Einstein Telescope: The Science Case

EGO, Cascina, Italy, May 20 2011

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on behalf of the Einstein Telescope Design Study Team

EINSTEIN TELESCOPE

Rutherford's Discovery of Atomic Structure

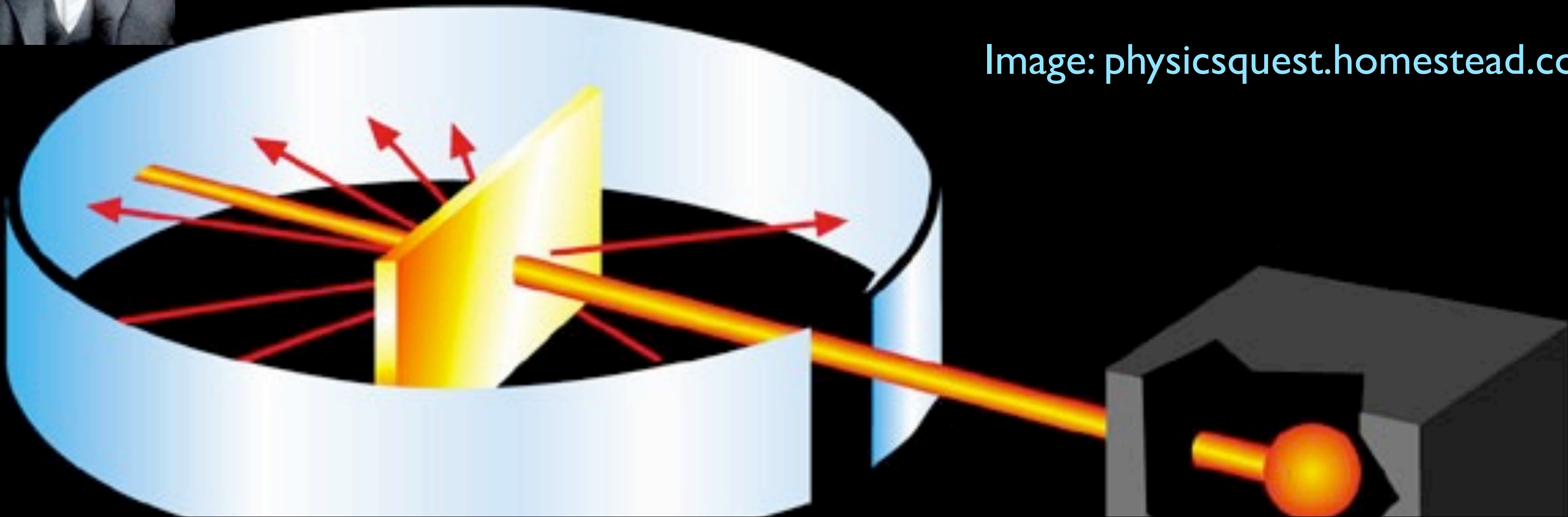
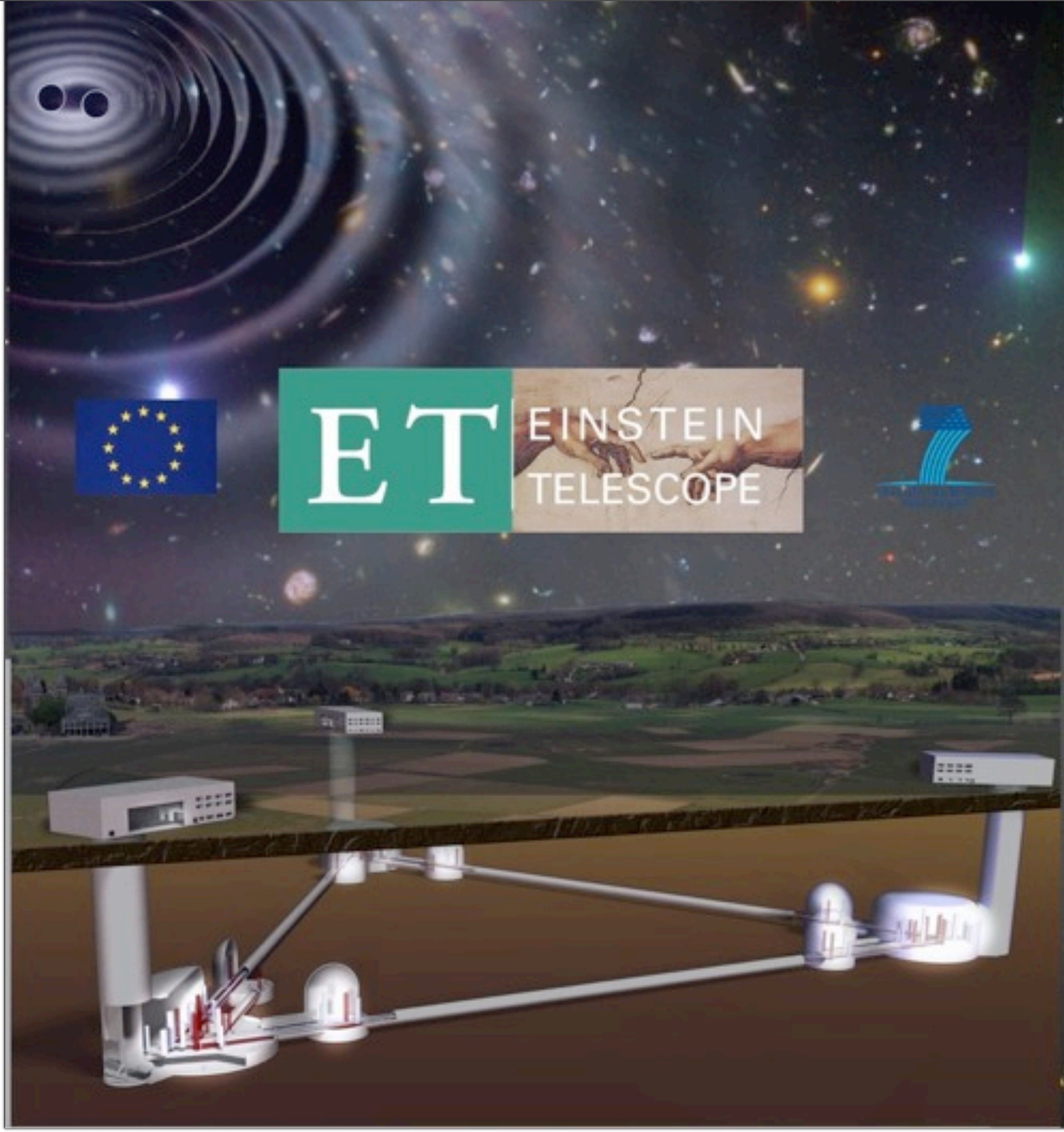


Image: physicsquest.homestead.com

- In 1909 Geiger and Marsden smashed α particles at gold foil & discovered atomic structure which led Rutherford to discover in 1911 the structure of the atom
- A 100 years hence we are at the verge of exploring the very structure of spacetime with a similar "experiment" by observing black holes - pure geometric objects - smashing against each other
- That'll only be the beginning: *Gravitational Astronomy* will herald a new era in fundamental physics, cosmology and astrophysics, giving access to processes with phenomenal energies, inconceivable in accelerators, and luminosities, far exceeding all but the Big Bang


ET
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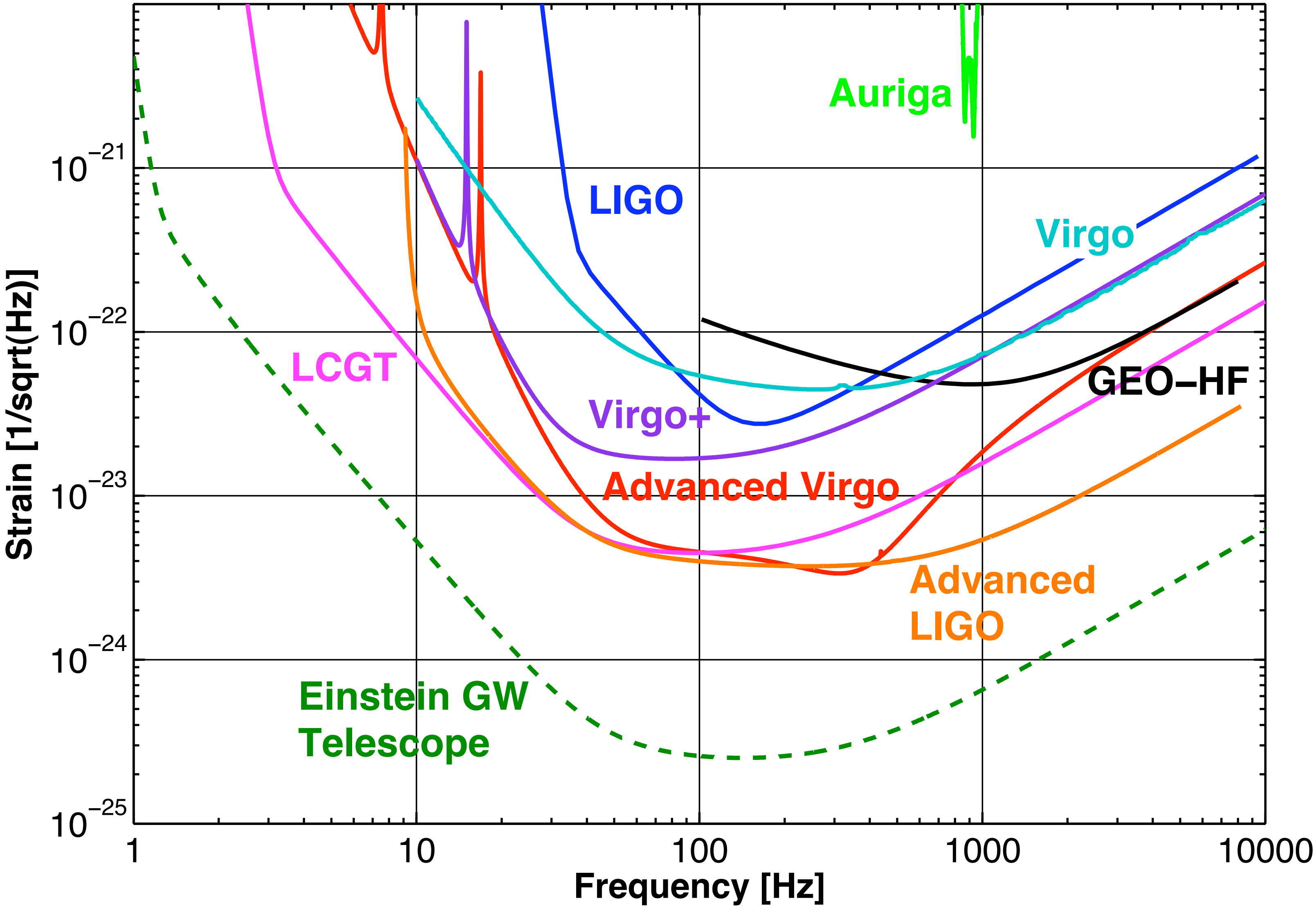
Expected ET Sensitivity



What will ET observe and what can it tell?

