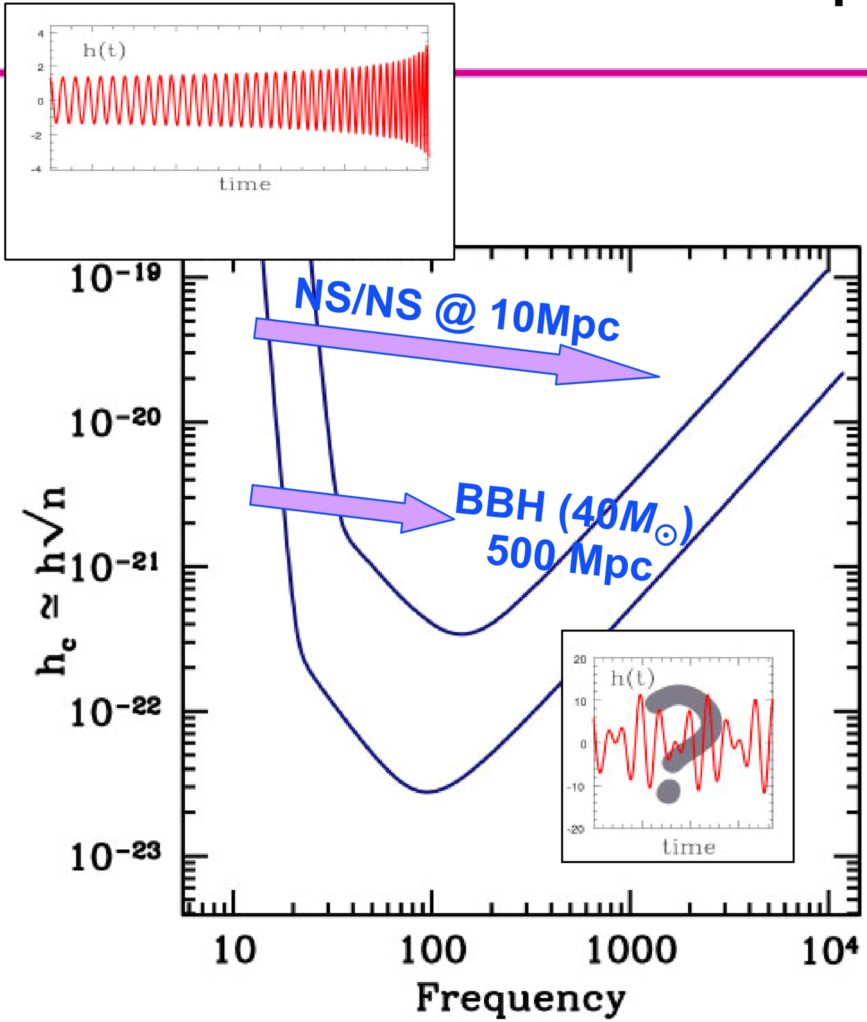
Fluctuations in the number of photons arriving at the photodiode

# LIGO Observatories

Hanford: two interferometers in same vacuum envelope (4km, 2km)

Livingston: one interferometer (4km)

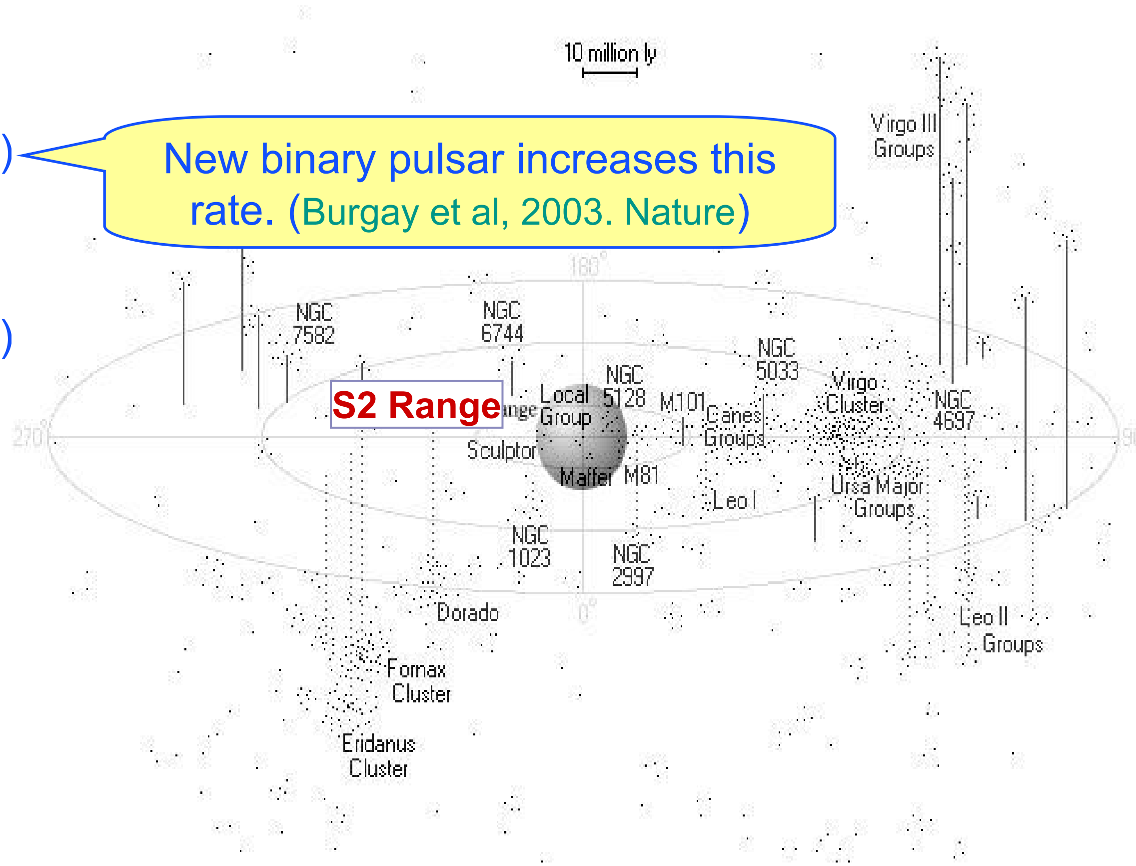
# Inspiral and Merger of Compact Binaries



