Sources and Science with LIGO Data

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www.ligo.org

LIGO

Overview

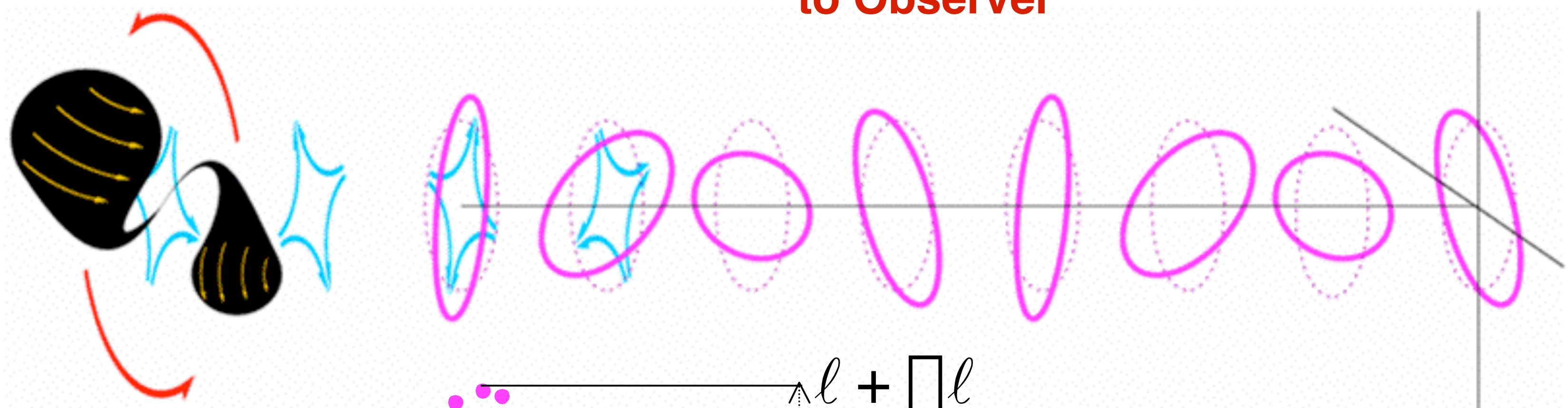
- » Gravitational Radiation and Detectors
- » Binary Coalescence Sources & Science
- » Unmodeled Burst Sources & Science
- » Pulsar Sources & Science
- » Stochastic Background Sources & Science