- ET will observe radiation arising from
  - black hole collisions when the Universe was still in its infancy assembling the first galaxies
  - neutron star collisions when star formation in the Universe was at its peak
  - formation of black holes and neutron stars in supernovae and collapsars in the local neighbourhood
  - stochastic backgrounds of cosmological and astrophysical origin
- ET will provide new insights into
  - the secret births and lives of black holes and neutron stars, their demographics, populations and their masses and spins
  - dark energy and its variation with redshift
  - equation of state of matter at supra-nuclear densities
  - early history of the Universe's evolution

Compact binaries for fundamental physics, cosmology and astrophysics

- Black holes and neutron stars are the most compact objects
  - The potential energy of a test particle is equal to its rest mass energy

$$\frac{GmM}{R} \sim mc^2$$

- Being the most compact objects, they are also the most luminous sources of gravitational radiation
  - The luminosity of a neutron star binary increases a billion times in the course of its evolution through a ET's sensitivity band
  - The GW luminosity of a binary black hole outshines, during merger, the EM luminosity of all the stars in the Universe
- Compact binaries are self-calibrating standard sirens
  - GW observations measure both the apparent luminosity (strain) and absolute luminosity (chirp rate) of a source

Schutz 86

Numerical Simulation of Merging Black Hole Binaries

Caltech-Cornell Simulation

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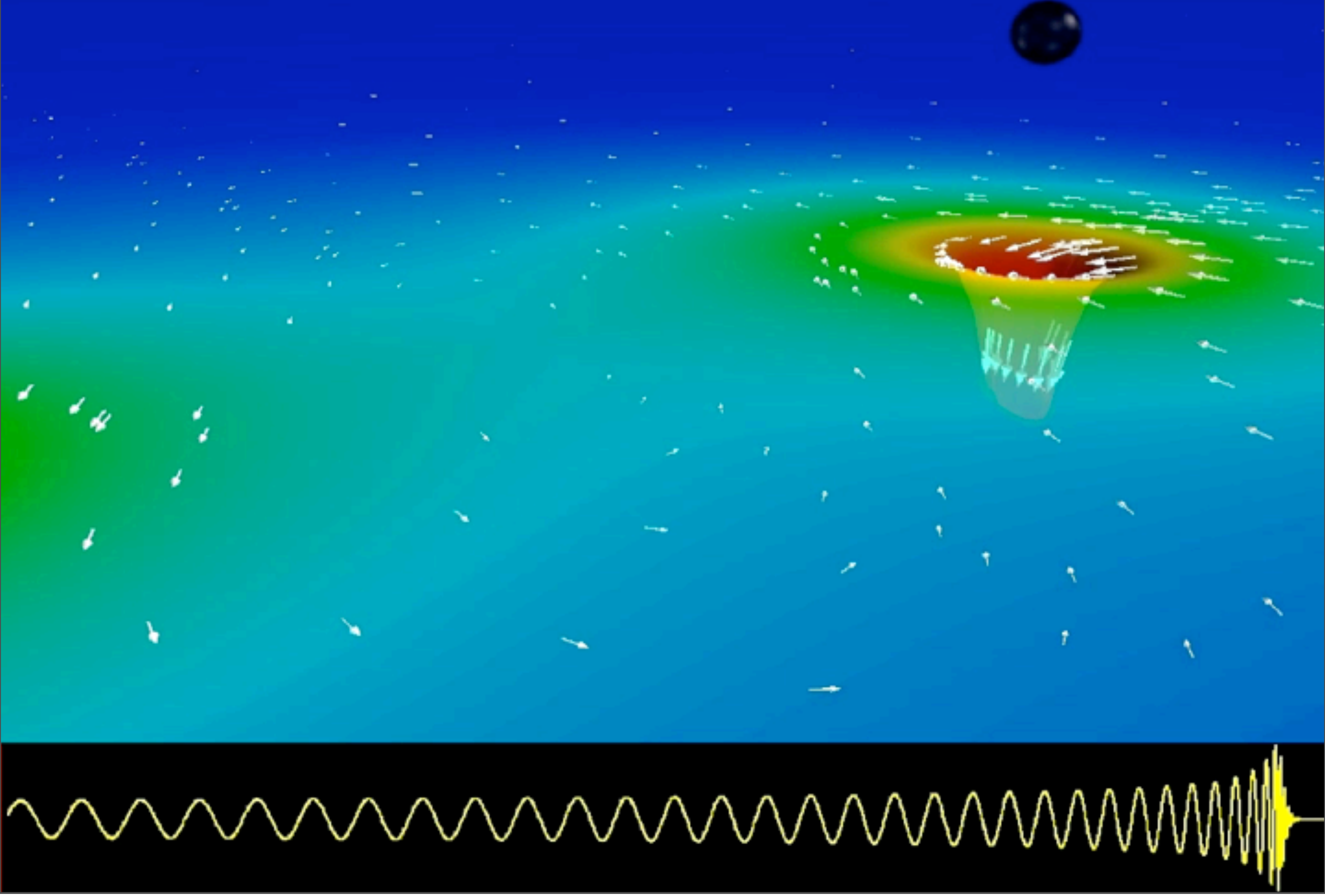
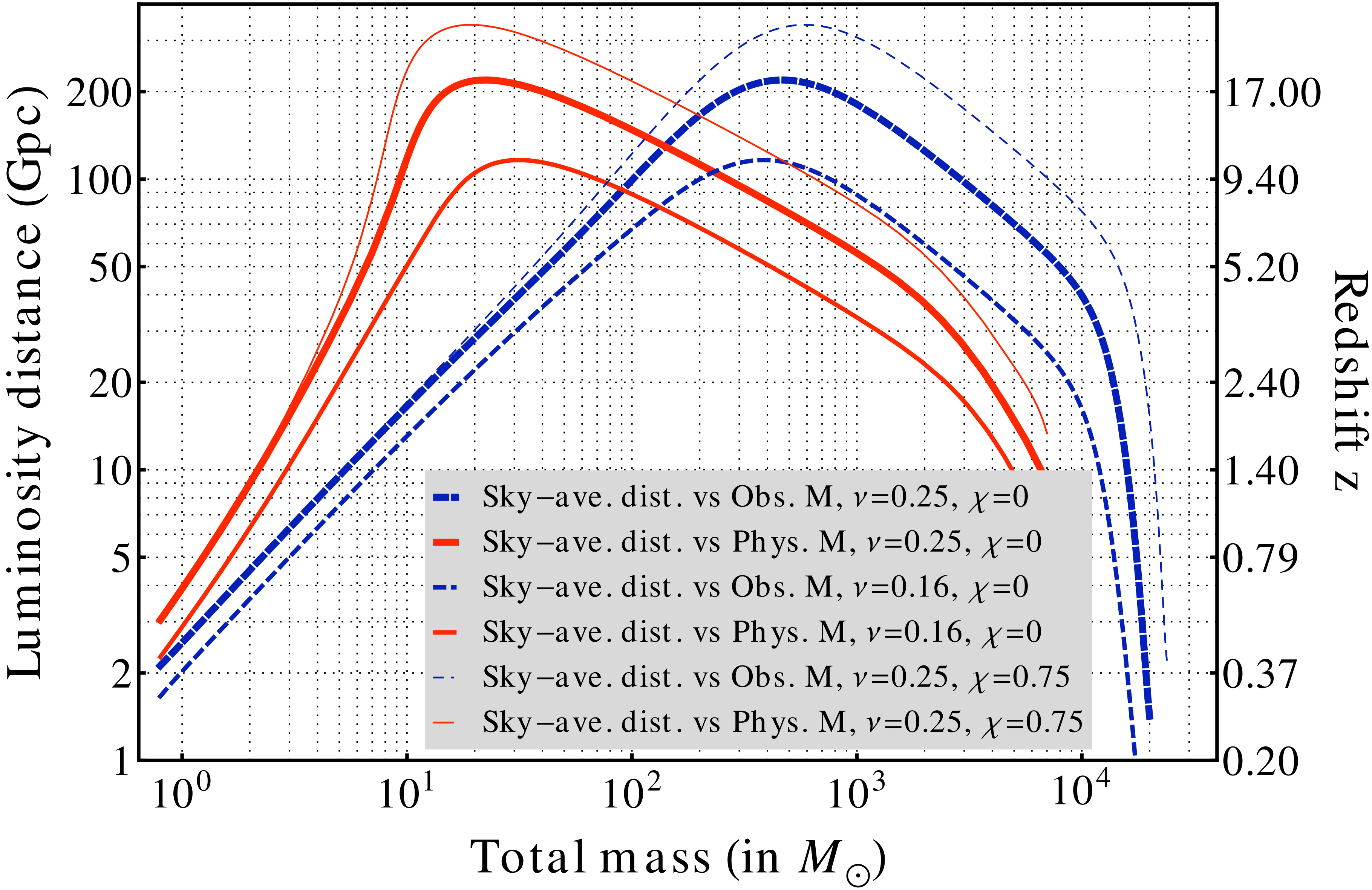


ET Distance Reach for Compact Binary Mergers



Fundamental Physics

- Properties of gravitational waves
  - Testing GR beyond the quadrupole formula
    - Binary pulsars consistent with quadrupole formula; they don't measure properties of GW
  - How many polarizations are there?
    - In Einstein's theory only two polarizations; a scalar-tensor theory could have six
  - Do gravitational waves travel at the speed of light?
    - There are strong motivations from string theory to consider massive gravitons
    - Binary pulsars constrain the speed to few parts in a thousand
    - GW observations can constrain to 1 part in 10^{18}
- EoS of dark energy
  - Black hole binaries are standard candles/sirens
- EoS of supra-nuclear matter
  - Signature of EoS in GW emitted when neutron stars merge
- Black hole no-hair theorem and cosmic censorship
  - Are BH (candidates) of nature BH of general relativity?
- An independent constraint/measurement of neutrino mass
  - Delay in the arrival times of neutrinos and gravitational waves

Do gravitational waves travel at the speed of light?

- Coincident observation of a supermassive black hole binary and the associated gravitational radiation can be used to constrain the speed of gravitational waves:
- If Δt is the time difference in the arrival times of GW and EM radiation and D is the distance to the source then the fractional difference in the speeds is

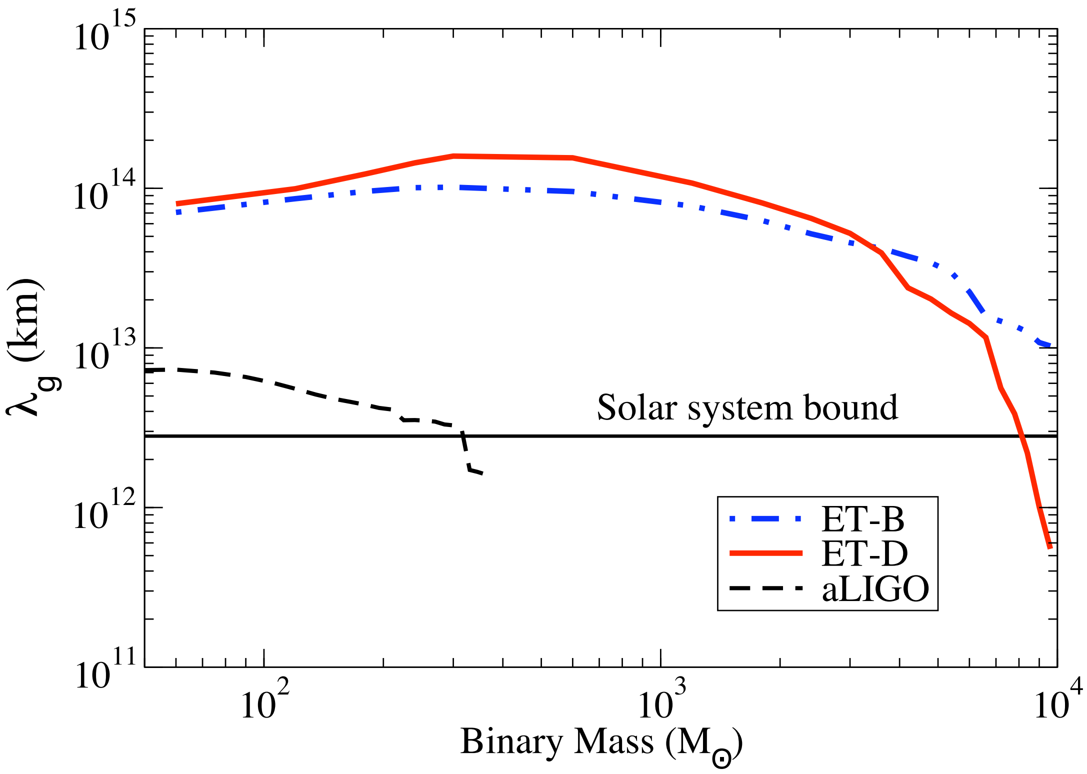
$$\frac{\Delta v}{c} = \frac{\Delta t}{D/c} \simeq 10^{-14} \left(\frac{\Delta t}{1\mathrm{sec}}\right) \left(\frac{D}{1\mathrm{Mpc}}\right)$$

- It is important to study what the EM signatures of massive BBH mergers are
- Can be used to set limits on the mass of the graviton slightly better than the current limits.