- LIGO is sensitive to:
  - » Gravitational waves from binary systems containing neutron stars & stellar mass black holes
  - » Last several minutes of inspiral driven by GW emission
- Neutron Star Binaries
  - » Known to exist (Hulse-Taylor)
- NS/BH, BH/BH
  - » New science: rates, dynamics of gravitational field, merger waves

# Possible Astronomical Studies

- Probe populations of
  - Neutron star binaries (NS/NS)
  - LIGO range =20Mpc, N< 1/(4yr)
  - Black hole binaries (BH/BH)
  - LIGO range=105Mpc, N<1/(2yr)
  - NS/BH binaries
- Probe the cores of dense star clusters
  - via waves from NS/NS, BH/BH, & NS/BH binaries formed there
- Study $\gamma$-ray bursts
  - NS/NS mergers?



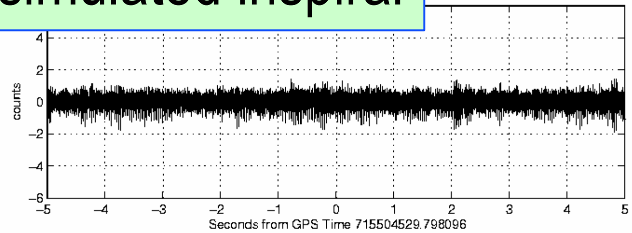
New binary pulsar increases this rate. (Burgay et al, 2003. Nature)

**S2 Range**

Image: R. Powell

# Data analysis: matched filtering

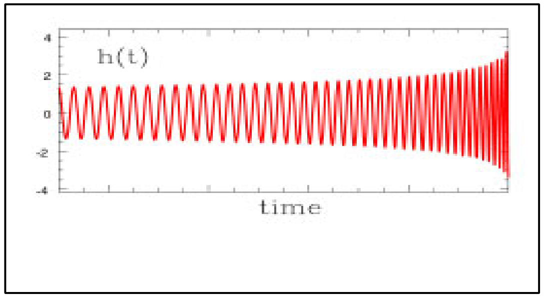
GW Channel
+ simulated inspiral



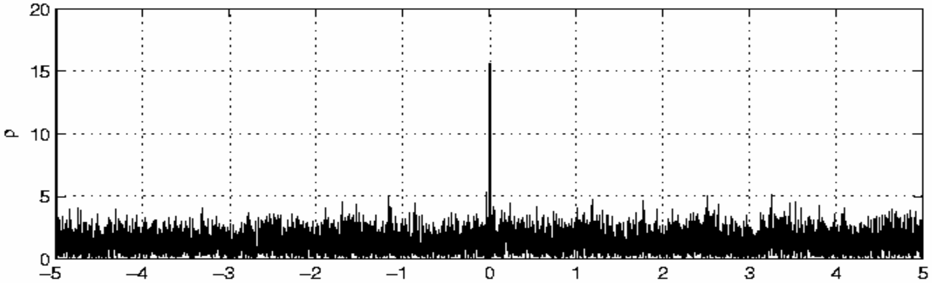
★

Filter to suppress
high/low freq

★



SNR

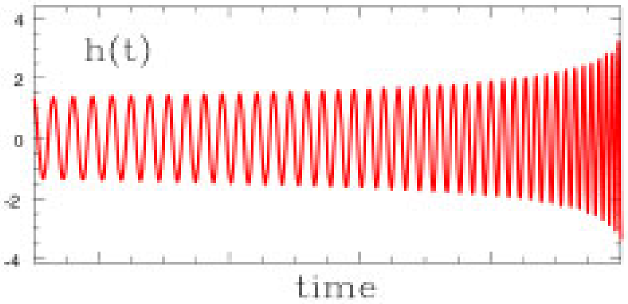


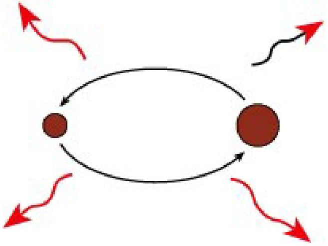
Coalescence Time

- **Theoretical challenge: compute waveforms to sufficient accuracy**

# Information content of gravitational waves

- Inspiral waves
  - » post-Newtonian approximation to Einstein's equations
- Relativistic effects are strong
  - » Frame dragging & wave tails affect the orbital evolution
- Parameter estimation ($\rho=10$)
  - » Masses (few %)
  - » Distance (~10%)
  - » Location (1 degree)





- Spins modulate waveform
  - » Important in NS/BH systems
  - » Measurement accuracy could be a few %, but uncertain