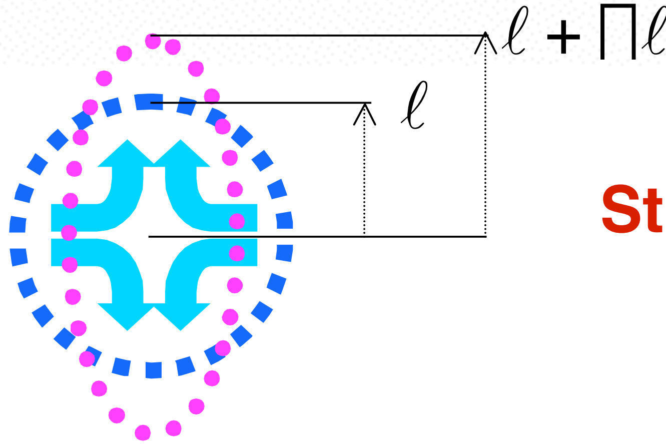
Gravitational Radiation

Source: Bulk Motion Produces Changing Tidal Field

Oscillating Tidal Field Propagates (Unobstructed) to Observer

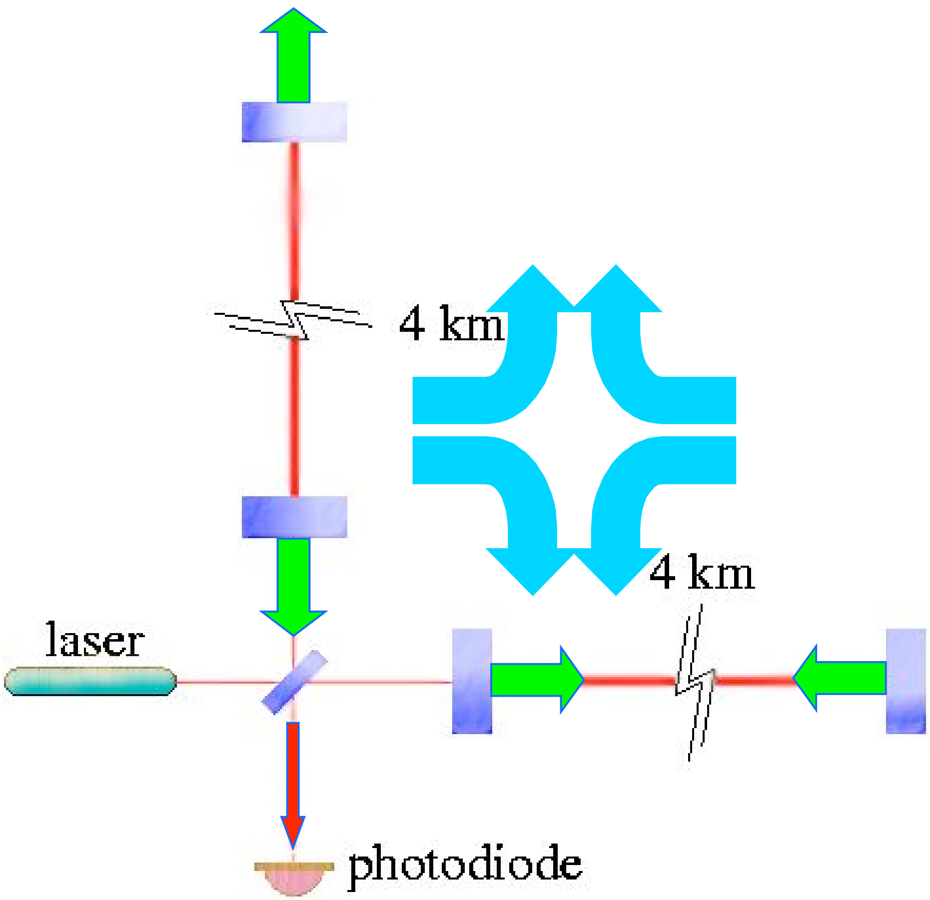
Observer Detects Distortion Strain

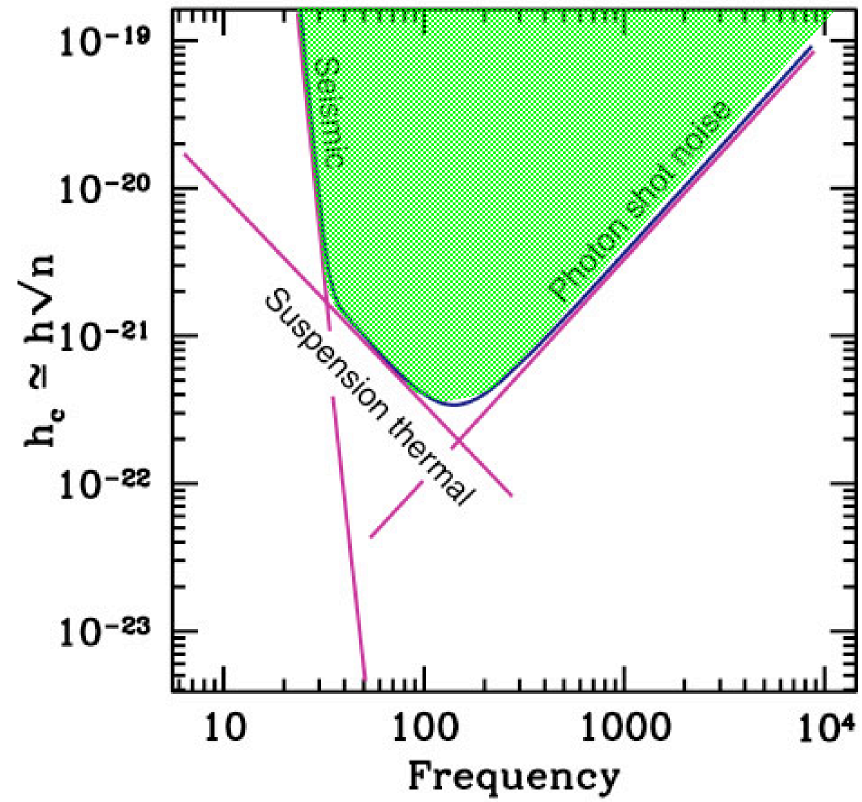




Strain: $h = \dfrac{\Delta\ell}{\ell}$

Gravitational Radiation and Detectors:
LIGO Interferometer



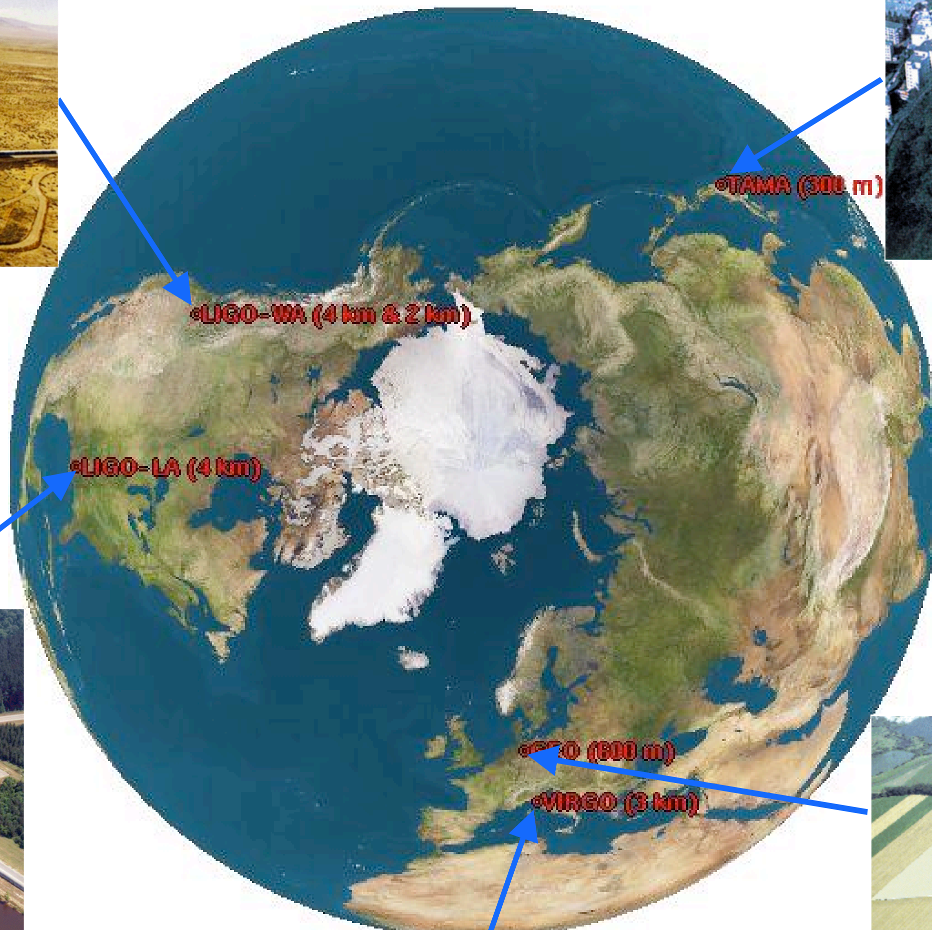


LIGO

Gravitational Radiation and Detectors:
Interferometer Network

LIGO Hanford WA (4km & 2km)

TAMA (300m)



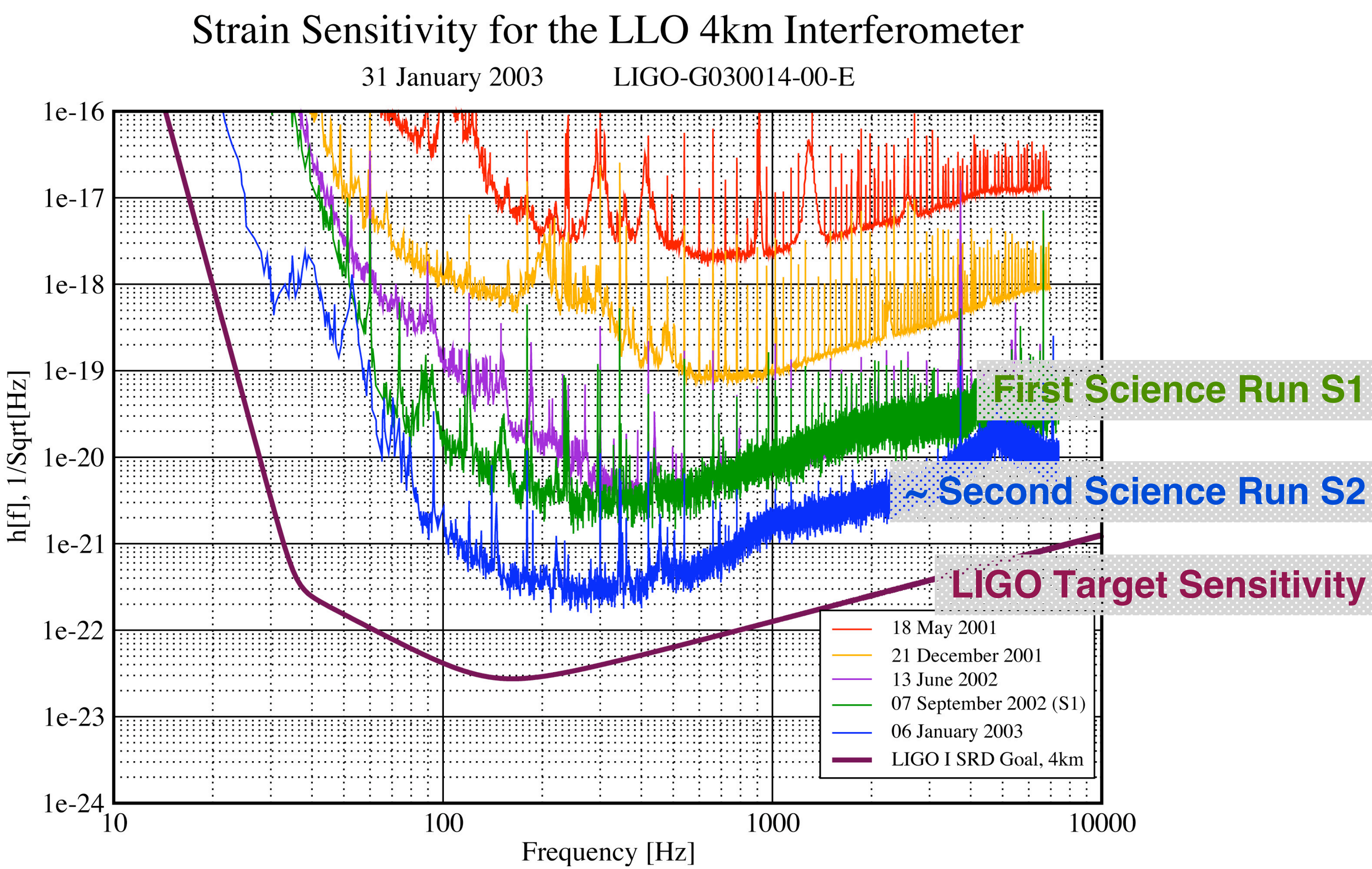
AIGO

LIGO Livingston LA (4km)

GEO (600m)

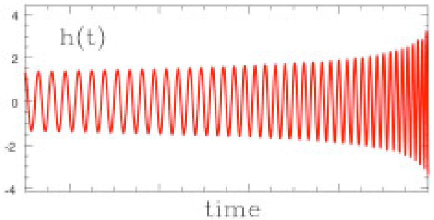
VIRGO (3km)

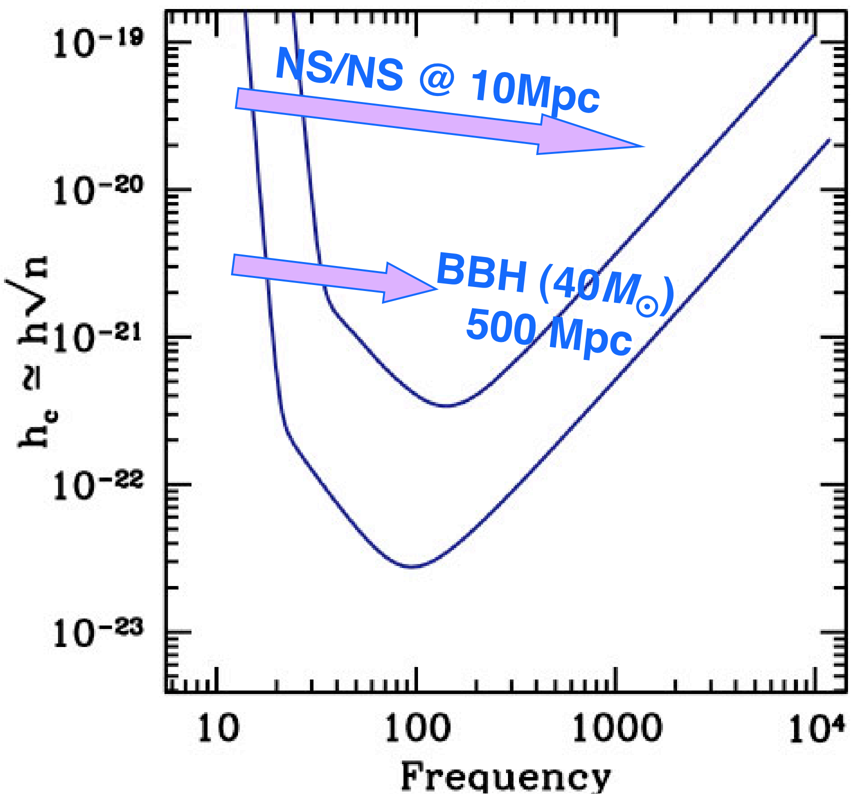
Gravitational Radiation and Detectors:
LIGO Sensitivity Improvements



LIGO

Binary Coalescence Sources & Science:
Binary Inspiral Sensitivity





V Kalogera et al, Astrophys J **556** 340 (2000)

S Portegies Zwart, S McMillan, Astrophys J **528** L17 (2000)

- Waveforms from slow motion (pN) approx.
- Measure:
  - » Inspiral rate → "chirp mass"
  - » Relativistic effects → component masses
  - » Amplitude → luminosity distance
  - » Polarization (network) → inclination
  - » Timing (network) → sky position
- Rates estimated from
  - » Empirical estimates based on observed binaries
    - – Sensitive to faint pulsar population
  - » Stellar evolution/dynamics models
    - – Sensitive to formation channels, stellar winds, supernova kick velocities, etc.