Will (1994, 98)

Bound on graviton Compton wave length as a function of total mass

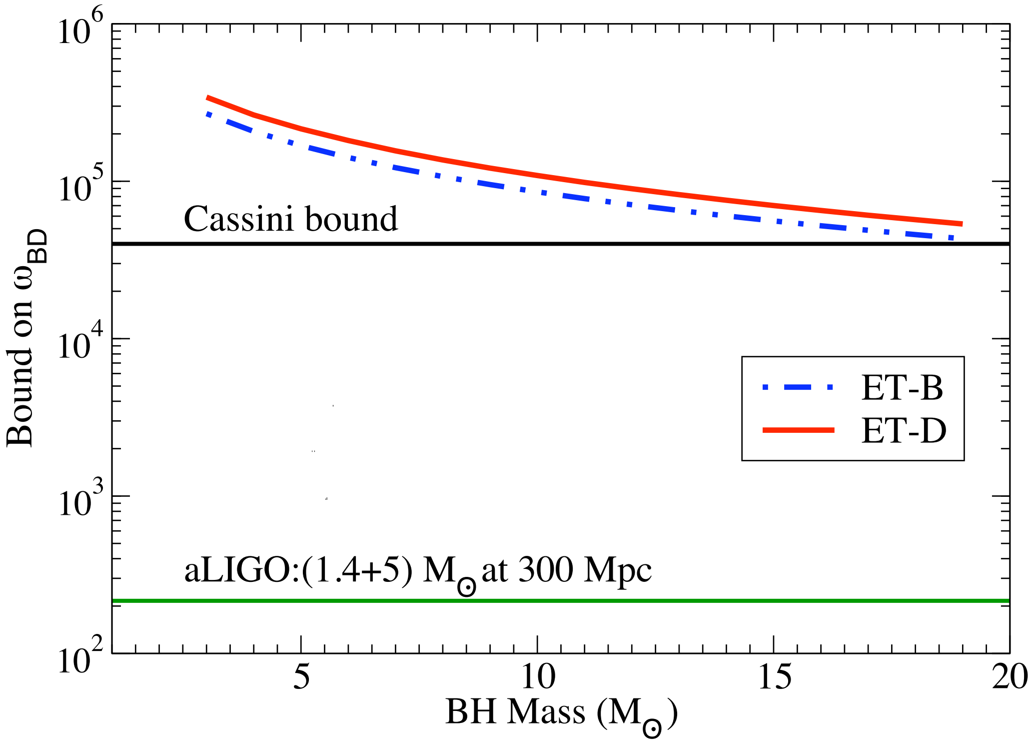
- The Compton wavelength of a particle is determined by its mass
  - The larger the mass smaller will be its wavelength
- Limit on the Compton wavelength of graviton based on ET observations will be two orders-of-magnitude better than solar system limits



Arun and Will (2009)

Testing Brans-Dicke Theory - An Alternative to Einstein's gravity

- Brans-Dicke theory has a parameter denoted ω_{BD}
- In Einstein's gravity this parameter takes the value infinity
- ET can constrain this value by an order of magnitude more than current limits

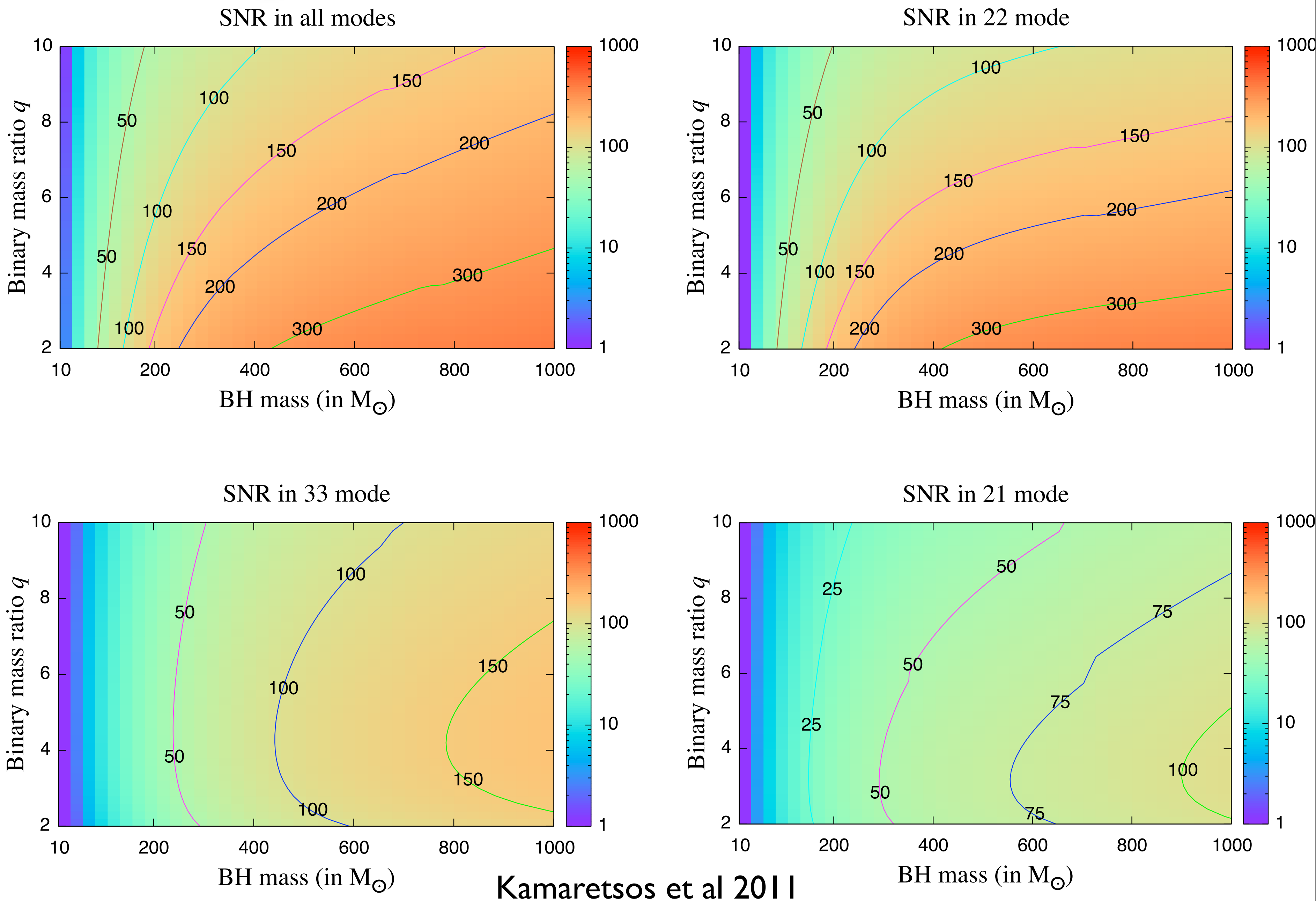


Arun 2011

Black Hole No-Hair Theorem

- Deformed black holes are unstable; they emit energy in their deformation as gravitational waves
  - Superposition of damped waves with many different frequencies and decay times
  - In Einstein's theory, frequencies and decay times all depend only on the mass M and spin j of the black hole
- Measuring two or modes would constrain Einstein's theory or provide a smoking gun evidence of black holes
  - If modes depend on other parameters (e.g., the structure of the central object), then test of the consistency between different mode frequencies and damping times would fail
- The amplitude of the modes cary additional information about what caused the deformity

Visibility of QNM in ET: Formation of BHs at *z=1*



Kamaretsos et al 2011

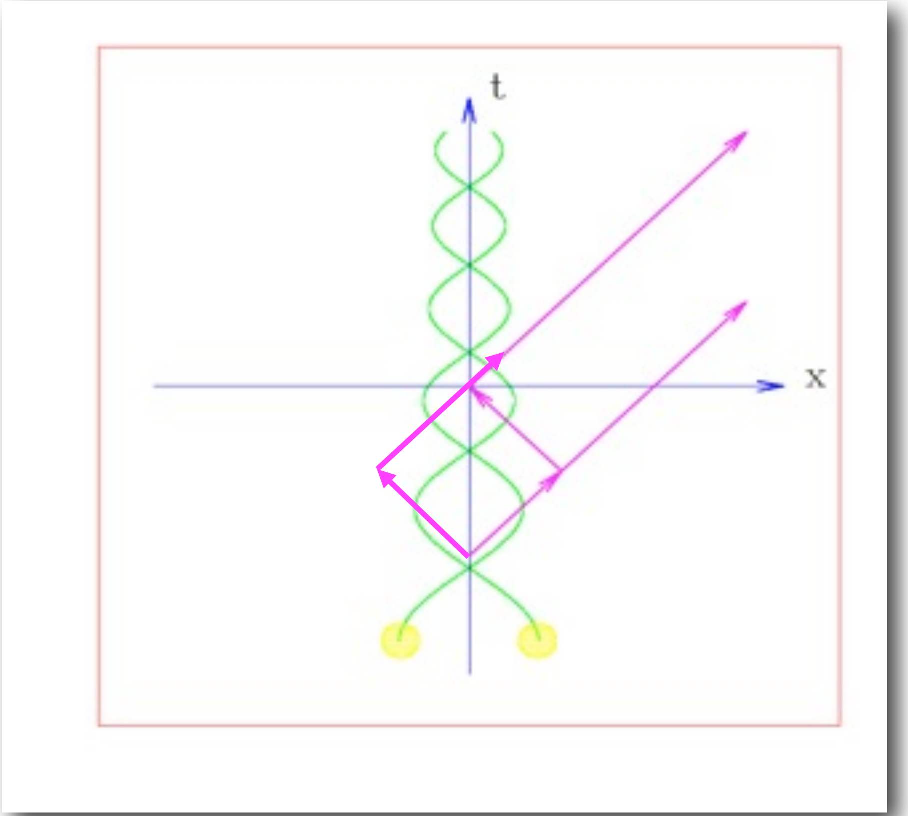
BBH Signals as Testbeds for GR

- Gravity gets ultra-strong during a BBH merger compared to any observations in the solar system or in binary pulsars
  - In the solar system: $\phi/c^2 \sim 10^{-6}$
  - In a radio binary pulsar it is still very small: $\phi/c^2 \sim 10^{-4}$
  - Near a black hole $\phi/c^2 \sim 1$
  - Merging binary black holes are the best systems for strong-field tests of GR
- Dissipative predictions of gravity are not even tested at the 1PN level
  - In binary black holes even $(v/c)^7$ PN terms will not be adequate for high-SNR (~100) events

Testing GR by observing non-linear effects

- Binary inspiral waveform depends on many post-Newtonian coefficients
  - $\Psi_0, \Psi_2, \Psi_3, \ldots$
  - They correspond to different physical effects, e.g. GW tails
- In the case of non-spinning binaries $\Psi_0, \Psi_2, \Psi_3, \ldots$ depend on just the two masses m_1 and m_2
- By assuming they are all independent one can check to see if GR is the correct theory

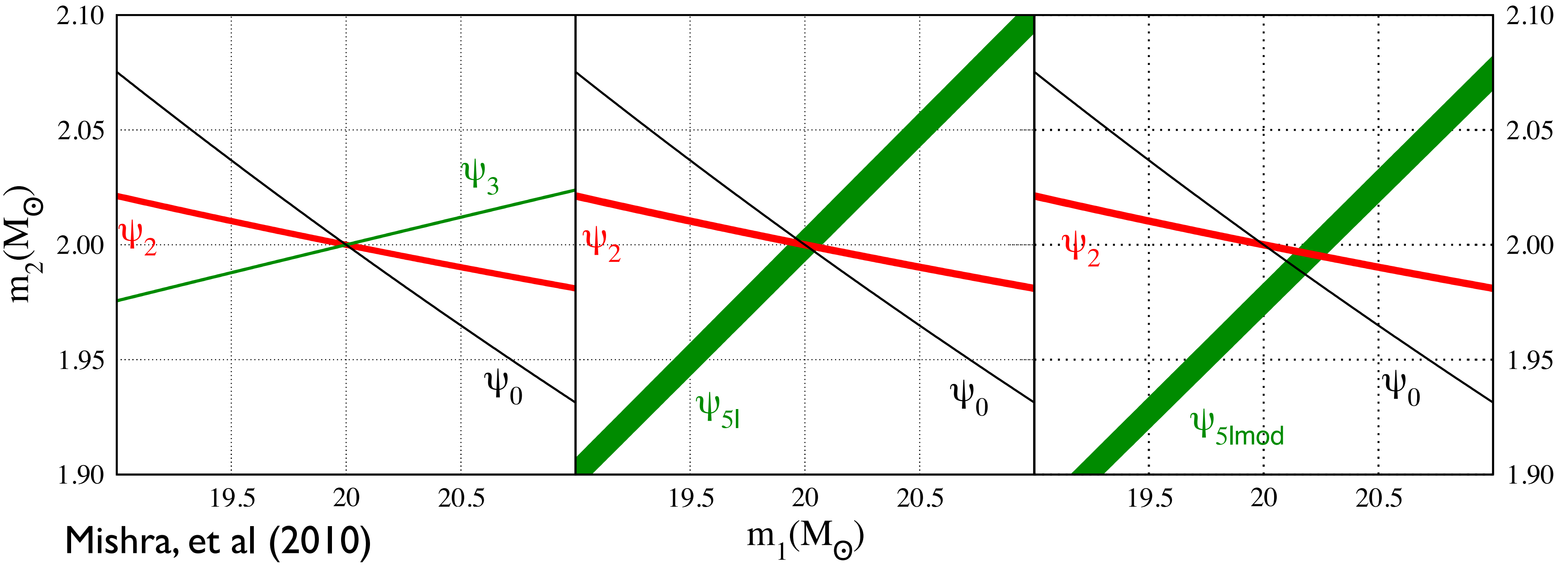
Gravitational wave tails



Blanchet and Schaefer (1994)

How well can ET measure non-linear effects?

