What Science with 3G?

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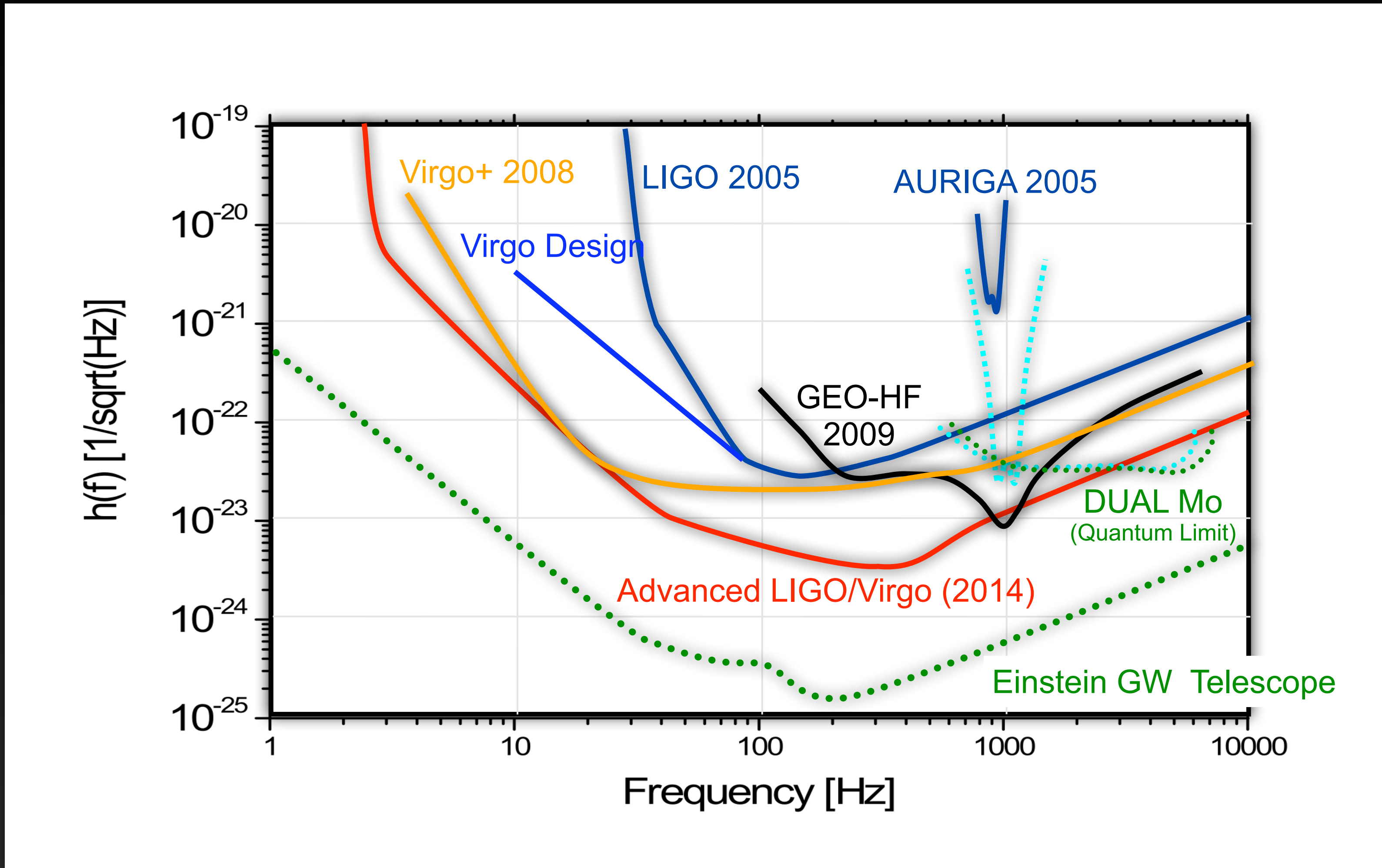
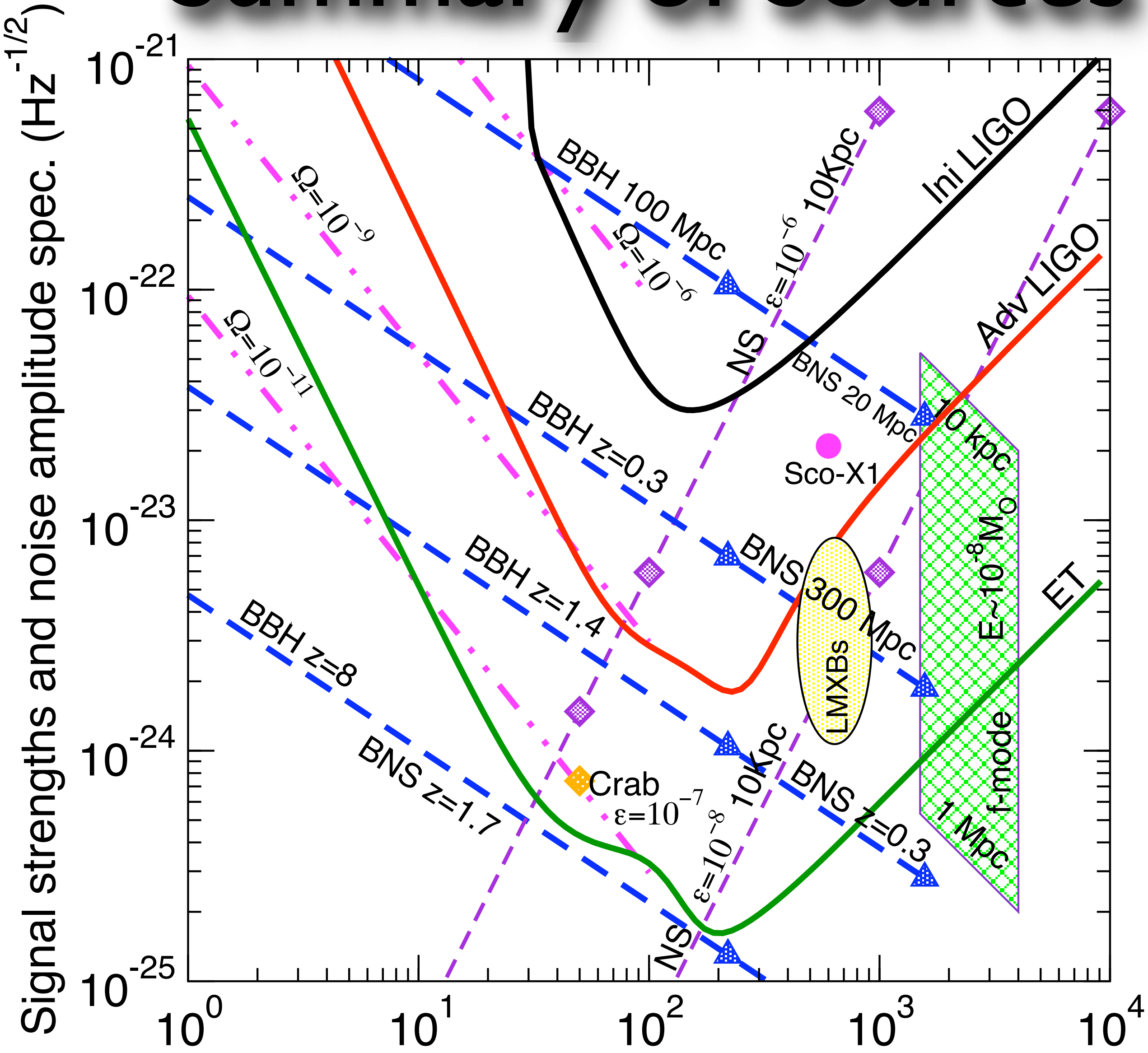
What this talk is about

- Assumptions about a 3G network
- Science from 3G
  - Fundamental physics
    - Testing strong-field gravity
    - Black hole “no-hair” theorem
  - Astrophysics
    - GRB progenitors
    - Mass function of neutron stars
  - Cosmology
    - Seeds of galaxy formation
    - Cosmological parameters with standard sirens