	LIGO	AdLIGO
Range (Mpc)	□20	□200
Event Rate (per year)	3□10^{-4} – 3□10^{-1}	2 – 1000
Event Rate (per year)	□0.5	□500

binary neutron stars

binary black holes

Binary Coalescence Sources & Science:
Binary Neutron Stars: S1 Range

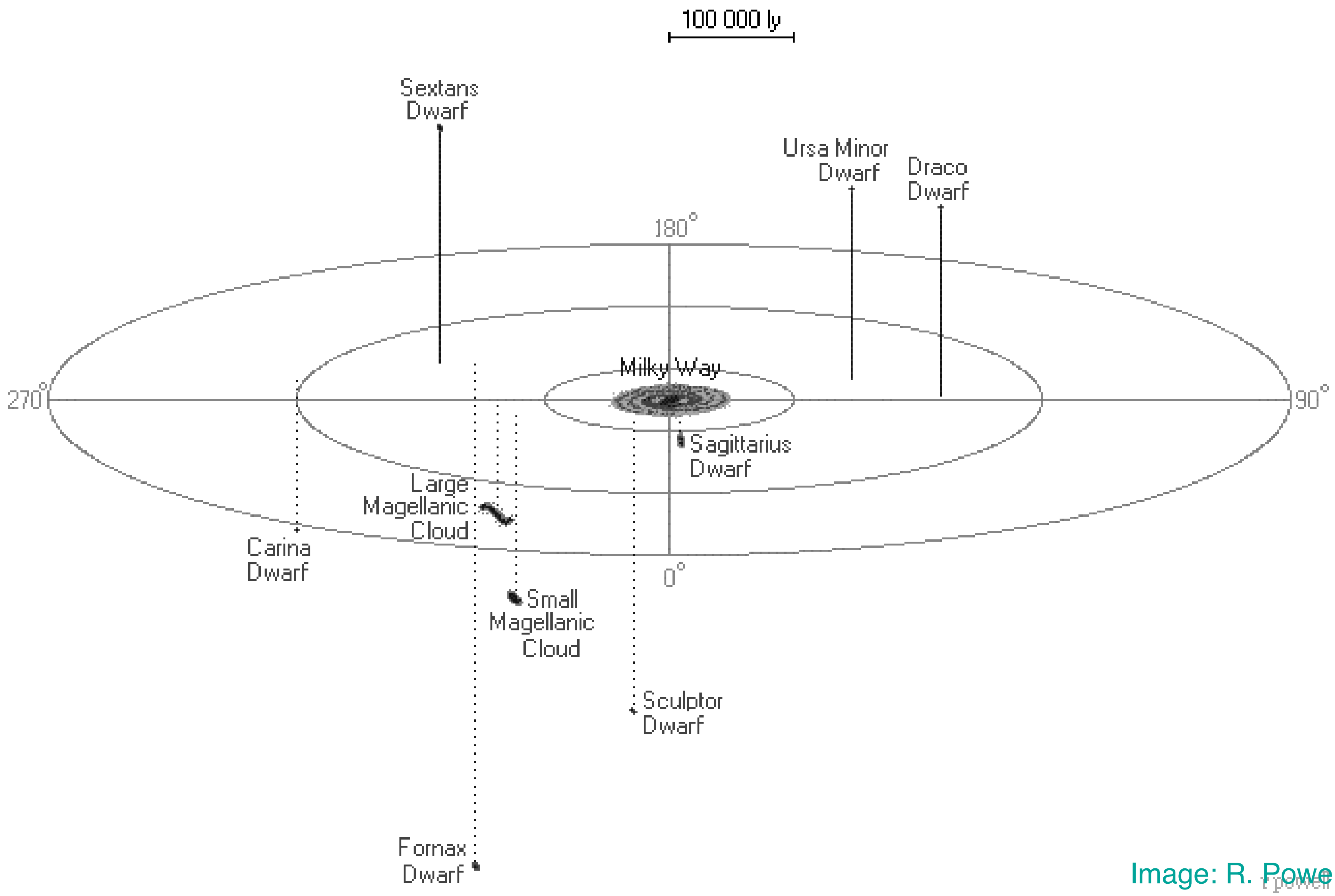


Image: R. Powell

Binary Coalescence Sources & Science:
Binary Neutron Stars: S2 Range

