# Sources of Gravitational Waves

**TAUP School, September 2013**

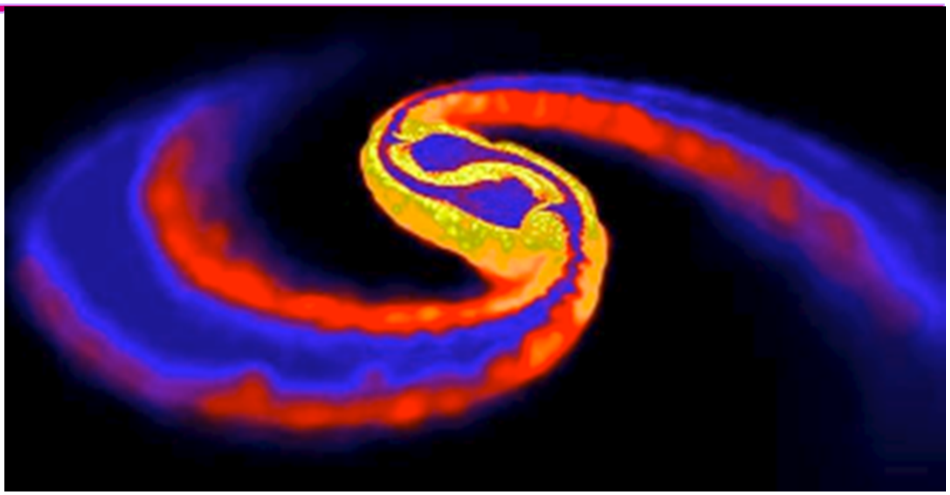
- Gravitational waves
- Survey of astrophysical sources and signal morphologies
- Compact Binary Coalescences
- What we can learn: physics and astrophysics

**No discovery to report here!**

Alan Weinstein, Caltech

for the LIGO Scientific Collaboration

LIGO-G1300902



*"Merging Neutron Stars" (Price & Rosswog)*

Fig. 1.1 – LIGO detector with 4 km arms at Livingston, Louisiana

Fig. 1.2 – Virgo Detector, with 3 km arms, at Cascina, near Pisa

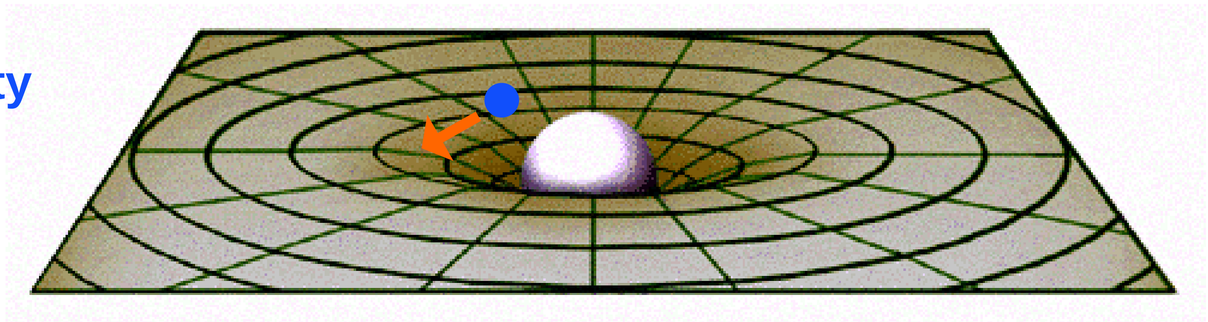
# Gravitational wave science

The **Study of gravitational waves** is at the ***frontiers of science*** in at least four different fields:

- **General Relativity (GR) – physics at the extremes: strong (non-linear) gravity, relativistic velocities**
- **Astrophysics of compact sources – neutron stars, black holes, the big bang – the most energetic processes in the universe**
- **Interferometric gravitational wave detectors – the most precise measuring devices ever built**
- **GW data analysis – the *optimal* extraction of the weakest signals possible out of noisy data.**

# Gravitational Waves

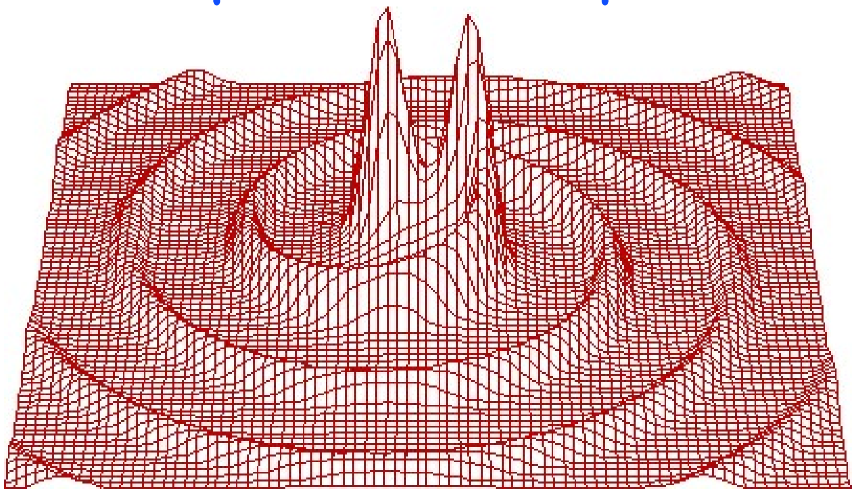
Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.



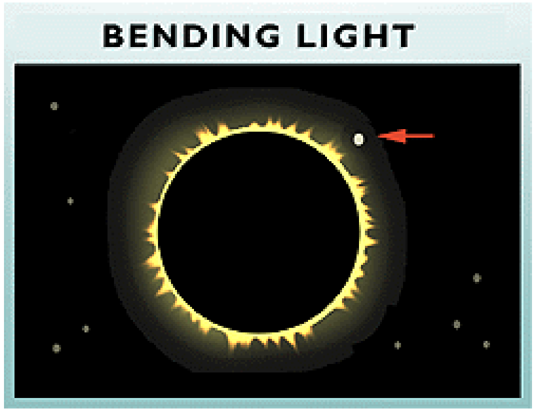
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

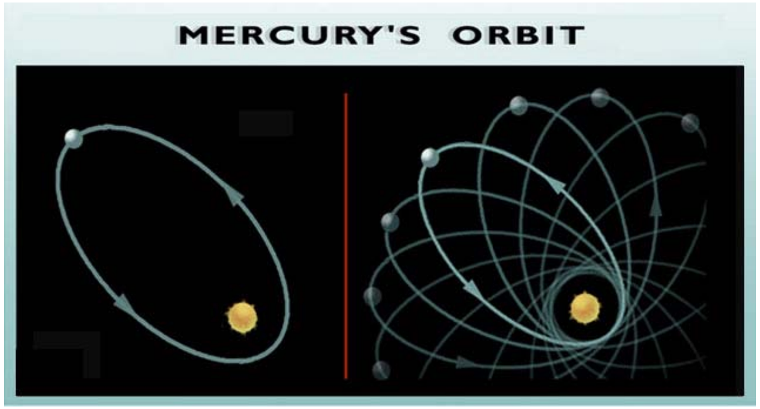
Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

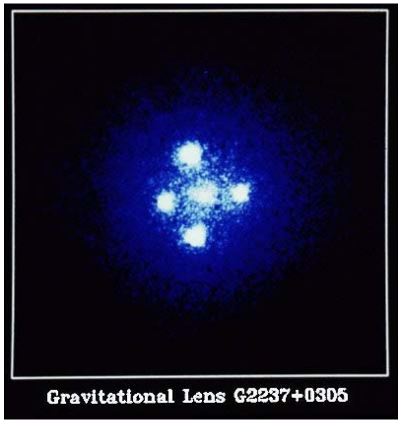
If the source is moving
(at speeds close to c),
*eg,* because it's orbiting a companion,
the "news" of the changing
gravitational field propagates outward
as gravitational radiation –
a wave of spacetime curvature



# Einstein's Theory of Gravitation
## *experimental tests*




**bending of light**
***As it passes in the vicinity of massive objects***

**First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster**

**Mercury's orbit**
***perihelion shifts forward twice Post-Newton theory***

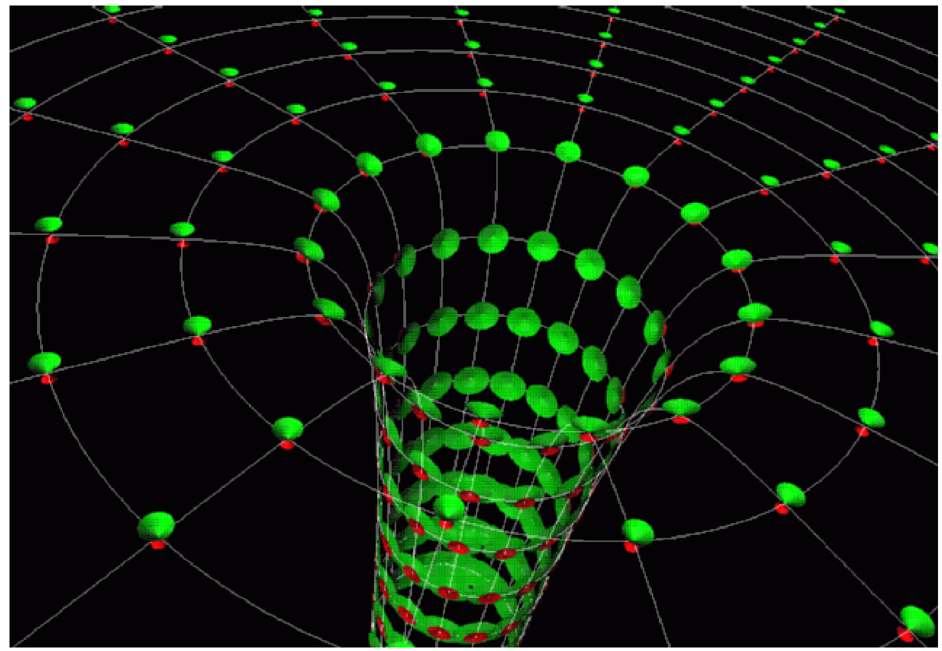
**Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.**

**"Einstein Cross"**
**The bending of light rays**
***gravitational lensing***

**Quasar image appears around the central glow formed by nearby galaxy. Such gravitational lensing images are used to detect a 'dark matter' body as the central object**

# Strong-field


- Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)
- Space-time curvature is a *tiny* effect everywhere except:
  - The universe in the early moments of the big bang
  - Near/in the horizon of black holes
- This is where GR gets *non-linear* and interesting!
- We aren't very close to any black holes (fortunately!), and can't see them with light or other EM radiation…

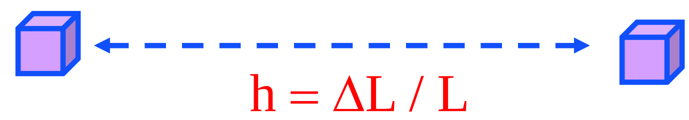


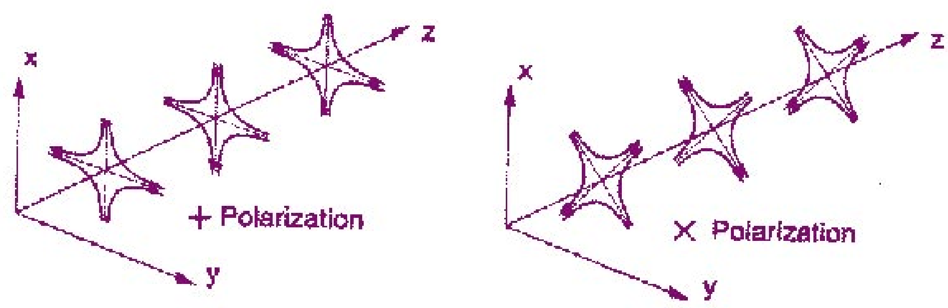
**But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics**

# Nature of Gravitational Radiation

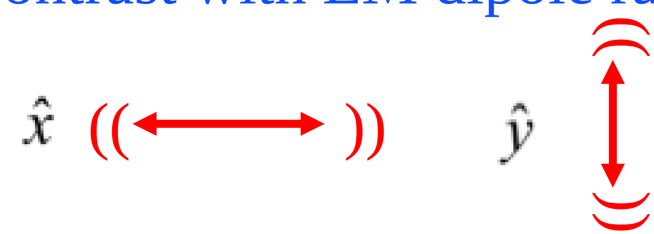
General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in fabric of spacetime

- Stretches and squeezes space between "test masses" – strain $h = \Delta L / L$
- propagating at speed of light
  - *mass of graviton = 0*
- space-time distortions are transverse to direction of propagation
- GW are tensor fields (EM: vector fields)
  two polarizations: plus (⊕) and cross (⊗)
  (EM: two polarizations, *x* and *y* )
  *Spin of graviton = 2*




Contrast with EM dipole radiation:



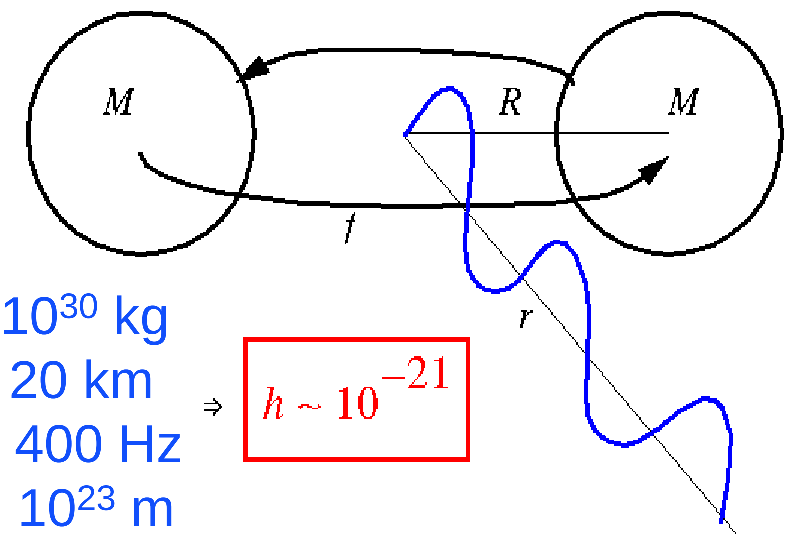
# Sources of GWs

- Accelerating charge ⇒ electromagnetic radiation (dipole)
- Accelerating mass ⇒ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \quad \Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- $G$ is a small number! (space-time is *stiff*).
- Waves can carry huge energy with minimal amplitude
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:

Energy-momentum conservation:
energy cons ⇒ no monopole radiation
momentum cons ⇒ no dipole radiation
⇒ lowest multipole is quadrupole wave