A global network of at least 3 detectors



Summary of Sources



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BSS and Schutz, LRR, 2009

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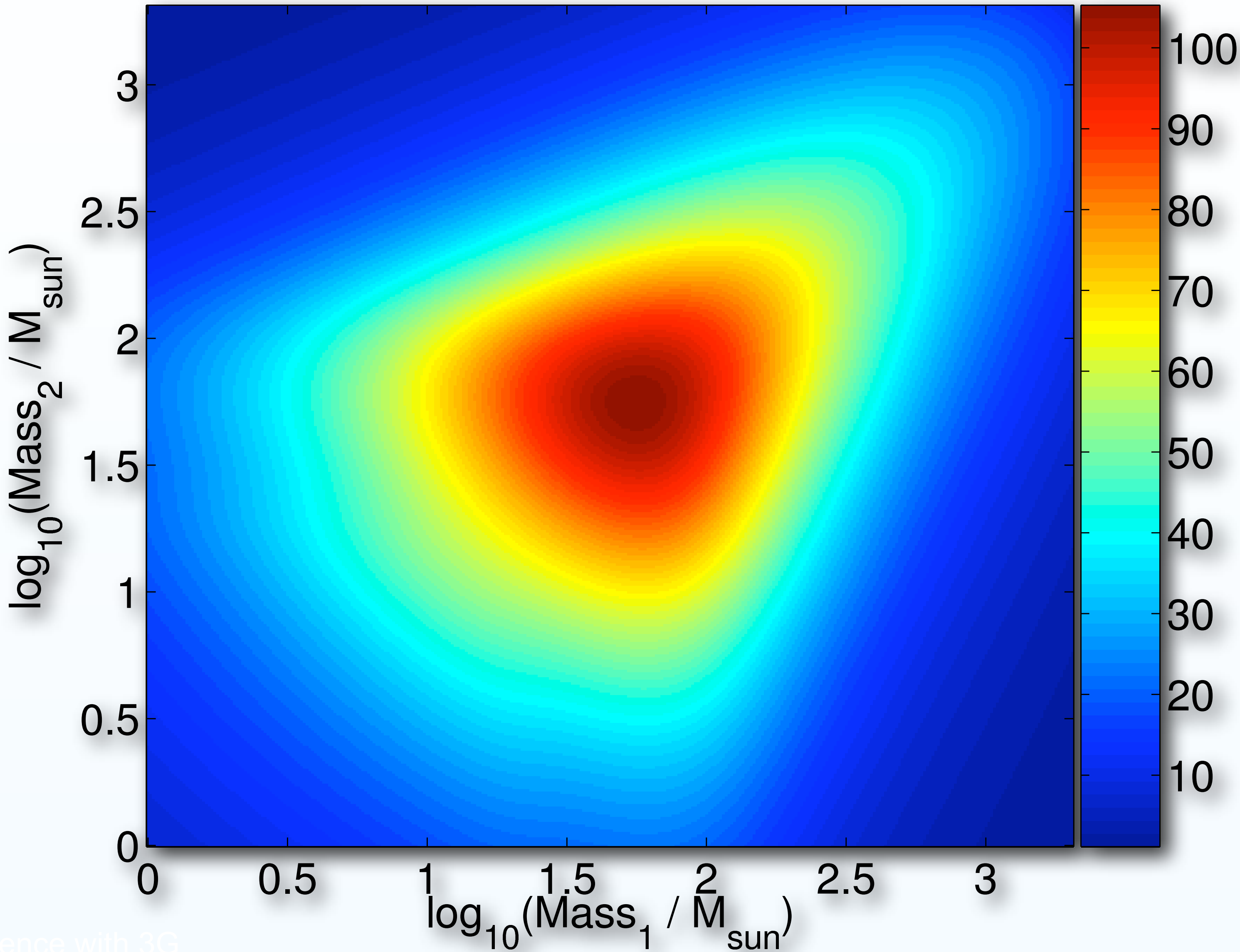
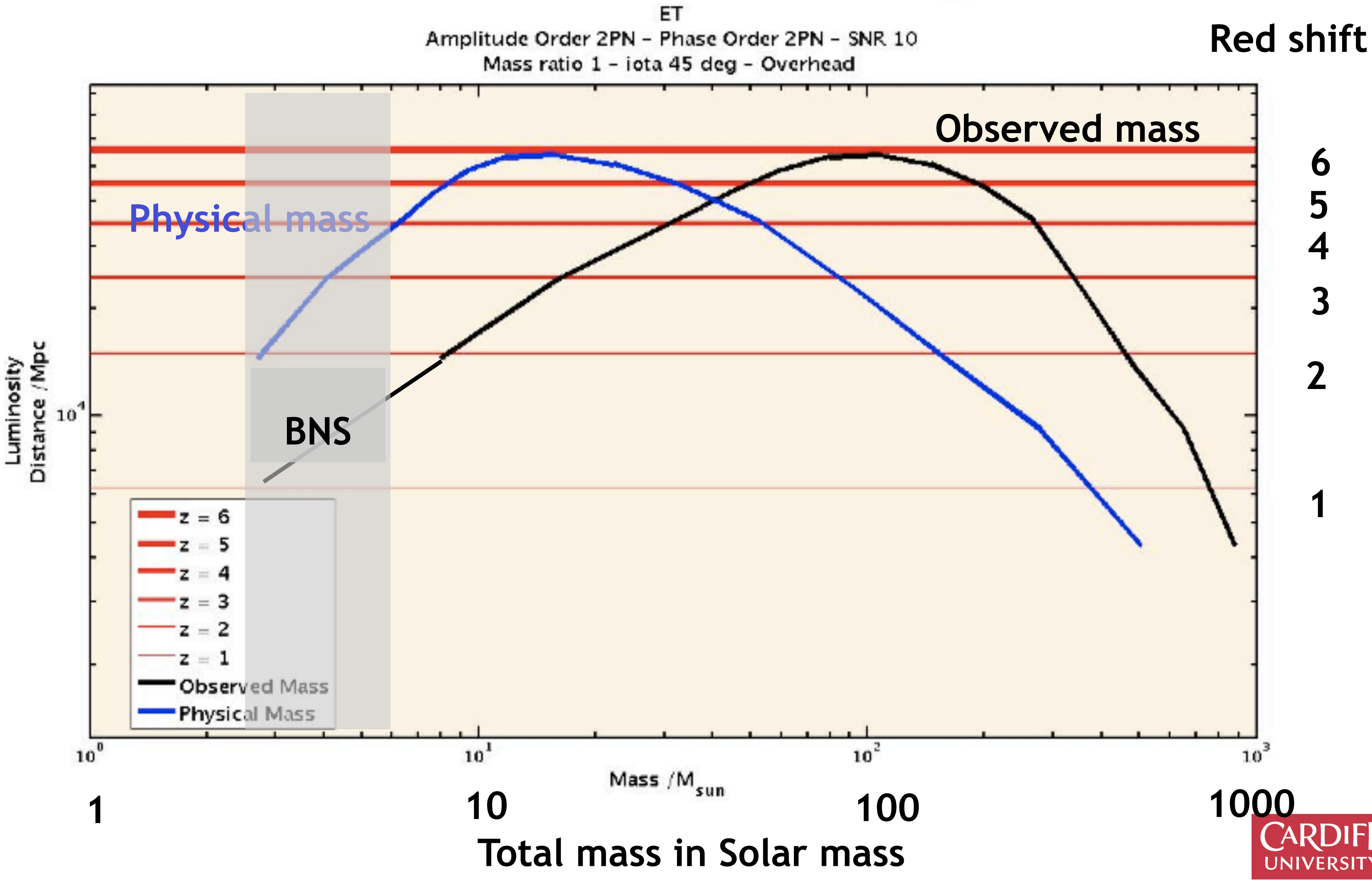
SNR for coalescences at z=0.5



Bose et al, 2009

Source redshift is important



Mckechan et al, 2009

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Expected Annual Coalescence Rates

- Binary Neutron Stars (BNS)
- Binary Black Boles (BBH)
- Neutron Star-Black Hole binaries (NS-BH)

	BNS	NS-BH	BBH
Initial LIGO (2002-06)	0.015-0.15	0.004-0.13	0.01-1.7
Enhanced LIGO x2 sensitivity (2009-10)	0.15-1.5	0.04-1.4	0.11-18
Advanced LIGO x12 sensitivity (2014+)	20-200	5.7-190	16-2700

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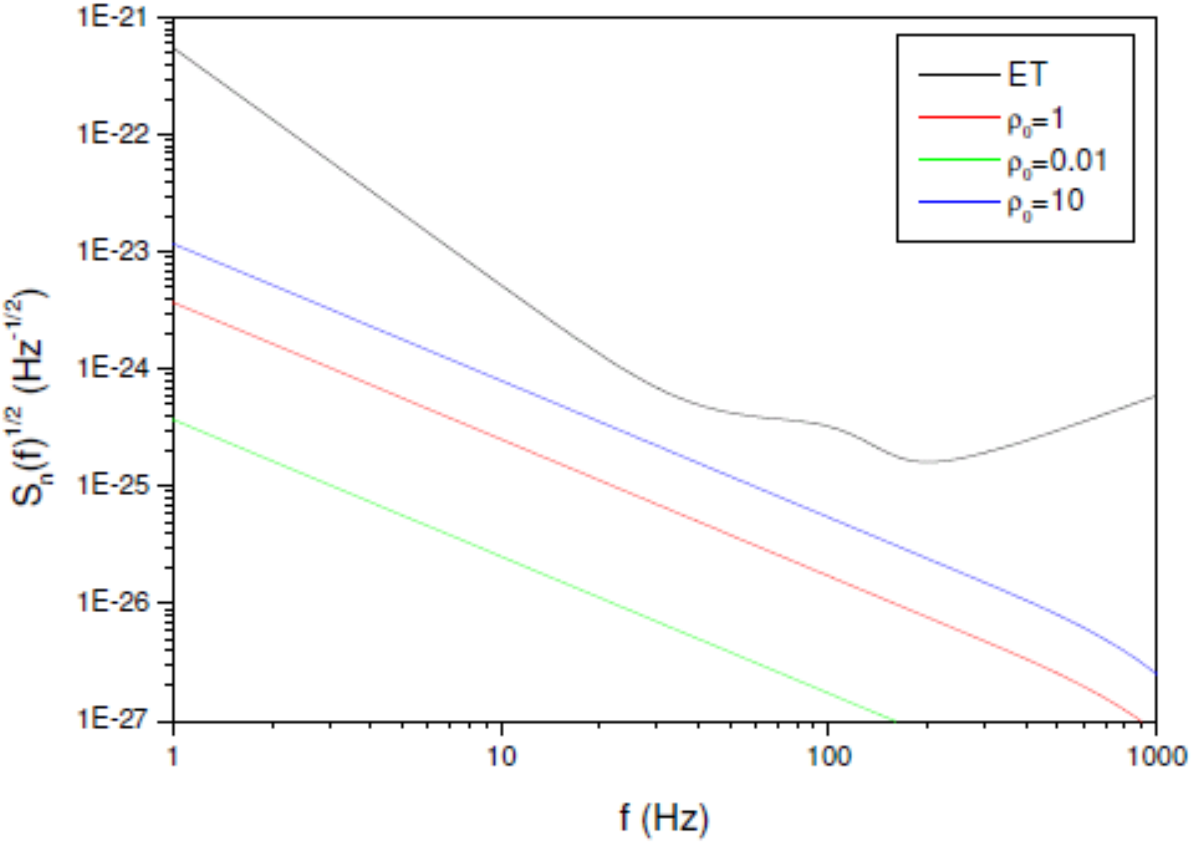
Confusion Background NS-NS

no PN corrections, first harmonic in eccentricity



Regimbau and Hughes 2009

What Science *from* 3G?

Is Einstein's theory the correct description of gravity on all scales

What Science with 3G

Do gravitational waves travel at the speed of light?

- Coincident observation of a supernova and the associated gravitational radiation can be used to constrain the speed of gravitational waves to a fantastic degree:
- If Δt is the time difference in the arrival times of GW and optical radiation and D is the distance to the source then the fractional difference in the speeds is

$$\frac{\Delta v}{c} = \frac{\Delta t}{D/c} \simeq 10^{-14} \left(\frac{\Delta t}{1\text{sec}}\right) \left(\frac{D}{1\text{Mpc}}\right)$$

- Should also be possible with coincident observation of inspirals and gamma-ray bursts

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Counting the Polarization States

Only two states in GR: h_+ and $h_\times$

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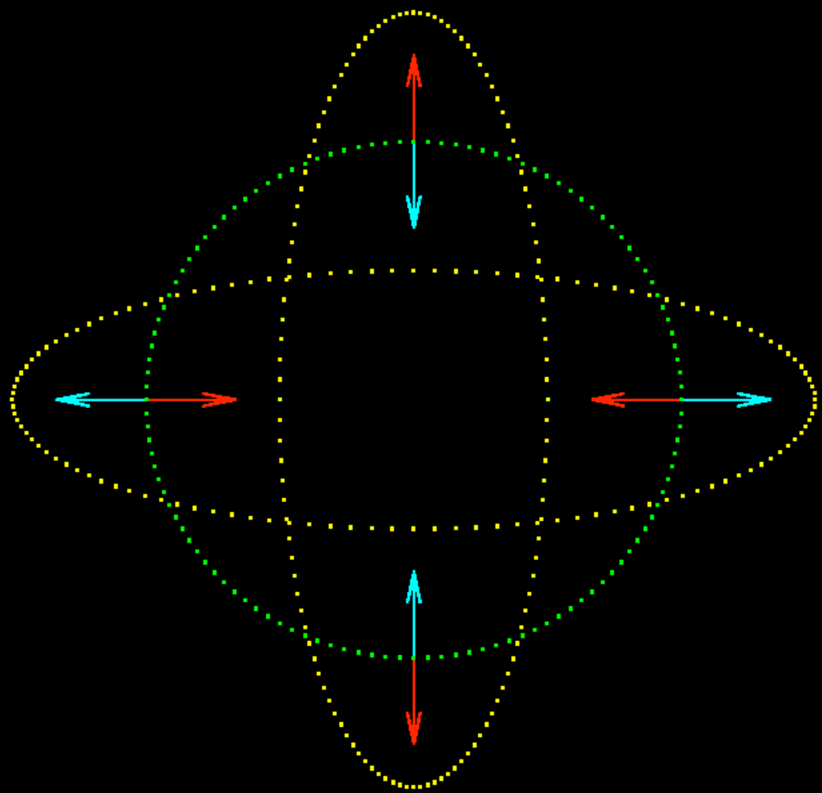
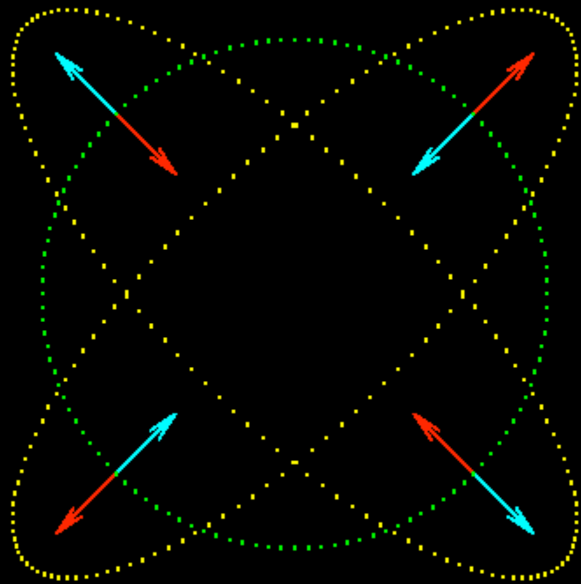