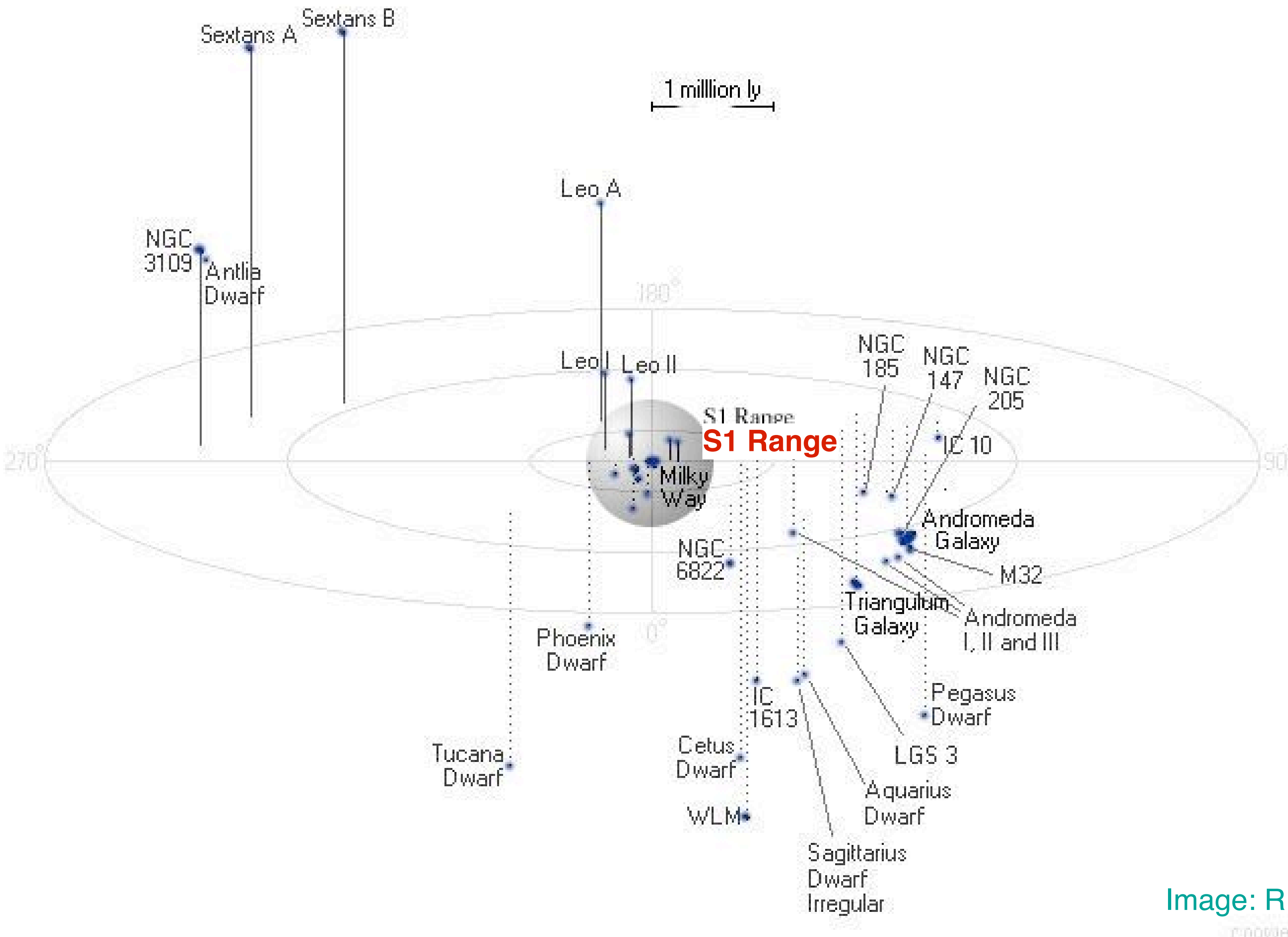


Image: R. Powell

Binary Coalescence Sources & Science:
Binary Neutron Stars: LIGO Range

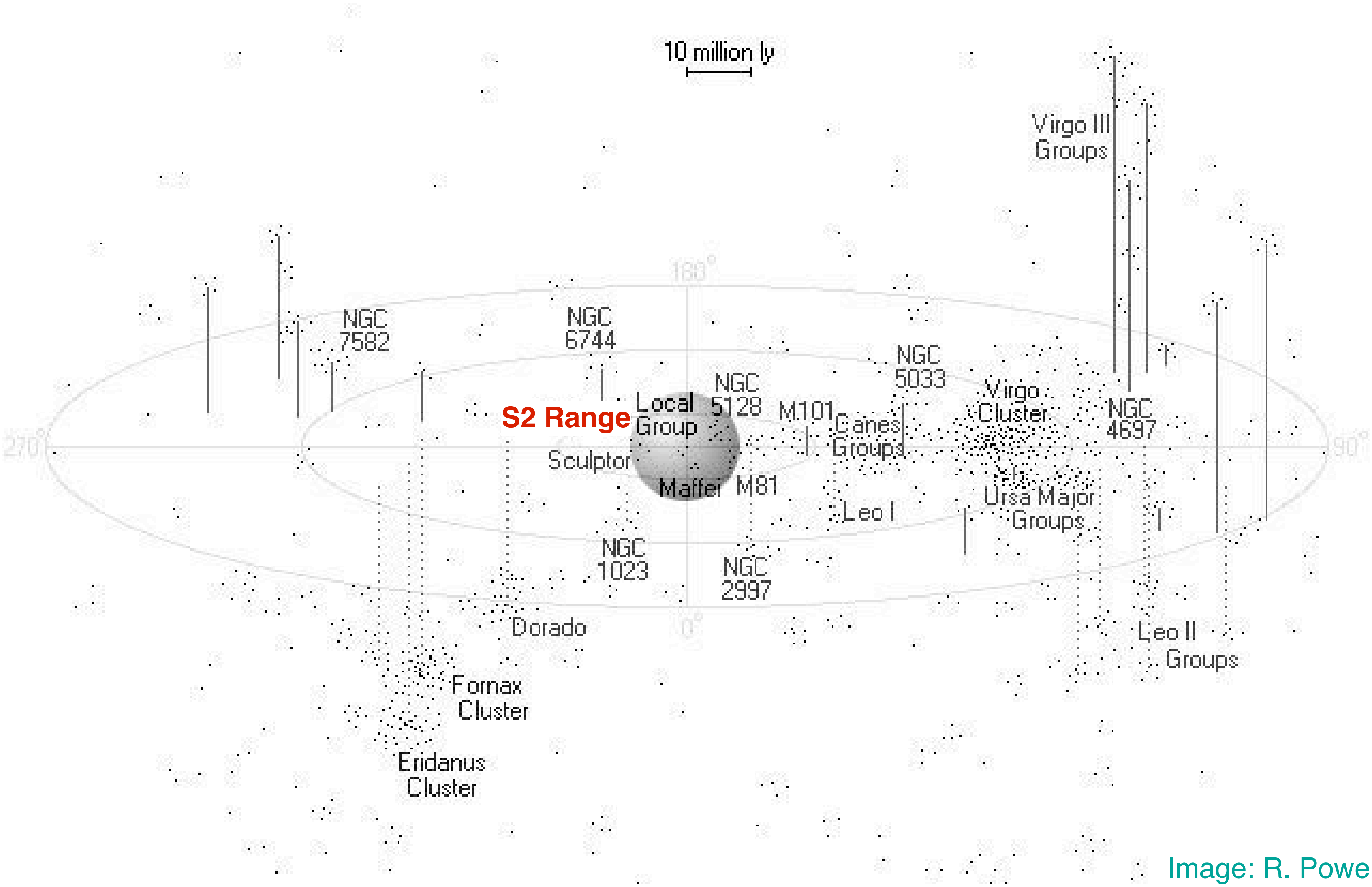


Image: R. Powell

Binary Coalescence Sources & Science:
Binary Neutron Stars: AdLIGO Range

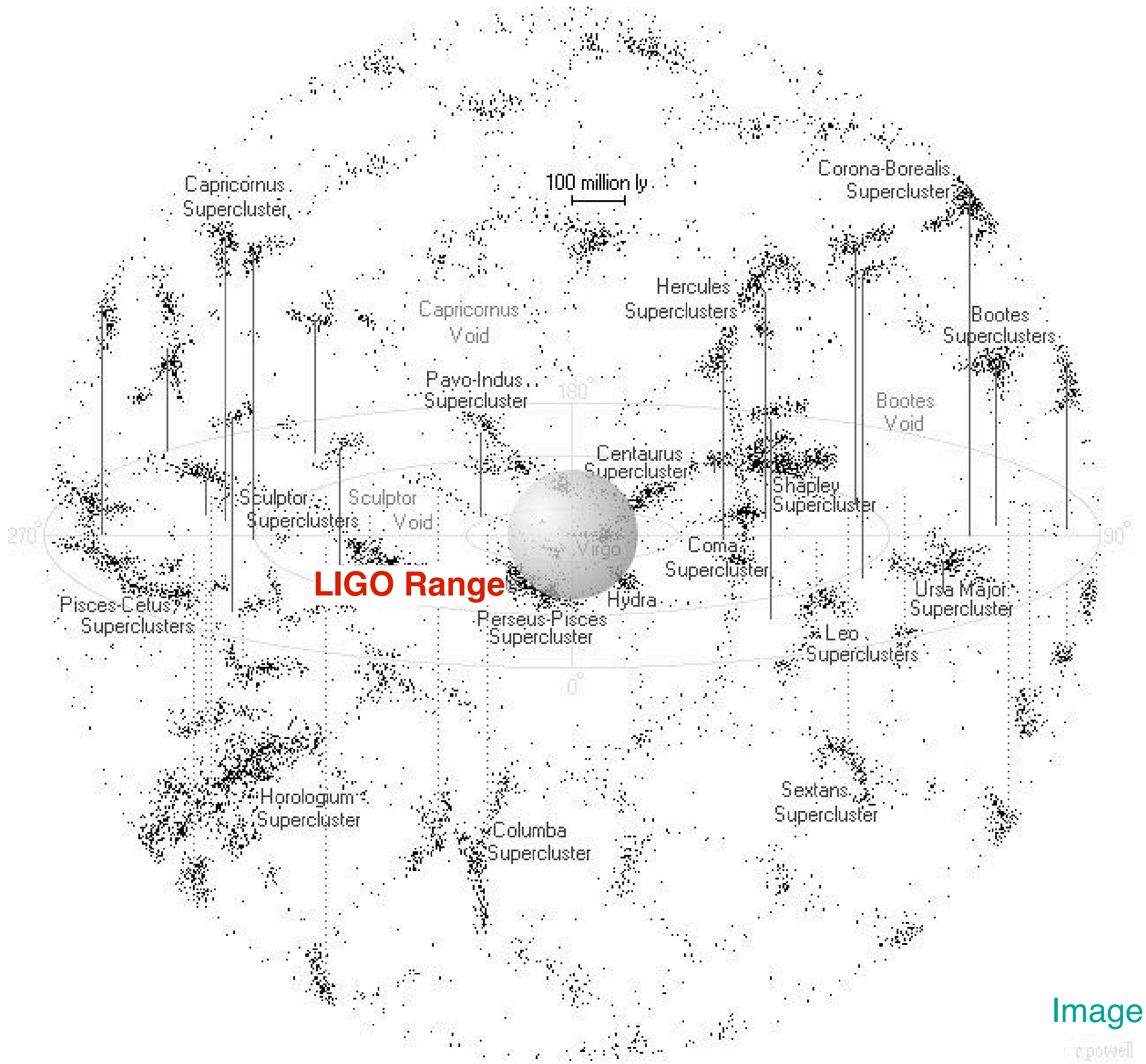
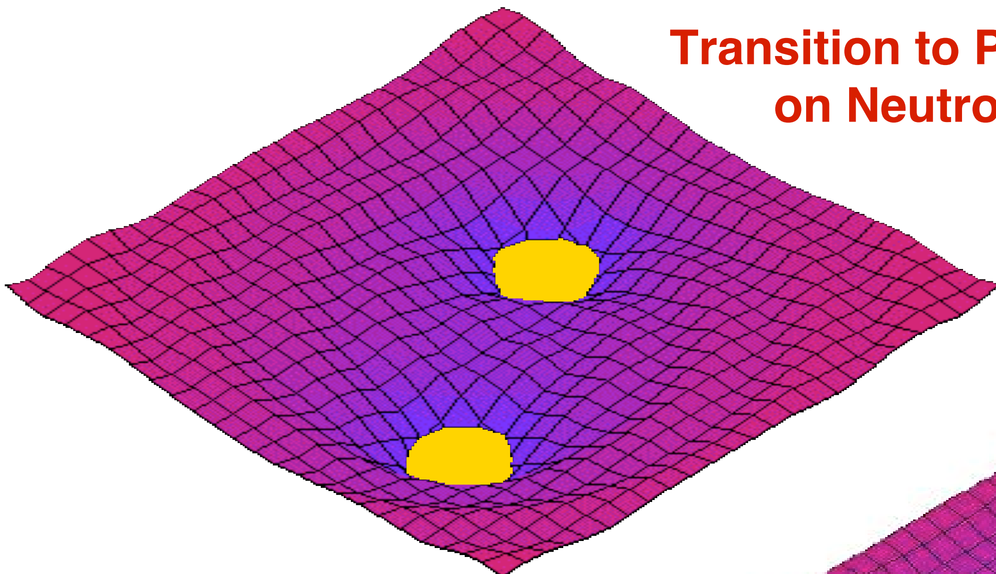
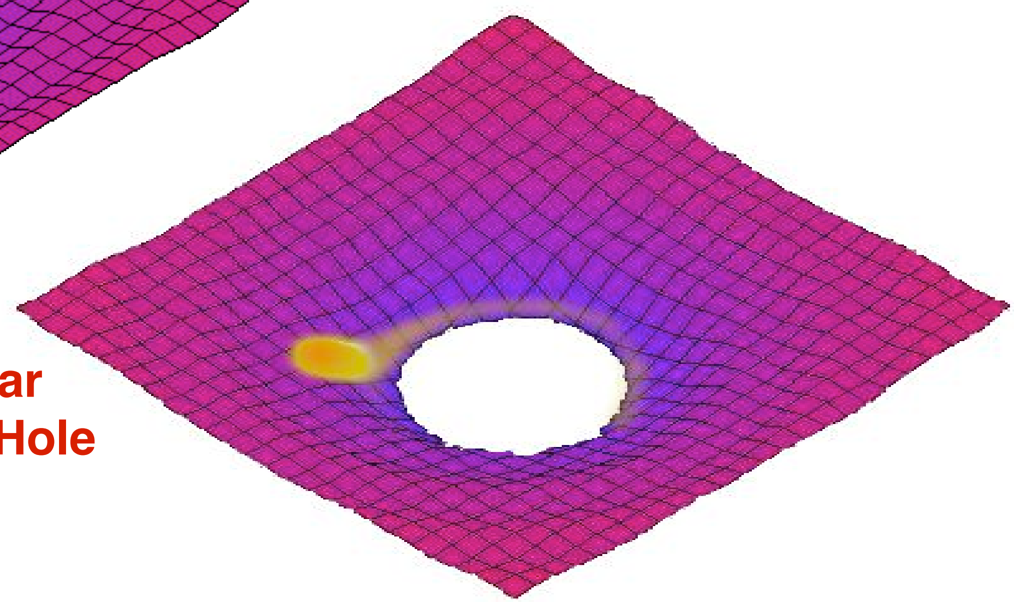