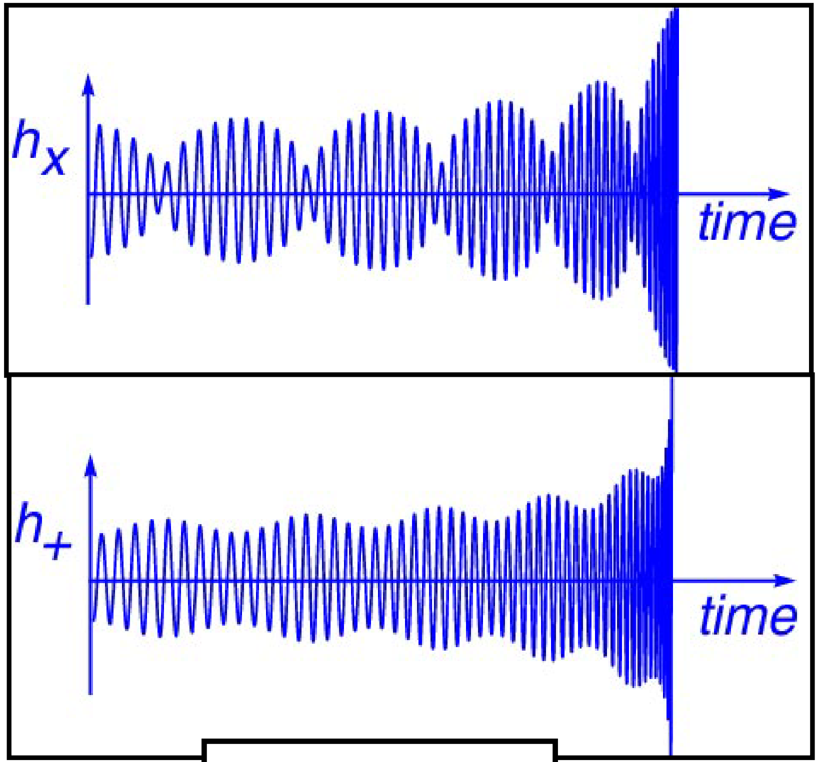


Image: Kip Thorne

# Post-Newtonian Expansions of Einstein's Field Eqns

- Expand spacetime metric in powers of
  - » (orbital velocity) / (speed of light) = v/c
  - » $\sim[(G/c^2)(M/R)]^{1/2}$
- Hulse & Taylor binary pulsar:
  - » Periodic effects [periastron shifts, …]: $(v/c)^2$ beyond Newton
  - » Secular effects [GW induced inspiral]: $(v/c)^5$ beyond Newton
- NS/NS with LIGO:
  - » Periodic - $(v/c)^6$ beyond Newton; Secular - $(v/c)^{11}$ beyond Newton
  - » PN approximation is in hand (Blanchet et al.)

# Explore non-linear dynamics of spacetime via BH/BH collisions

- About 10% of holes' mass converted to gravitational radiation
- Contrast with nuclear explosions where figure is about 0.5%

- PN expansion fails [last ~30 cycles of inspiral waves]
- Non-matched filtering search strategy only decreases amplitude sensitivity by factor ~4, but we need PN + numerical relativity for information extraction