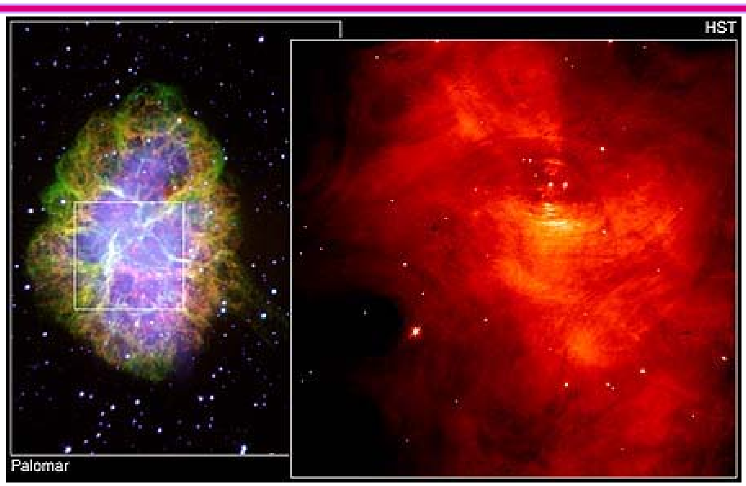



$M \sim 10^{30}$ kg
$R \sim 20$ km
$f \sim 400$ Hz
$r \sim 10^{23}$ m

⇒ $h \sim 10^{-21}$

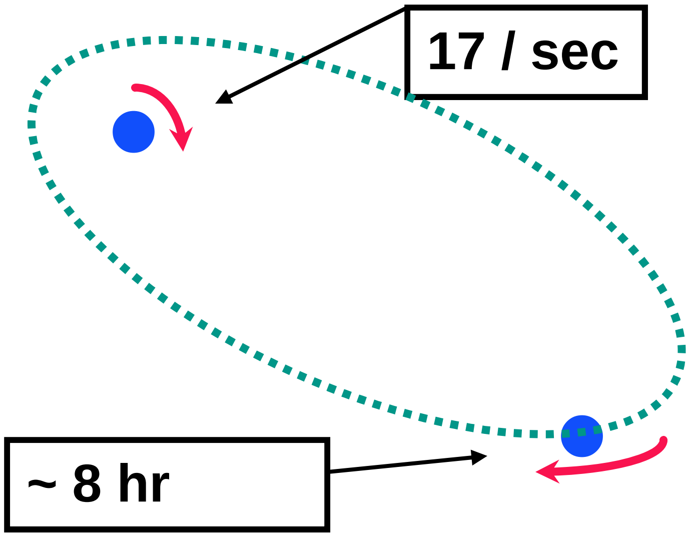
**Terrestrial sources *TOO WEAK*!**

# Hulse-Taylor binary pulsar




<u>Neutron Binary System</u>

PSR 1913 + 16 -- Timing of pulsars

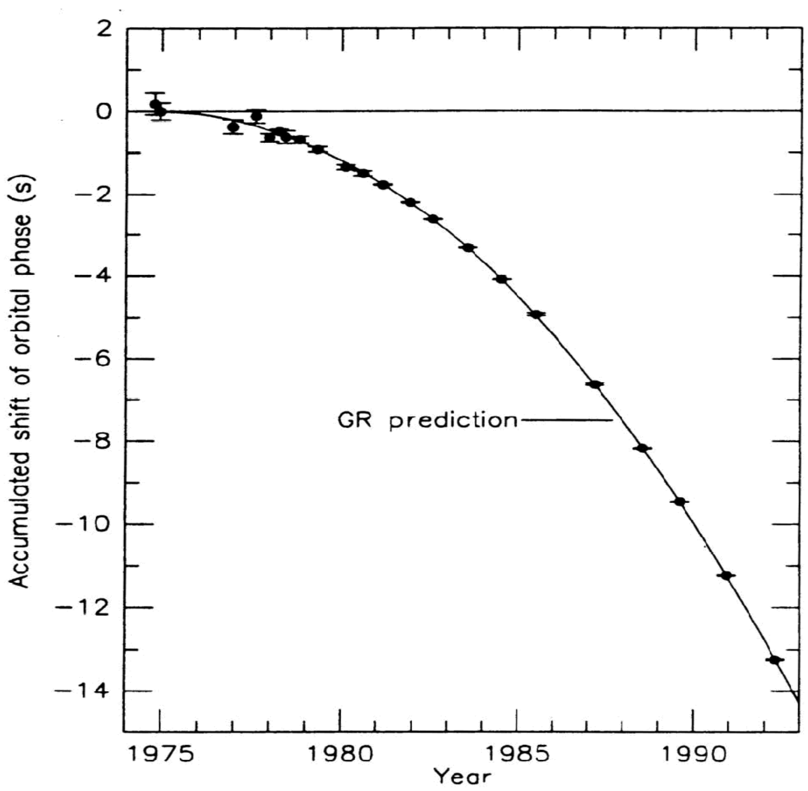



- A rapidly spinning pulsar (neutron star beaming EM radiation at us 17 x / sec)
- Orbiting around an ordinary star with 8 hour period
- Only 7 kpc away
- Discovered in 1975, orbital parameters measured continuously over 25 years!

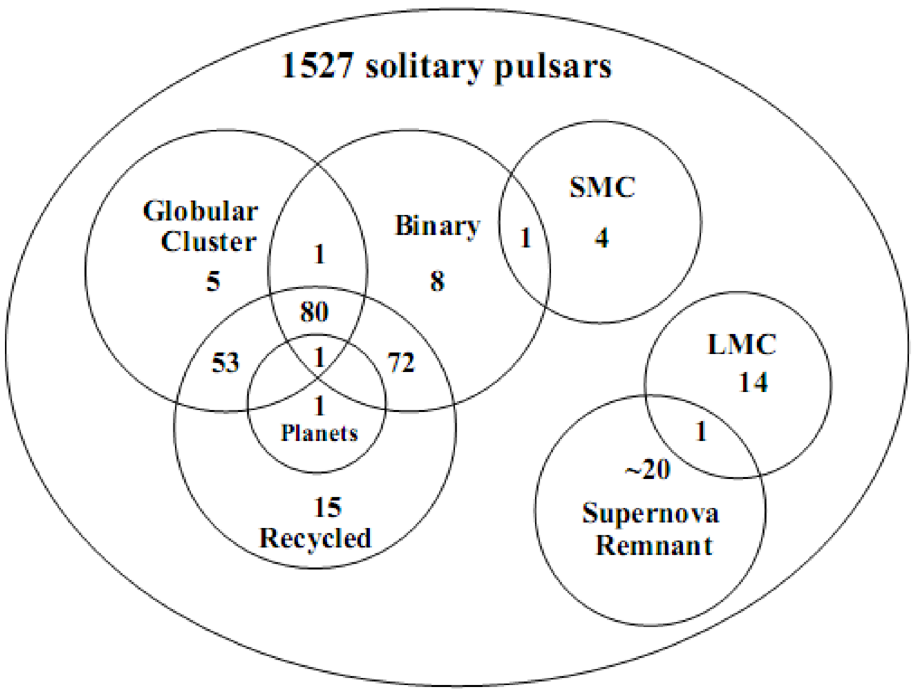
# GWs from Hulse-Taylor binary

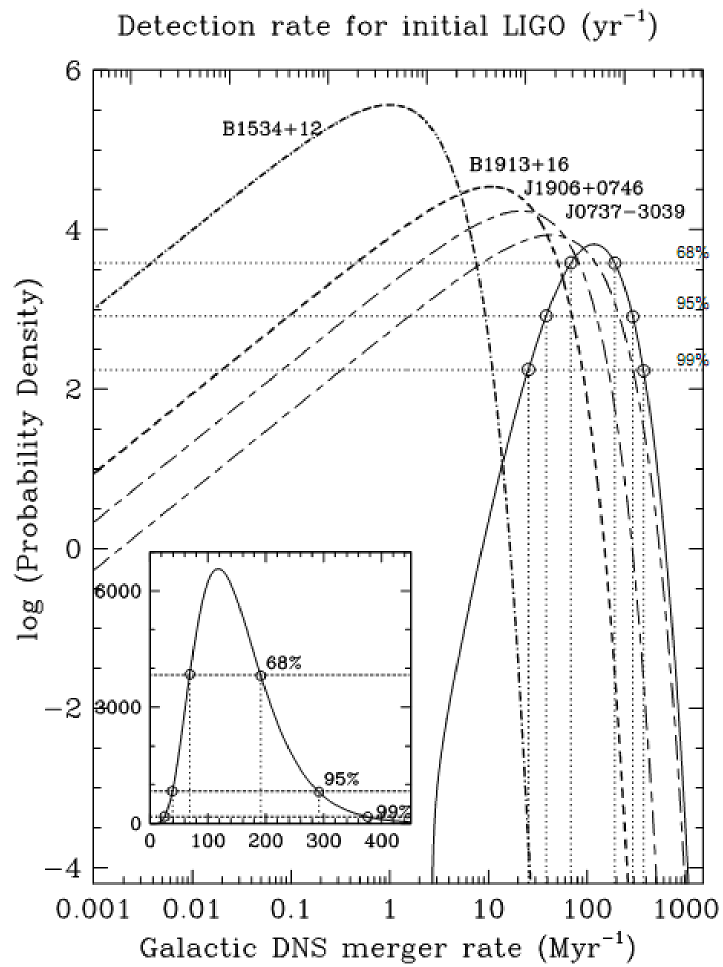
**emission of gravitational waves by compact binary system**

- **Period speeds up 14 sec from 1975-94**
- **Measured to ~50 msec accuracy**
- **Deviation grows quadratically with time**
- **Merger in about 300M years**
  **(<< age of universe!)**
- **shortening of period ⇐ orbital energy loss**
- **Compact system:**
  **negligible loss from friction, material flow**
- **Beautiful agreement with GR prediction**
- **Apparently, loss is due to GWs!**
- **GW emission will be strongest near the end:**
  - **Coalescence of neutron stars!**
- **Nobel Prize, 1993**
- **By 2013, there are ~8**



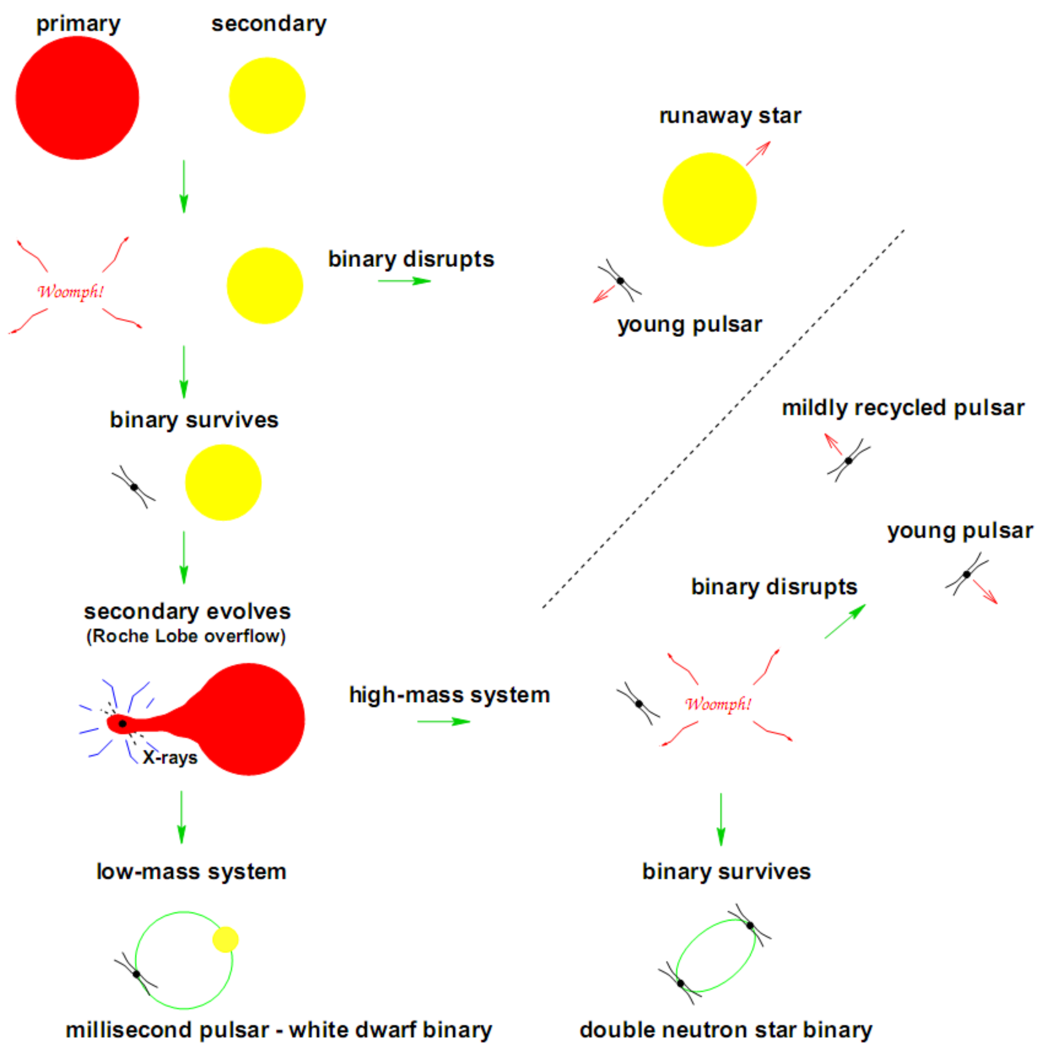
# Galactic binary pulsars, and inferred merger rate




Duncan R. Lorimer
*Living Reviews in Relativity*
http://www.livingreviews.org/lrr-2008-8

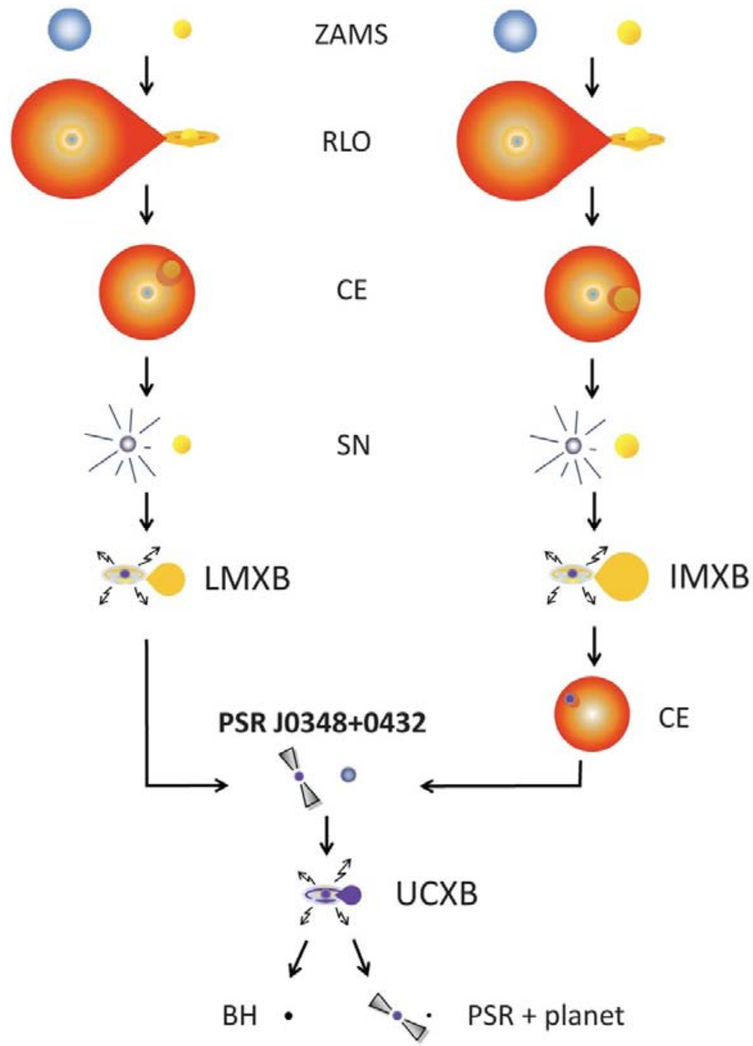
# BNS formation scenario



# Massive Binary Evolution

These systems are the progenitors of:

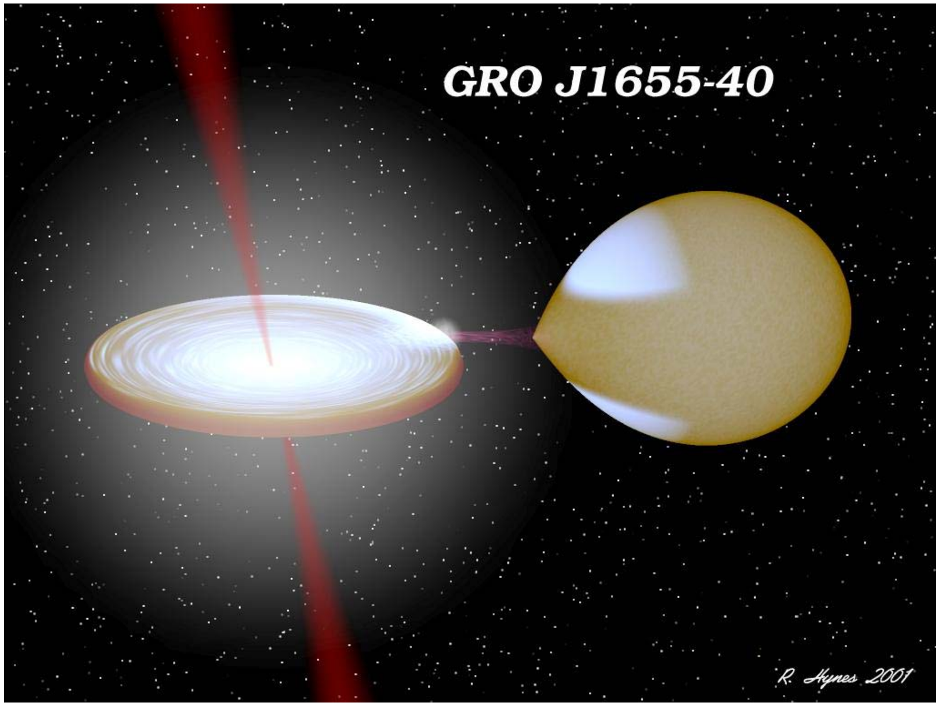
- Type-1a SNe
- Accretion disks
- Millisecond pulsars
- Low-mass X-ray binaries (LMXB)
- High-mass X-ray binaries (HMXB)
- Binary neutron stars (BNS)
- NS-BH
- Binary black holes (BBH)