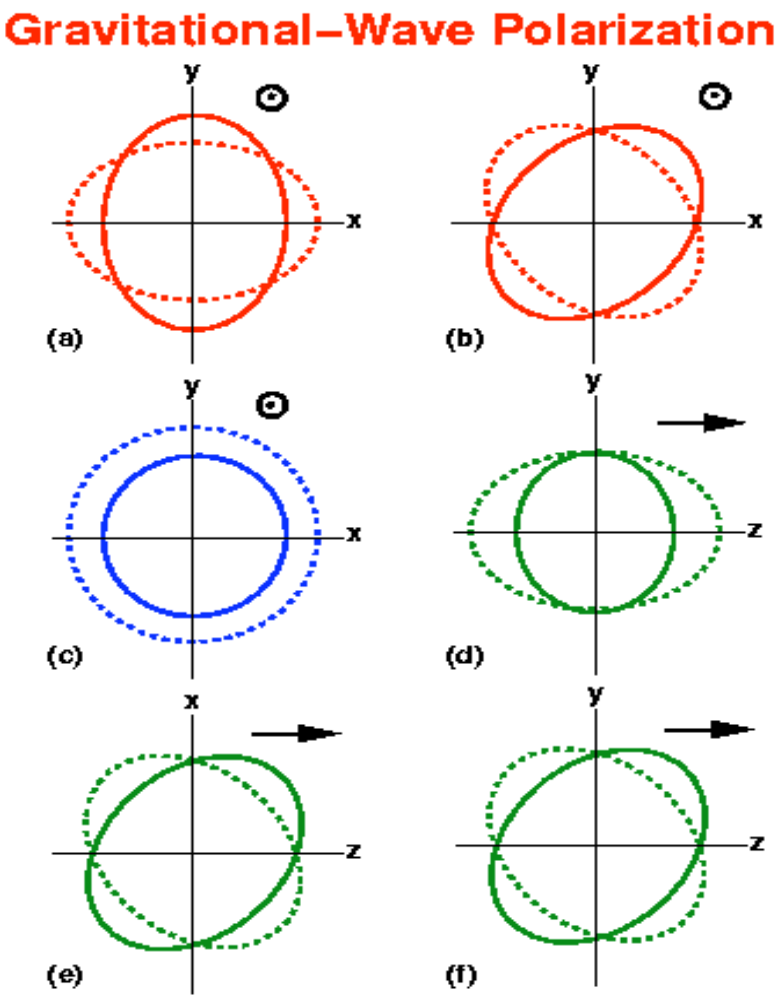
Plus polarization



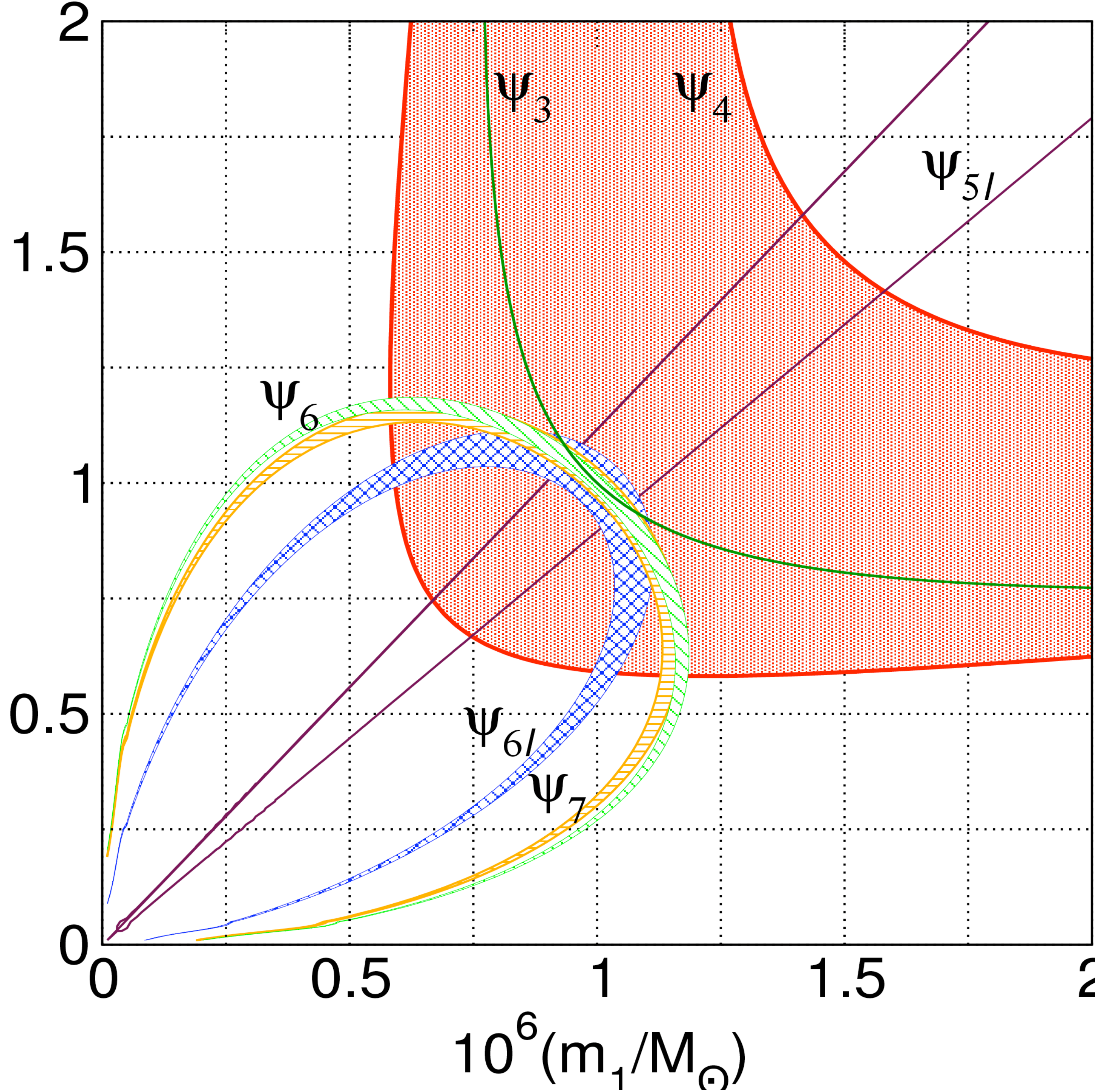
Cross polarization

Polarization States in a Scalar-Tensor Theory

Cliff Will

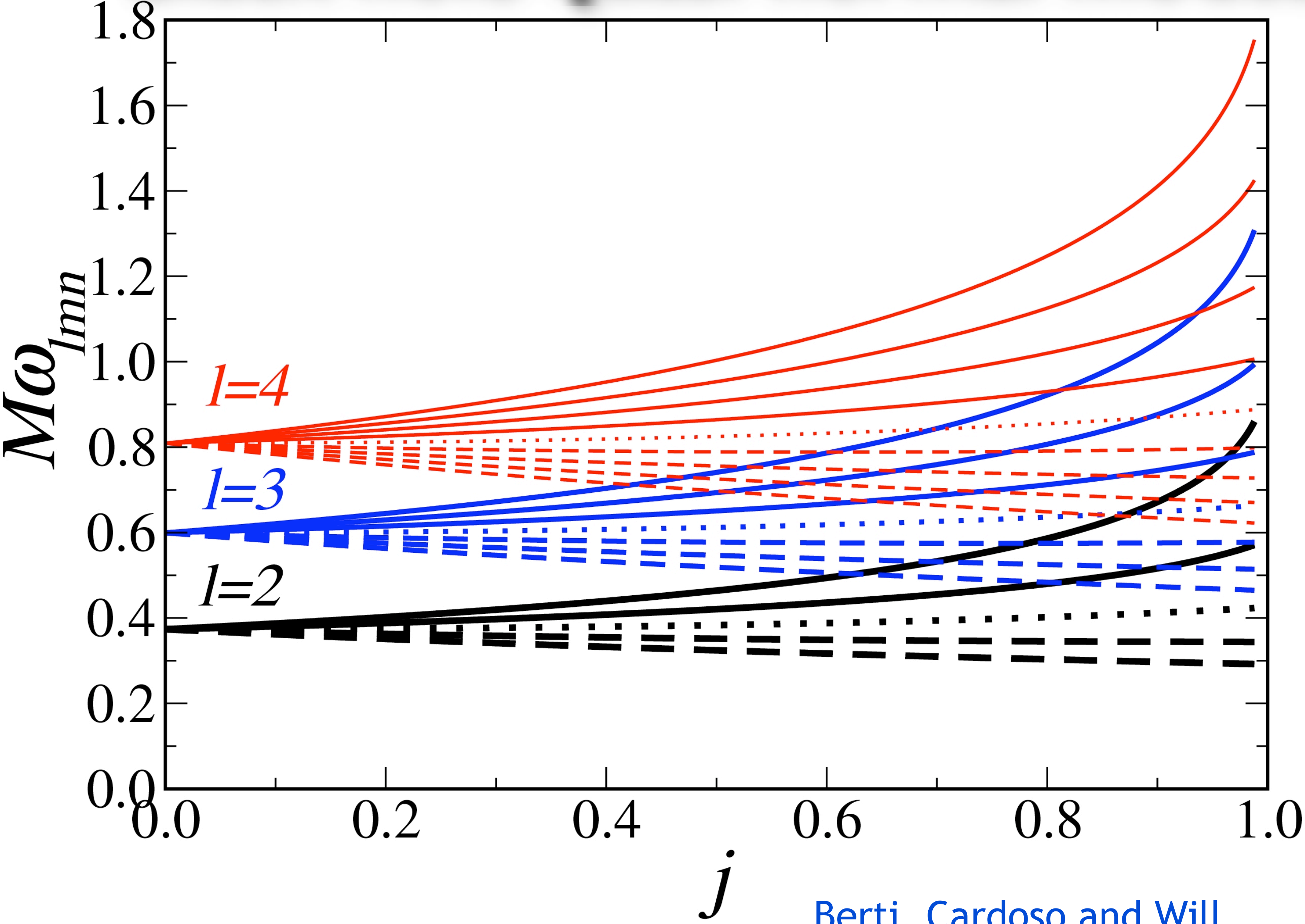


Testing the post-Newtonian formalism



Are black holes the end state of gravitational collapse and is the no-hair theorem valid?