- If Einstein's theory is a correct description of gravity, masses measured using different parameters will all be consistent with each other (left and middle plots)
- One percent departure of a parameter from predictions of Einstein's theory will lead to discrepancies in the measured masses (right plot)



Mishra, et al (2010)

Cosmology

- Cosmography
  - Build the cosmic distance ladder, strengthen existing calibrations at high z
  - Measure the Hubble parameter, dark matter and dark energy densities, dark energy EoS w, variation of w with z
- Black hole seeds
  - Black hole seeds could be intermediate mass black holes
  - Might explore hierarchical growth of central engines of black holes
- Dipole anisotropy in the Hubble parameter
  - The Hubble parameter will be "slightly" different in different directions due to the local flow of our galaxy
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of H on the sky should show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe could produce a stochastic b/g
- Production of GW during early Universe phase transitions
  - Phase transitions, pre-heating, re-heating, etc., could produce detectable stochastic GW

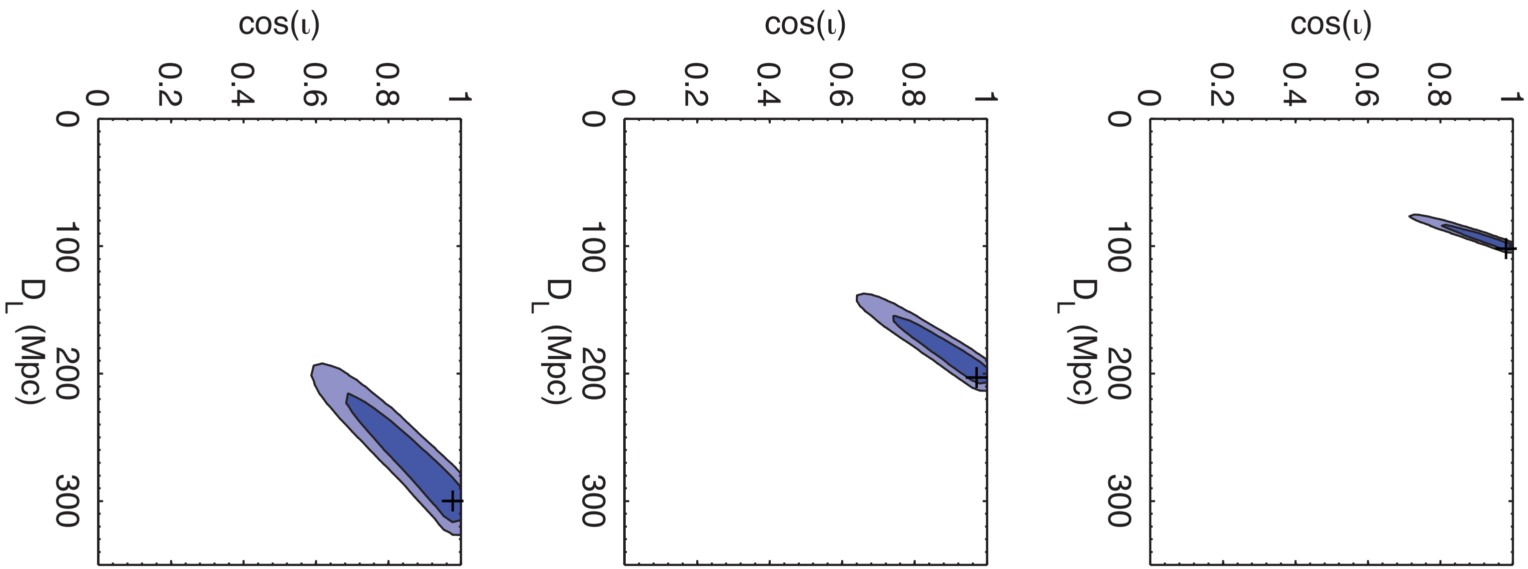
Hubble Constant from Advanced Detectors

EXPLORING SHORT GAMMA-RAY BURSTS AS GRAVITATIONAL-WAVE STANDARD SIRENS

SAMAYA NISSANKE[1,2], SCOTT A. HUGHES[2], DANIEL E. HOLZ[3], NEAL DALAL[1], JONATHAN L. SIEVERS[1]

Draft version April 7, 2009

is further augmented by a factor of 1.12. At this rate, we find that *one* year of observation should be enough to measure H_0 to an accuracy of $\sim 1\%$ if SHBs are dominated by beamed NS-BH binaries using the "full" network of LIGO, Virgo, AIGO, and LCGT—admittedly,



ET: Measuring Dark Energy and Dark Matter

- ET will observe 100's of binary neutron stars and GRB associations each year
- GRBs could give the host location and red-shift, GW observation provides D_L

Class. Quantum Grav. **27** (2010) 215006 B S Sathyaprakash *et al*

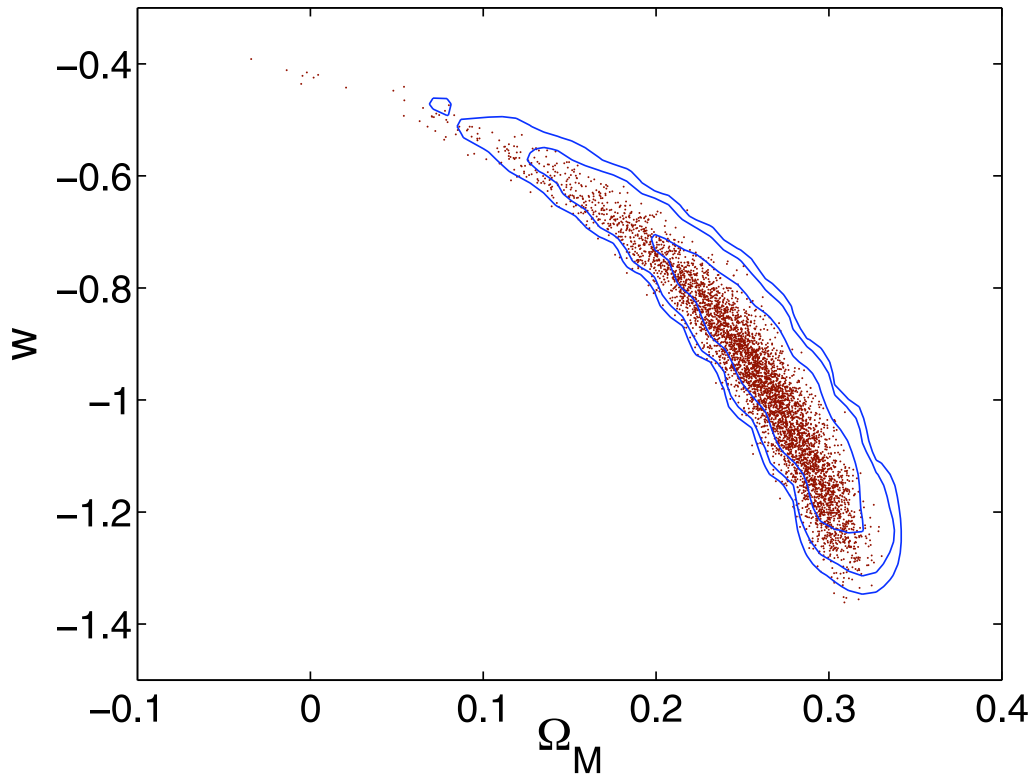
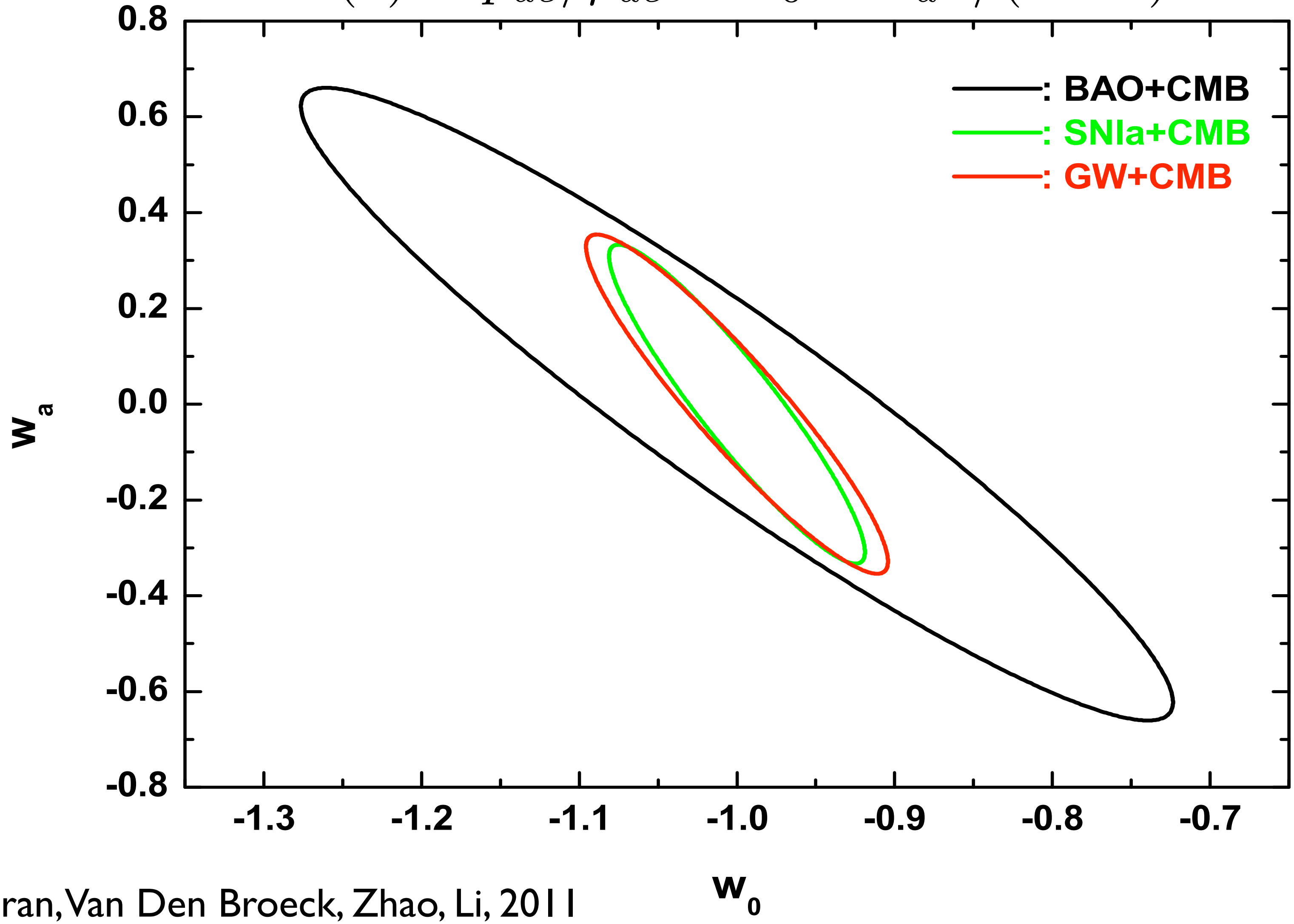


Figure 3. Scatter plot of the retrieved values for (Ω_Λ, w), with 1-σ, 2-σ and 3-σ contours, in the case where weak lensing is not corrected.