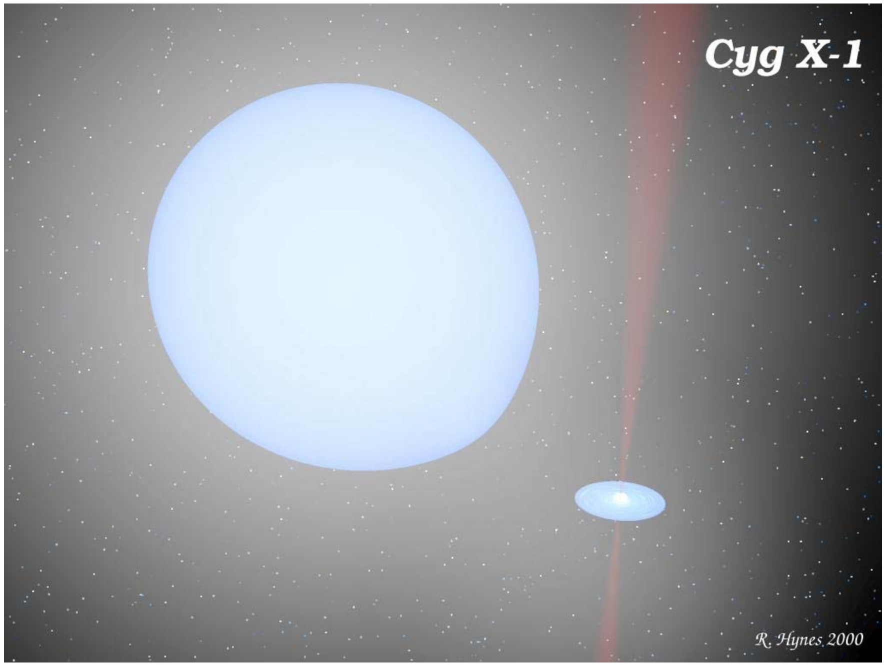



A Massive Pulsar in a Compact Relativistic Binary
Science 26 April 2013, vol. 340 no. 6131