**Most Violent Events in Universe ---**

**No EM signal !**

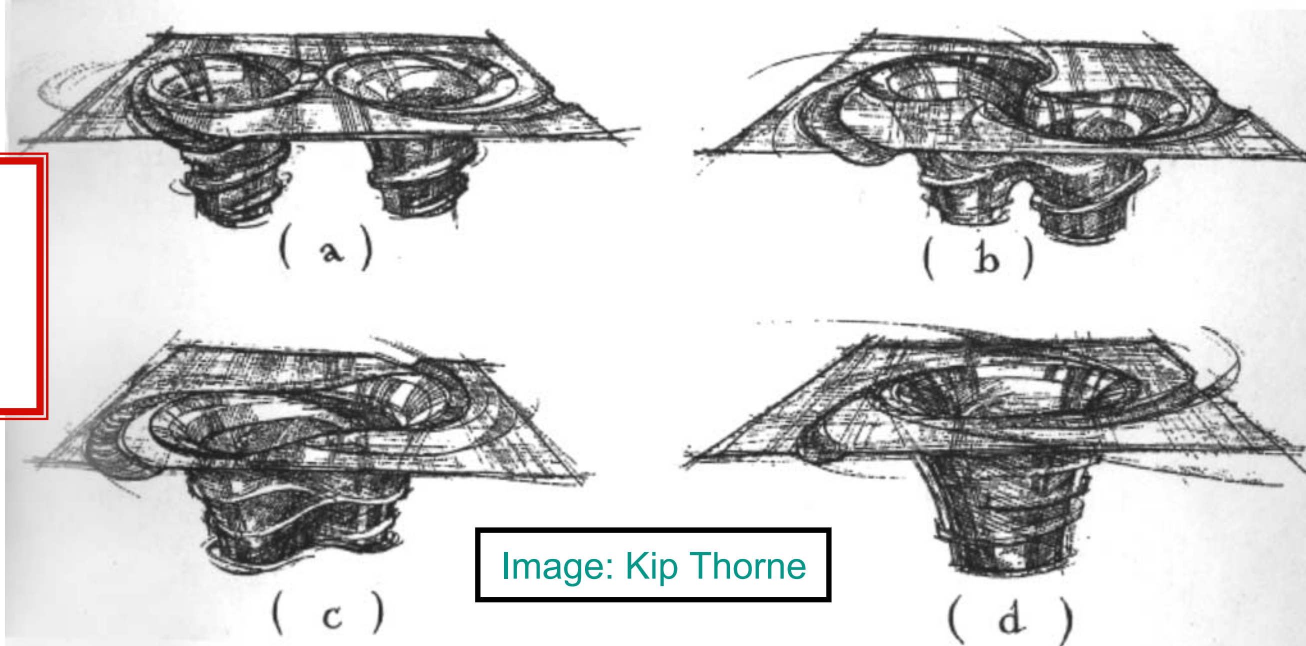


Image: Kip Thorne

# Compact binaries with Advanced LIGO

- Neutron star binaries
  - Range =350Mpc
  - N ~ 2/(yr) – 3/(day)
- Black hole binaries
  - Range=1.7Gpc
  - N ~ 1/(month) – 1/(hr)
  - Non-linear dynamics of merger
  - Ringdown accessible for high masses
- BH/NS binaries
  - Range=750Mpc
  - N ~ 1/(yr) – 1/(day)
  - Tidal disruption brings NS radius and EOS information (if combined with numerical simulations)

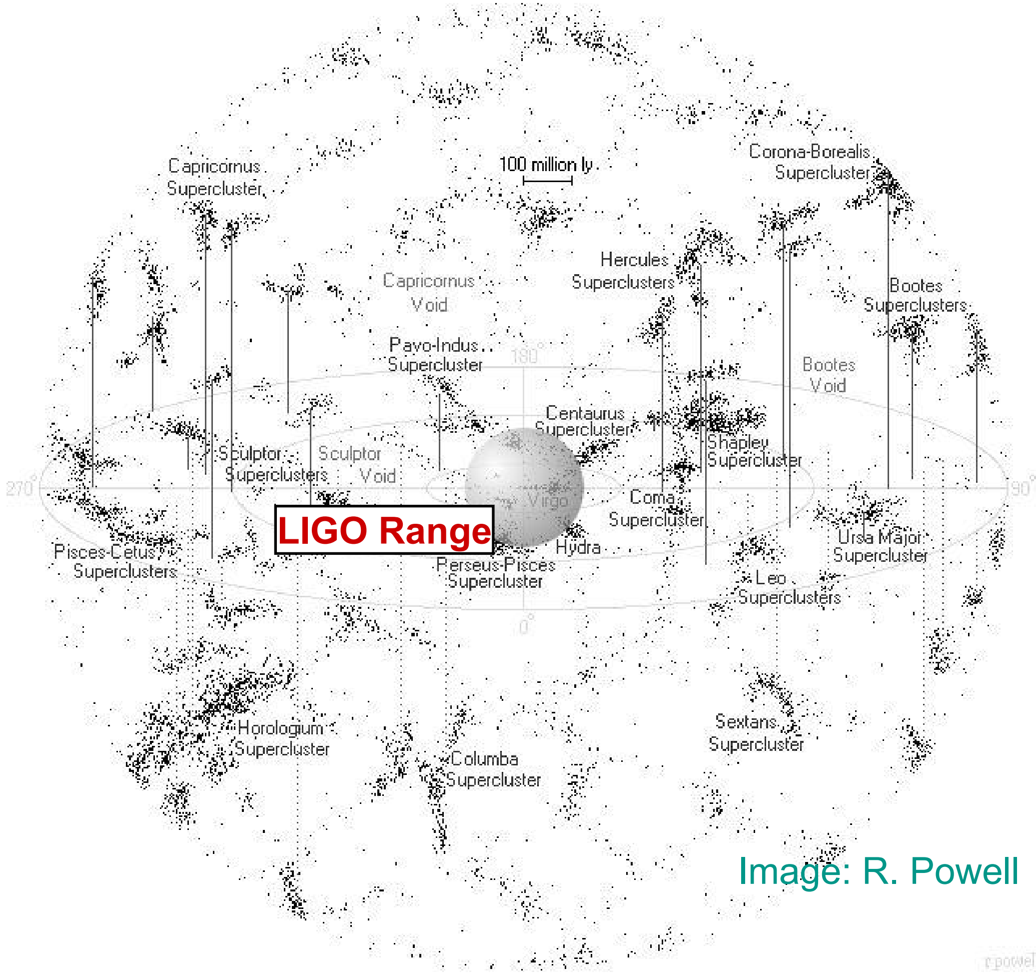
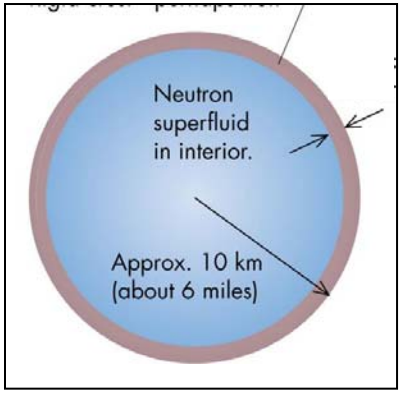
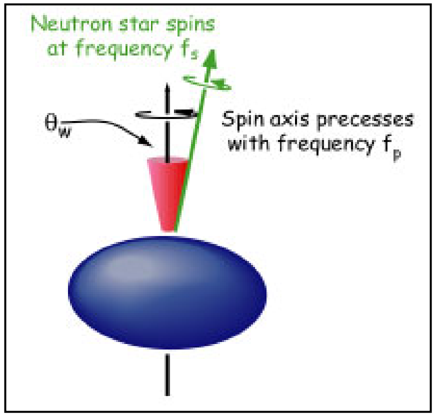