Friday, 20 May 2011

Measuring w and its variation with z

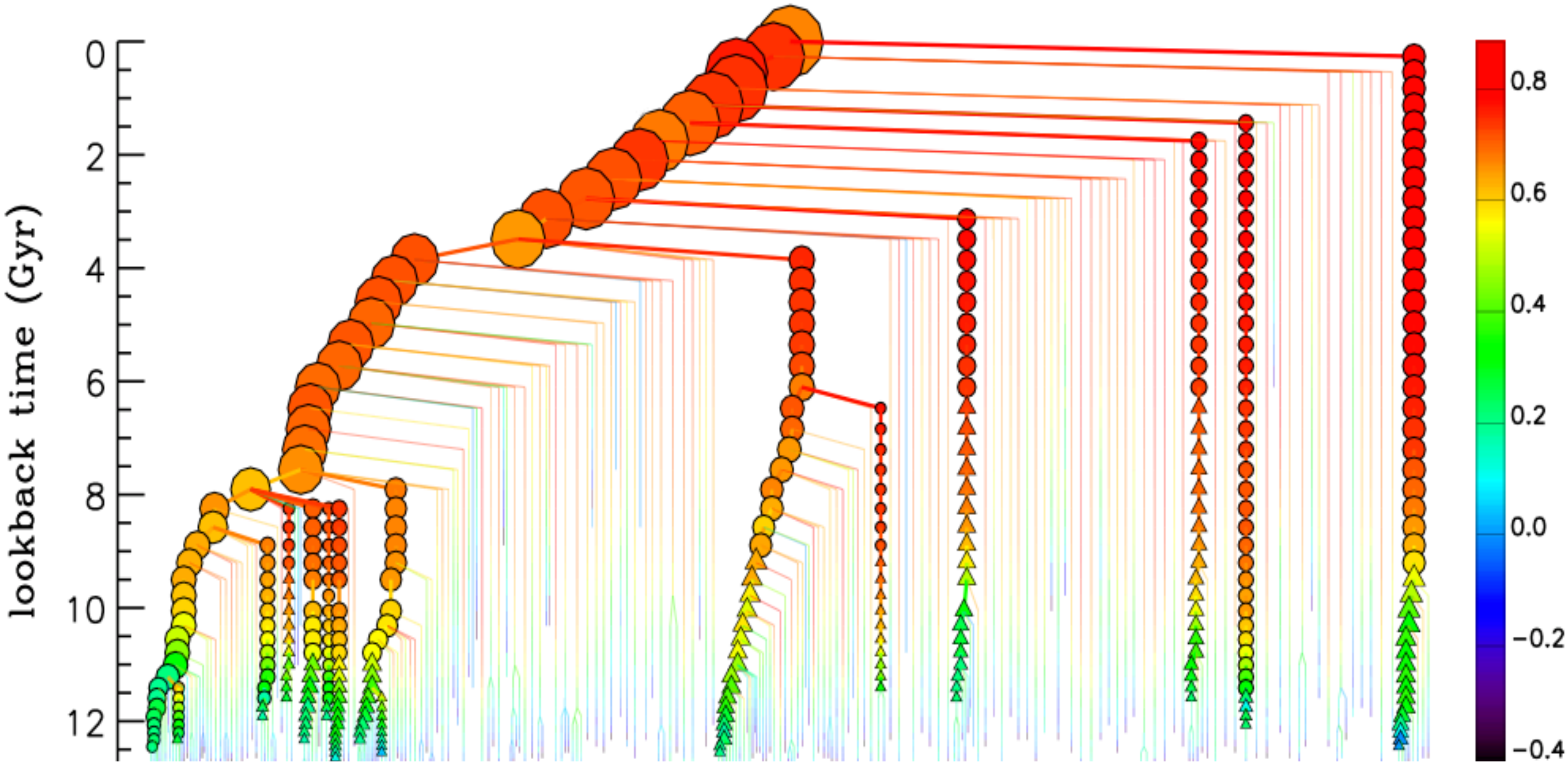
$$w(z) \equiv p_{de}/\rho_{de} = w_0 + w_a z/(1+z)$$



Baskaran, Van Den Broeck, Zhao, Li, 2011

Hierarchical Growth of Black Holes in Galactic Nuclei

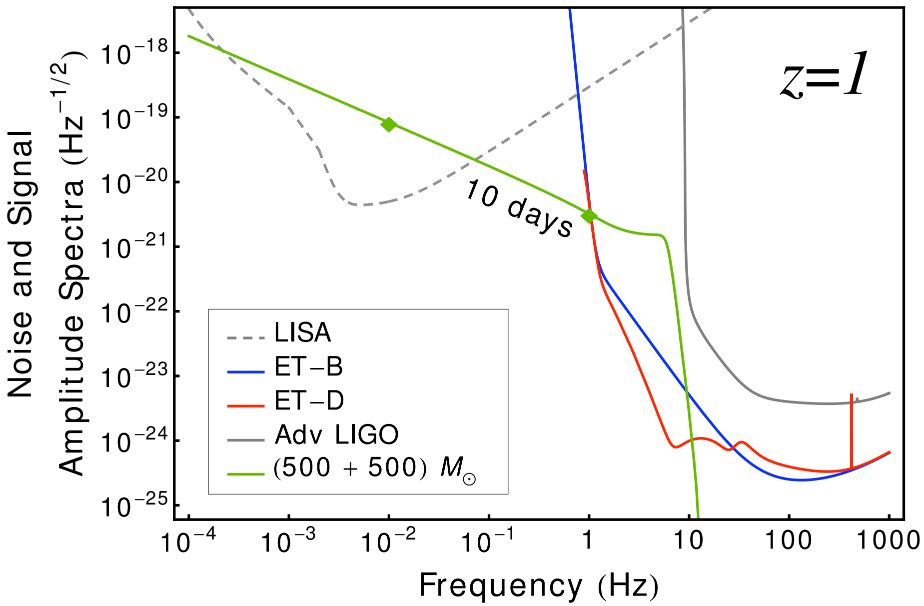
Slide from Sesana

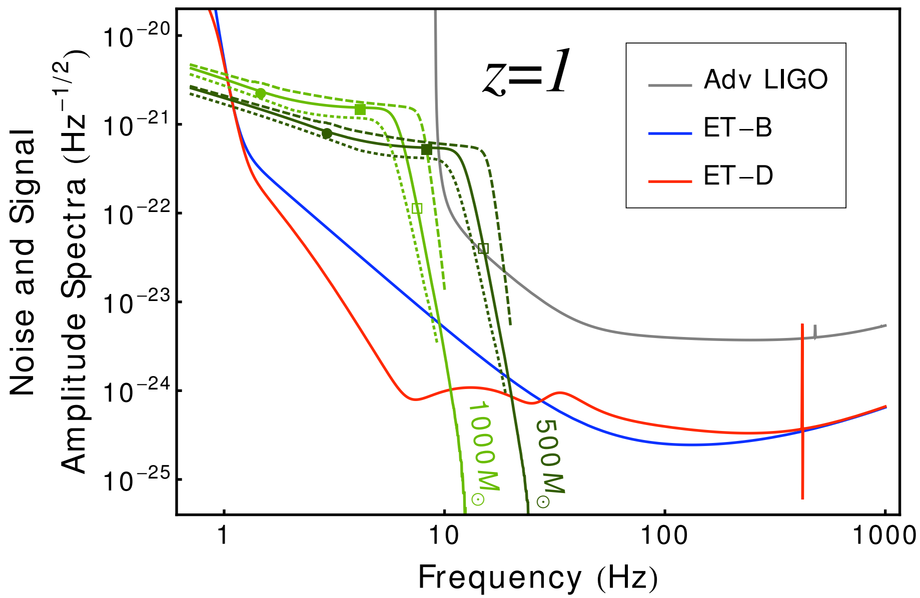


- Initially small black holes may grow by hierarchical merger
  - ET could observe seed black holes if they are of order 1000 solar mass

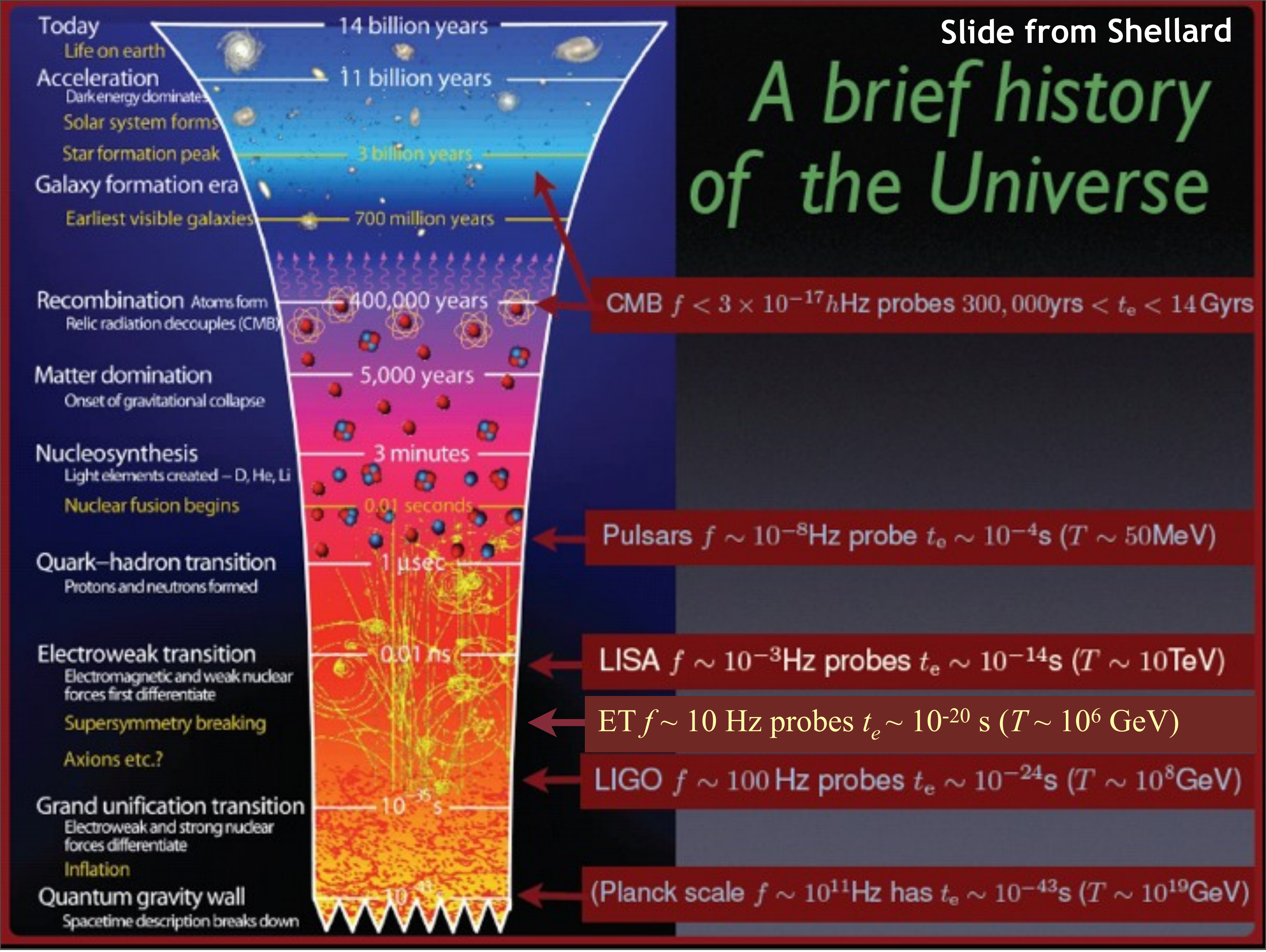
Observing Intermediate-mass Black Hole Binaries

- Ultra-luminous X-ray sources might be hosting black holes of mass one thousand solar masses
- 100 solar mass black holes could be seeds of galaxy formation
- ET could observe black hole populations at different red-shifts and resolve questions about black hole demographics