# Progenitors of compact binaries

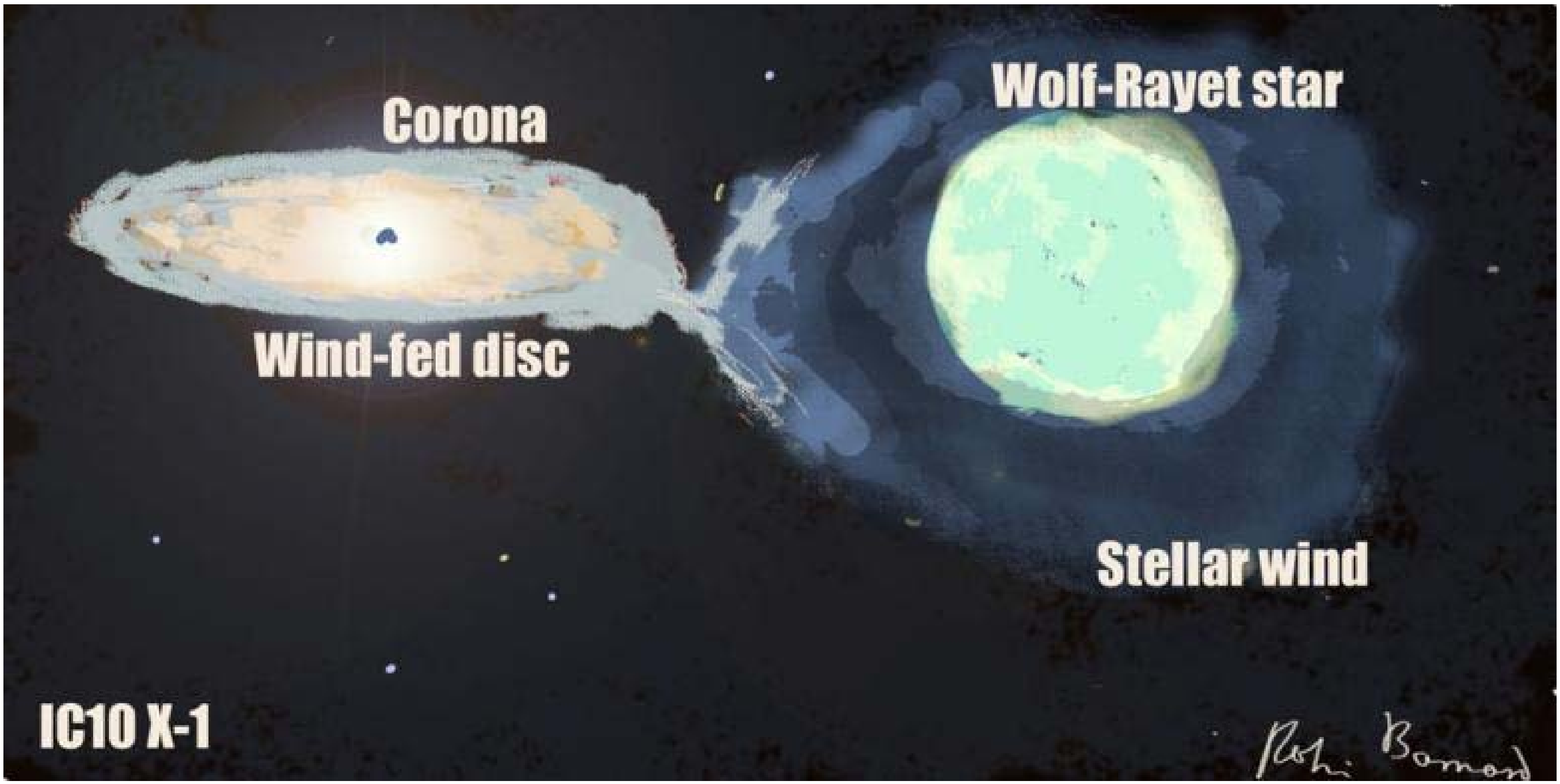
- LMXB HMXB



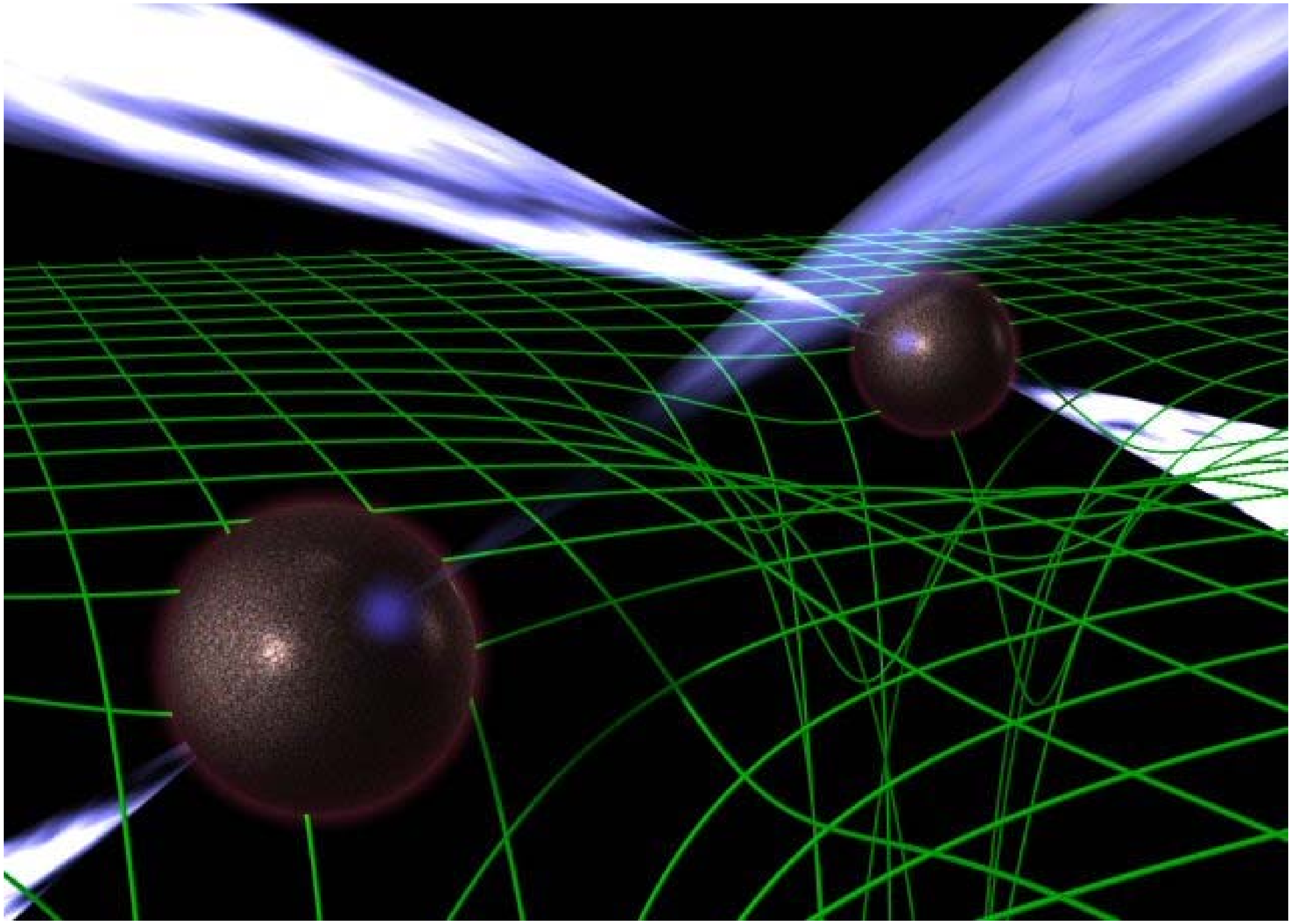

http://www.phys.lsu.edu/~rih/binsim/gallery.html

# Progenitors of binary black holes




http://www.robinbarnard.com/web_images/ic10-x-1.jpg

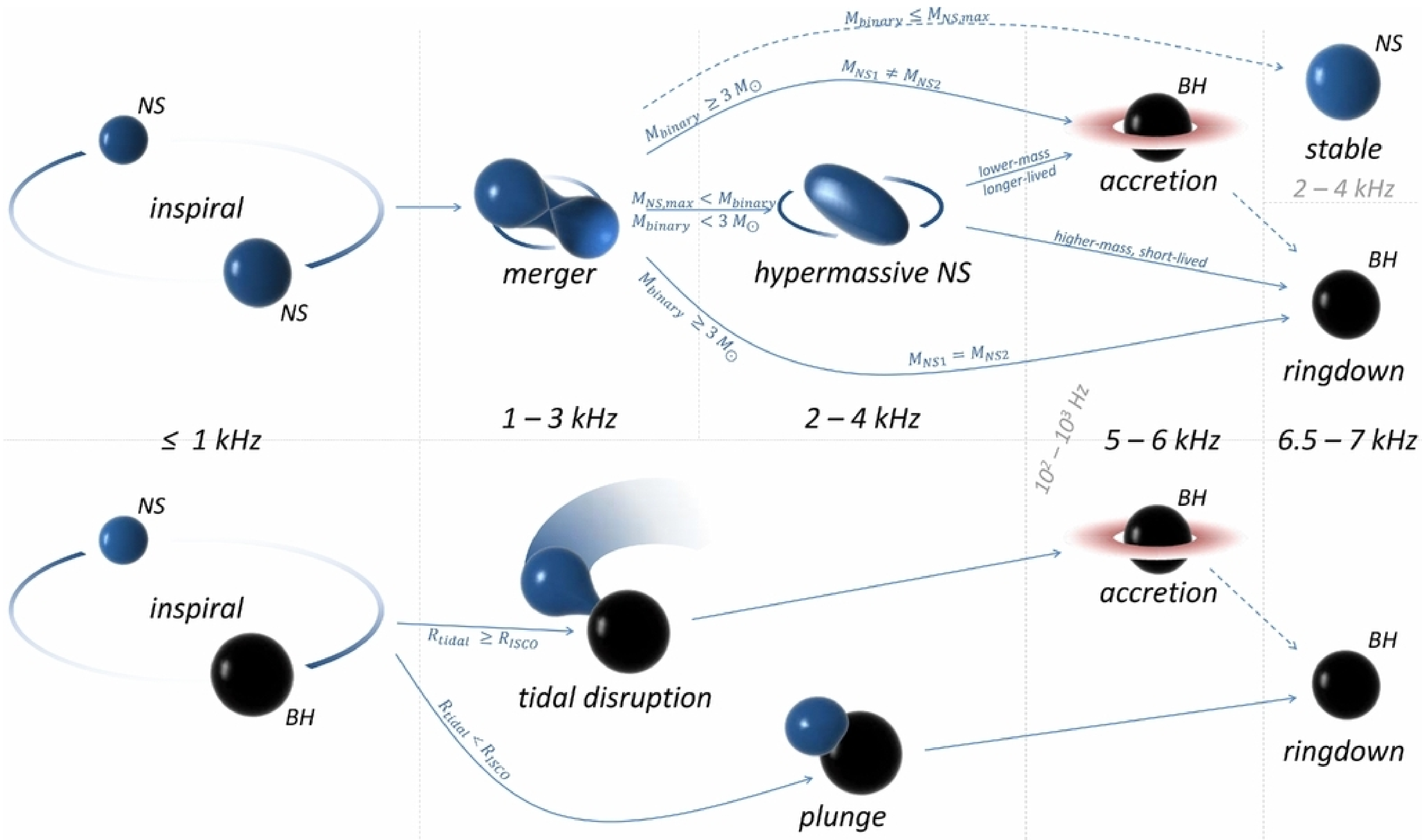
# The double pulsar PSR J0737-3039



http://www.jb.man.ac.uk/~pulsar/doublepulsarcd/

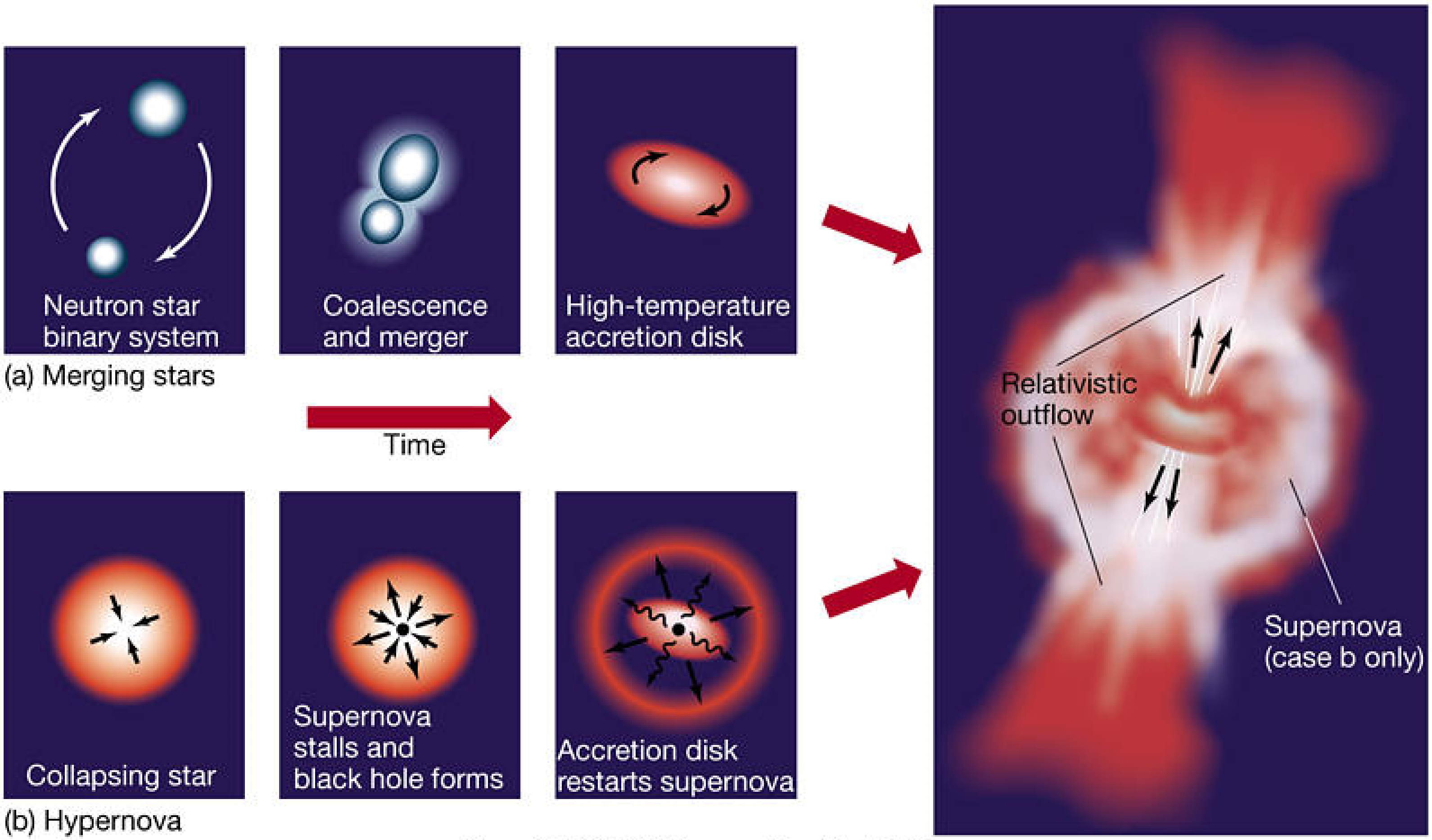
# And in the end … binary mergers

Figure 1 from I Bartos et al 2013 Class. Quantum Grav. 30 123001

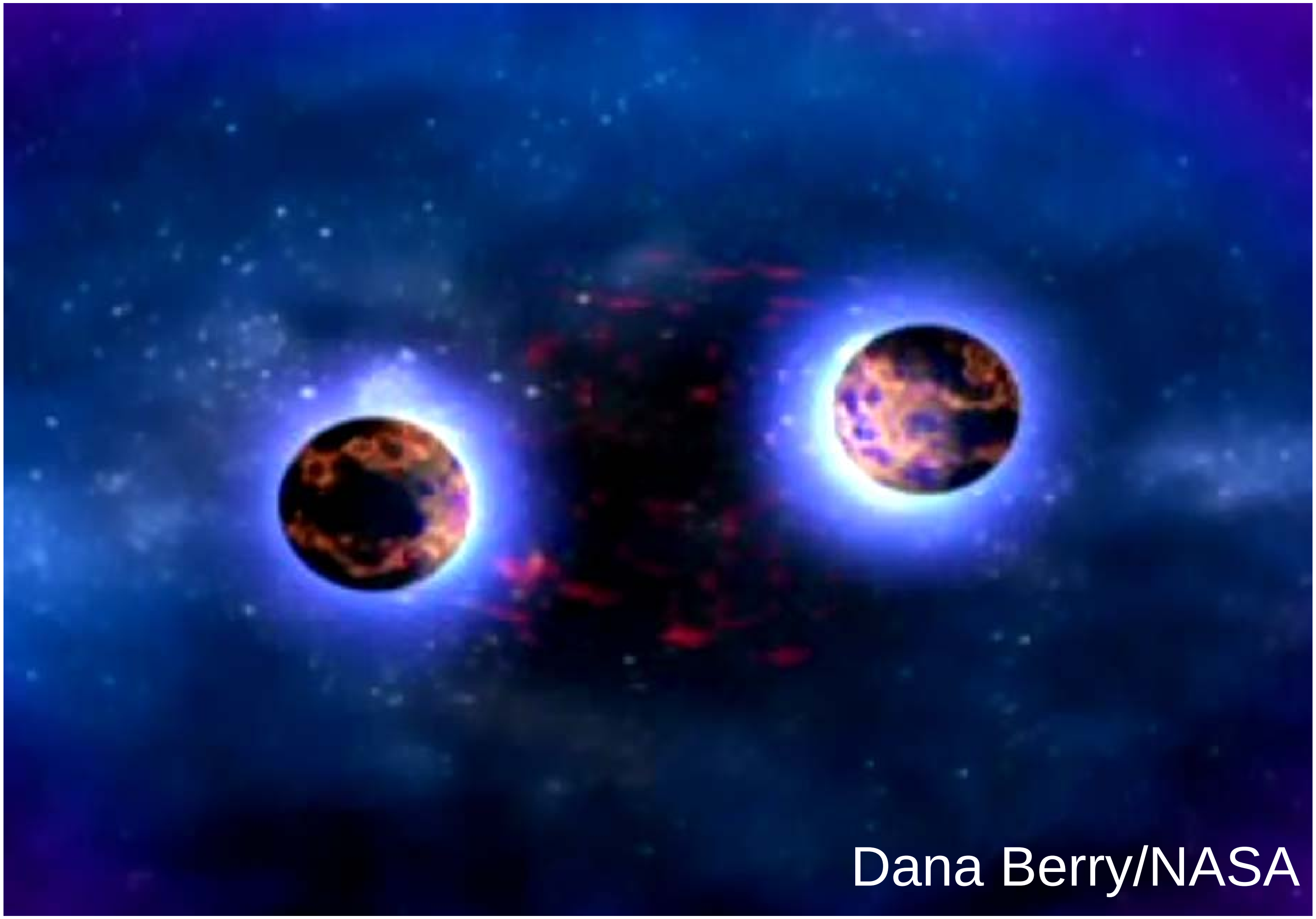


# Binary neutron star mergers

# Short-hard and Long-soft GRBs

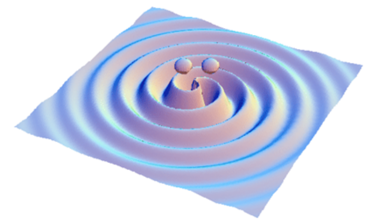


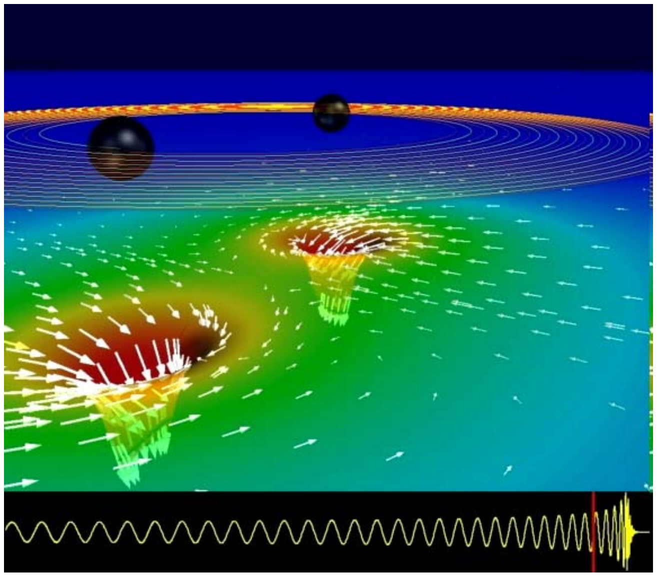
# Binary neutron star merger



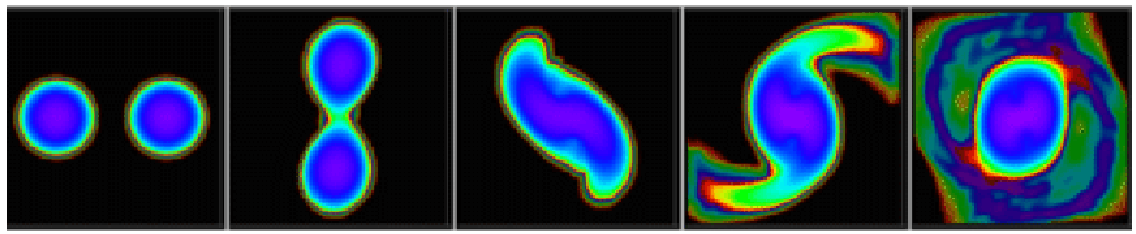

http://www.nasa.gov/mission_pages/swift/bursts/short_burst_nsu_multimedia.html

# GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





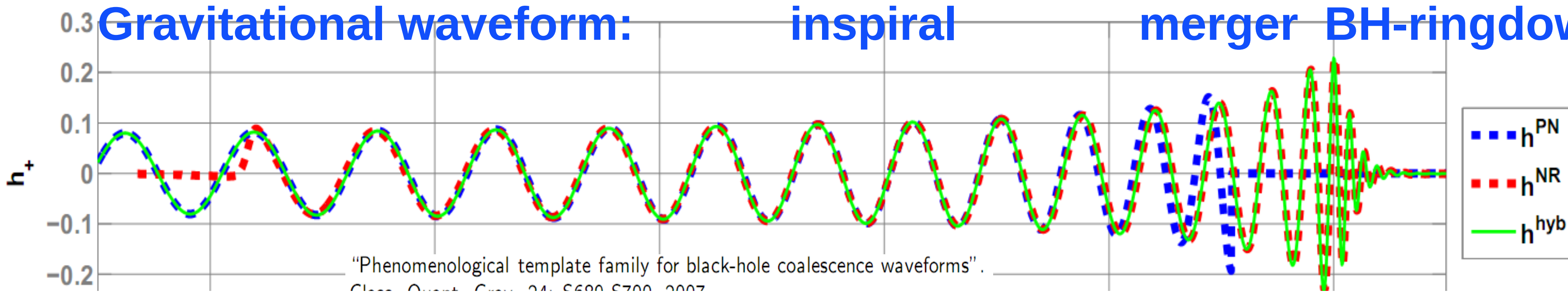
- Neutron star – neutron star (Centrella et al.)



**Tidal disruption of neutron star**

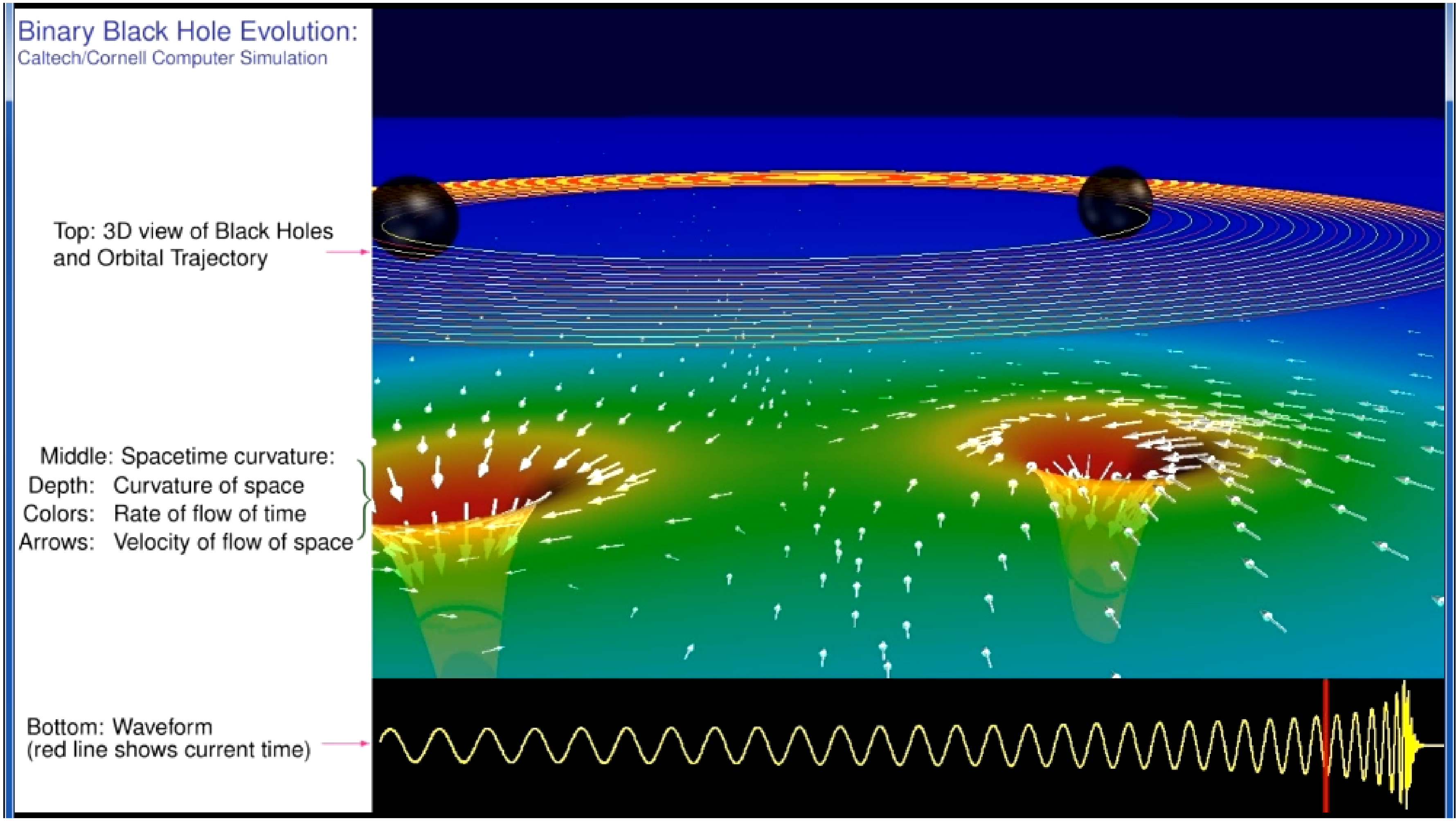
**A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions**

**Gravitational waveform: inspiral merger BH-ringdown**



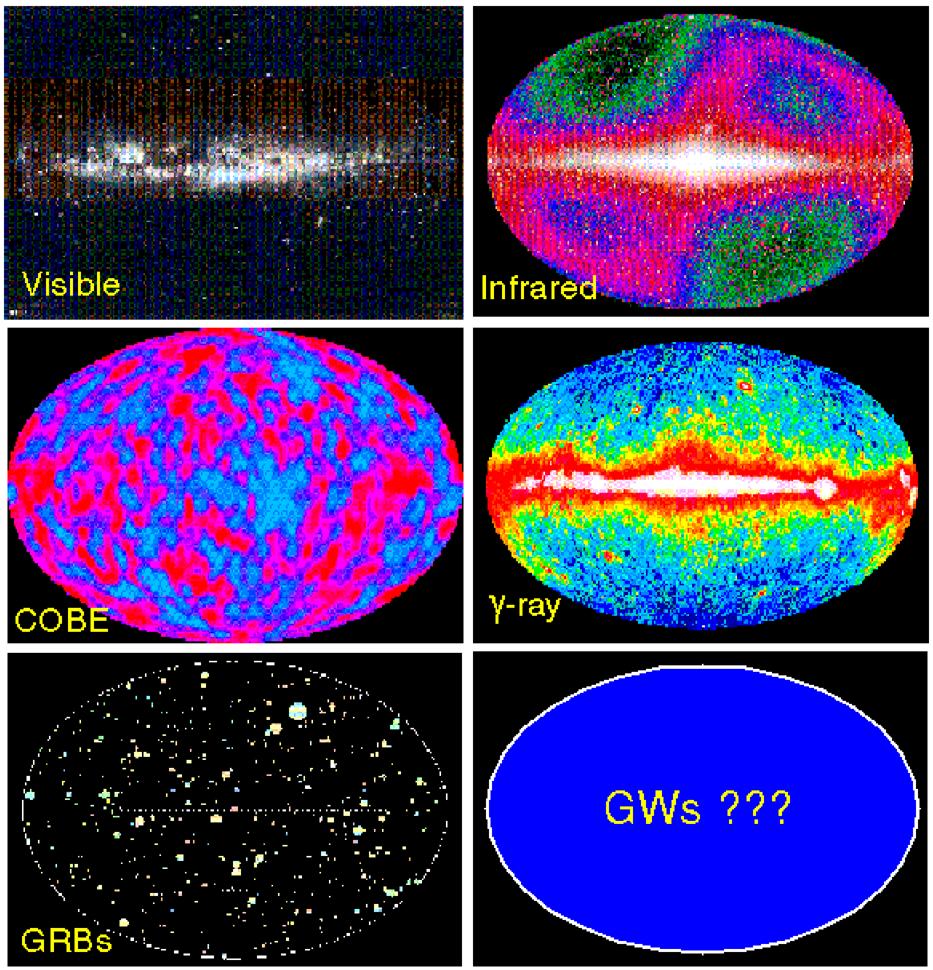

**Waveform carries lots of information about binary masses, orbit, merger**

# Binary black hole inspiral, merger, ringdown




http://www.black-holes.org/explore2.html

# A NEW WINDOW ON THE UNIVERSE



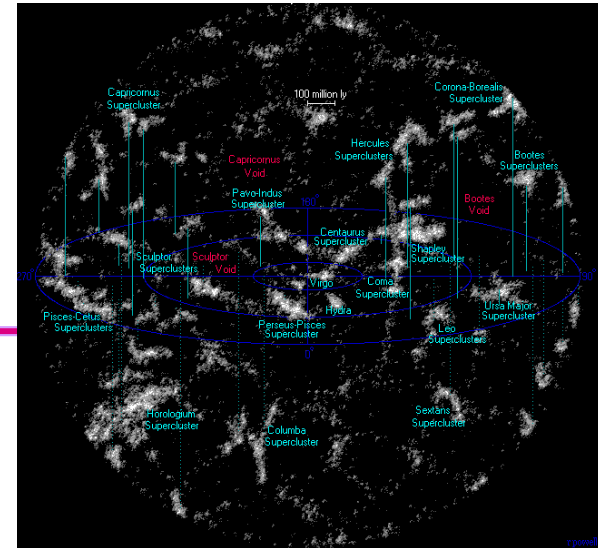

The history of Astronomy:
new bands of the EM spectrum opened → major discoveries!