Image: R. Powell

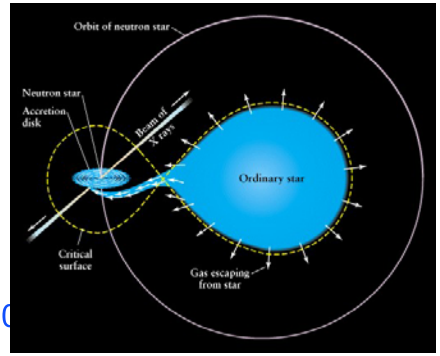
# Spinning Neutron Stars



$$\varepsilon = \frac{I_1 - I_2}{I_3} < 10^{-5}$$



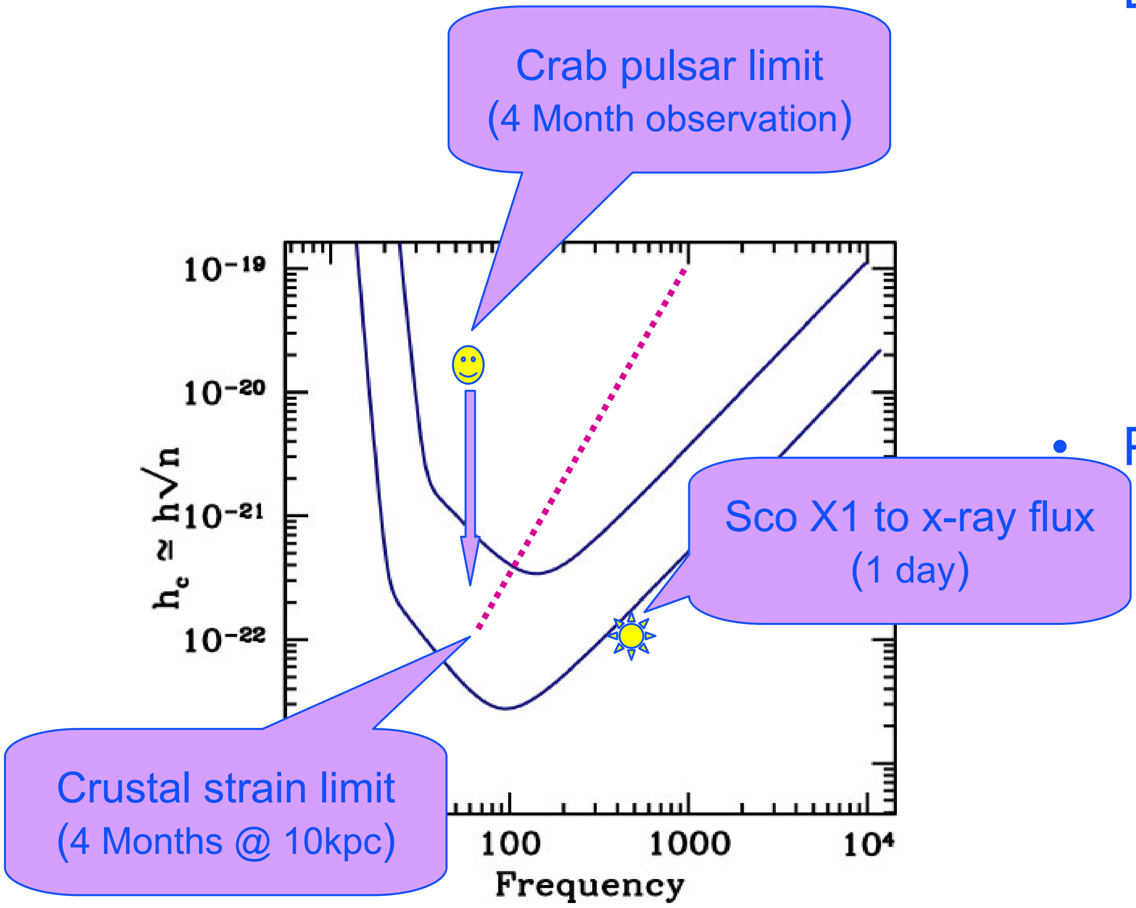
$$\varepsilon = \frac{I_3 - I_1}{I_3}\theta_w$$



- General properties.
  - » Long lasting, nearly periodic.
  - » No accurate modeling, use phenomenological models for waveforms.
- Electromagnetically loud sources:
  - » Known isolated pulsars: waves from crustal strain or wobbling
  - » Accretion driven instabilities or asymmetries

$$h_{char} \approx 10^{-19}\,\frac{\varepsilon}{10^{-5}}\left(\frac{f}{1\,\mathrm{kHz}}\right)^{5/2}\left(\frac{T}{10^{7}\ \mathrm{s}}\right)^{1/2}$$