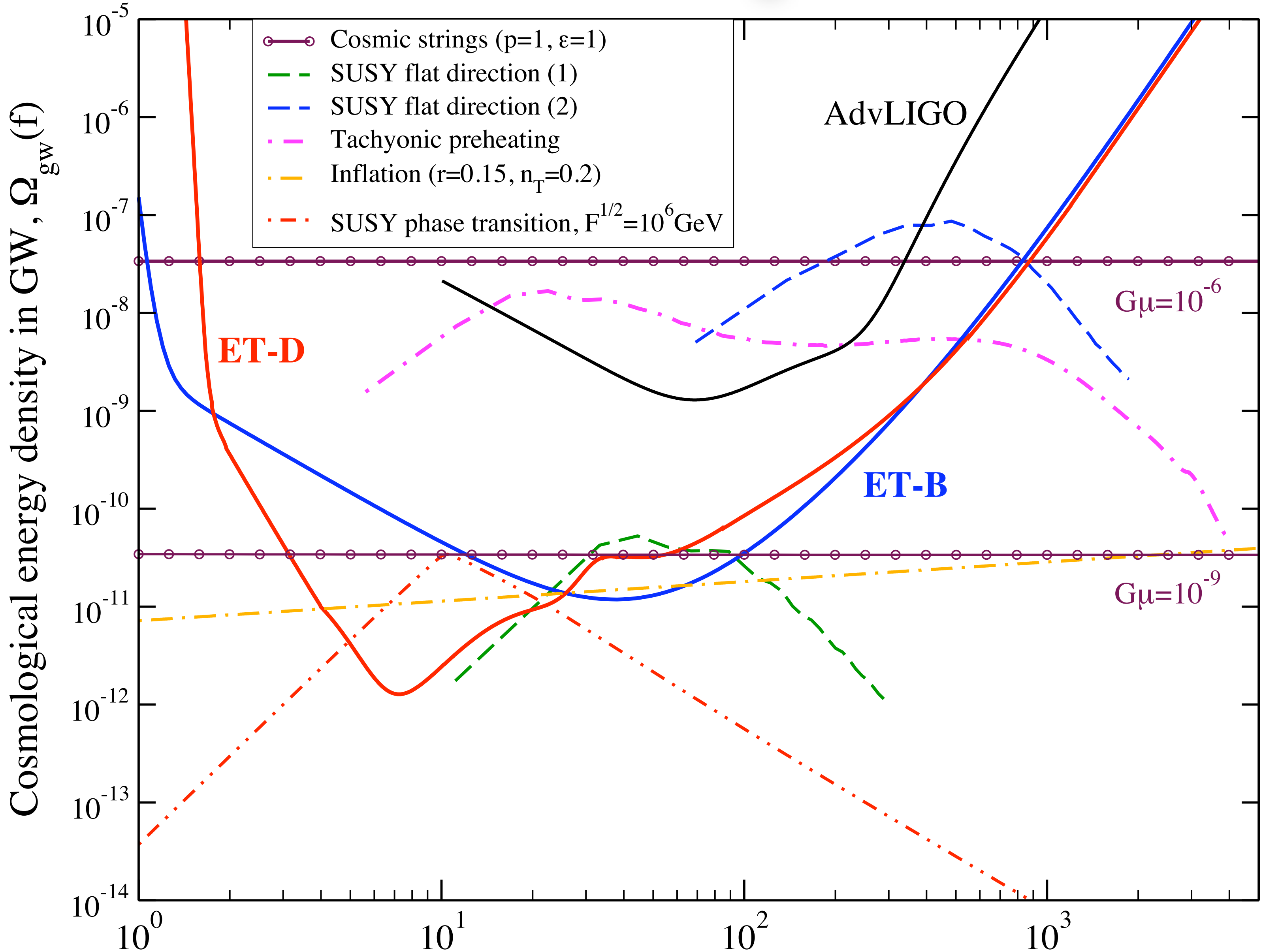




Pau and Santamaria 2010


Slide from Shellard
A brief history of the Universe
Today
Life on earth
Acceleration
Dark energy dominates
Solar system forms
Star formation peak
Galaxy formation era
Earliest visible galaxies
Recombination Atoms form
Relic radiation decouples (CMB)
Matter domination
Onset of gravitational collapse
Nucleosynthesis
Light elements created – D, He, Li
Nuclear fusion begins
Quark–hadron transition
Protons and neutrons formed
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
Spacetime description breaks down
14 billion years
11 billion years
3 billion years
700 million years
400,000 years
5,000 years
3 minutes
0.01 seconds
1 µsec
0.01 ns
10^{-35} s
CMB $f < 3 \times 10^{-17} h$Hz probes 300,000yrs $< t_e <$ 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)

Primordial Backgrounds



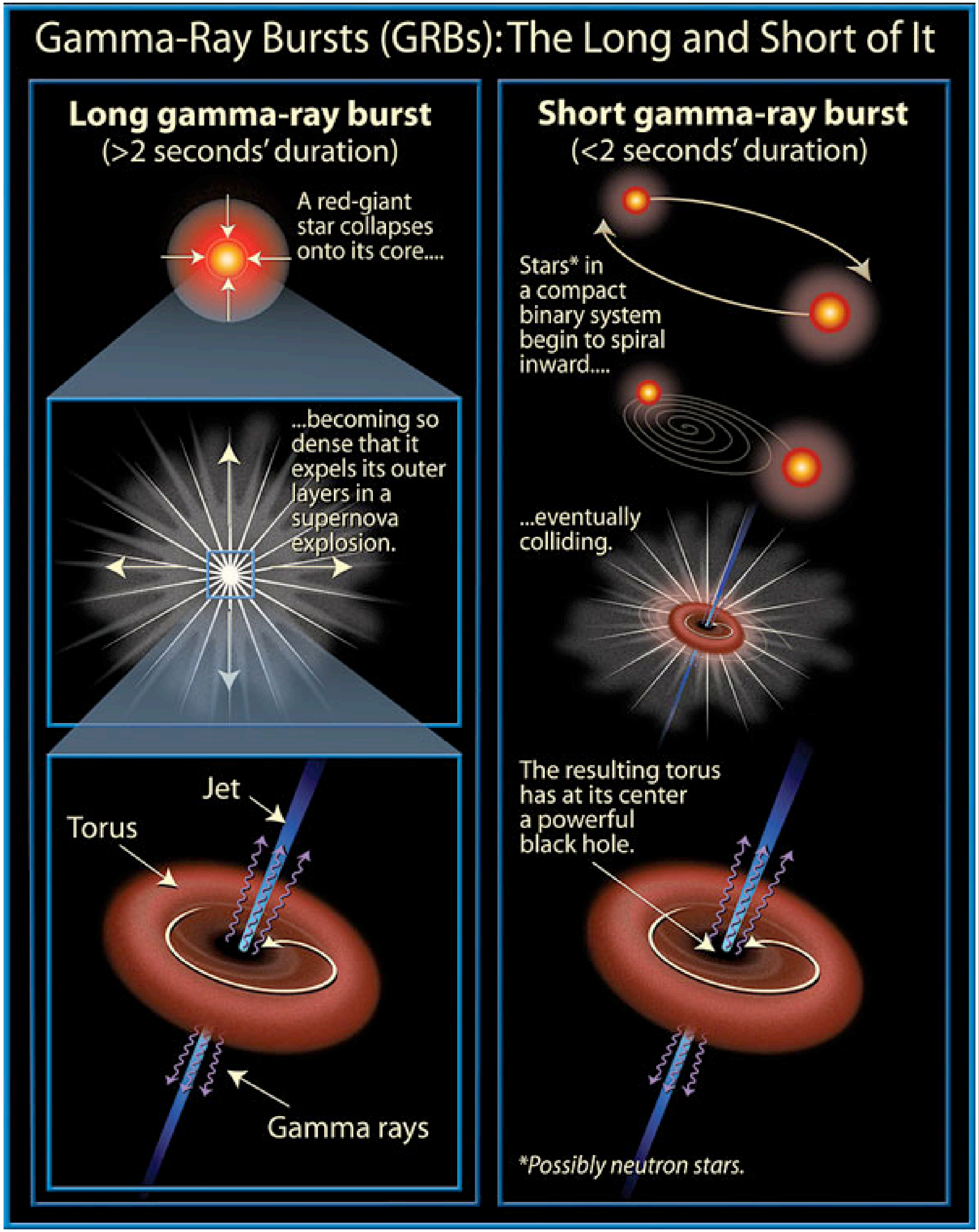
Dent 2011

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Understand the demographics and different classes of short-hard GRBs
- Understanding Supernovae
  - Astrophysics of gravitational collapse and accompanying supernova?
- Evolutionary paths of compact binaries
  - Evolution of compact binaries involves complex astrophysics
    - Initial mass function, stellar winds, kicks from supernova, common envelope phase
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies and what is behind ultra high-energy transients of EM radiation in magnetars
    - Could reveal the composition and structure of neutron star cores
- Ellipticity of neutron stars as small as 1 part in a billion (10μm)
  - Mountains of what size can be supported on neutron stars?
- NS spin frequencies in LMXBs
  - Why are spin frequencies of neutron stars in low-mass X-ray binaries bounded?
- Onset/evolution of relativistic instabilities
  - CFS instability and r-modes

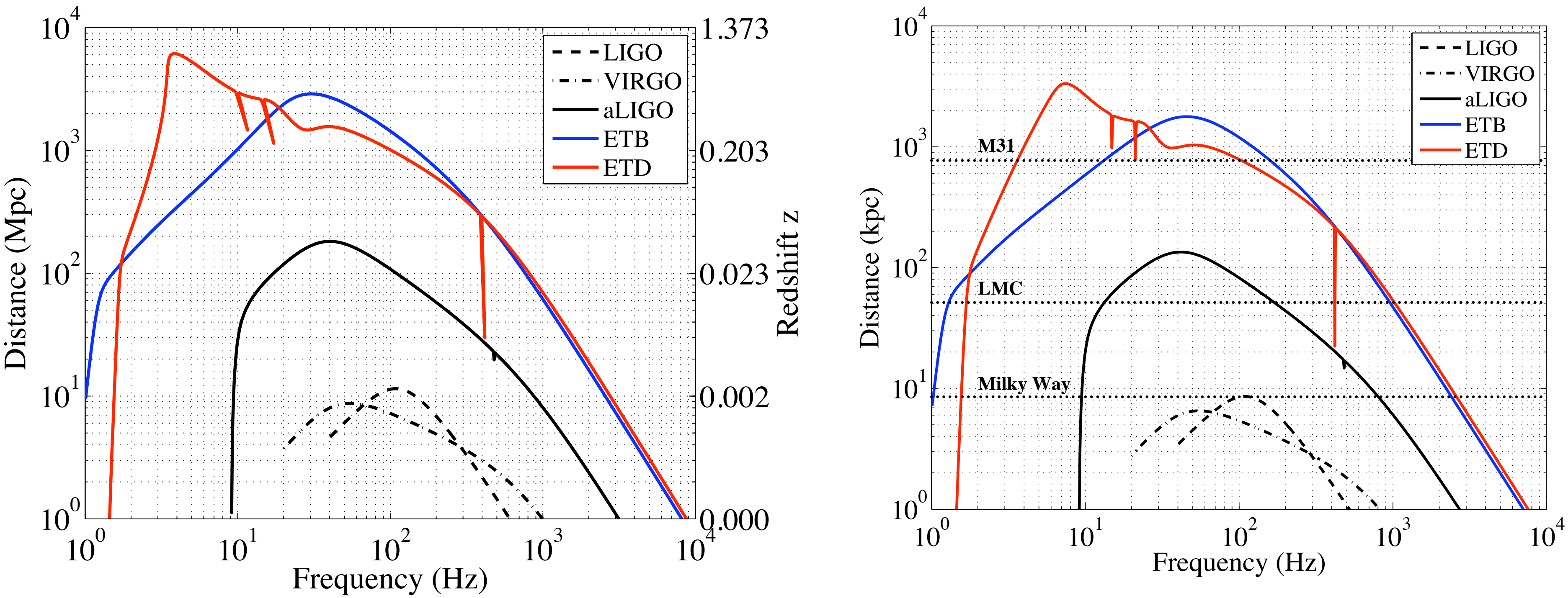
Progenitors of GRBs

- Long GRBs
  - Core-collapse SNe, GW emission not well understood
    - Could emit burst of GW
- Short GRBs
  - Could be the end state of the evolution of compact binaries
    - BNS, NS-BH