Black hole quasi normal modes



Berti, Cardoso and Will

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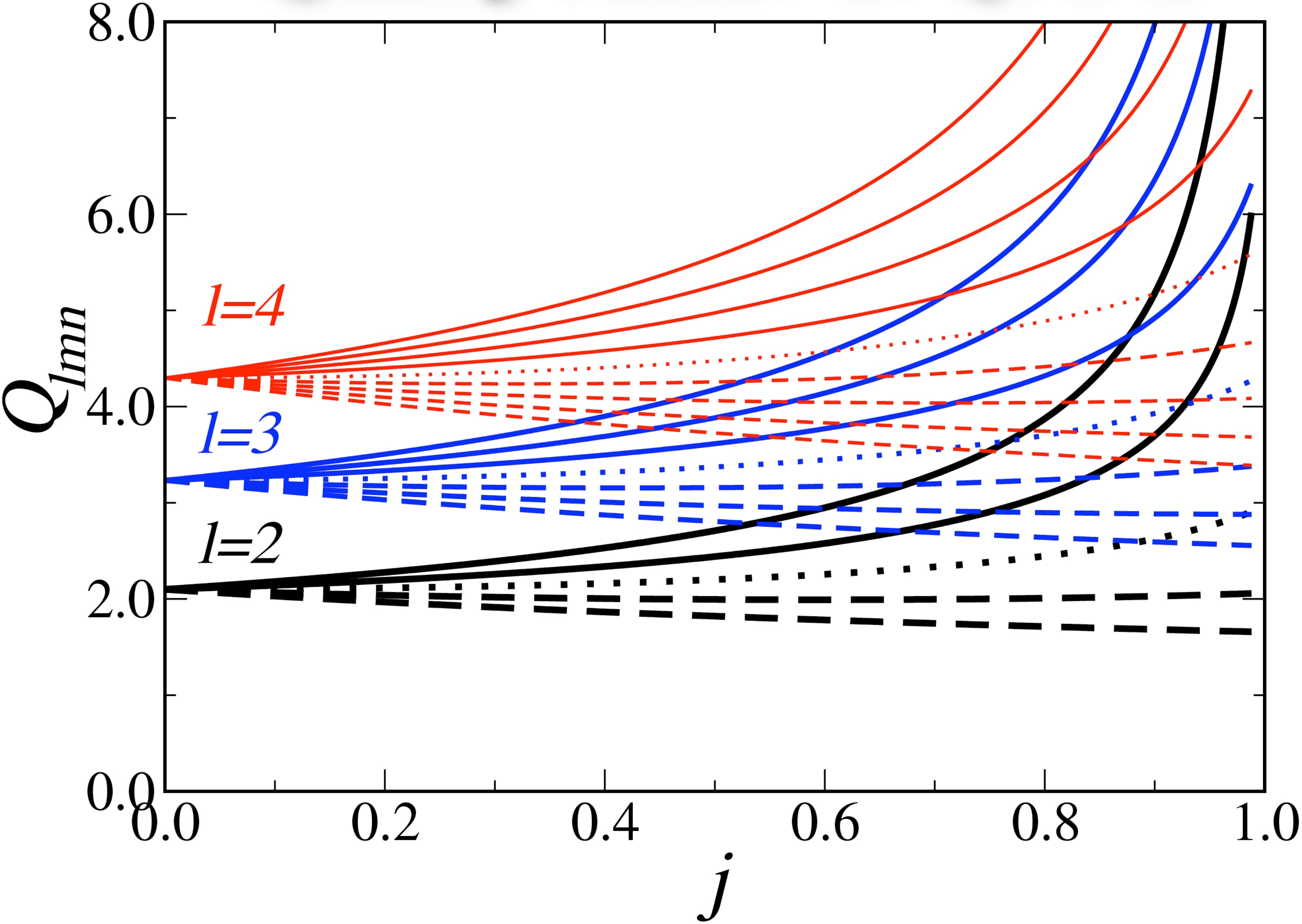
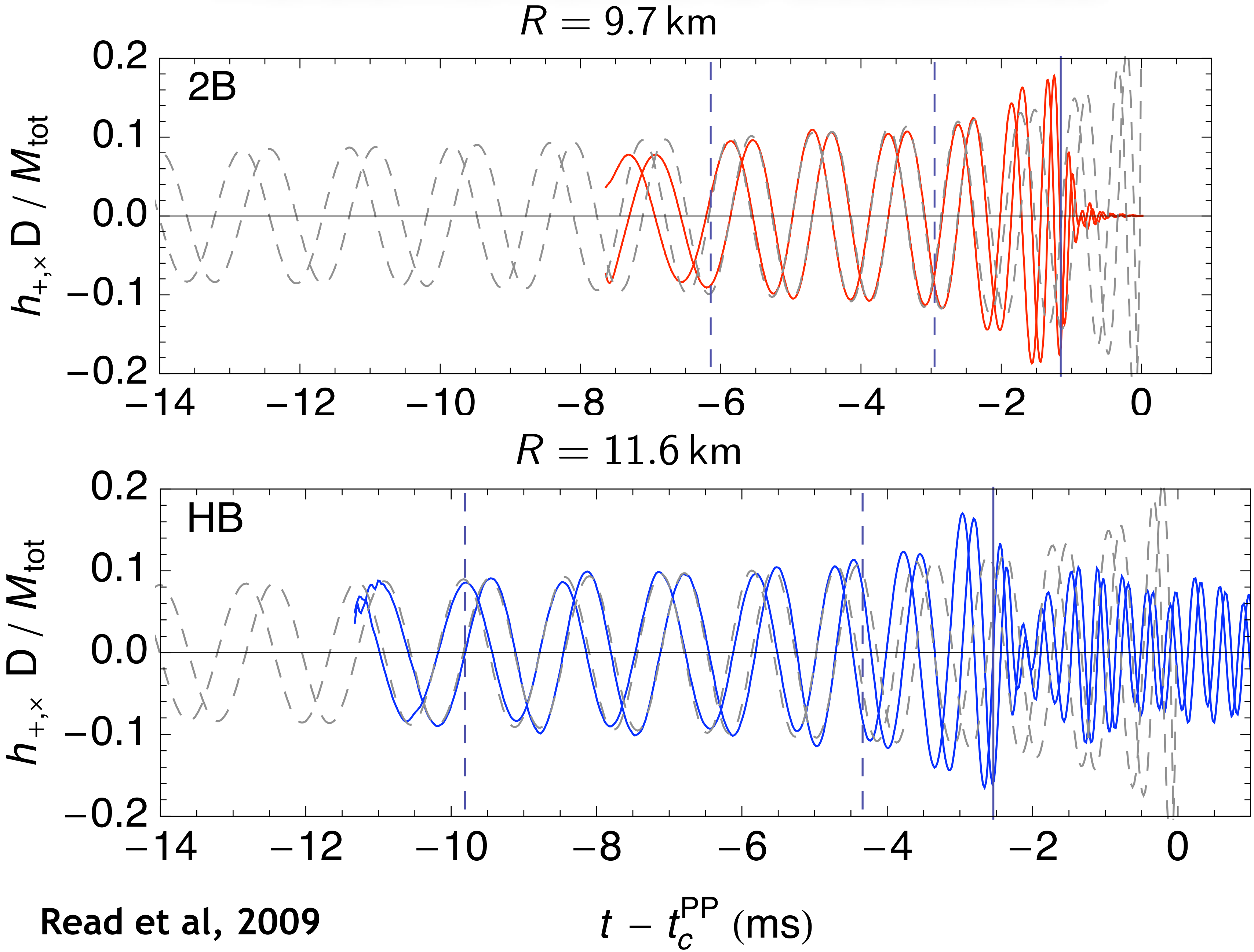
Quality Factor of QNMs



What is the state of matter in neutron star cores?