Image: R. Powell

Binary Coalescence Sources & Science:
Determination of Neutron Star Size



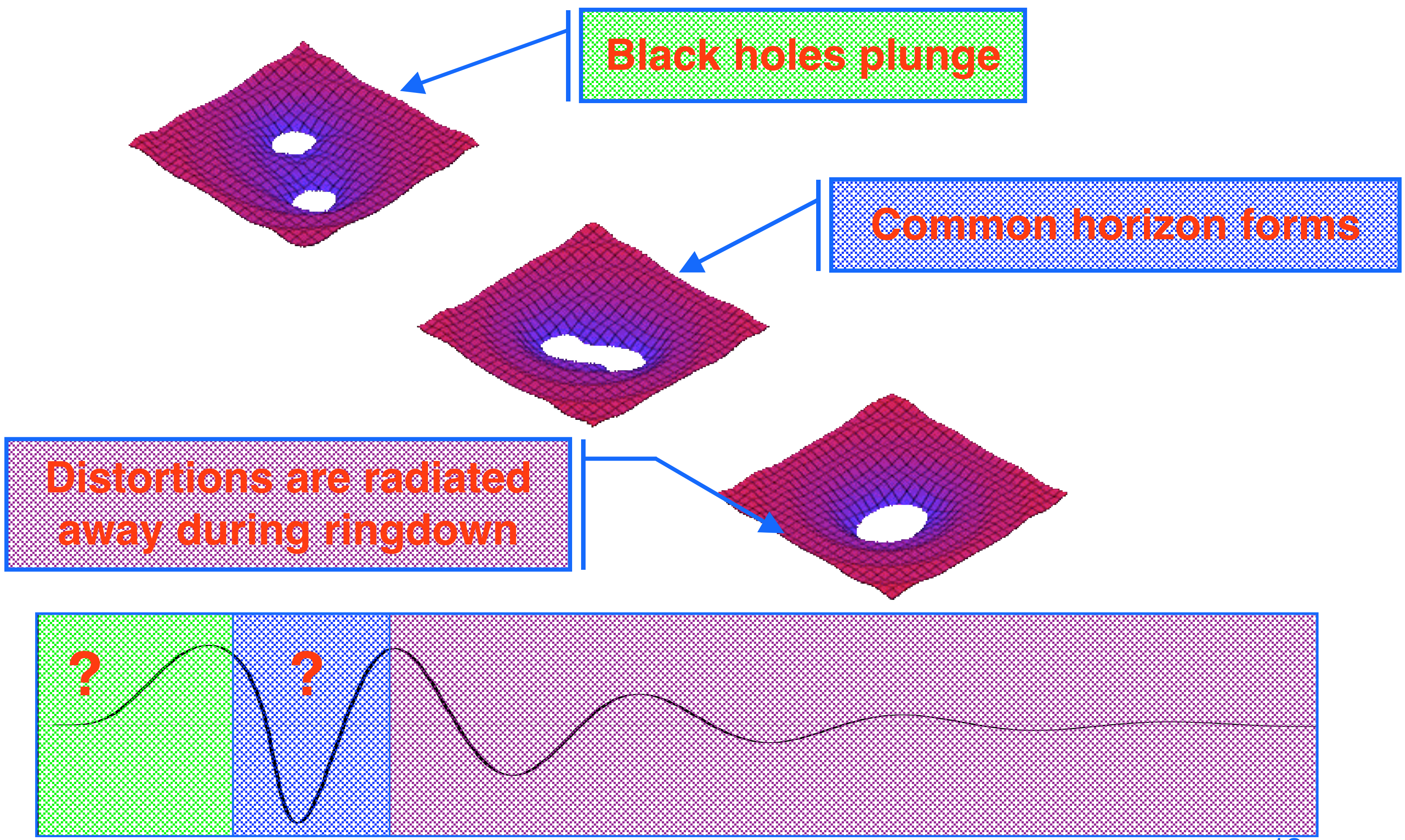
Transition to Plunge Depends on Neutron Star Size



Disruption of Neutron Star by Rapidly Rotating Black Hole

Candidates for γ-ray bursts

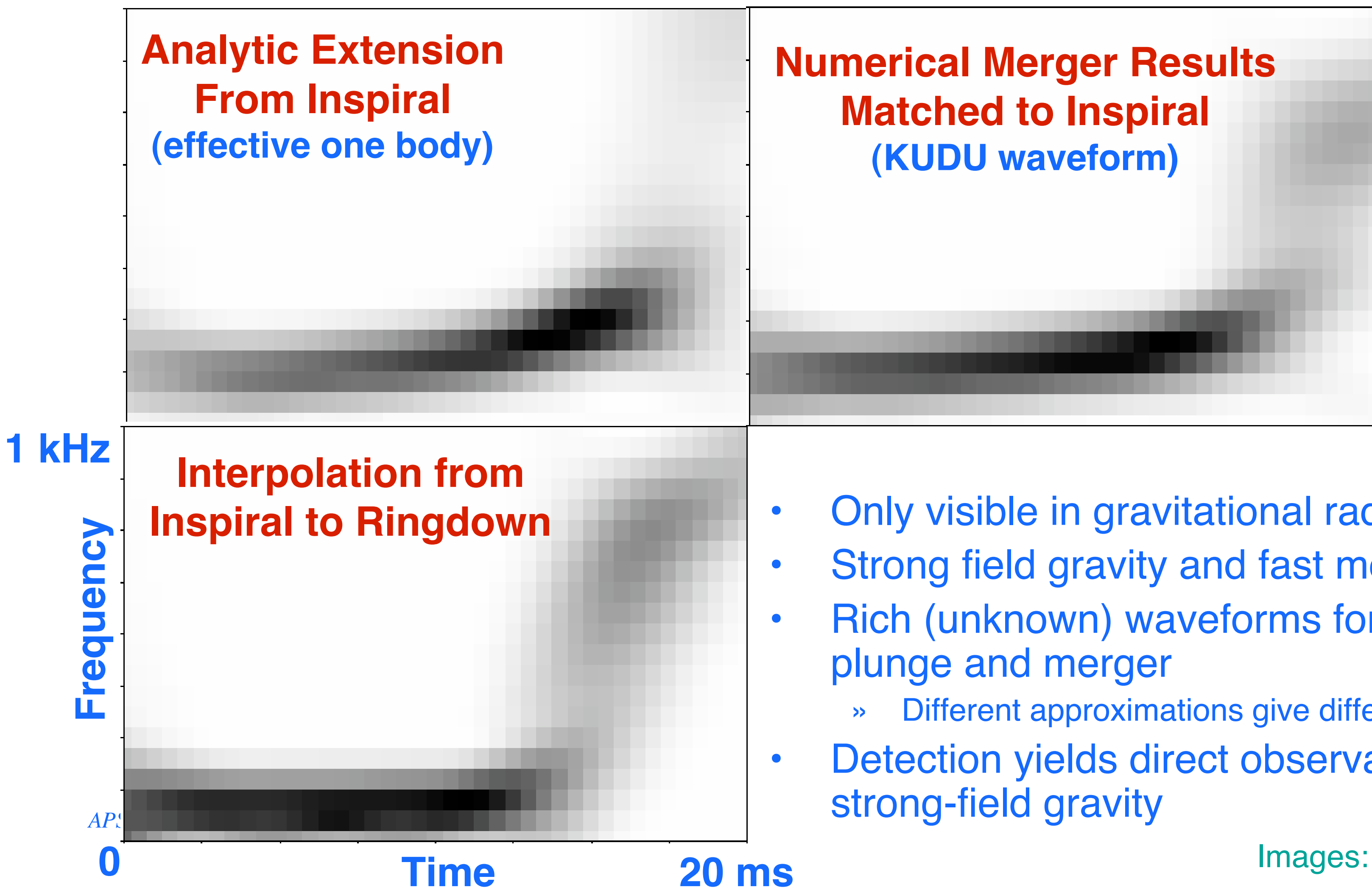
Binary Coalescence Sources & Science:
Binary Black Hole Merger



Binary Coalescence Sources & Science:

Binary Black Hole Merger

Collision of Two 10 $M_{\odot}$ Black Holes



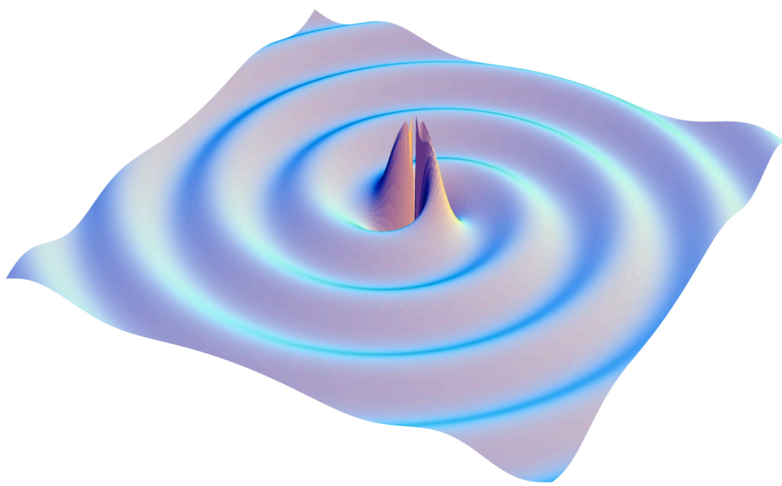
- Only visible in gravitational radiation
- Strong field gravity and fast motion
- Rich (unknown) waveforms for black hole plunge and merger
  - Different approximations give different results
- Detection yields direct observation of pure strong-field gravity