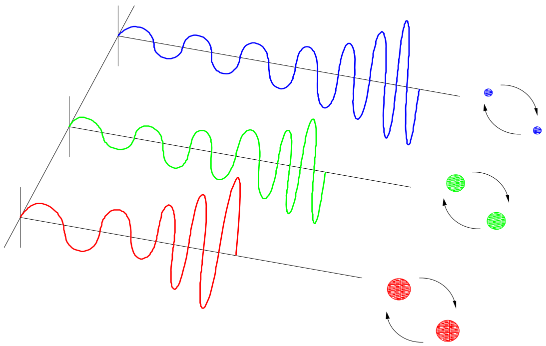
GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

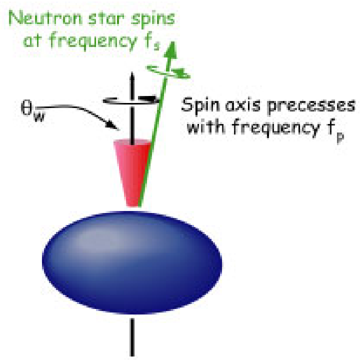
- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

# What will we see?

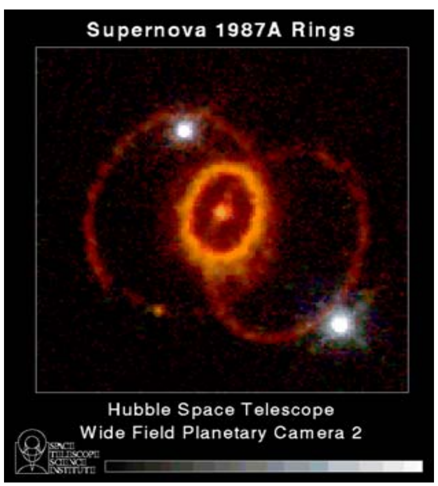


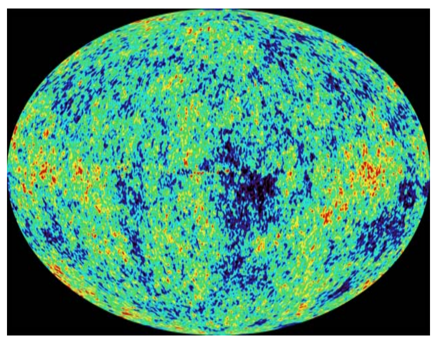





GWs from the most energetic processes in the universe!

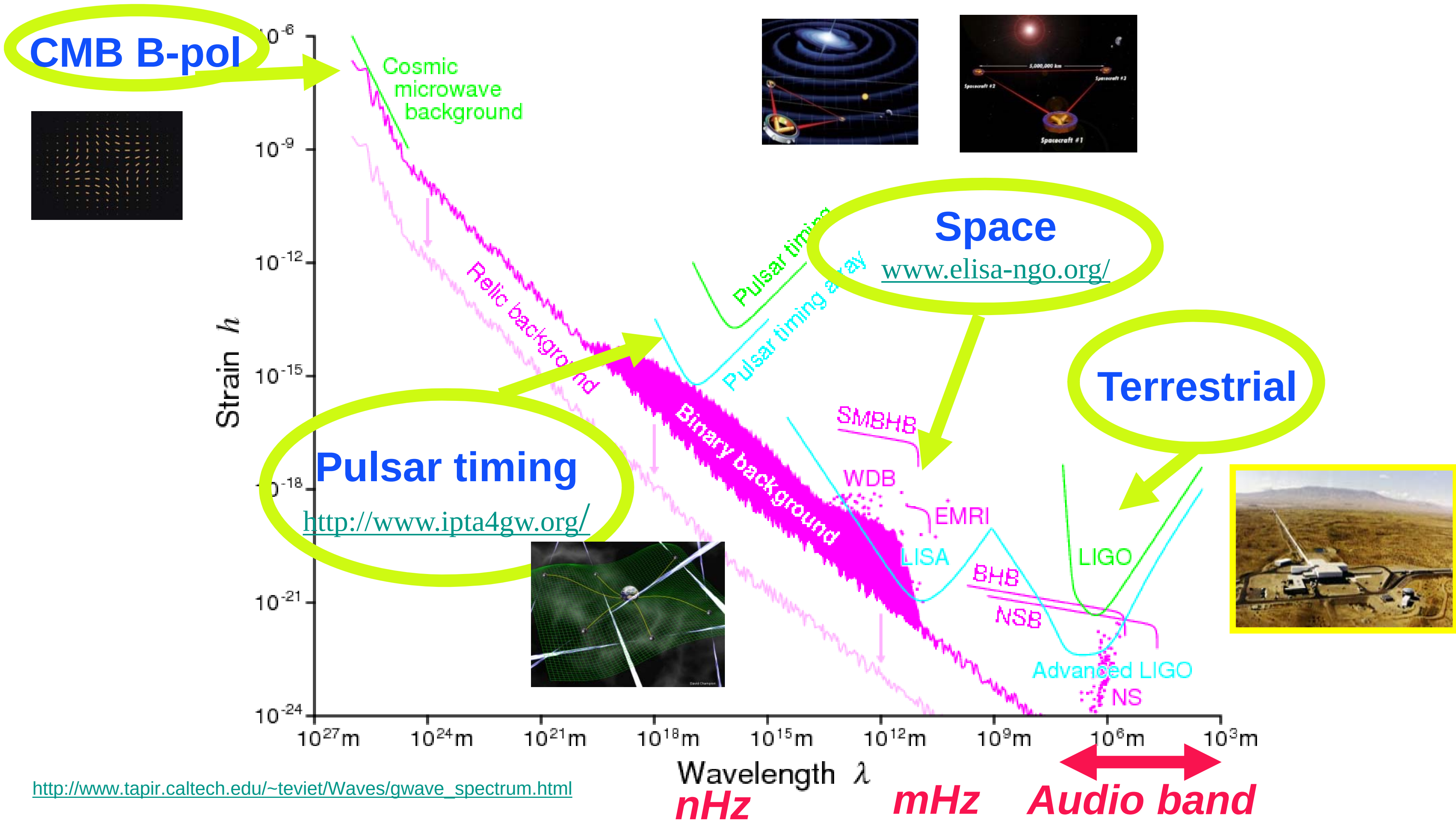
- Compact Binary Coalescences: black holes orbiting each other and then merging together
- GW bursts of unknown waveform: Supernovas, SGRs, GRB engines
- Continuous waves from pulsars, rapidly spinning neutron stars
- Stochastic GW background from vibrations from the Big Bang



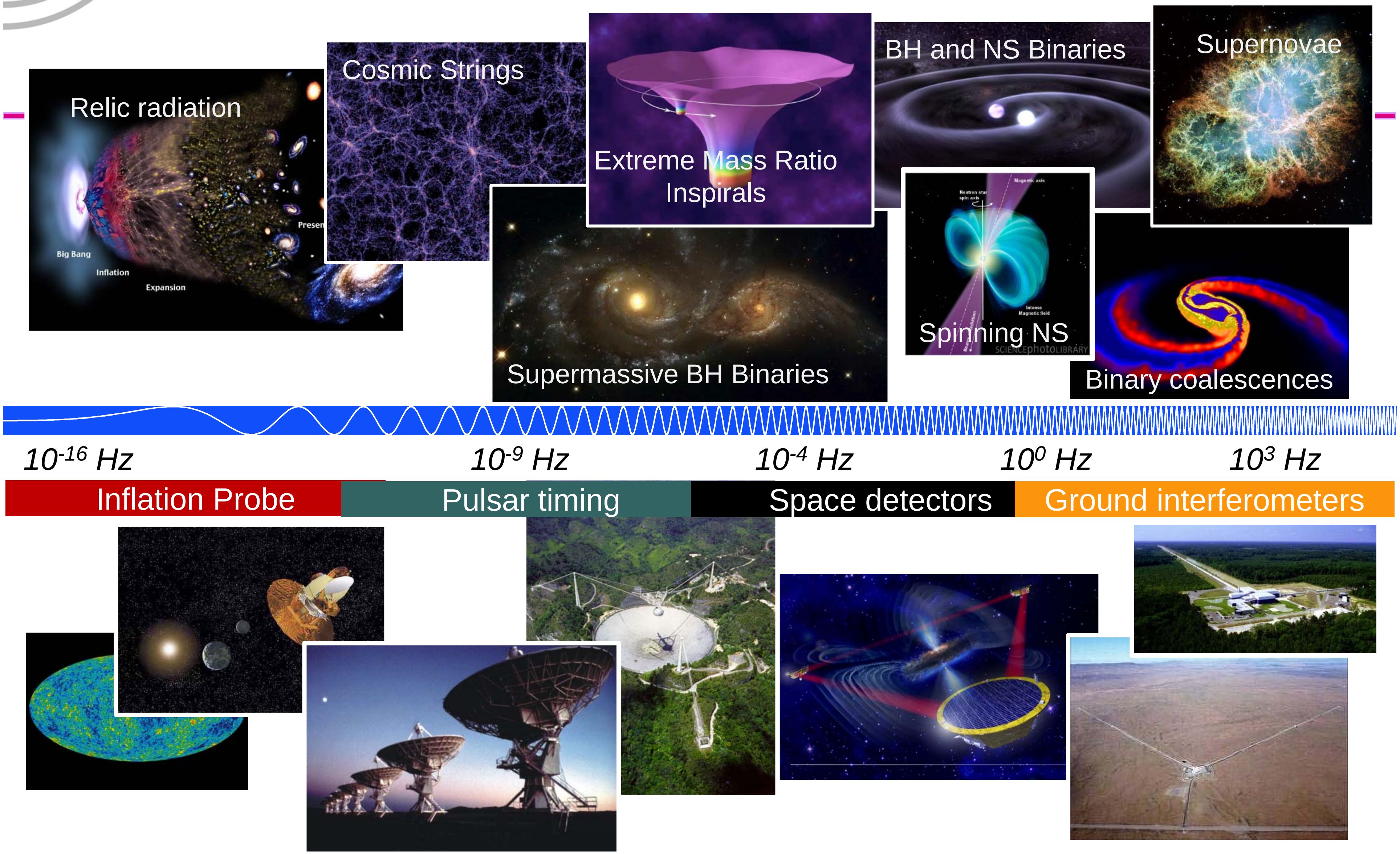
**Analog from cosmic microwave background -- WMAP 2003**

# Frequency range of GW Astronomy

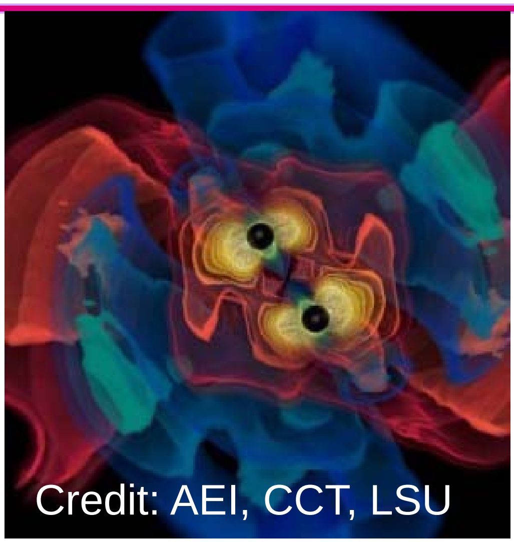



http://www.tapir.caltech.edu/~teviet/Waves/gwave_spectrum.html

# The GW Spectrum



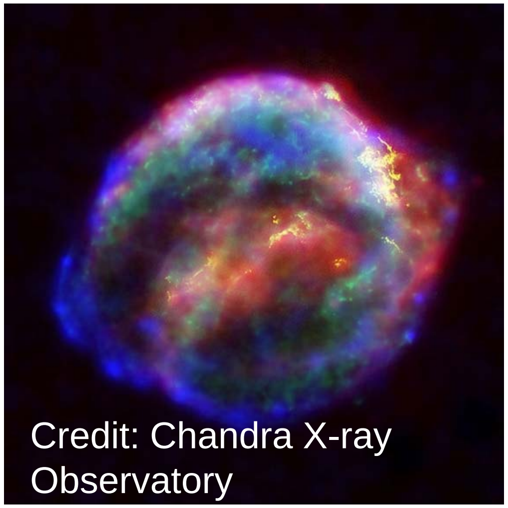
# GW sources for ground-based detectors: The most energetic processes in the universe




*Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH*

- Strong emitters, well-modeled,

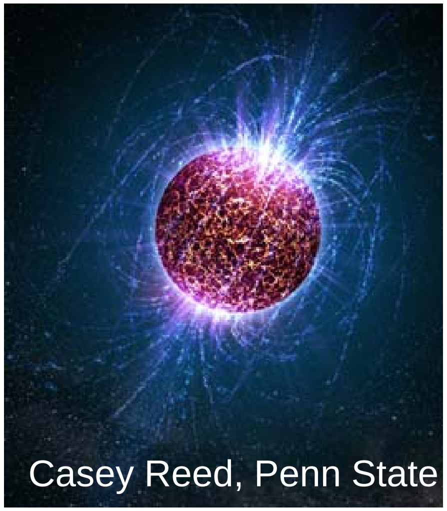
- (effectively) transient




*Asymmetric Core Collapse Supernovae*

- Weak emitters, not well-modeled ('bursts'), transient

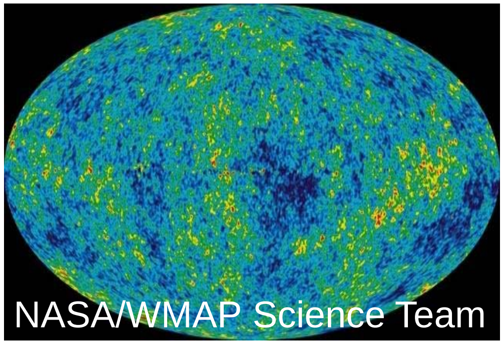
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class