Waveforms from BNS Coalescence



Read et al, 2009

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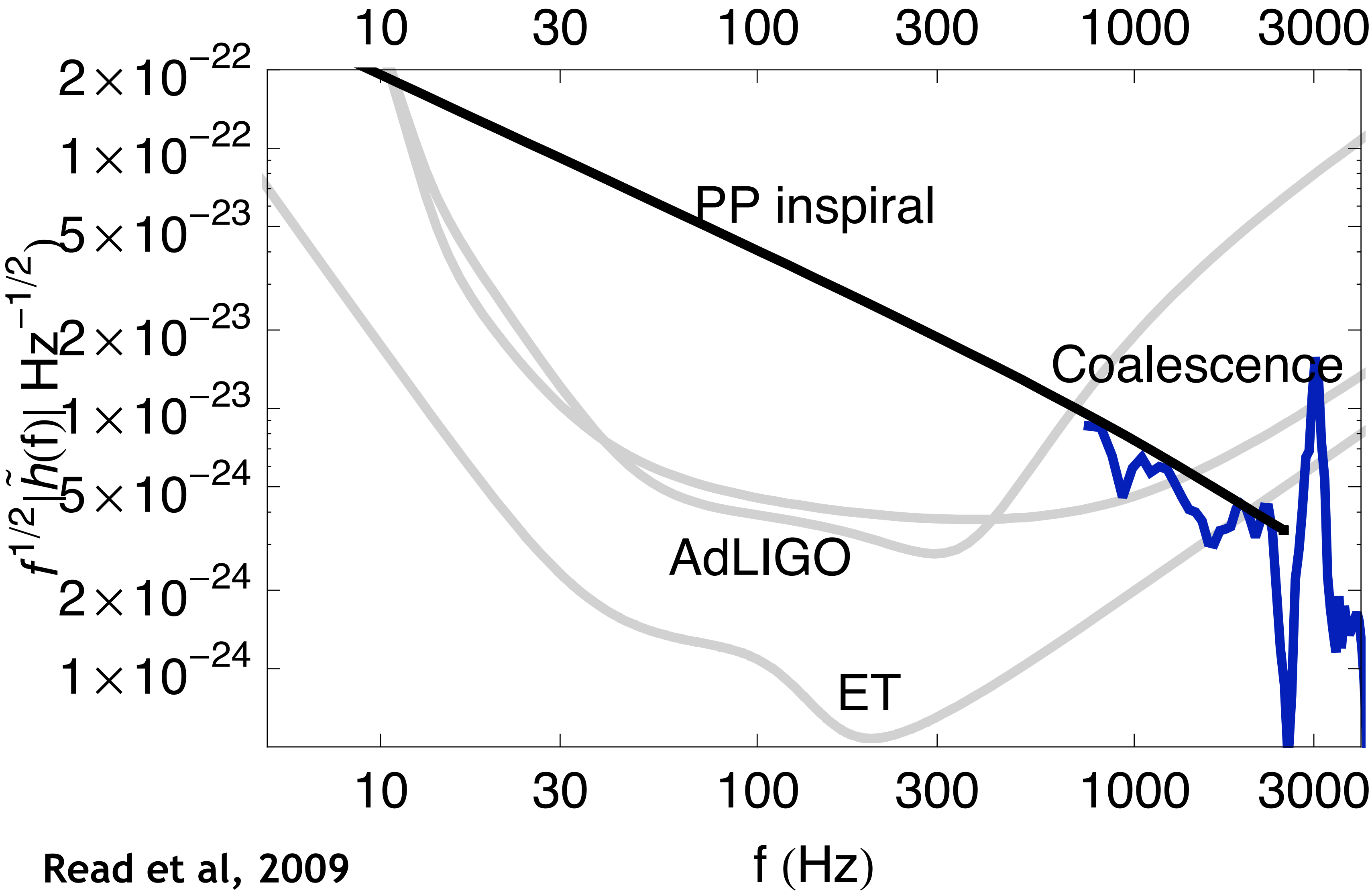
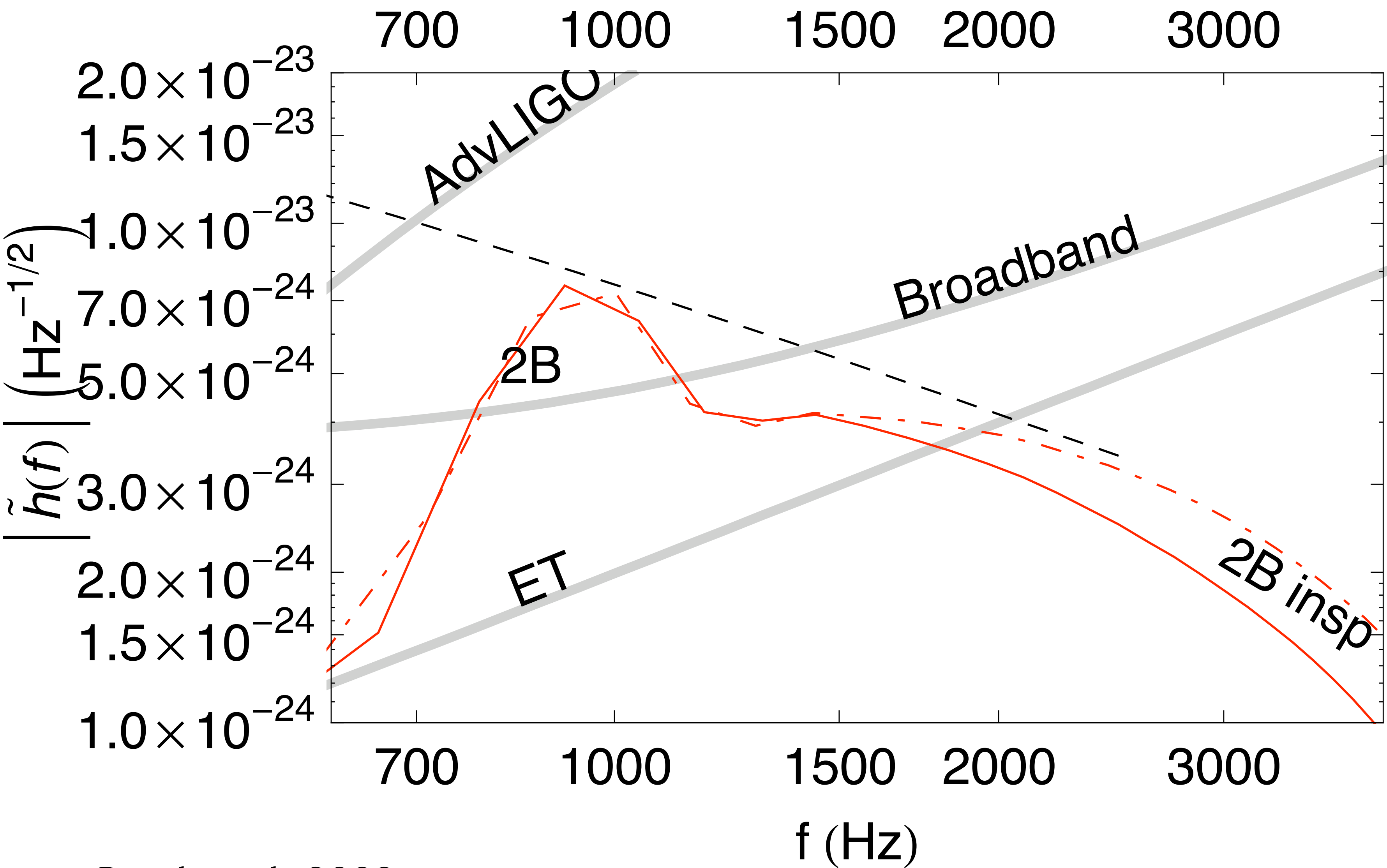
Equivalent strain at 100 Mpc



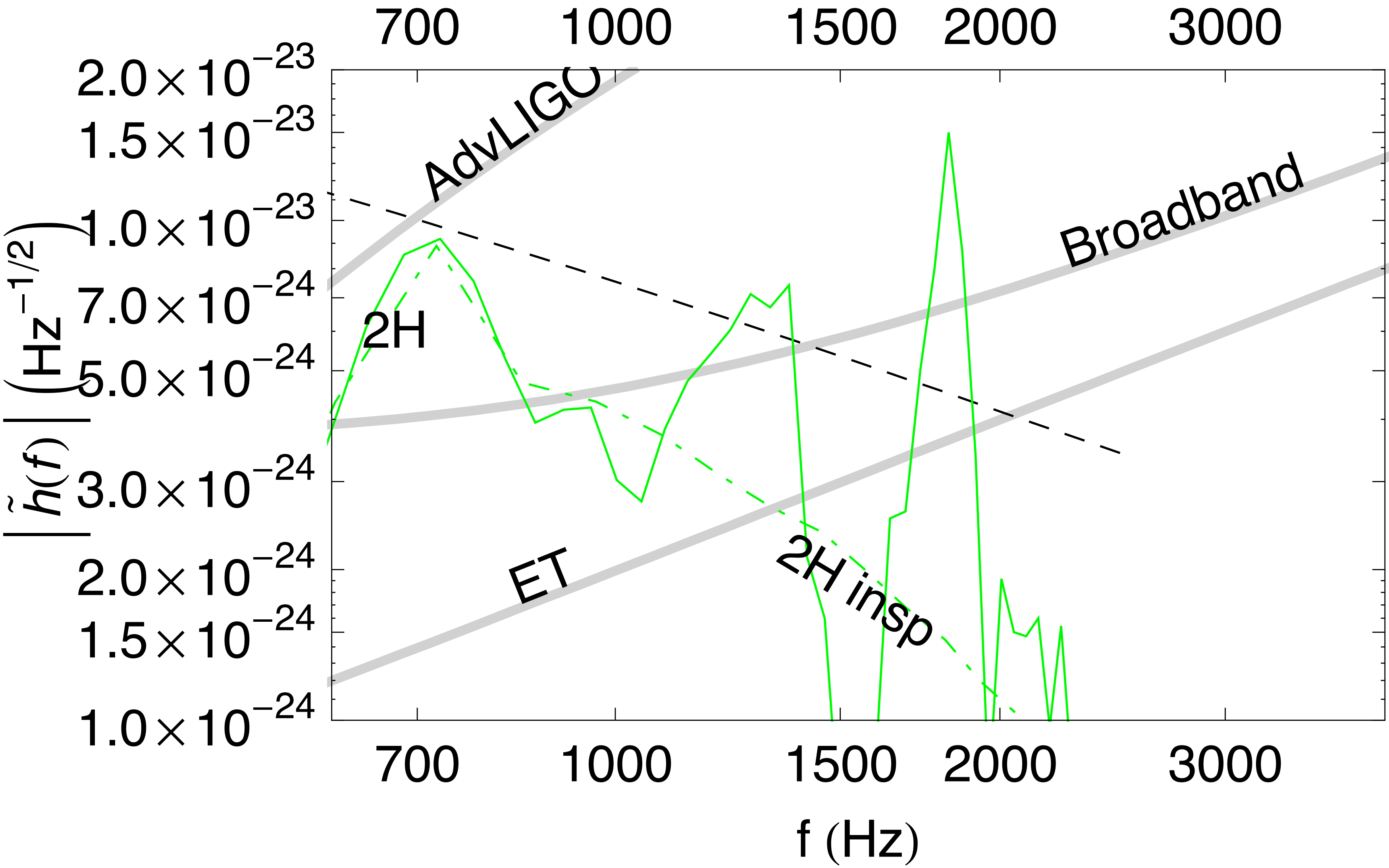
Read et al, 2009

Equivalent strain at 100 Mpc



Read et al, 2009

Equivalent strain at 100 Mpc

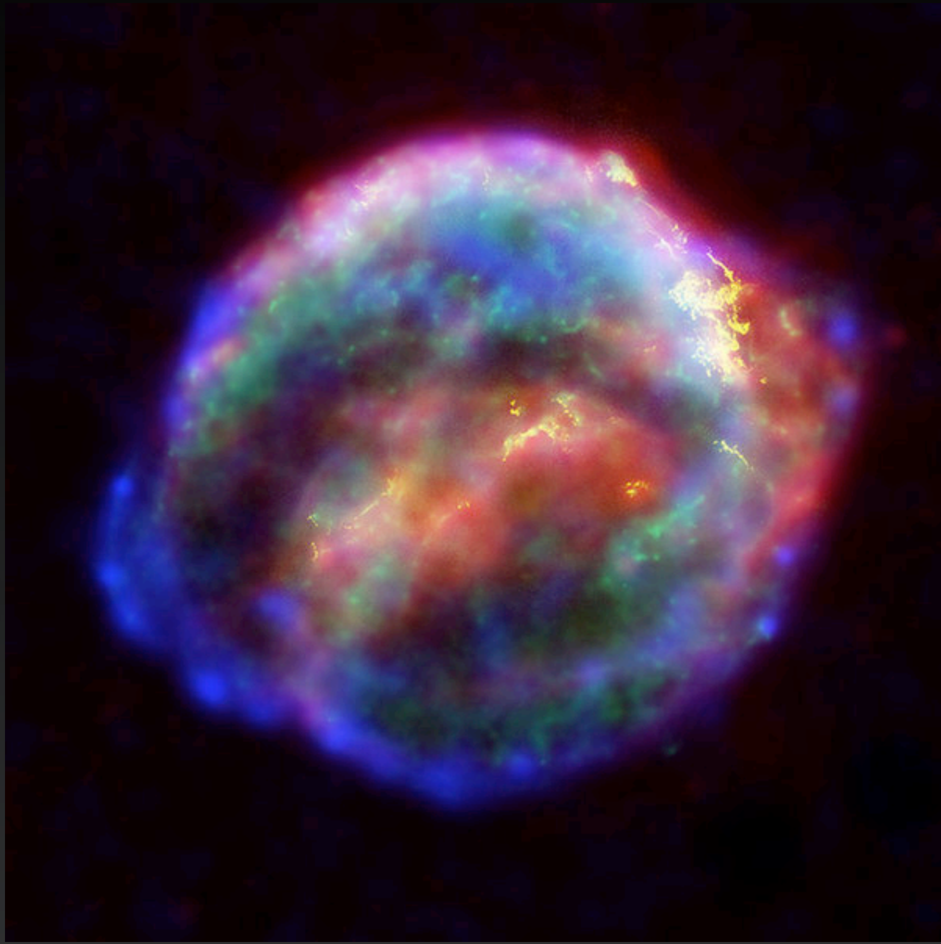


Read et al, 2009

What is the nature of gravitational collapse and what is the origin of gamma-ray bursts?