Images: W. Anderson

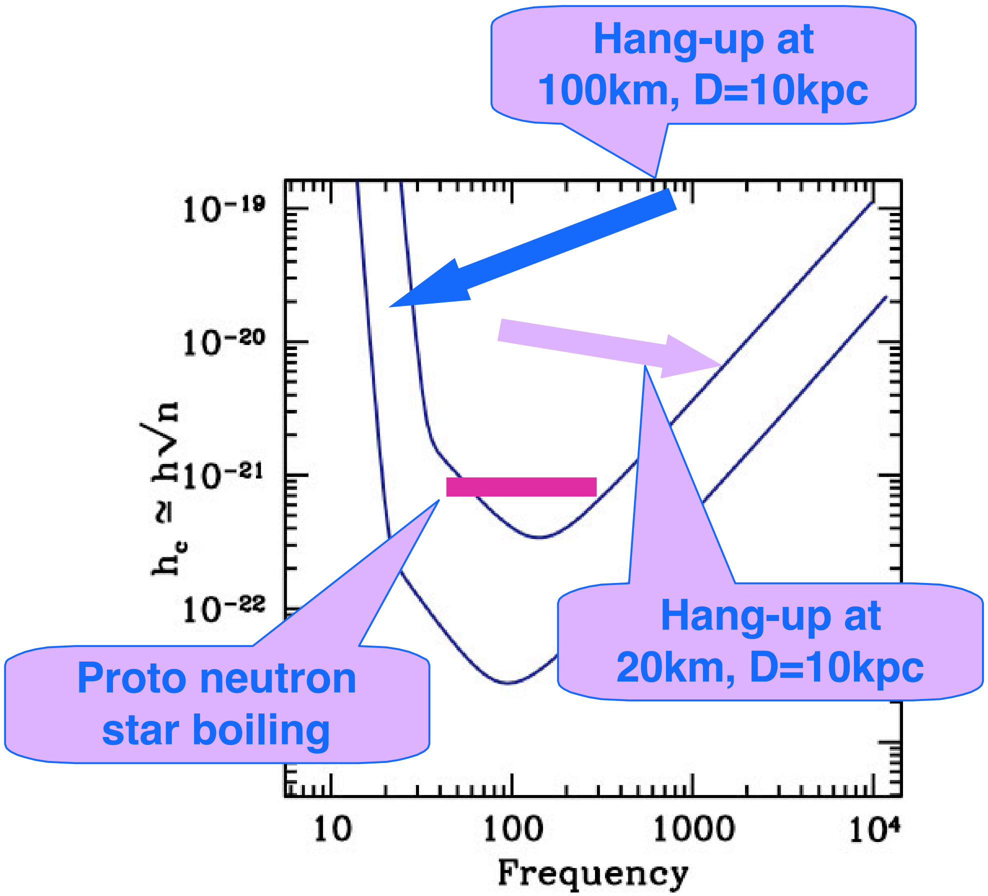
Binary Coalescence Sources & Science:
Science Goals

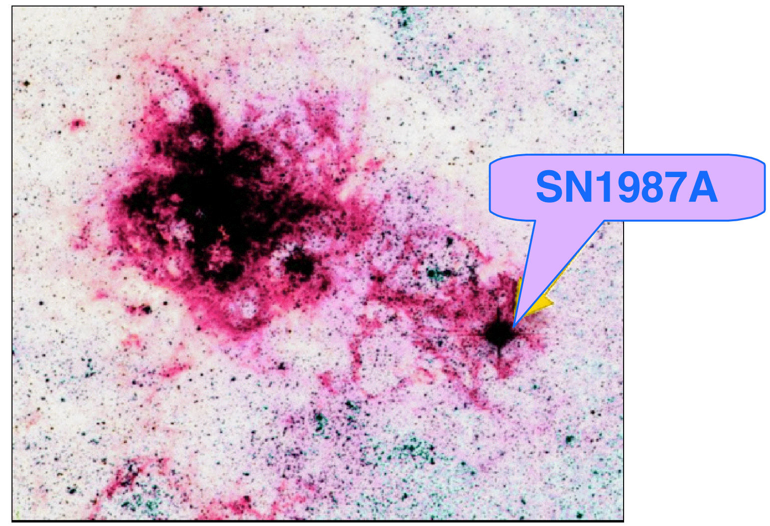
- S1 Result:
  - » Less than 164 binary neutron star collisions per year per Milky Way equivalent galaxy (90% confidence)

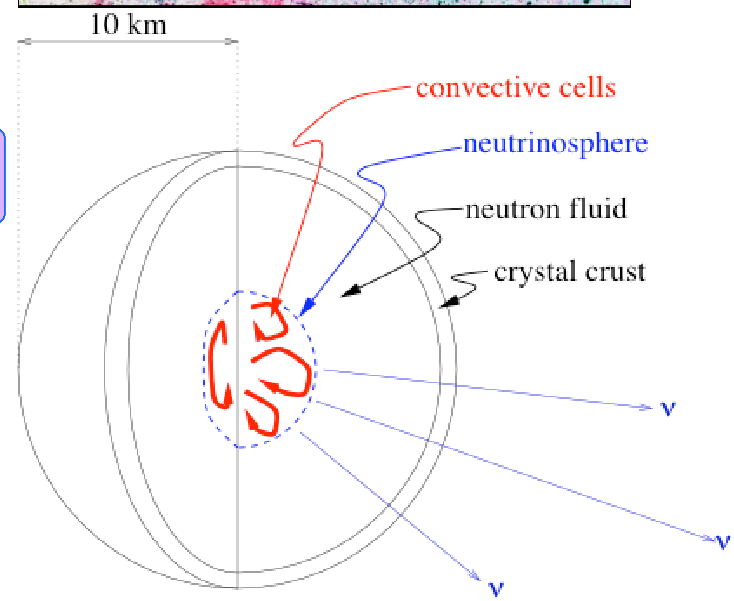
- LIGO Goals:
  - » Search for binaries with neutron stars and/or black holes
  - » Rate limits or detections of binary inspirals beyond Virgo cluster:
    - Constraint on stellar evolution and faint pulsar population
    - Measurement of neutron star size and equation of state
    - Determine if neutron star disruption causes γ-ray bursts
    - Constraints on black hole MACHO population
  - » Detection and measurement of black hole merger:
    - Only produce gravitational waves
    - Observation of strong-field gravity



Unmodeled Burst Sources & Science:
Supernovae and Core Collapse







Unmodeled Burst Sources & Science:
γ-Ray Bursts

- Gravitational radiation may accompany γ-ray bursts
- Observed gravitational waves may determine source of bursts
- Example of possible engine:
  black hole + torus of dense matter
  - » Formed from collapsars, hypernovae, binary neutron star collisions etc…
  - » Energy comes from black hole spin coupled to torus via magnetic fields
  - » Deformations of rotating torus would produce gravitational radiation

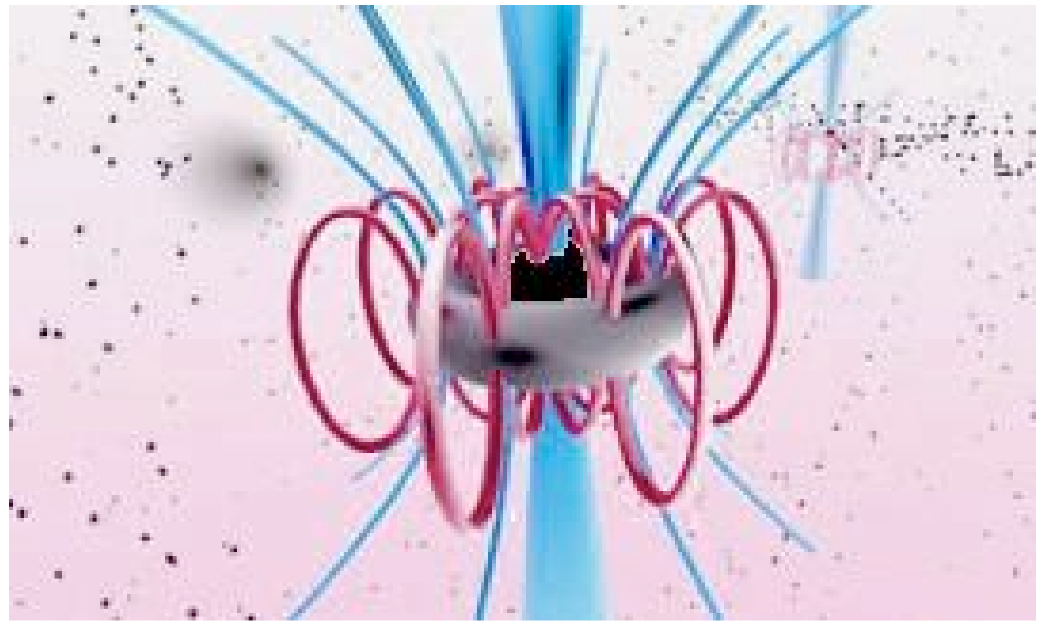
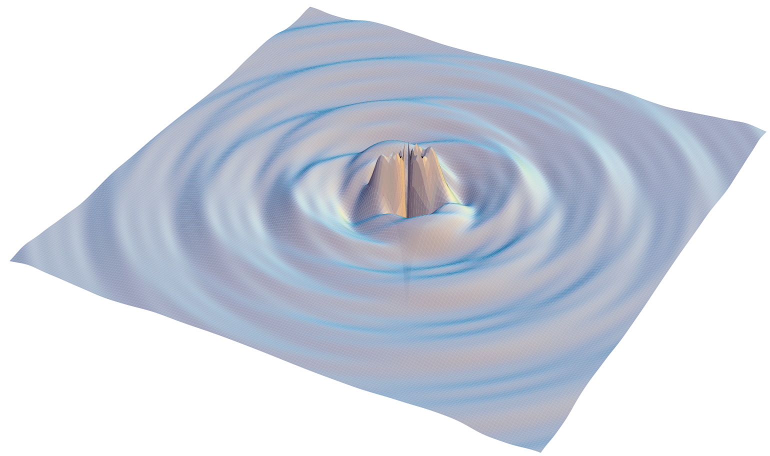