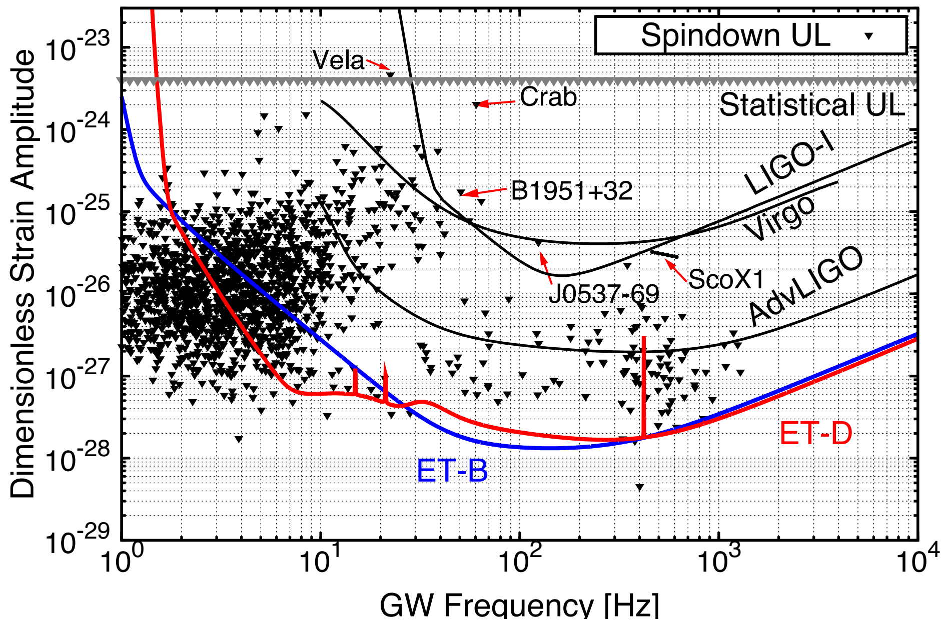
Unveiling the Origin of GRBs

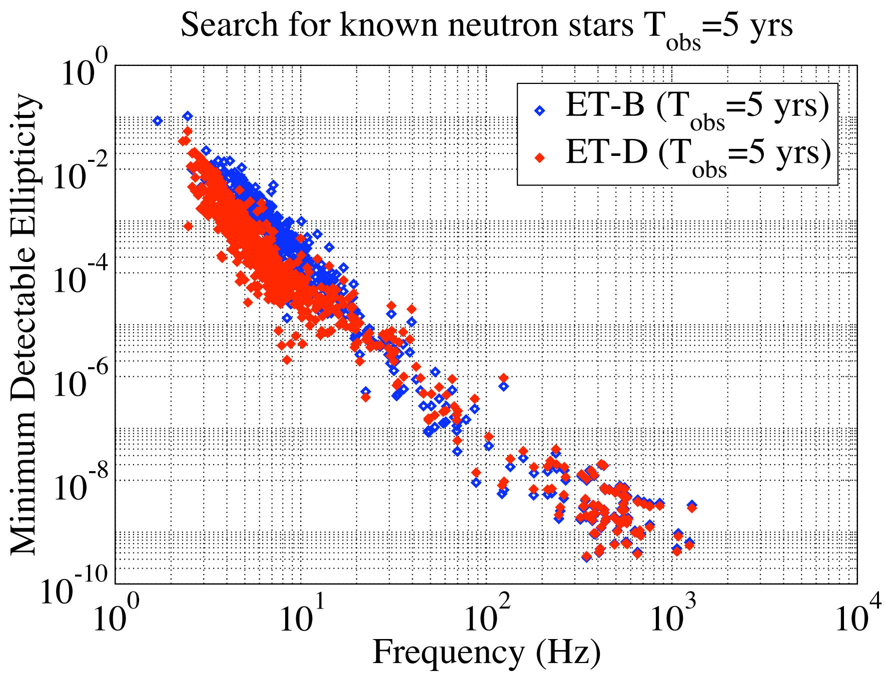
- ET can detect model-independent radiation from collapsars if $E_{GW} > 5\% \, M_\odot$
- Soft Gamma Repeaters could be seen both in the Milky Way and the local neighbourhood provided if $E_{GW} > 10^{-8} \, M_\odot$



Mountains on Neutron Stars

- ET will check if neutron stars (10 km in radius) have mountains that are smaller than 10 micro meters
- This could constrain models about their crustal strengths

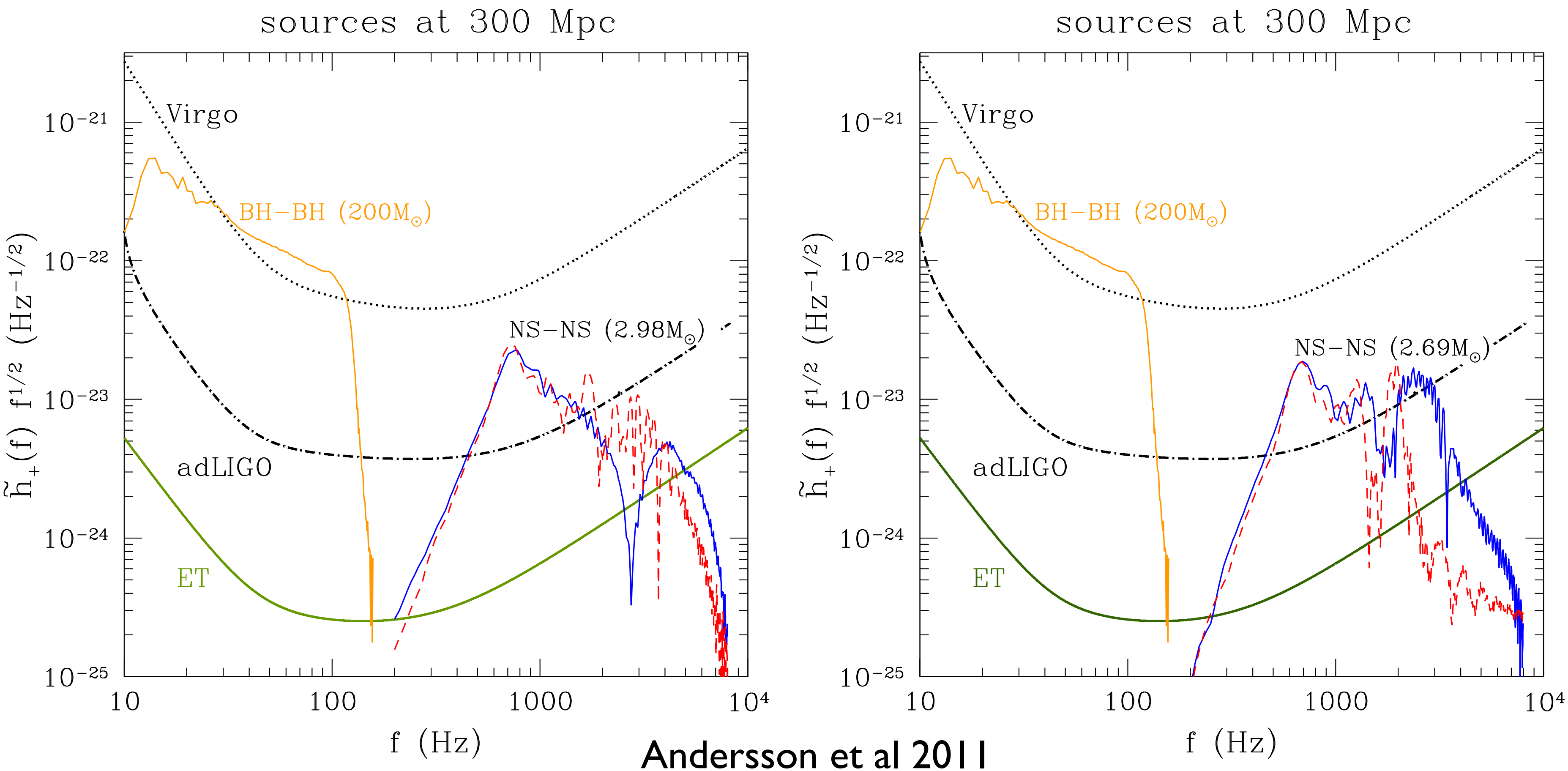




Krishnan, Palomba and Prix 2011

Neutron star mergers and equation of state of neutron stars

- Spectrum of gravitational radiation from black hole binaries is featureless (that's why they are standard candles)
- Radiation from binary neutron star mergers carries an imprint of the star's mass and equation of state

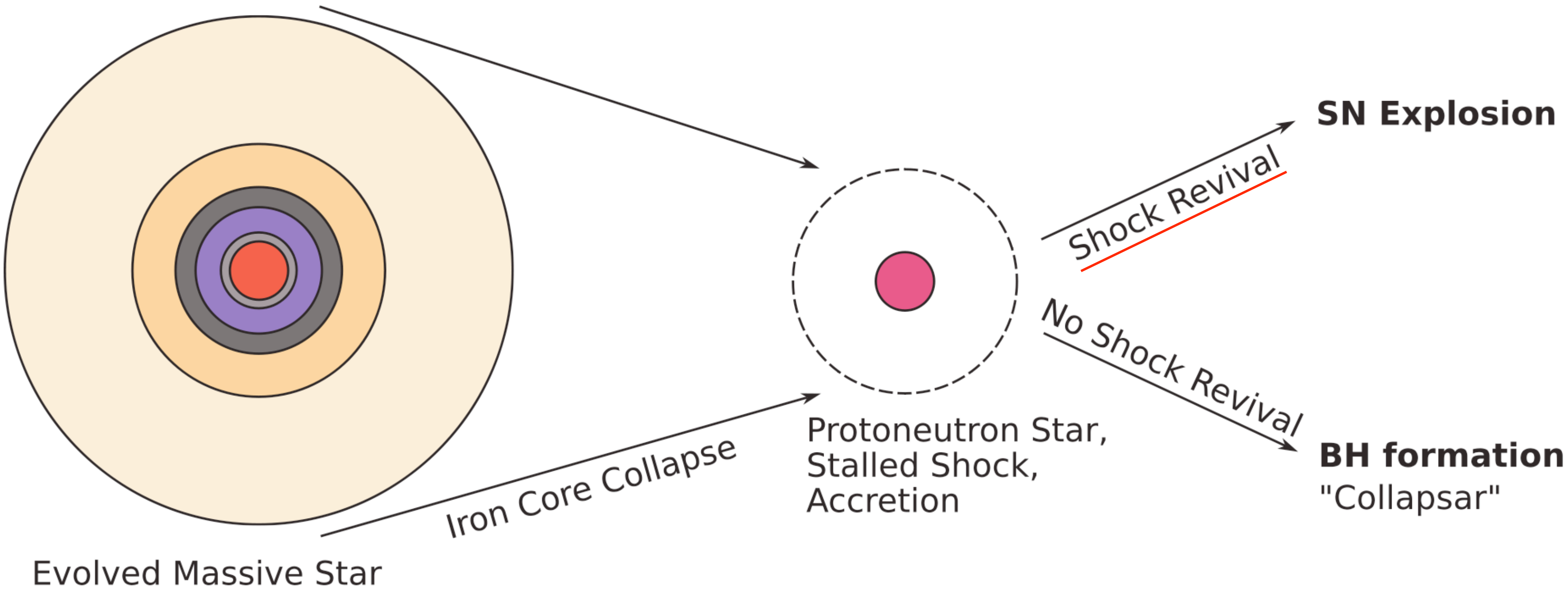


Andersson et al 2011

Supernovae

- Standard candles of astronomy
  - Our knowledge of the expansion rate of the Universe at redshift of z=1 comes from SNe
- Produce dust and affect evolution of galaxies
  - Heavy elements are only produced in SNe
- They are precursors to formation of neutron stars and black holes
  - The most compact objects in the Universe
- SNe cores are laboratories of complex physical phenomena
  - Most branches of physics and astrophysics needed in modelling
    - General relativity, nuclear physics, relativistic magnetohydrodynamics, turbulence, neutrino viscosity and transport, ...
- Unsolved problem: what is the mechanism of shock revival?