*Spinning neutron stars*

- (effectively) monotonic waveform

- Long duration

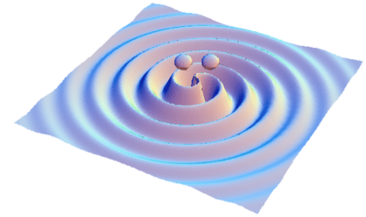


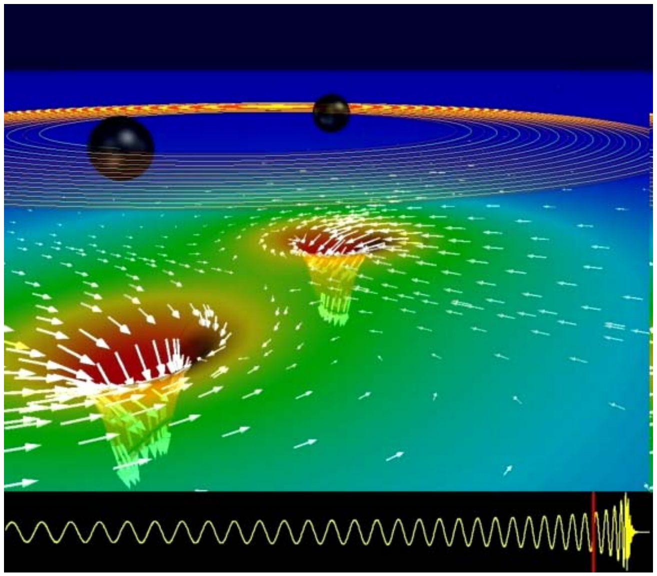

*Cosmic Gravitational-wave Background*

- Residue of the Big Bang, long duration

- Long duration, stochastic background

# GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





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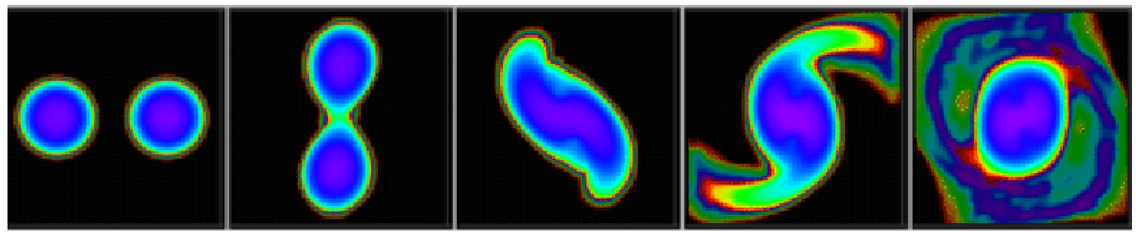
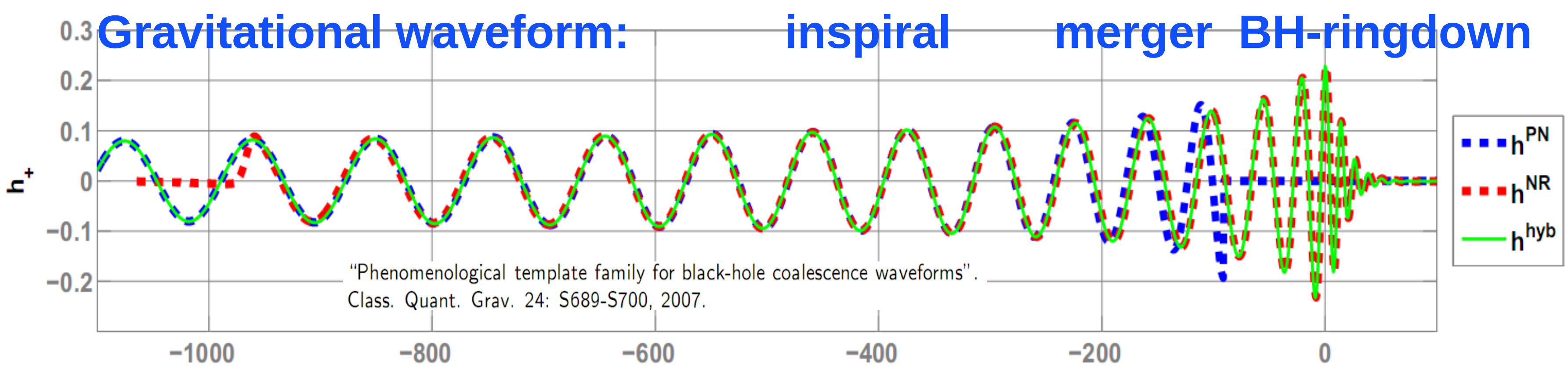
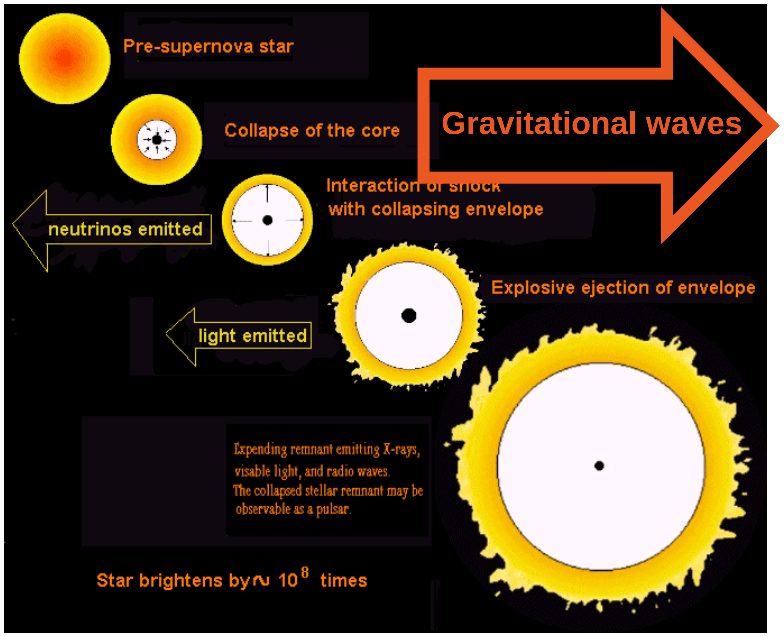


**Tidal disruption of neutron star**

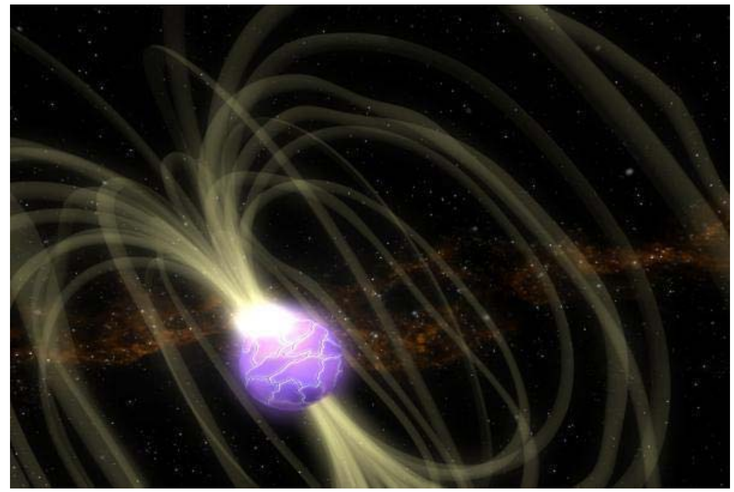
**A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions**



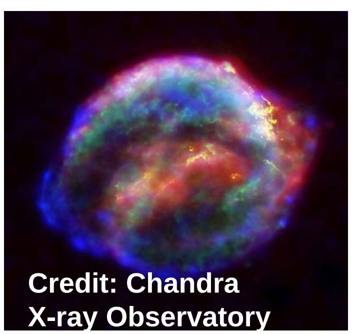
# Unmodeled, short-duration (<~ 1 s) GW Bursts

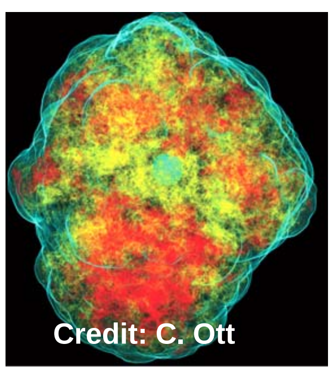



Core collapse supernova

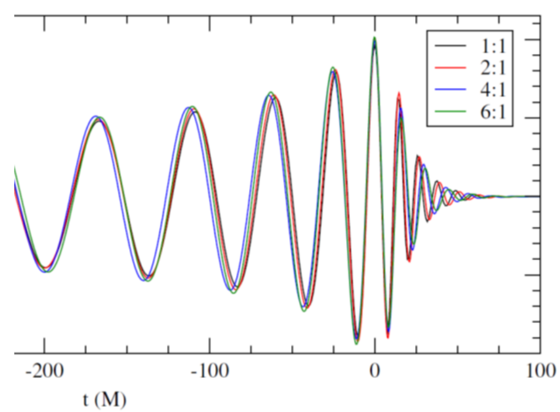


Magnetar flares / storms


Credit: Chandra X-ray Observatory


Credit: C. Ott

High-mass binary merger and ringdown



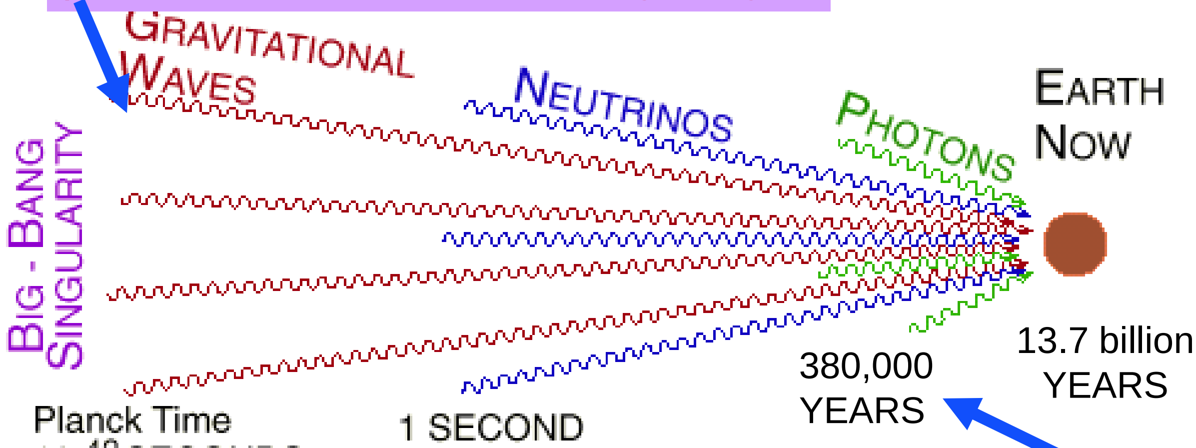
# Gravitational waves from Big Bang

*Waves now in the LIGO band were produced $10^{-22}$ sec after the big bang*

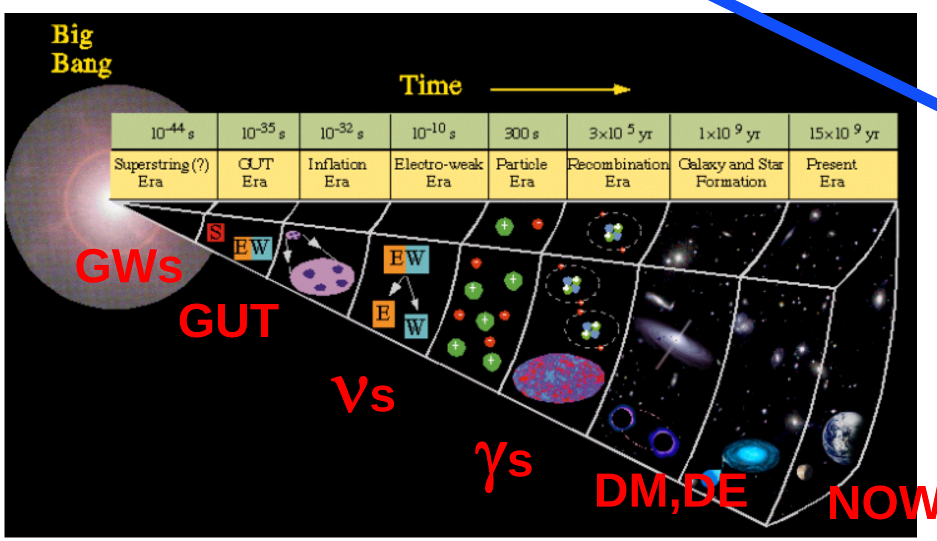
$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f}$$

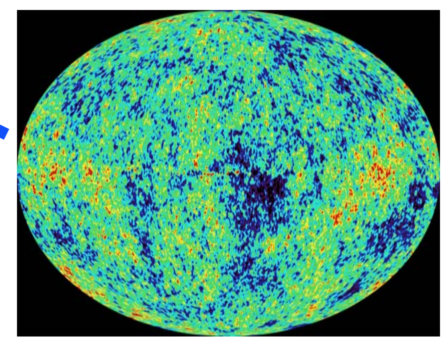
$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\, \dot{h}^{ab} >$$

$$h(f) = 6.3 \times 10^{-22} \sqrt{\Omega_{GW}(f)} \left(\frac{100\ \text{Hz}}{f}\right)^{3/2} \text{Hz}^{-1/2}$$



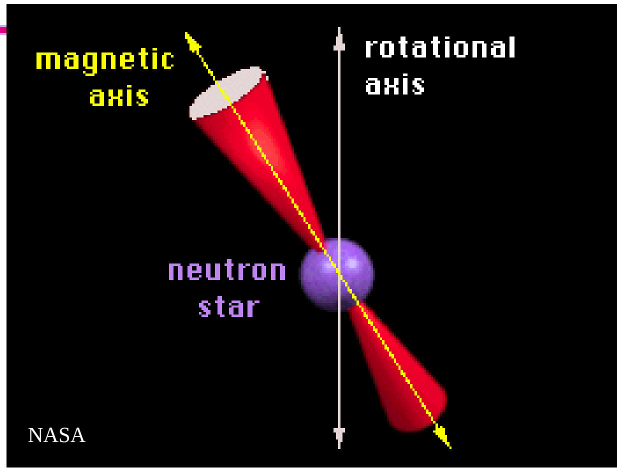

Planck Time
$10^{-43}$ SECONDS
Singularity creates Space & Time of our universe



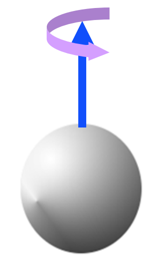
**cosmic microwave background -- WMAP 2003**

# Pulsars and continuous wave sources

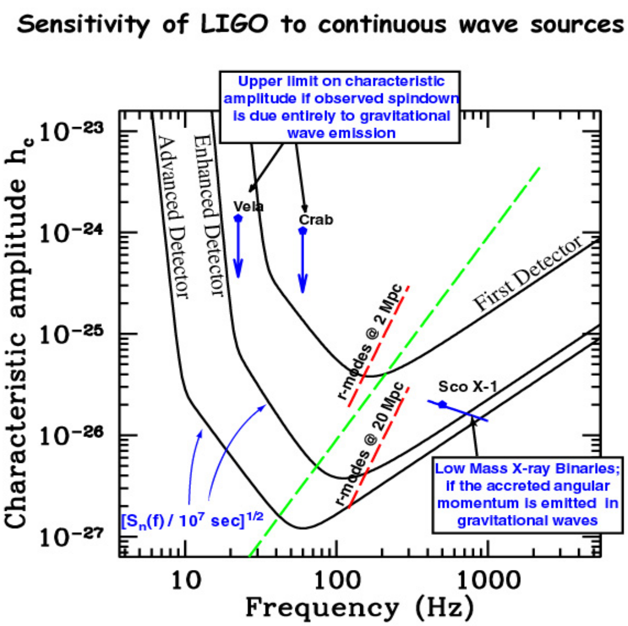


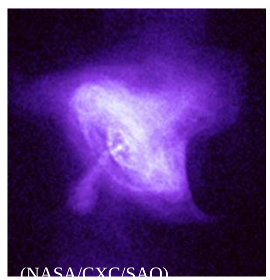

- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < $\varepsilon$ < 10-6
  - »science: EOS; precession; interiors
  - »"R-mode" instabilities
  - »narrow band searches best

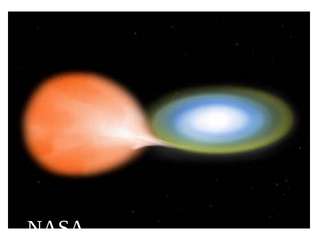
$$h = \frac{4\pi^2 G}{c^4}\frac{I f_{GW}^2}{d}\varepsilon$$