Image: P. F. A. M. van Putten

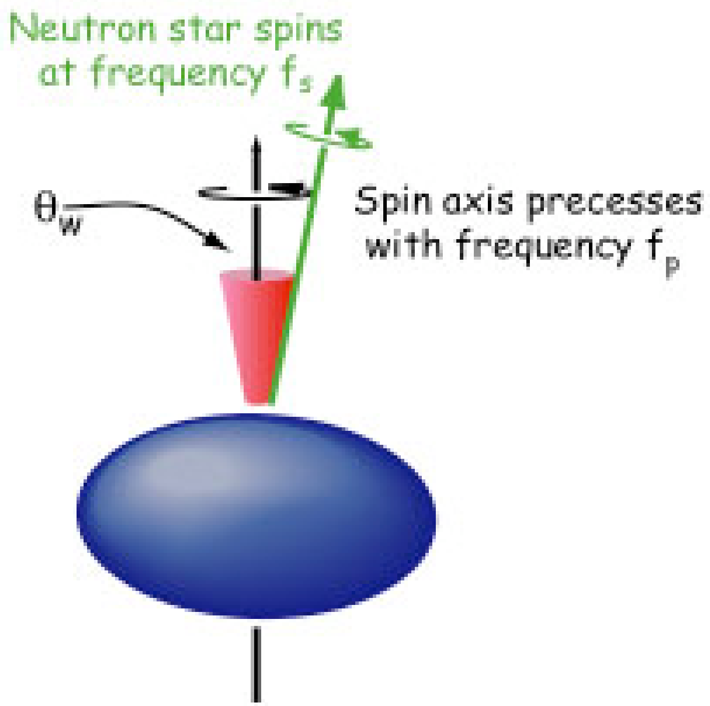
Unmodeled Burst Sources & Science:
Science Goals

- S1 Result:
  - » Rate of broad-band bursts less than 1.4 events per day (90% confidence)

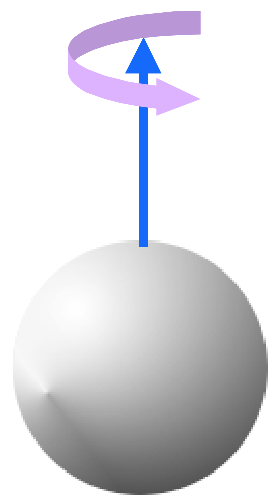
- LIGO Goals:
  - » Serendipitous discovery of unexpected sources
  - » Searches tuned to specific types of bursts (supernovae, black hole formation, etc.)
  - » Triggered search for bursts associated with supernovae and γ-ray bursts
    - – Information about core-collapse in supernovae
    - – Determine origin of γ-ray bursts
    - – Gravitational waves let us see the dynamical processes



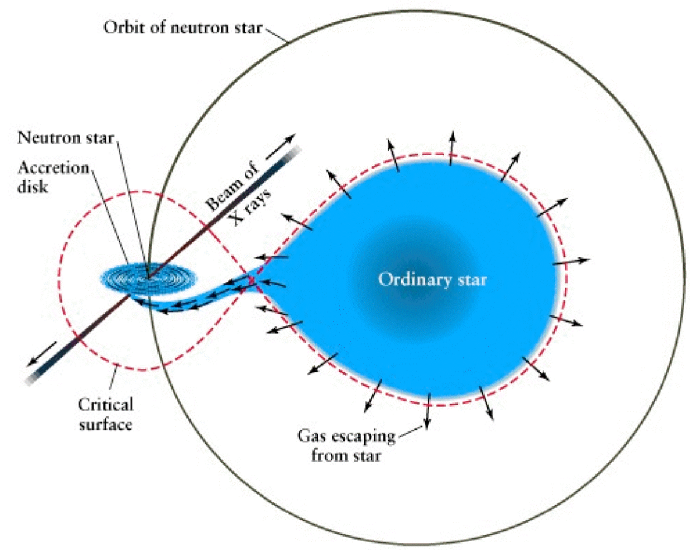
Pulsar Sources & Science:
Distorted Neutron Stars



Wobbling Neutron Star

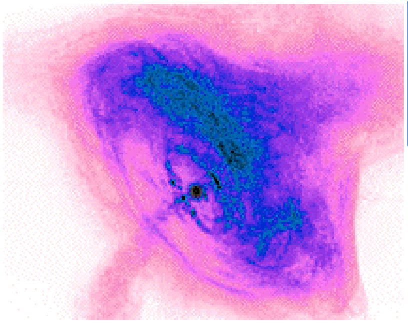


Bumpy Neutron Star



Low Mass X-Ray Binaries

Pulsar Sources & Science:
Sensitivity to Pulsars



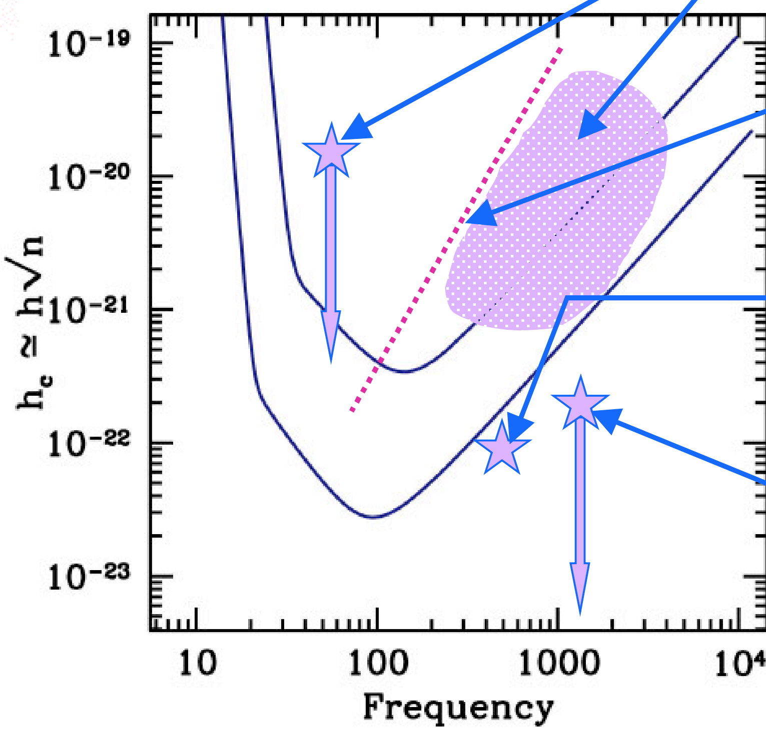
Crab pulsar limit
(4 month observation)

Hypothetical population of young, fast pulsars
(4 months @ 10 kpc)

Crustal strain limit
(4 months @ 10 kpc)

Sco X-1 to X-ray flux
(1 day)

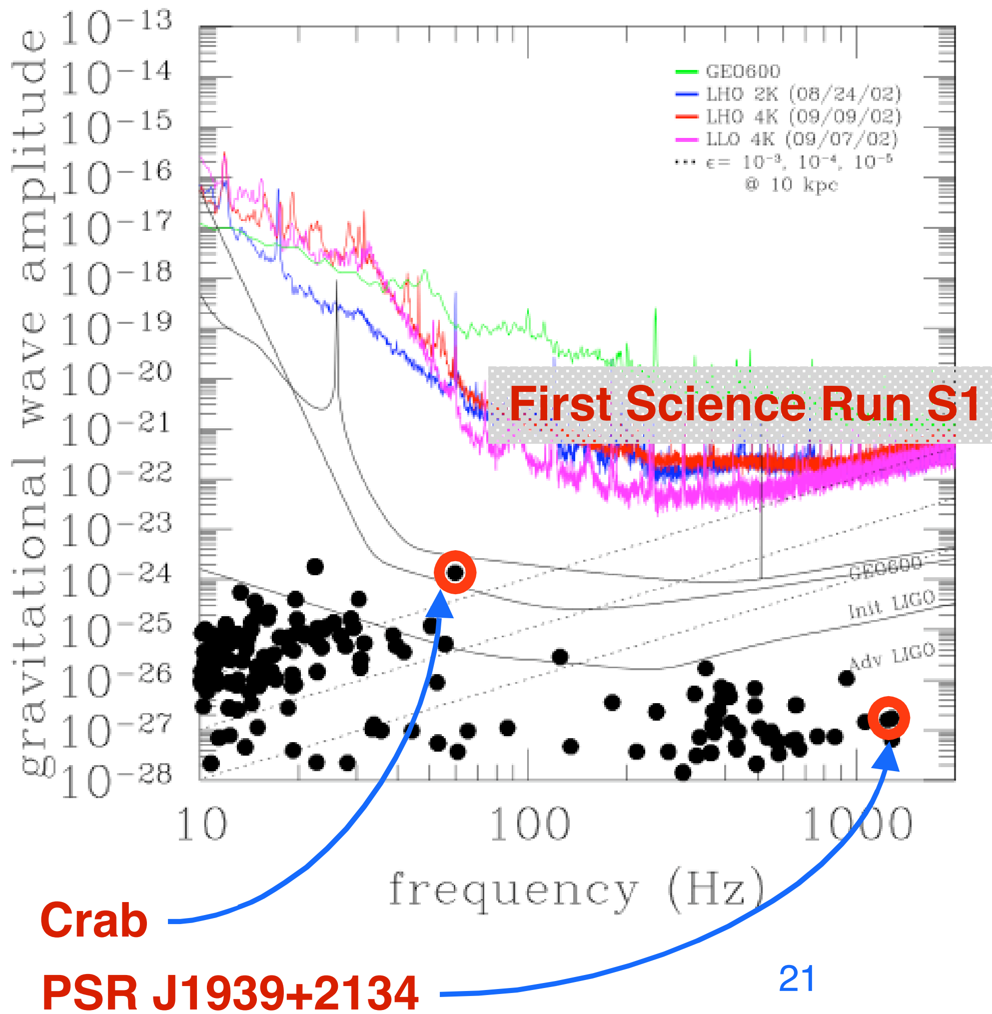
PSR J1939+2132
(4 month observation)