# Electromagnetically Visible Sources



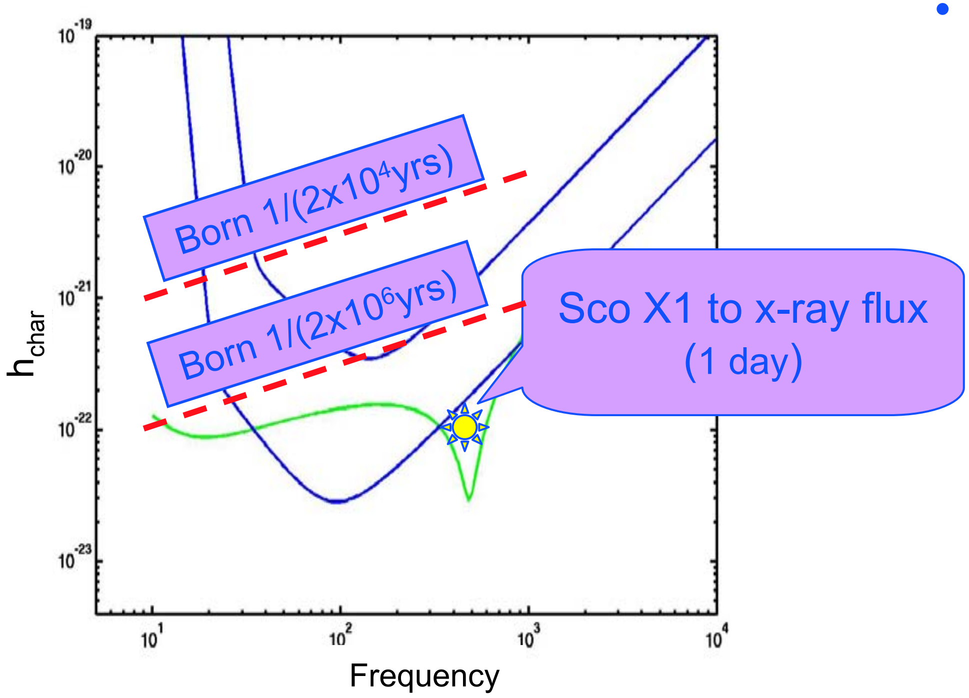
Crab pulsar limit
(4 Month observation)

Sco X1 to x-ray flux
(1 day)

Crustal strain limit
(4 Months @ 10kpc)

- Long lasting signals
  - » Account for Doppler induced frequency shifts and intrinsic spin evolution
  - » No accurate modeling, use phenomenological waveforms which account for intrinsic spin-down & Doppler modulation
- Probe:
  - » Nature of neutron star crust via gravitational ellipticity
  - » Strength and nature of magnetic fields inside neutron stars
  - » Origin of clustered spin-period (~300 Hz) observed for low-mass x-ray binaries (Bildsten)

# Electromagnetically quiet or occluded sources



Born $1/(2\text{x}10^{4}\text{yrs})$

Born $1/(2\text{x}10^{6}\text{yrs})$

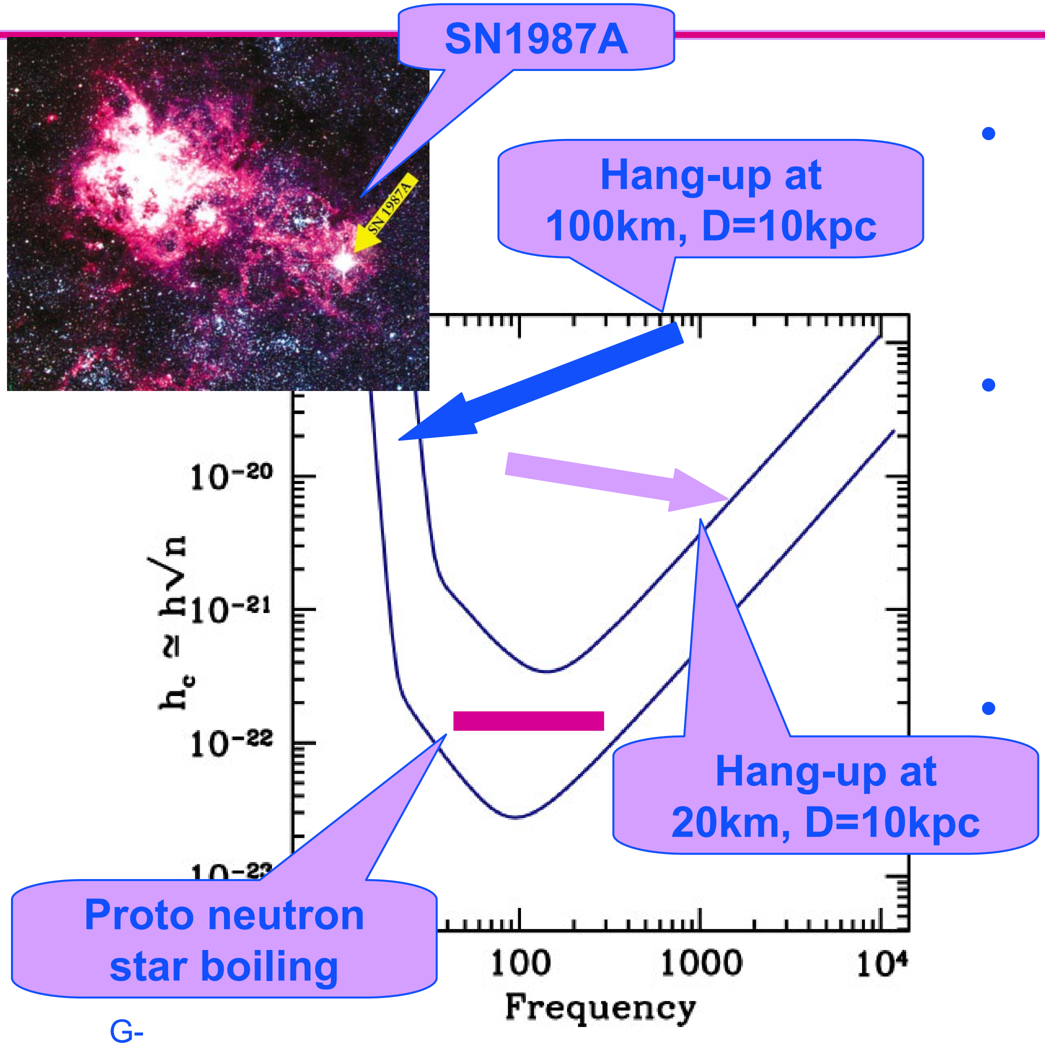
Sco X1 to x-ray flux (1 day)