Burst Sources

- Gravitational wave bursts
  - Low-mass X-ray binaries
  - Supernovae
  - High-energy EM transients
- Short-hard GRBs
  - could be the result of merger of a neutron star with another NS or a BH
- Long-hard GRBs
  - could be triggered by supernovae



What Science with 3G

Monday, 11 May 2009

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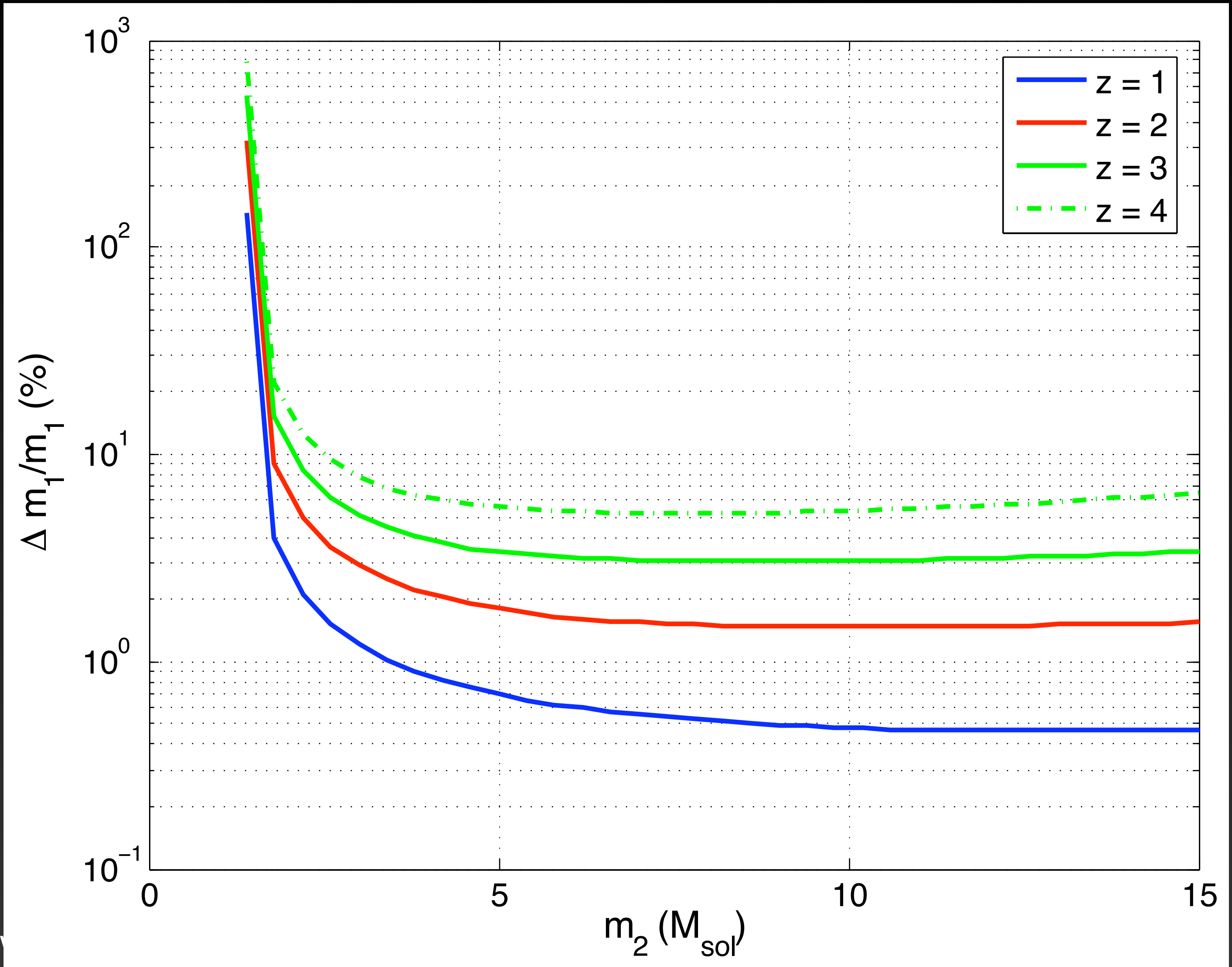
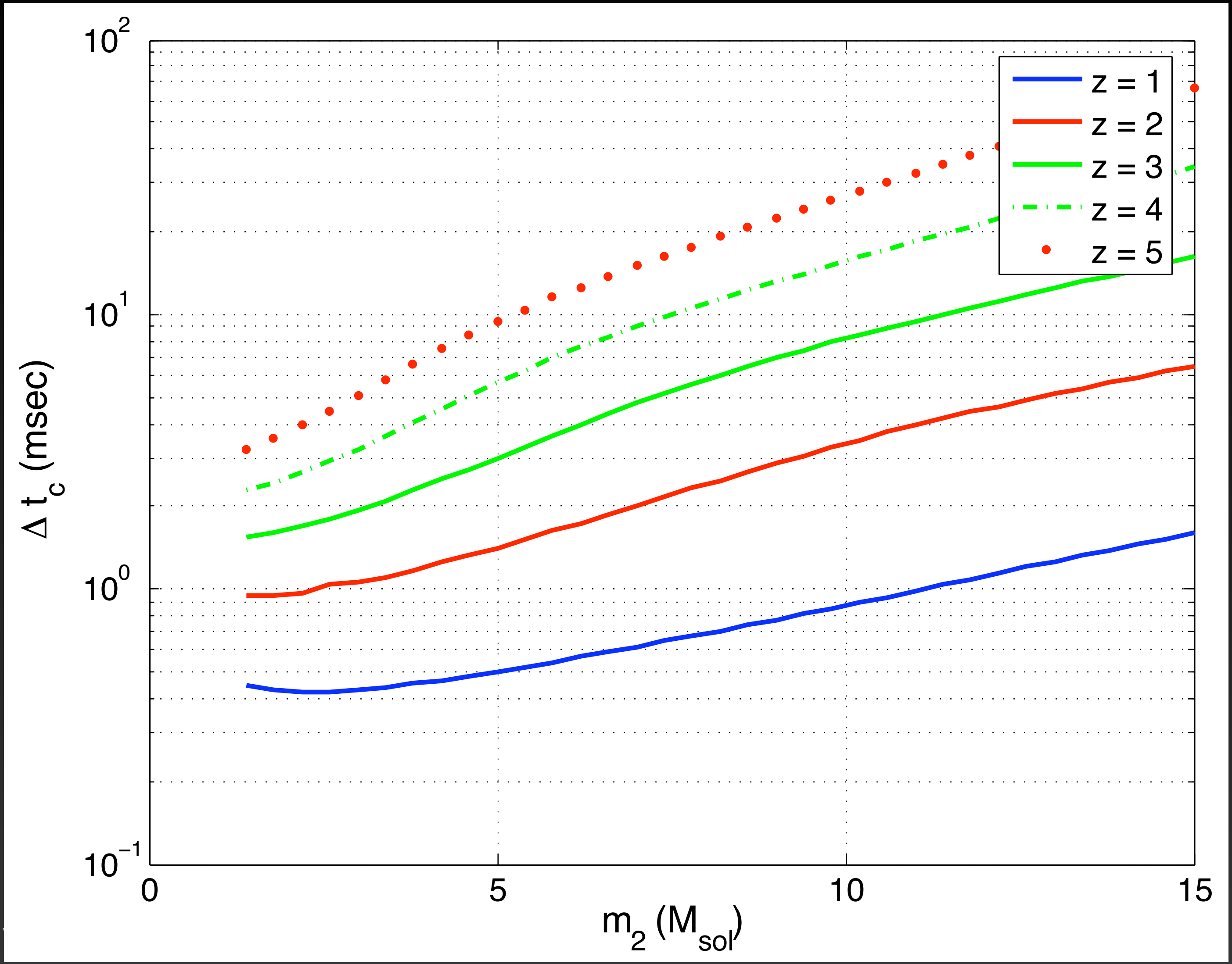
Measuring the mass-function of Neutron Stars



What Science v

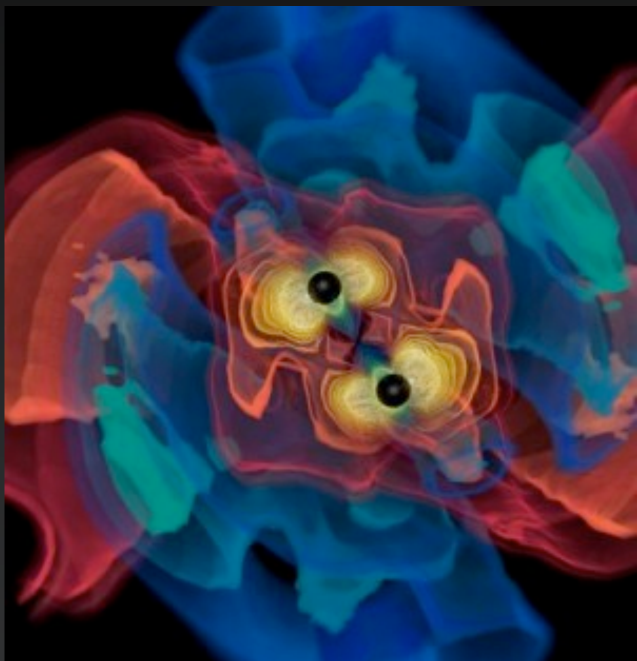
Timing: Coincidence with GRBs

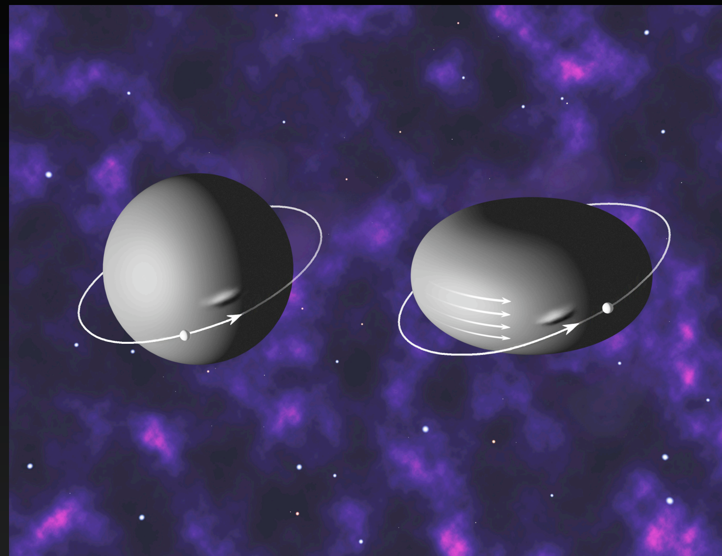


What is the large-scale geometry and dynamics of the Universe?

Binary Mergers

- Compact binary mergers
  - Binary neutron stars
  - Binary black holes
  - Neutron star–black hole binaries





- Loss of energy leads to steady inspiral whose waveform has been calculated to order v^7 in post-Newtonian theory
- Knowledge of the waveforms allows matched filtering

Why are compact binaries standard sirens?