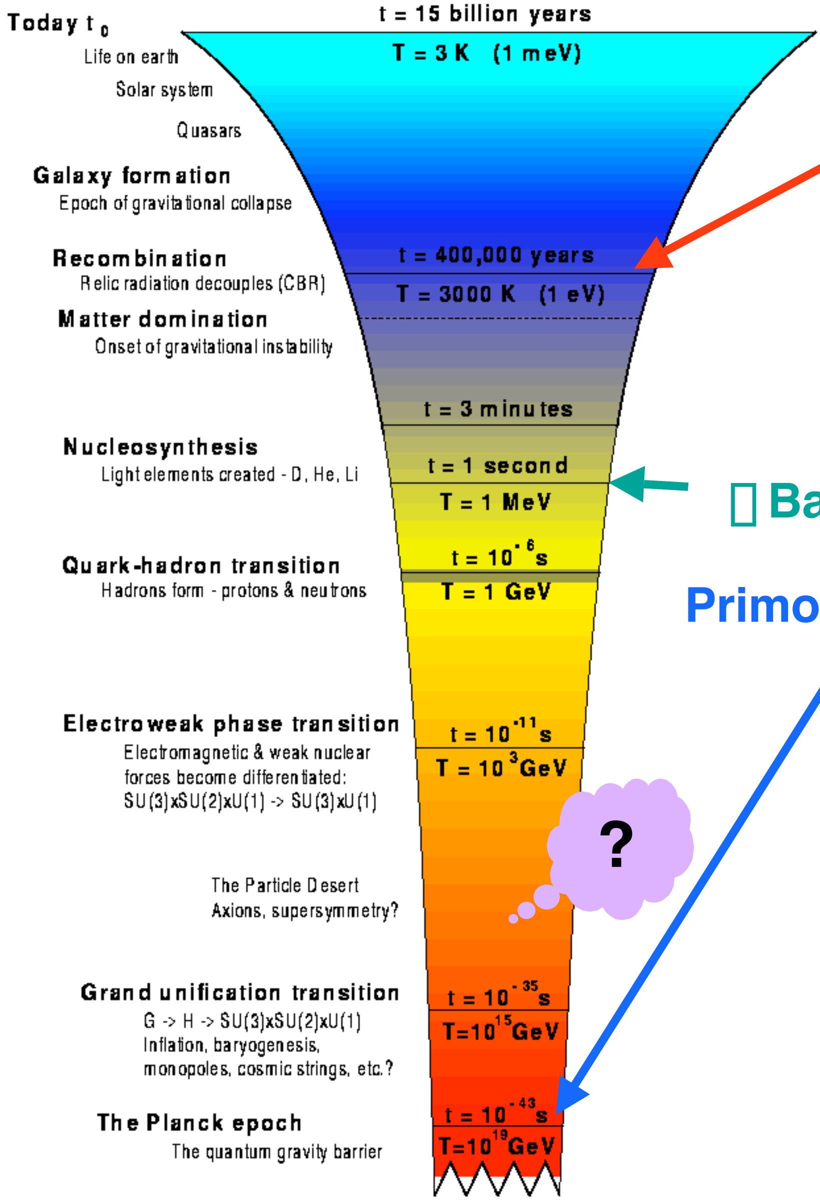
Pulsar Sources & Science:
Science Goals

- S1 Result:
  - » Gravitational wave strain upper limit from PSR J1939+2134: $h < 1.0 \times 10^{-22}$ (95% confidence)

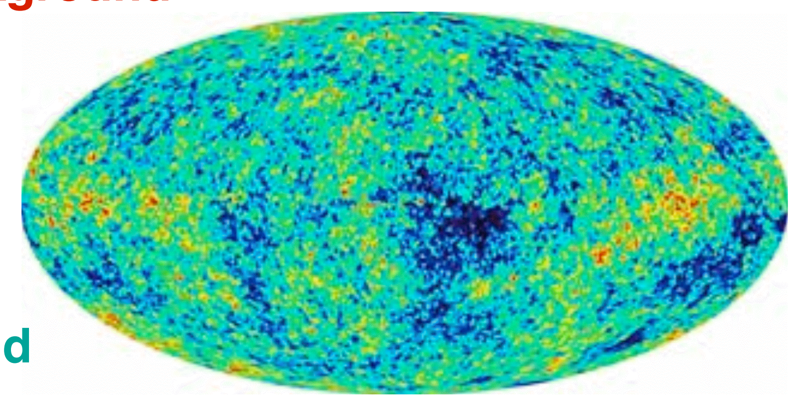
- LIGO Goals:
  - » All-sky and targeted surveys for known and unknown pulsars
    - – Discovery of new class of young, rapidly-rotating pulsars
    - – Constraint on neutron star crustal strength/deformation
  - » Targeted observations of low-mass X-ray binaries:
    - – Evidence for torque from gravitational radiation



Stochastic Background Sources & Science:
Stochastic Background

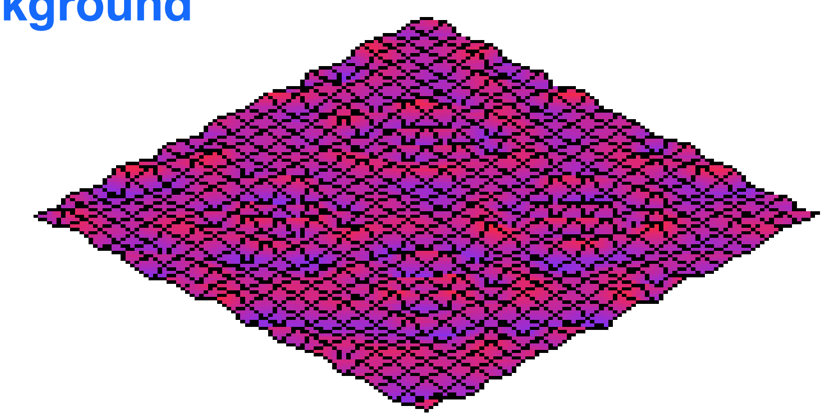


Cosmic Microwave Background



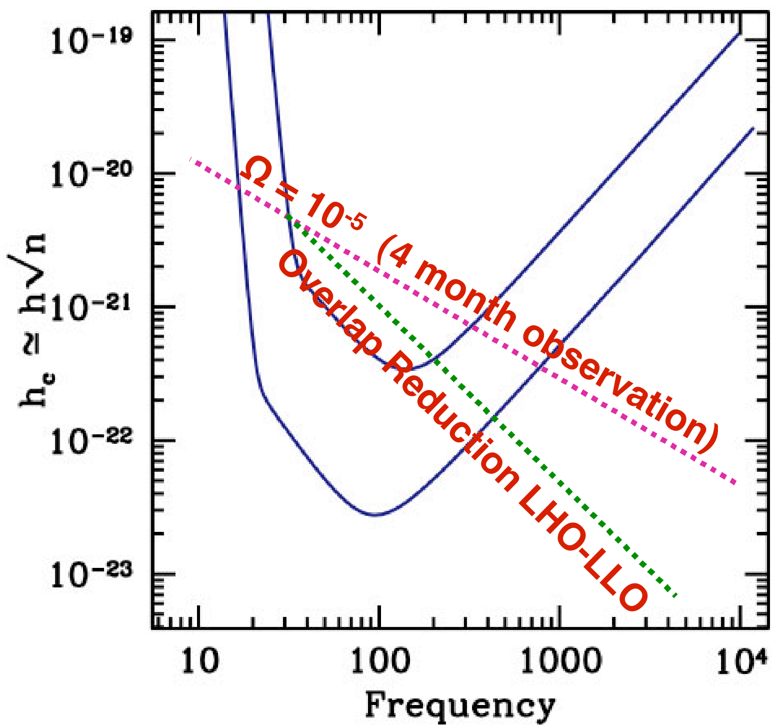
ν Background

Primordial Gravitational-Wave Background



Stochastic Background Sources & Science:

Stochastic Background Sensitivity



- Fraction of energy density in Universe in gravitational waves:

$$\frac{\rho_{GW}}{\rho_{critical}} = \int \Omega_{GW}(f)\, d\ln f$$

- Constraint from nucleosynthesis:

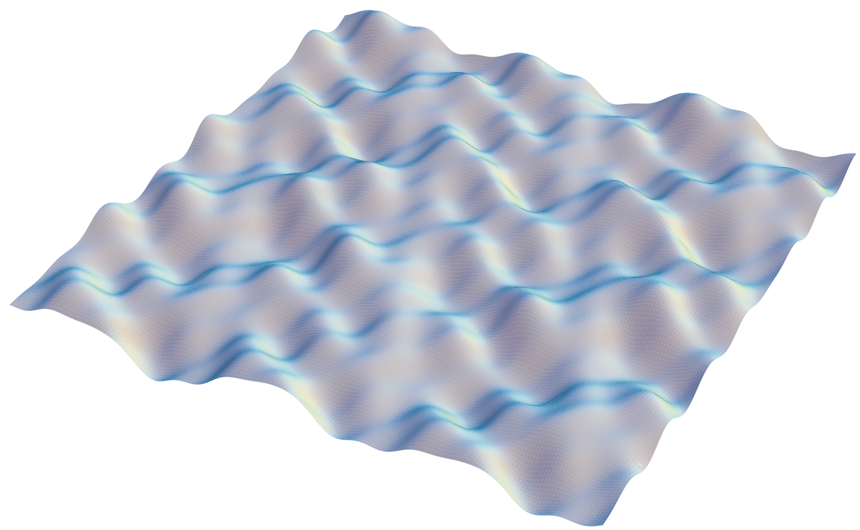
$$\int \Omega_{GW}(f)\, d\ln f < 10^{-5}$$

- More recent processes may also produce stochastic backgrounds

Stochastic Background Sources & Science:
Science Goals

- S1 Result:
  - » Upper limit on energy in gravitational wave background: $\Omega_{GW} < 72.4$ (90% confidence)

- LIGO Goals:
  - » Improved energy limit on stochastic background
    - – Detect or rule out early universe effects, e.g., cosmic strings etc.
    - – Bound primordial gravitational radiation below existing limits from nucleosynthesis
  - » Search for background of unresolved gravitational wave bursts



Outlook

- Gravitational waves will allow us to observe new aspects of the universe
  - » Electromagnetically quite objects
    - – Binary black holes
    - – Rotating neutron stars that are not pulsars
    - – Unexpected sources of gravitational waves
  - » Bulk dynamics hidden from us
    - – Central engines of supernovae and γ-ray bursts
    - – Early universe sources of gravitational waves
- First generation instruments now operating and approaching design sensitivity