- Advanced LIGO
  - Can tune to target specialized searches on narrow frequency bands, e.g Sco X1

- Computationally bound search
  - Slowly varying frequency: use FFT based search methods
  - Account for Doppler induced frequency shifts and intrinsic spin evolution using phenomenological approach

  Computationally bound
  - Efficient algorithms promise to only lose 2–4 in amplitude sensitivity for all sky searches
  - Large number of trials requires source strength ~10 x $h_{char}$ at 1% false alarm probability
- Possible studies
  - Probe population/birth rate of neutron stars in Galaxy
  - R-mode instabilities in nascent NS; combine with supernova triggers

# Burst Sources

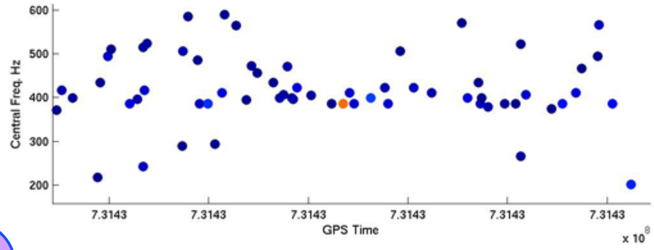


- General properties.
  - » Duration << observation time.
  - » Modeled systems are dirty, i.e. no accurate gravitational waveform
- Possible Sources
  - » NS merger
  - » Supernovae hang-up (Muller, Brown....)
  - » Instabilities in nascent NS (Burrows…)
  - » Cosmic string cusps (Damour/Vilenkin)
- Promise
  - » Unexpected sources and serendipity.
  - » Detection uses minimal information.
  - » Possible correlations with $\gamma$-ray or neutrino observations

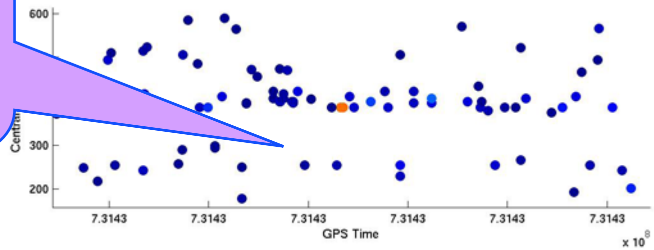
# Burst search methods

- Time-frequency methods.
- Calculates time-frequency planes at multiple resolutions
- Compute power in tiles defined by a start-time, duration, low-frequency, frequency band
- Search over all tiles satisfying user supplied criteria for excess power
- Can get within ~4 in amplitude sensitivity for BBH merger if we do know