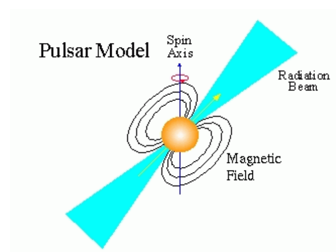


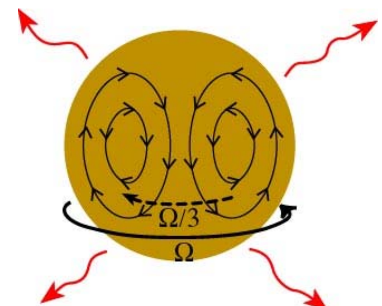
$$f_{GW} = 2\, f_{ROT}$$



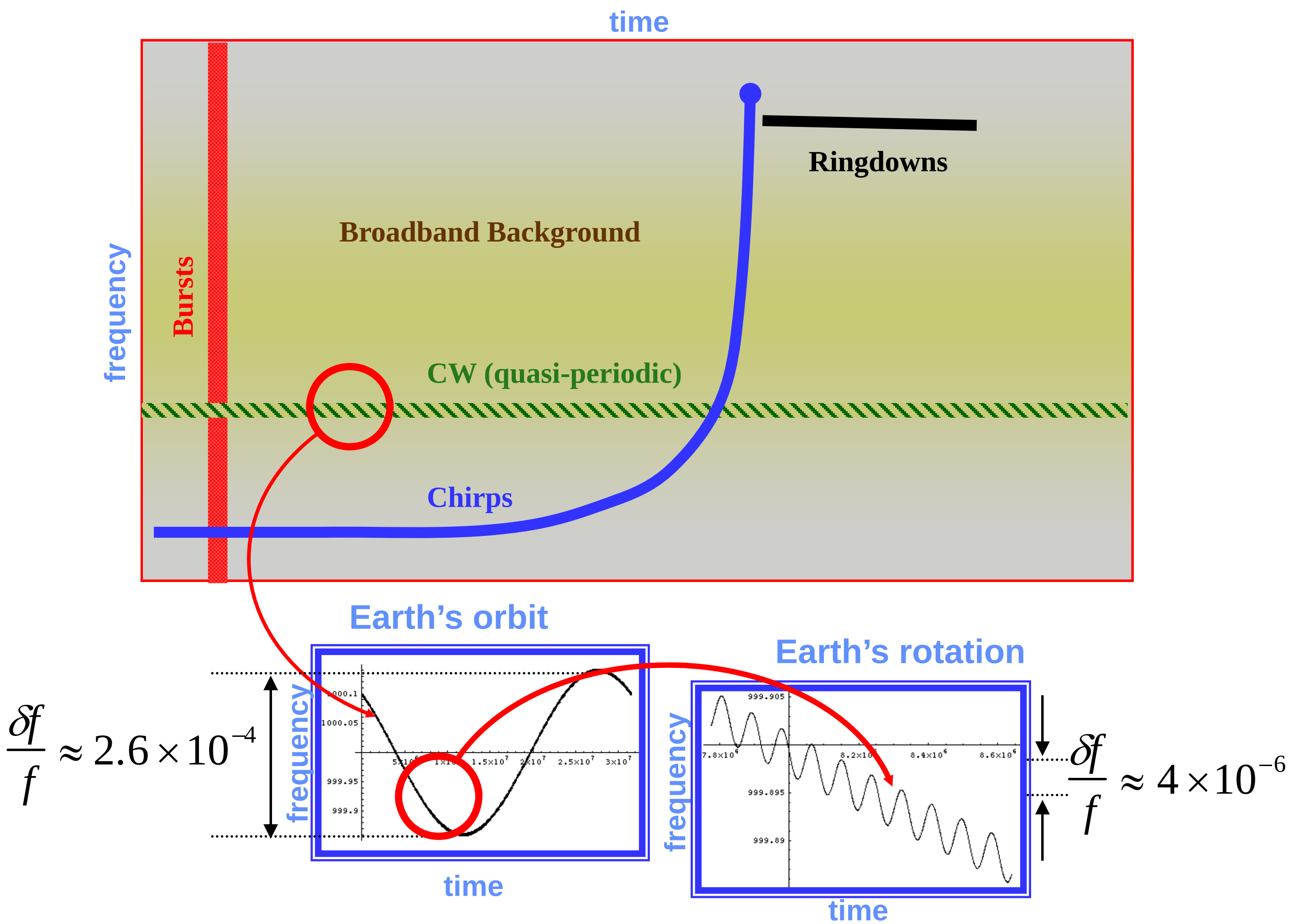



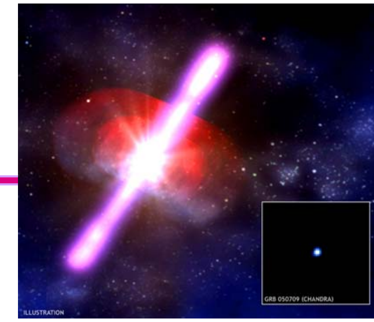




R-modes

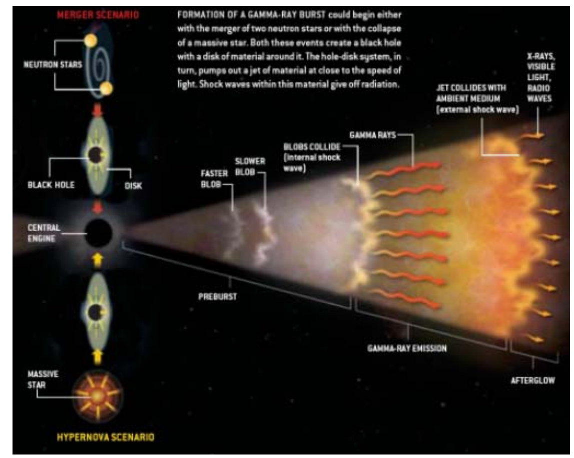
# Frequency-Time Characteristics of GW Sources



# Astrophysics with joint GW – EM observations




- Short-hard GRBs, with or without the GRB
  - » Confirm (or rule out) merger progenitor
  - » Study progenitor systems, including orientation and beaming
  - » Relate GW and EM energy release
  - » Relate merger parameters to hosts (metallicity, SFR, …)




- Follow-ups: detect optical afterglow, host galaxy, redshift…
  - » Low latency pipeline, sky localization
- CBC mergers as cosmological standard sirens.
  - » Independent measurement of Hubble constant
  - » a(z), dark energy EoS

# GW and EM Multi-messenger Astronomy

Gravitational Waves:

- » Bulk motion dynamics
- » Binary parameters
- » Direct probe of central engine
- » Progenitor mass
- » GW energetics
- » Luminosity distance

Light Curve & Spectrum:

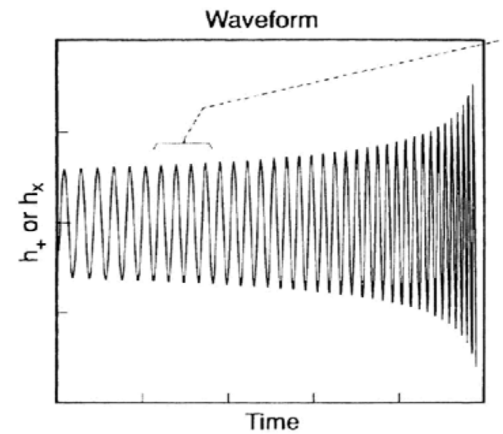
- » Precise sky location
- » Host galaxy
- » Gas environment
- » Progenitor star
- » EM energetics
- » Red shift

**more complete picture of progenitor physics**

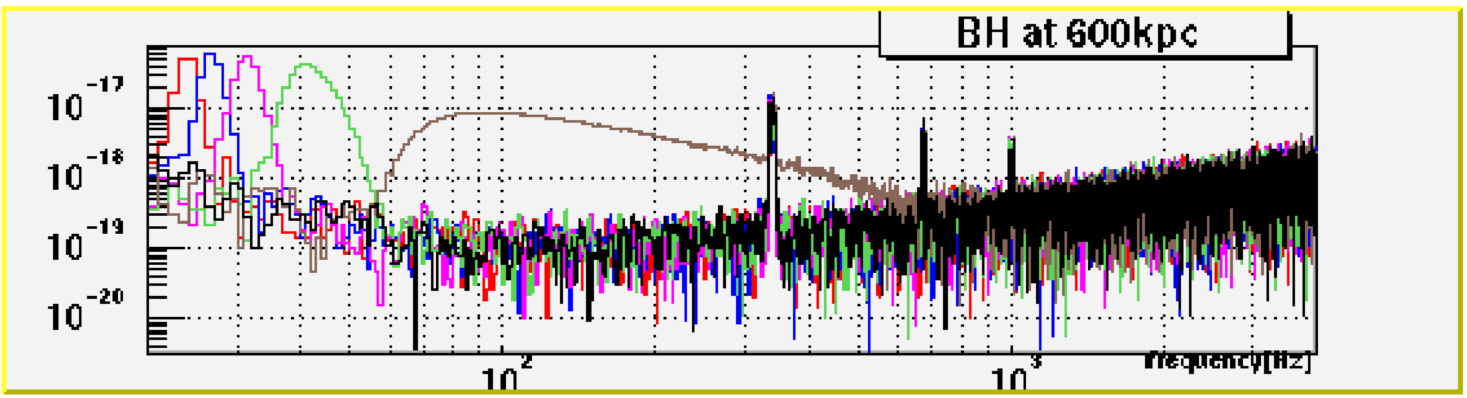
Combining these observations will also
- increase detection confidence,
- allow a measurement of the local Hubble constant.

# The sound of a chirp

BH-BH collision, no noise

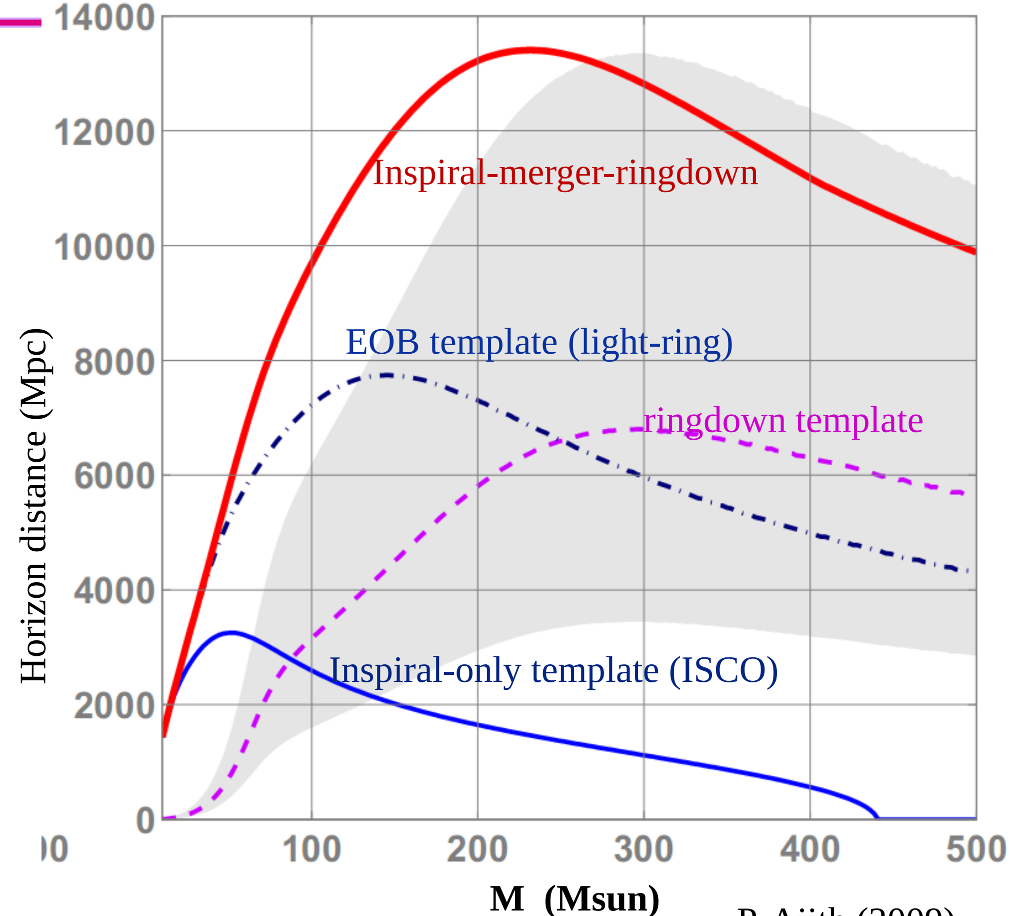



The sound of a BH-BH collision,
Fourier transformed over 5 one-second intervals
(red, blue, magenta, green, purple)
along with expected IFO noise (black)



# Horizon distance for compact binary mergers

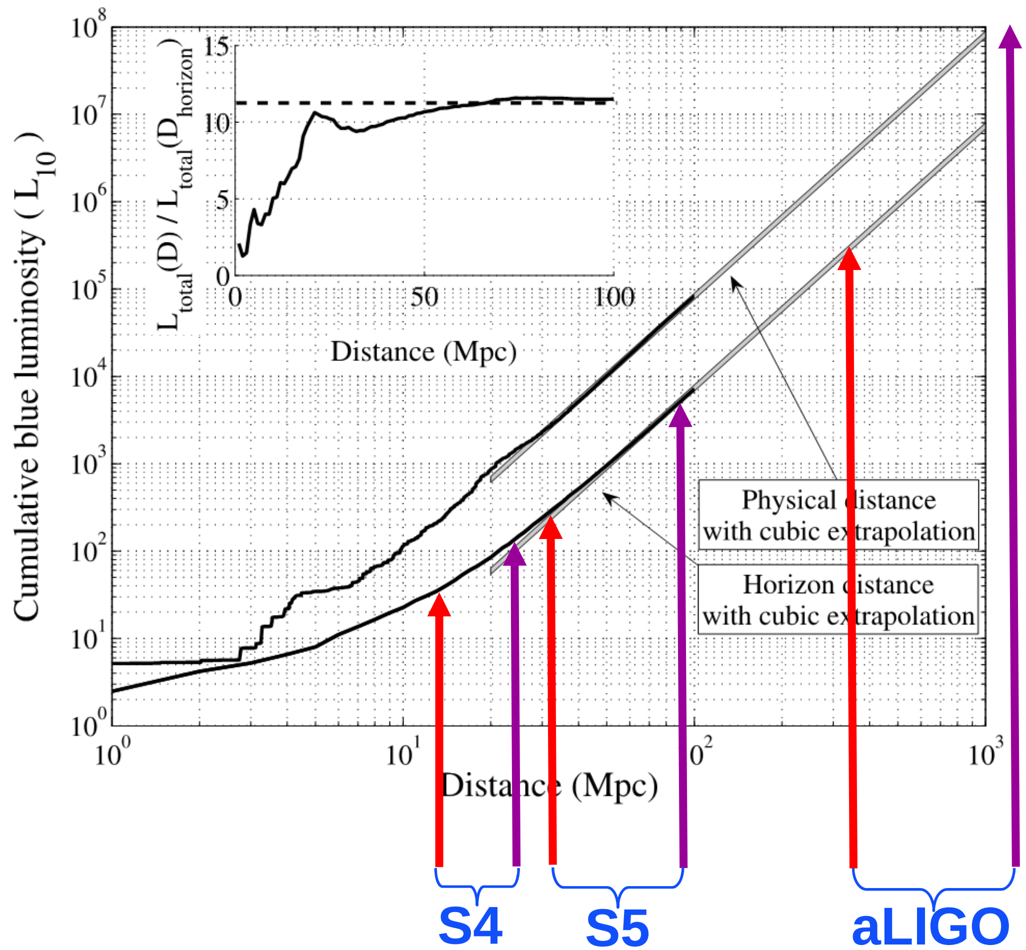
- **Horizon distance: Distance in Mpc at which one Advanced LIGO detector can see an optimally-located, optimally oriented binary merger with an SNR=8, as a function of total mass.**
- **Averaging over sky location and orientation degrades this by ~2.26.**
- **Important to use the right templates, including IMR, and spin effects!**
- **Experience from Initial LIGO-Virgo suggests that reliable detection is possible with an average SNR/detector ~ 8.**




P. Ajith (2009)

# Expected detection rate: How many sources can we see?

- CBC waveforms have known amplitude
  $h \sim (GM/c^2 r) \times F(\alpha, \delta, \iota)$
- Measured detector sensitivity defines a *horizon distance*
- This encloses a known number of sources:
  MWEG = $1.7 \times 10^{10}$ $L_s$ = 1.7 $L_{10}$
- From galactic binary pulsars:
  R(BNSC) ~10-170 /Myr/$L_{10}$
- From population synthesis:
  R(BBHC) ~0.1 - 15 /Myr/$L_{10}$
- To see more than 10 events/yr, we need to be sensitive to
  $10^5$ - $10^7$ galaxies!