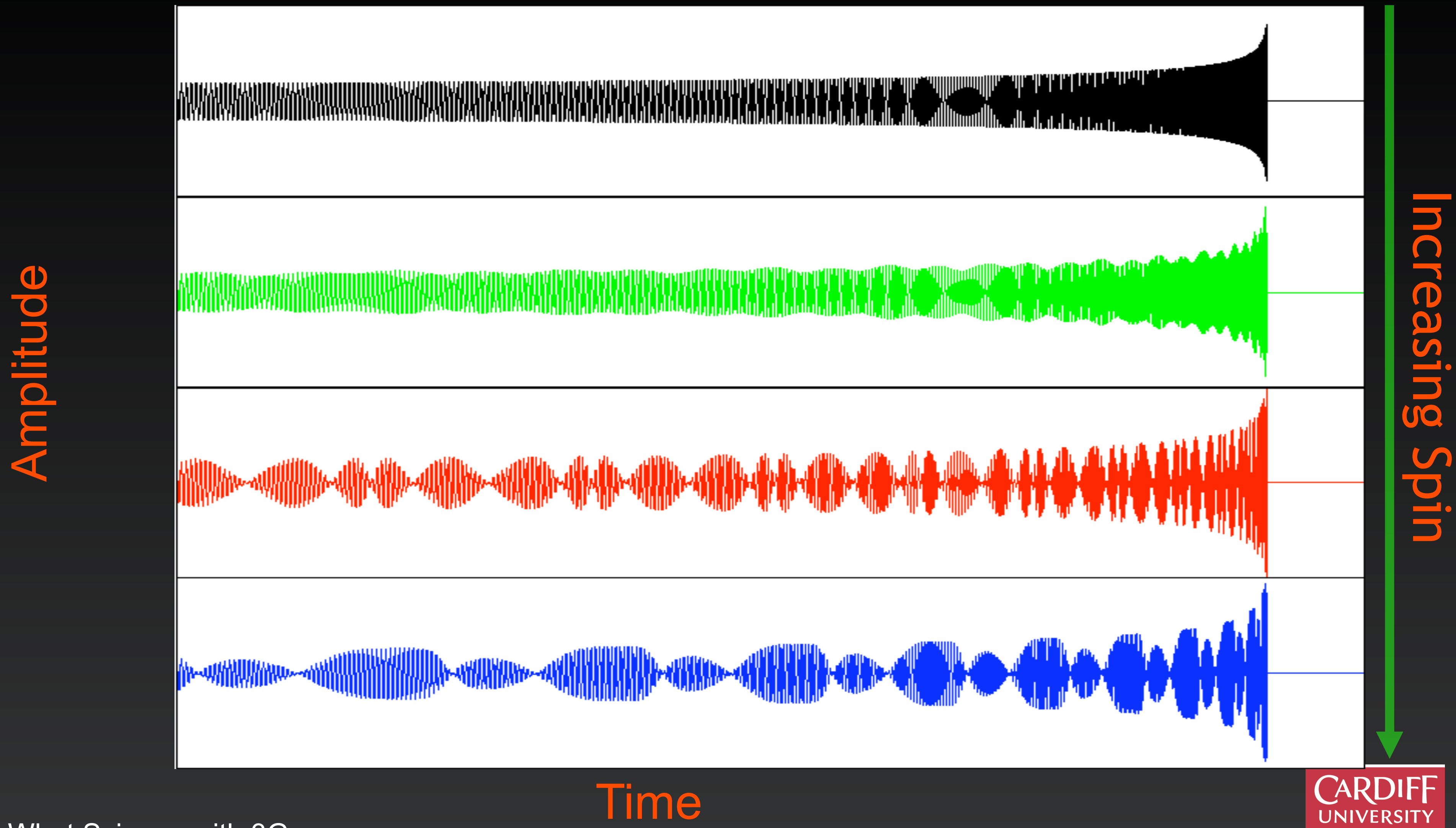
Compact binaries are standard sirens

Schutz 86

- Amplitude of gravitational waves depends on the ratio Chirp-mass/Distance: Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - amplitude (this is the strain caused in our detector)
  - chirp-mass (because the chirp rate depends on the chirp mass)
- Therefore, binary black hole inspirals are standard sirens
  - from the apparent luminosity (the strain) we can conclude the luminosity distance
- However, GW observations alone cannot determine the red-shift to a source
- Joint gravitational-wave and optical observations can facilitate a new cosmological tool

What do we know about the waveforms from compact

Compact Binary Waveforms



What Science with 3G

What can we expect to learn by observing compact binaries?

Stellar mass functions, star formation rate

- Accurate parameter measurement can be used via population synthesis models to obtain, using ground-based observations,
  - Neutron star mass function
  - Stellar mass functions
  - Star formation rate
- One can identify
  - seeds of galaxy formation an open problem in cosmology
  - mass-function of black hole seeds with observation of intermediate-mass black hole binaries

How can we measure cosmological parameters?

- Luminosity distance Vs. red shift has cosmological parameters H_0, Ω_M, Ω_b, Ω_Λ, w, etc.

$$D_L = \frac{c(1+z)}{H_0} \int \frac{dz}{\left[\Omega_M (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}\right]^{1/2}}$$

- Einstein Telescope will detect 1000's of compact binary mergers for which the source can be identified (e.g. GRB) and red-shift measured.
- A fit to such observations can determine the cosmological parameters to better than a few percent.

Sathyaprakash et al

Hubble Diagram

- Luminosity distance Vs. red shift depends on the cosmological parameters H_0, Ω_M, Ω_b, Ω_Λ, w, etc.

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\left[\Omega_M (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}\right]^{1/2}}$$

- Einstein Telescope will detect 1000's of compact binary mergers for which the source can be identified (e.g. GRB) and red-shift measured.
- A fit to such observations can determine the cosmological parameters to better than a few percent.

How well can cosmological parameters be measured

- True values of the cosmological parameters

$$H_0 = 0.70, \Omega_M = 0.27, \Omega_\Lambda = 0.73, w = -1$$

- Measured values
  - Measuring w as a function of red-shift (CVDB's talk)
  - Two unknown parameters

$$w = -0.999 \pm 0.015, \quad \Omega_\Lambda = 0.733 \pm 0.0067$$

  - Three unknown parameters

$$w = -0.96 \pm 0.041, \Omega_M = 0.255 \pm 0.014, \Omega_\Lambda = 0.741 \pm 0.012$$

- Four unknown parameters
  - Errors are too large to be interesting

When did black hole seeds form and how heavy were they?

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Computing Merger Rates

- Construct semi-analytic merger trees by following mergers of dark matter halos (e.g., Volonteri, Haardt & Madau 2003).

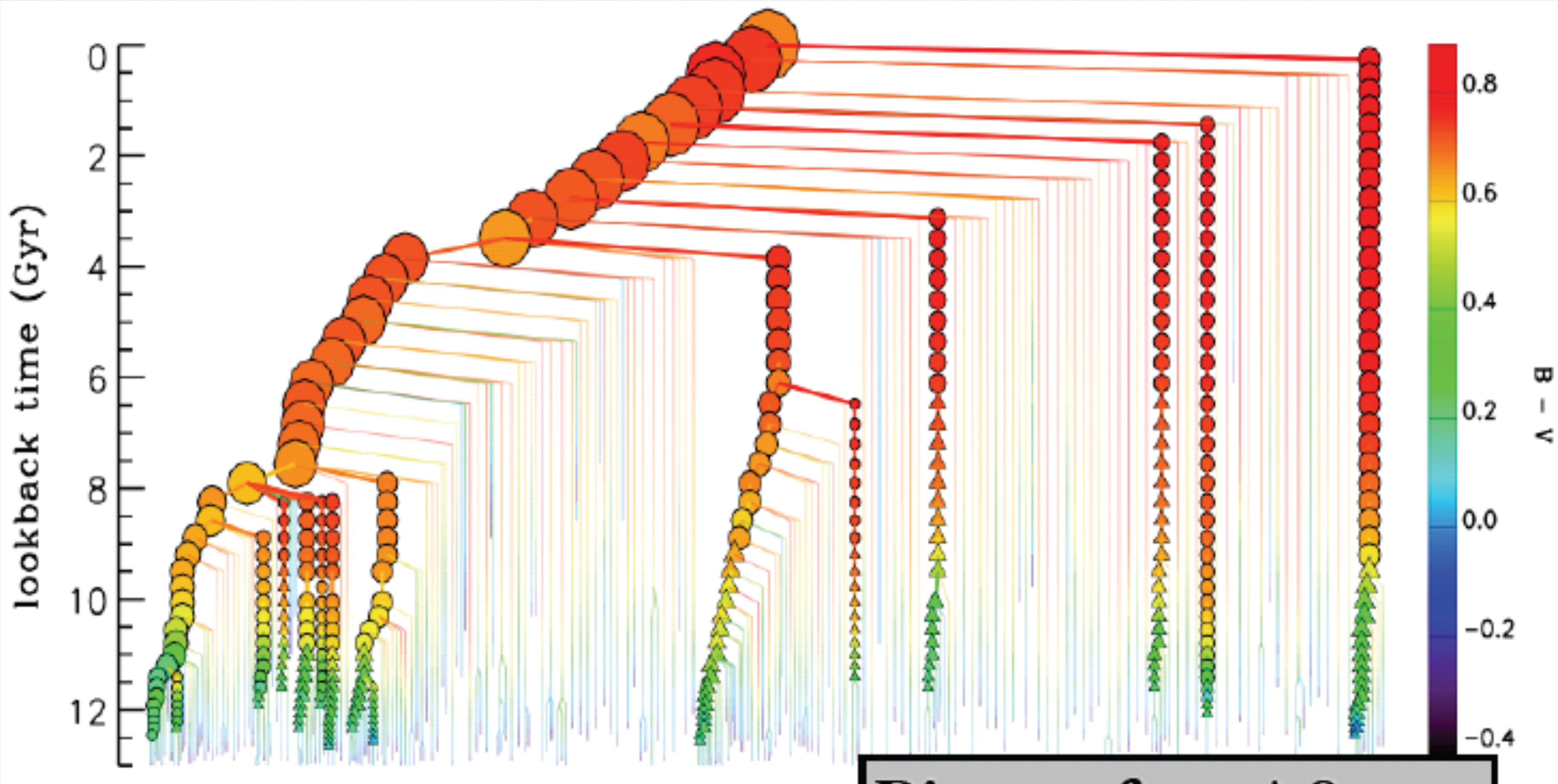
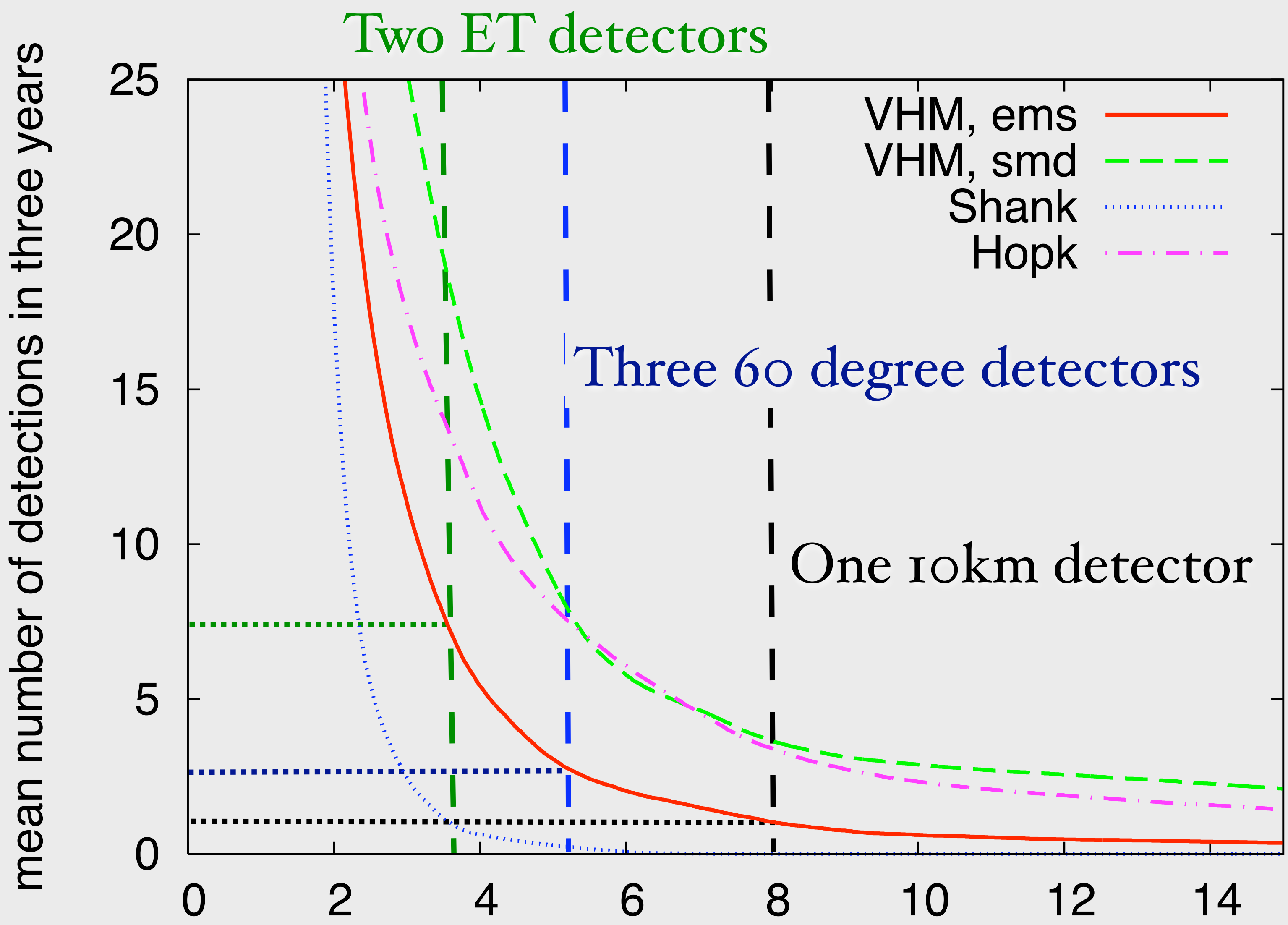