600 Seconds Real Data

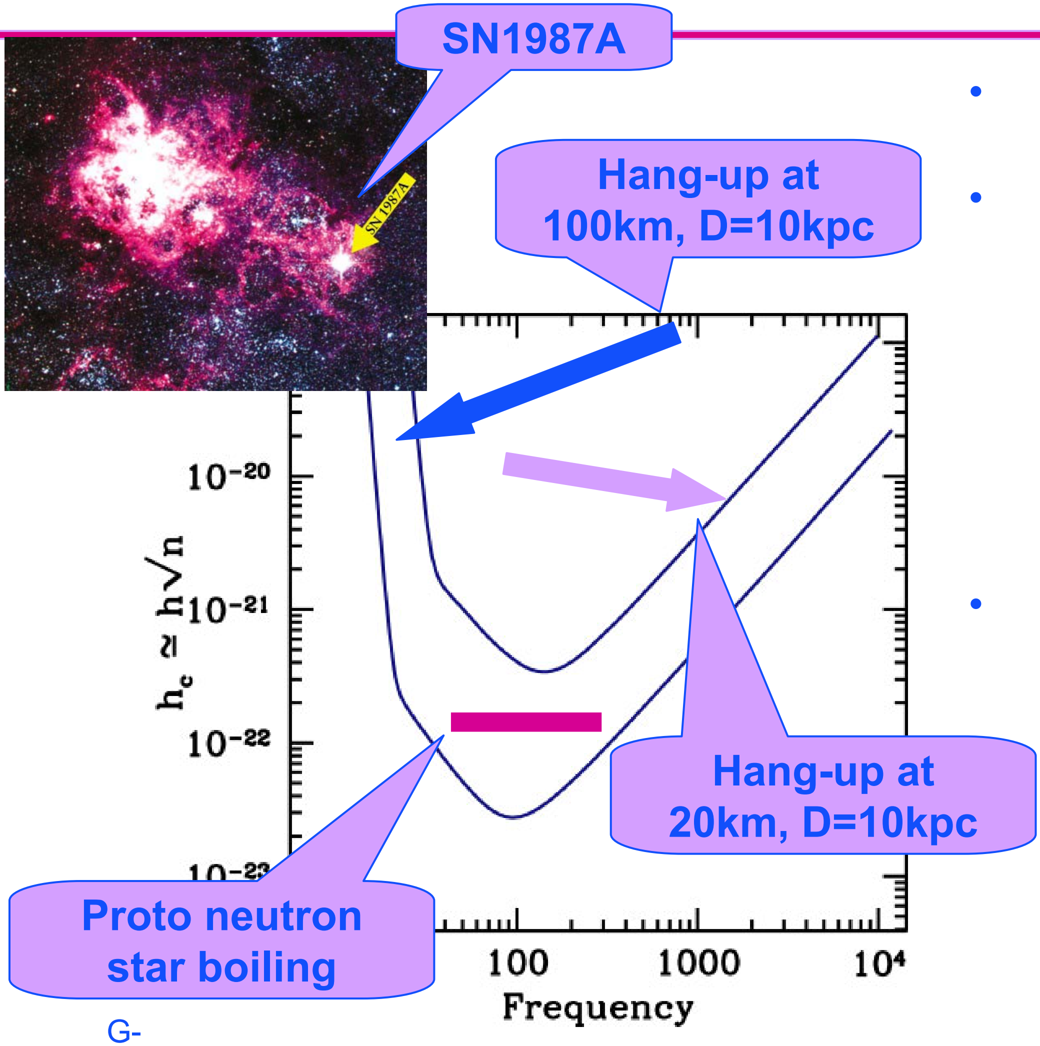


+ Sine-Gaussians at 250Hz, h0 = 6e-20



Coincidence with other GW or EM observations is most powerful tool without accurate waveform information from simulations

# Burst Source Rates



SN1987A

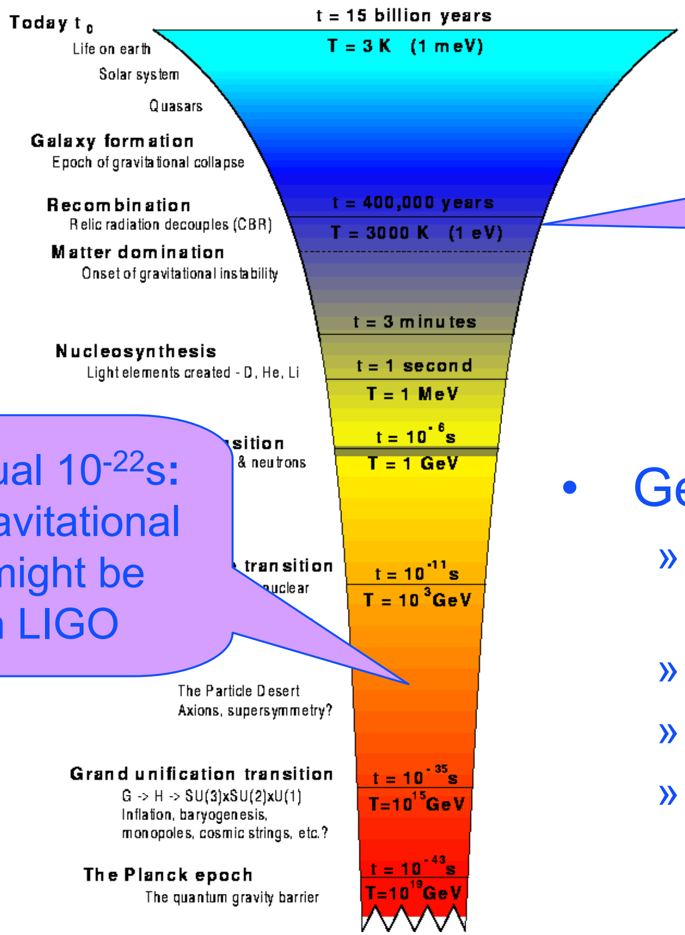
Hang-up at 100km, D=10kpc

Hang-up at 20km, D=10kpc

Proto neutron star boiling

- Supernovae & core collapse
  - Rotating NS progenitor.
- Very fast spin:
  - Centrifugal hang-up gives tumbling bar
  - With enough waveform information, detectable to ~5Mpc (M81 group, ~1 supernova/3yr)
  - Without modeling can probably get to 1Mpc using unmodelled burst search method.
- If slow spin:
  - Convection in first ~1 sec.
  - Unlikely source for initial LIGO (<10 kpc range)
  - Advanced IFOs: detectable within our Galaxy (~1/30yrs)
  - GW / neutrino correlations!

# LIGO Stochastic Background of Gravitational Waves



100,000 years after big bang: production of photons in Cosmic Microwave Background

Less than or equal $10^{-22}$s: production of gravitational waves which might be detected with LIGO

- General properties
  - Weak superposition of many incoherent sources.
  - Only characterized statistically.
  - Either early universe or contemporary.
  - Characterized by

    $\Omega = (\text{Energy})_{GW} / (\text{Energy})_{\text{closure}} < 10^{-5}$

    constrained by nucleosynthesis

# Information Content of Stochastic Background

- Early universe sources
  - 100 Hz today, Gaussian background.
  - Epoch of production is t<=$10^{-22}$s.
  - Cosmic strings, slow-roll inflation, …..
  - Initial LIGO (1 year) sensitive to $\Omega > 10^{-6}$
  - Competitive with limits from nucleosynthesis
- Contemporary sources
  - Unresolved supernovae (Blair, ….)
  - R-mode in nascent neutron stars (Vecchio, … ).
  - Carry information about formation, rates and population distribution
- Surprising or unknown sources
  - GW from excitations of our Universe as 3-dimensional brane in higher dimensional universe. (C. Hogan)
- AdLIGO
  - sensitive to $\Omega > 10^{-9}$ with 3 month search

# Conclusions

- Possible Astronomical Studies available to LIGO
  - » Population studies of neutron stars in binaries and in isolation
  - » Correlations between EM events and GW searches
  - » Mostly limits on source strengths and rates in the near term
- Detection is plausible with initial LIGO detectors
  - » Would bring information about bulk dynamics of the source
  - » Could bring information about internal structure of neutron stars, dynamics of spacetime geometry in strong gravitational field, or dynamics of hitherto unexpected sources
- Advanced LIGO will bring us into the range where detection is probable
- LIGO brings exciting prospects for gravitational-wave astronomy during the next 5-10 years