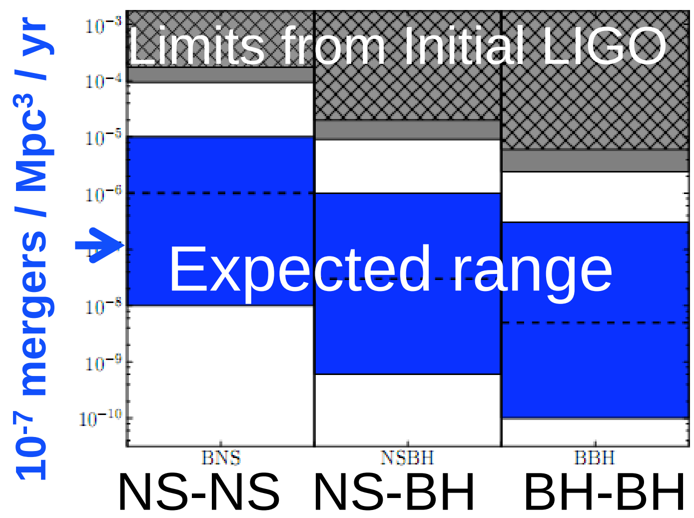



Kopparapu etal ApJ 675 (2008) 1459

# Expected ranges of binary merger rates

- Estimates of astrophysical event rate (mergers / $Mpc^3$ / yr) from known NS-NS close binaries in our galaxy, and population synthesis models.
  - LVC, Class. Quant. Grav. 27 (2010) 173001

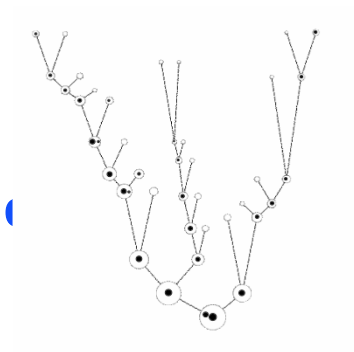
- Detection range in Mpc (SNR = 8 in one detector, averaged over source sky location and orientation) based on aLIGO Mode 1b noise model (P=125 W, $T_{SRM}$=20%, $F_{SRM}$=0° )




| System | Masses ($M_{sun}$) | Range (Mpc) | Low rate est. ($yr^{-1}$) | Realistic rate ($yr^{-1}$) | High rate est. ($yr^{-1}$) |
|---|---|---|---|---|---|
| NS-NS | 1.4/1.4 | 200 | 0.4 | 40 | 400 |
| NS-BH | 1.4/10 | 410 | 10 | 300 | |
| BH-BH | 10/10 | 970 | 20 | 1000 | |

# Astrophysical science with binary mergers

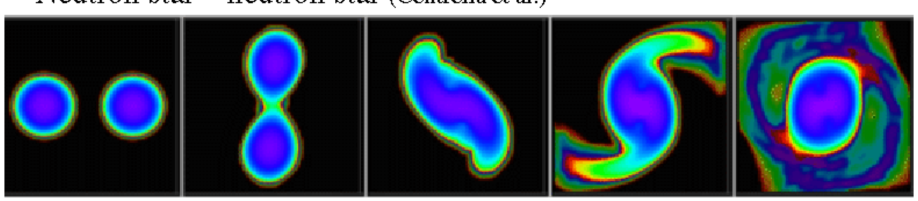
- **Merger rates as function of mass, mass ratio, spin**
  - » **Establish existence of black hole binaries**
  - » **Neutron star mass distribution**
  - » **Black hole number, mass, spin and location distribution**
  - » **Search for intermediate-mass black holes**
- **Inform / constrain astrophysical source distribution mod**
  - » **Extract population synthesis model parameters.**
  - » **Binary formation and evolution history**
  - » **Explore hierarchical merger scenarios**

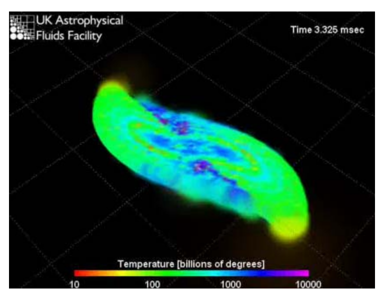


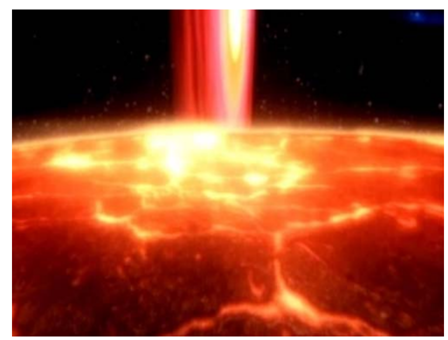
ciera.northwestern.edu/rasio

- **Study matter effects in waveform: tidal disruption, NS EOS.**

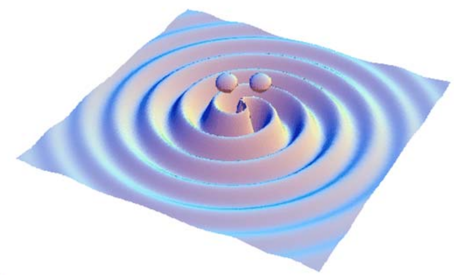
• Neutron star – neutron star (Centrella et al.)



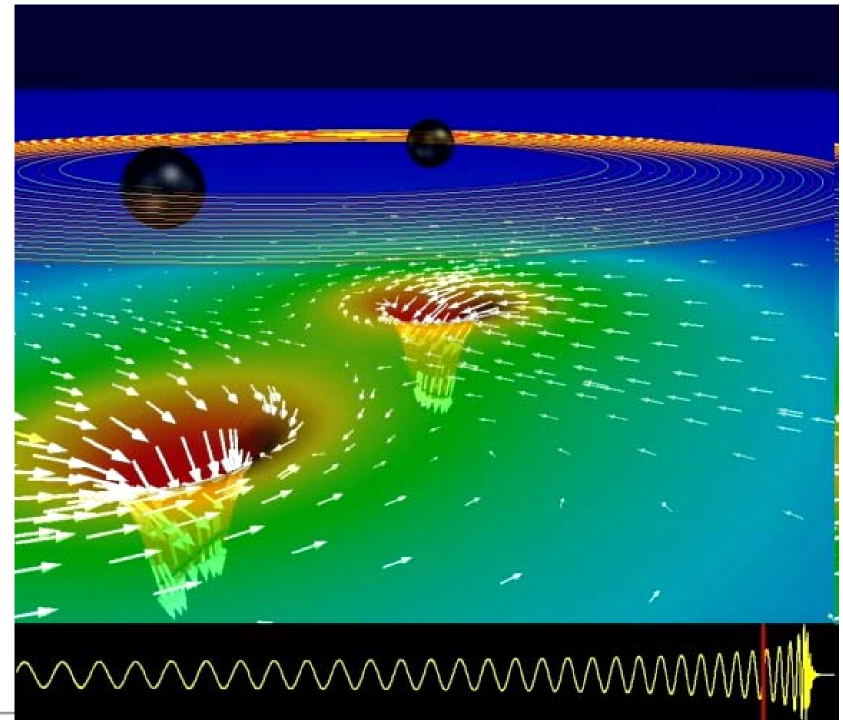


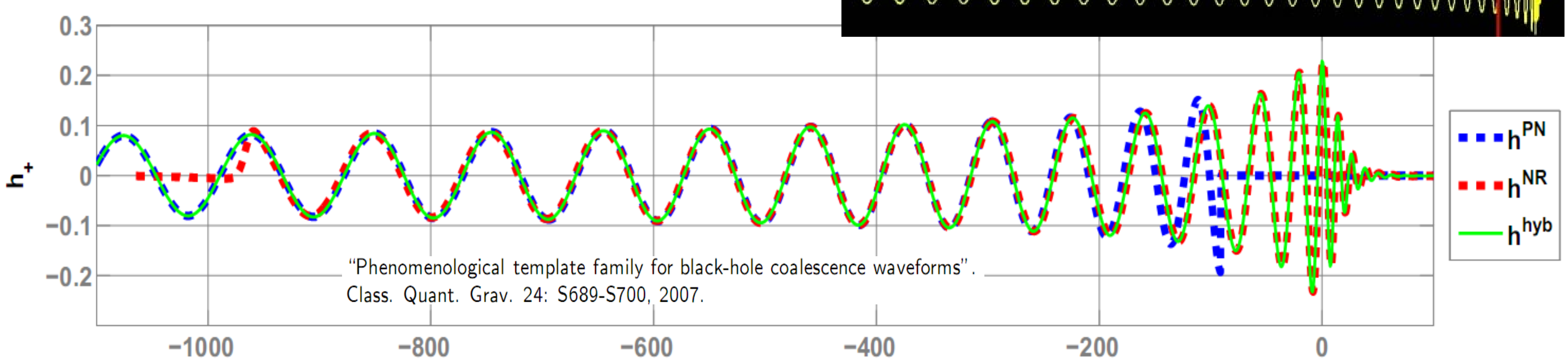



# Understanding Inspiral-Merger-Ringdown

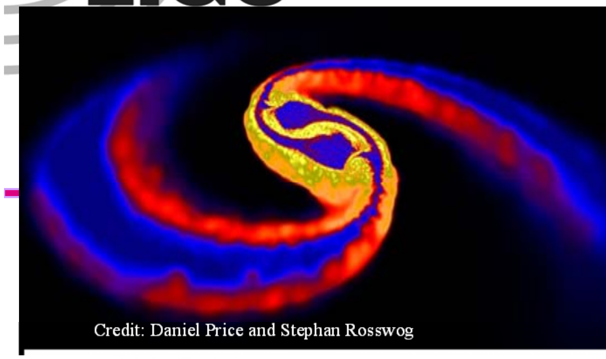


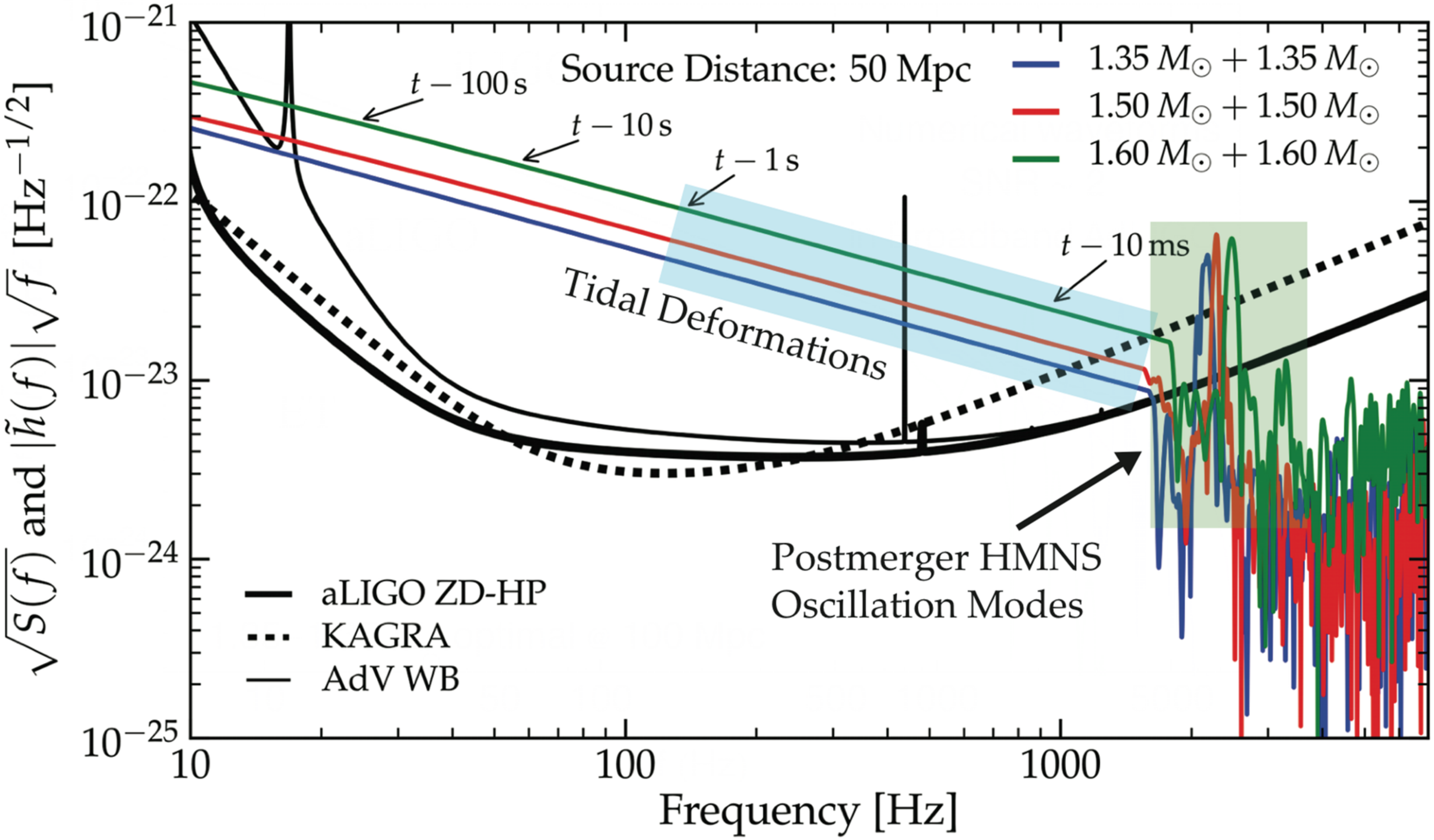
- The key to optimal detection is a well-modeled waveform, especially the phase evolution
- Low-mass systems (BNS) merge above ~1500 Hz, where LIGO noise is high - we see the inspiral
- Higher-mass systems (BBH) merge or ring down in-band.
- These systems are unique: highly relativistic, dynamical, strong-field gravity – exactly where Einstein's equations are most non-linear, intractable, interesting, and poorly-tested.
- Numerical relativity is devoted to deriving waveforms for such systems, to aid in detection and to test our understanding of strong-field gravity.
- HUGE progress in the last few years!





# Effects of tidal disruption of neutron stars near merger



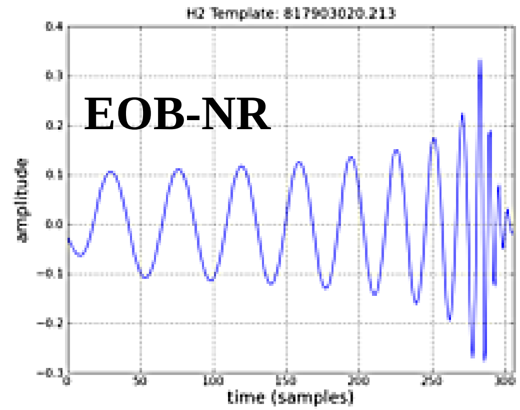



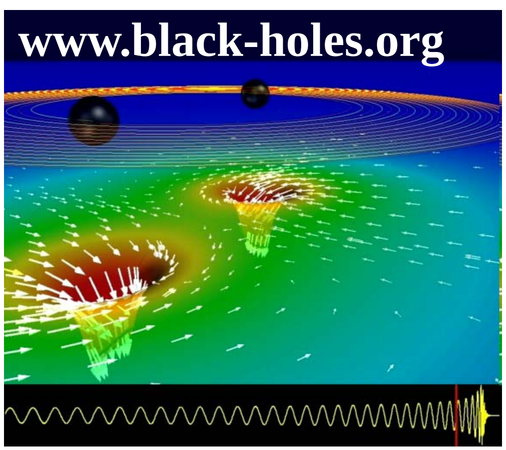
# Testing General Relativity in the strong-field, dynamical regime

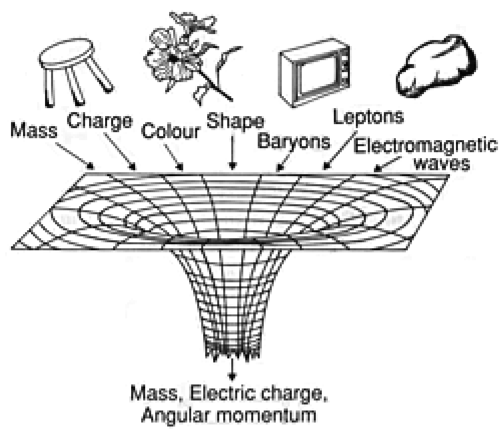
- **Test post-Newtonian expansion of inspiral phase.**

$$\Psi(f) \equiv 2\pi f t_0 + \varphi_0 + \frac{3}{128\eta v^5}\left(1 + \sum_{k=2}^{7} v^k \psi_k\right).$$

- **Test Numerical Relativity waveform prediction for merger phase.**
- **Test association of inspiral and ringdown phases: BH perturbation theory, no-hair theorem.**

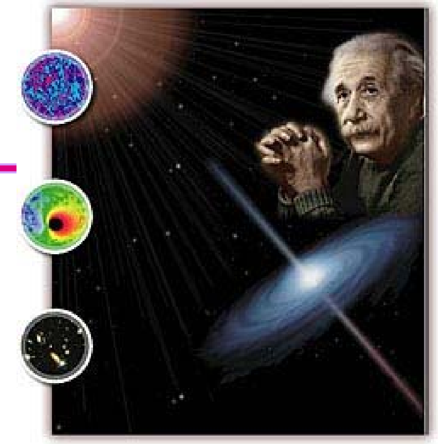



nonlocal.com/hbar/blackholes.html

# Testing beyond-GR



- Constrain beyond-GR parameters (Will, 2006)
- Directly measure speed of gravitational waves, constrain (or measure) the mass of the graviton.
- Constrain (or measure) longitudinal or other polarizations.
- Constrain (or measure) parity-violating effects in wave generation/propagation (Yunes et al, 2010).
- Constrain “parameterized post-Einsteinian framework” (Yunes & Pretorius, 2009)
- Test specifically for scalar-tensor and other alternative-gravity theories

# … Fin …

**We look forward to the coming advanced detector era:**

- **the discovery and exploration of the GW sky;**
- **unique tests of General Relativity in the strong-field, highly non-linear and dynamical regime;**
- **joint observations and discoveries with EM and neutrino telescopes;**
- **and a rich new branch of astrophysics.**

**But most of all, we look forward to …**

*the unexpected!*