Diagram from A Sesana

IMBH Event Rates in ET



Gair et al, 2009

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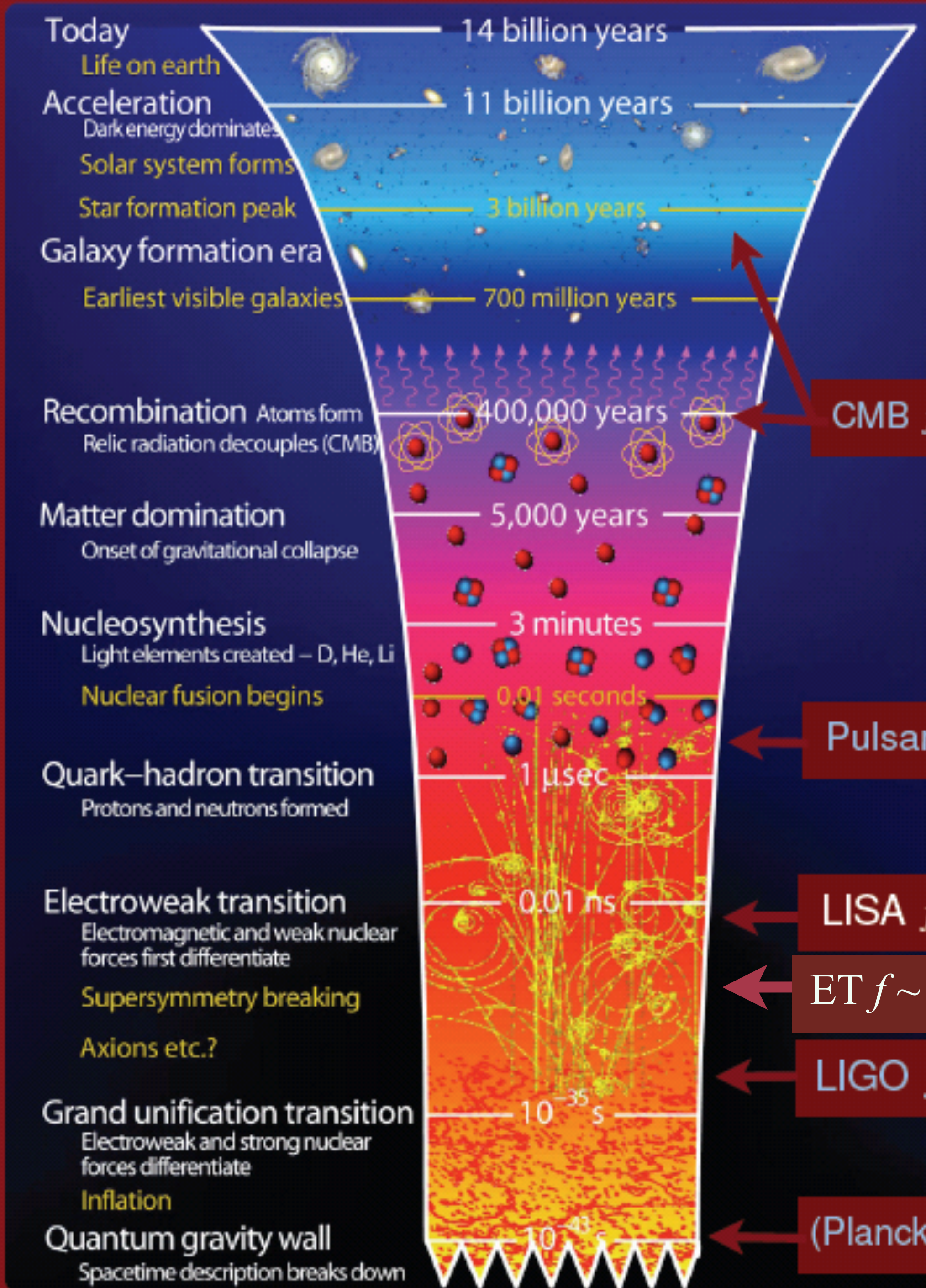
What physical processes took place in the Universe’s early history?

Stochastic Backgrounds

- Stochastic background
  - Primordial background
  - Astrophysical background
- Phase transitions in the Early Universe
- Cosmic strings and other cosmological defects
- Superstrings

A brief history of the Universe



CMB $f < 3 \times 10^{-17} h$ Hz probes $300,000$ yrs $< t_e < 14$ Gyrs

Pulsars $f \sim 10^{-8}$ Hz probe $t_e \sim 10^{-4}$ s ($T \sim 50$ MeV)

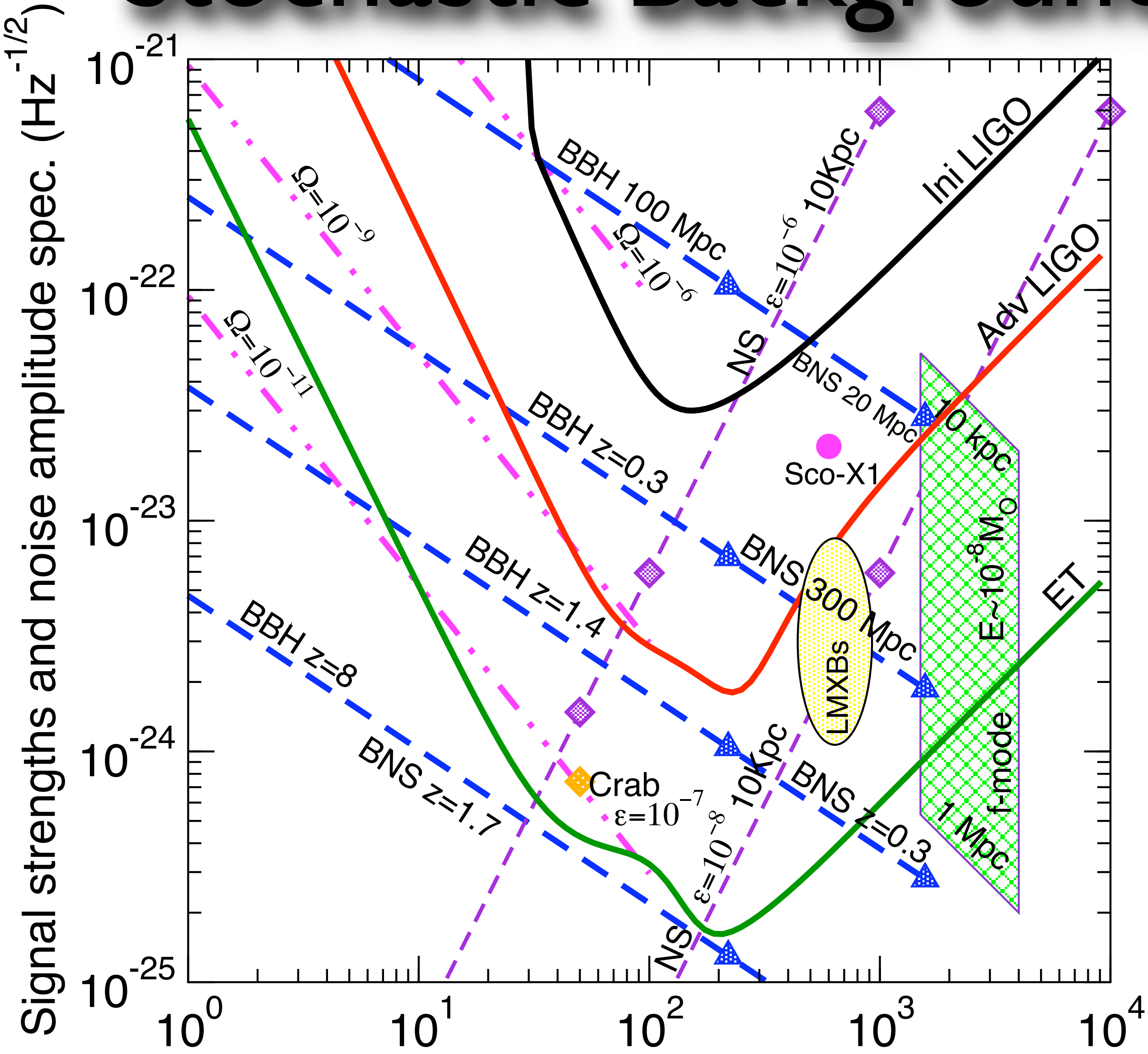
LISA $f \sim 10^{-3}$ Hz probes $t_e \sim 10^{-14}$ s ($T \sim 10$ TeV)

ET $f \sim 10$ Hz probes $t_e \sim 10^{-20}$ s ($T \sim 10^6$ GeV)

LIGO $f \sim 100$ Hz probes $t_e \sim 10^{-24}$ s ($T \sim 10^8$ GeV)

(Planck scale $f \sim 10^{11}$ Hz has $t_e \sim 10^{-43}$ s ($T \sim 10^{19}$ GeV)

Stochastic Background



BSS and Schutz, LRR, 2009

What problems should 3G detectors address?

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes hairless and are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - What is dark energy?
  - How did massive black holes at galactic nuclei form?
- Fundamental questions
  - What were the physical conditions at the big bang?
  - Are there really ten spatial dimensions?