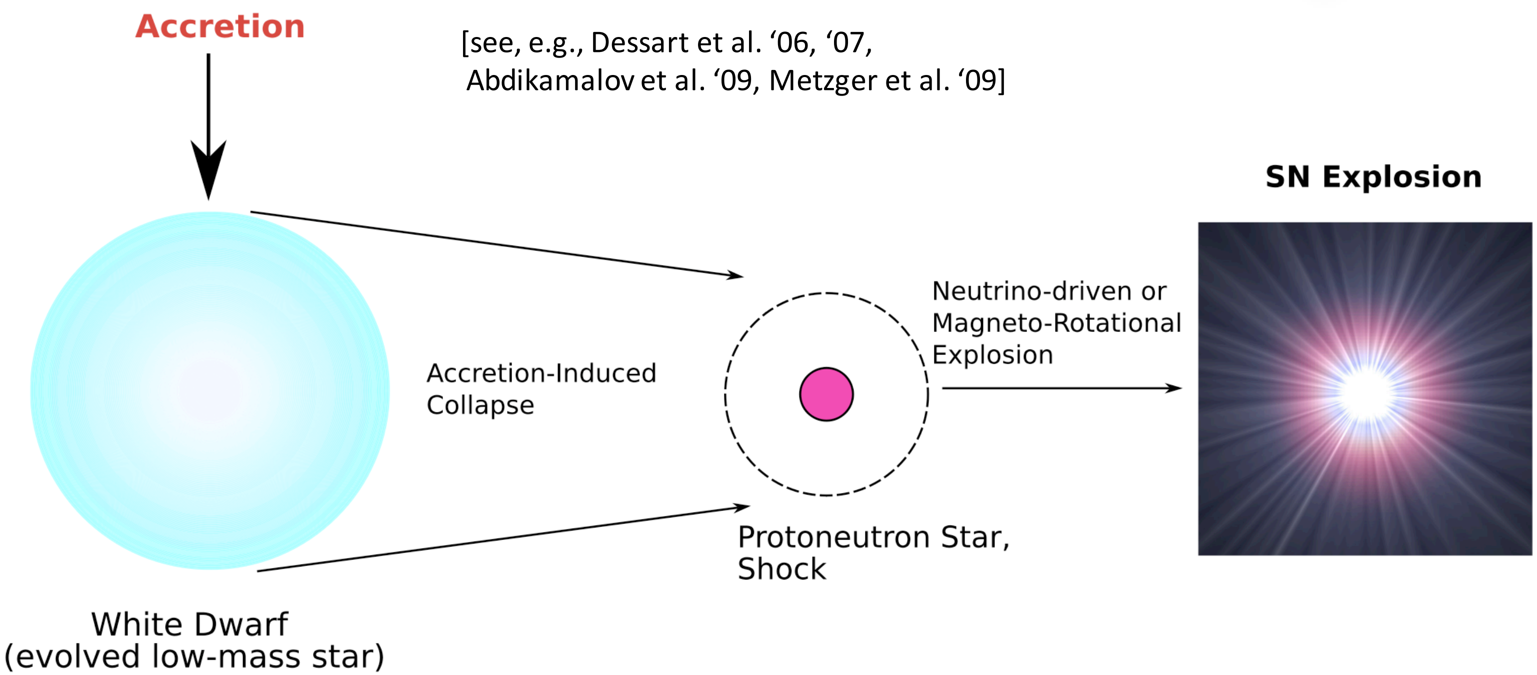
Core Collapse SNe



- Energy reservoir
  - few x 10^{53} erg
- Explosion energy
  - 10^{51} erg
- Time frame for explosion
  - 300 - 1500 ms after bounce
- Formation of black hole
  - At baryonic mass > 1.8-2.5 M

Accretion Induced Collapse

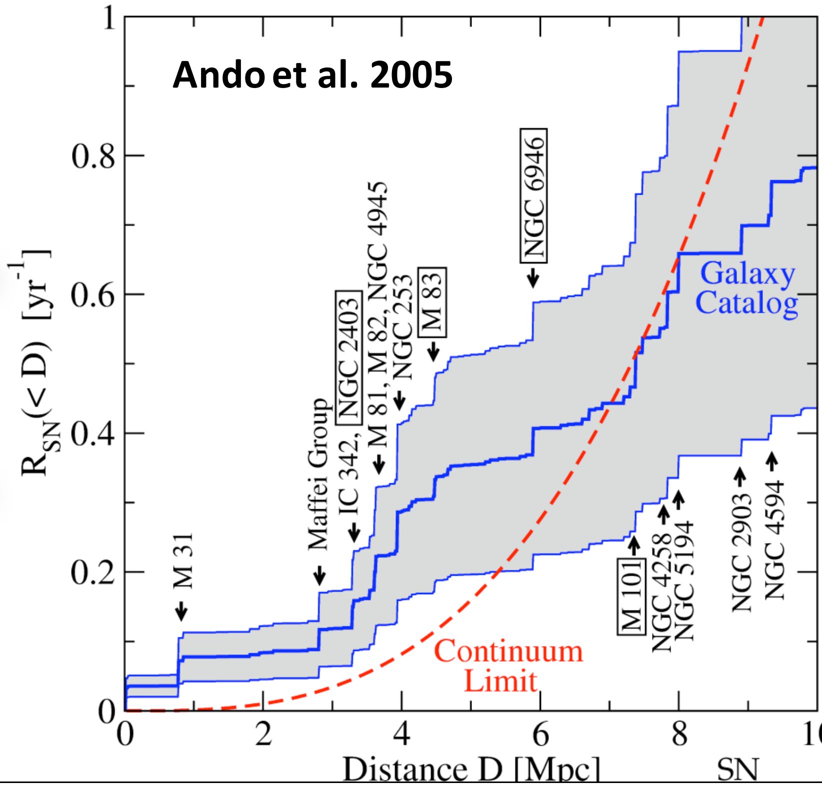
[see, e.g., Dessart et al. ‘06, ‘07, Abdikamalov et al. ‘09, Metzger et al. ‘09]

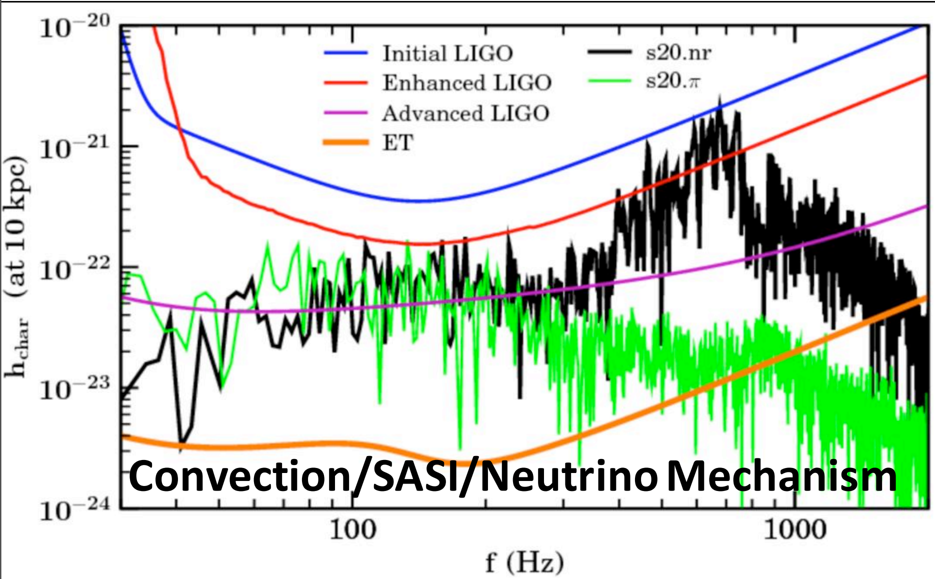


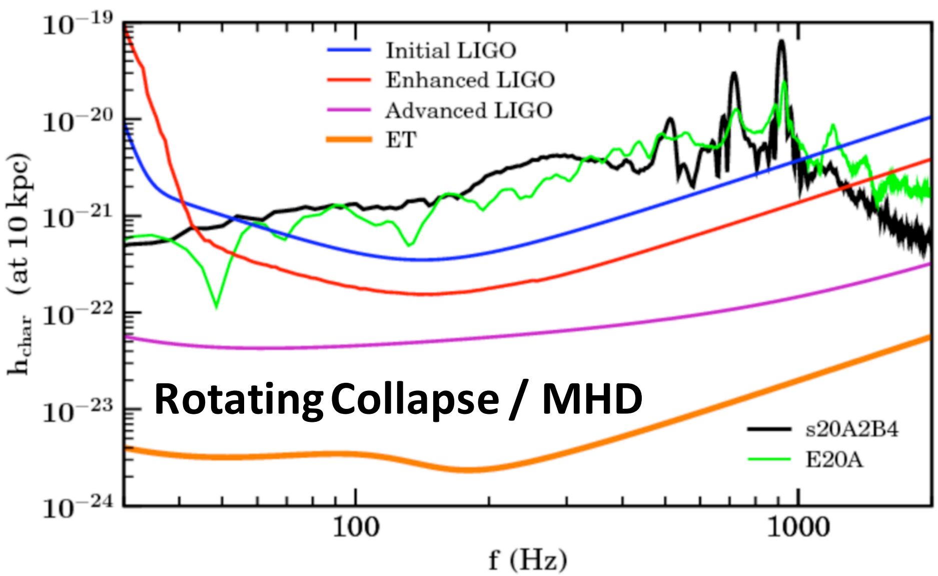
- Collapse of accreting, probably rotating White Dwarfs
  - Neutrino-driven or magneto-rotational explosion
- Explosion probably weak, sub-luminous
  - Might not be seen in optical
- Potential birth site of magnetars - highly (10^{15}- 10^{16} G) magnetized neutron stars

SNe Rate in ET

- ET sensitive to SNe up to 5 Mpc
  - Could observe one SN once in few years
- Coincident observation with neutrino detectors
  - Might be allow measurement of neutrino mass
- Plots show the spectra of SNe at 10 Kpc for two different models







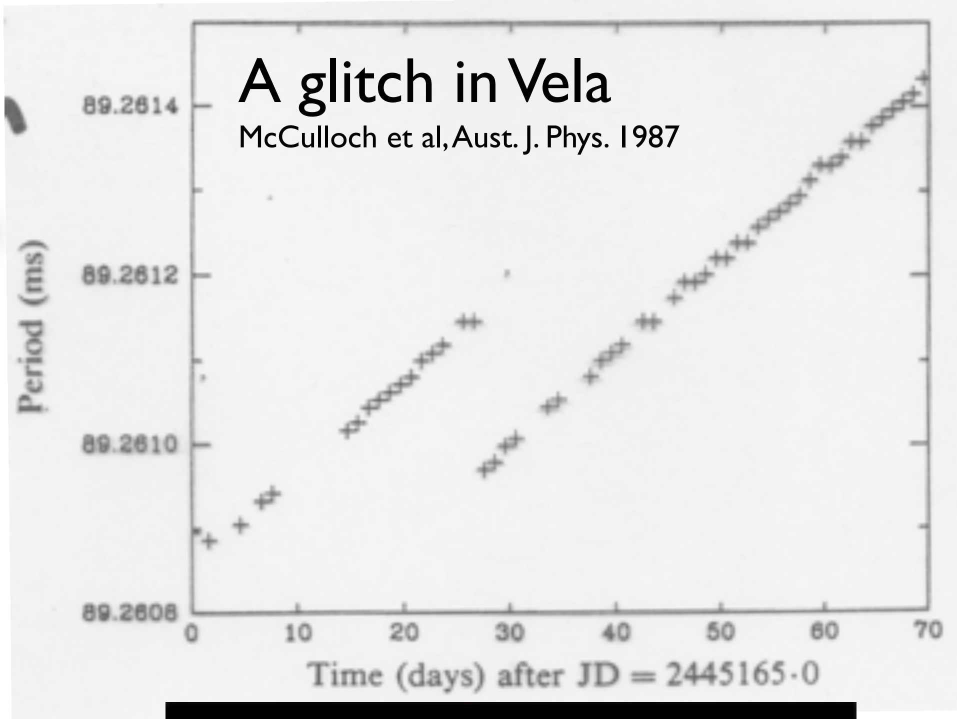
Pulsar Glitches

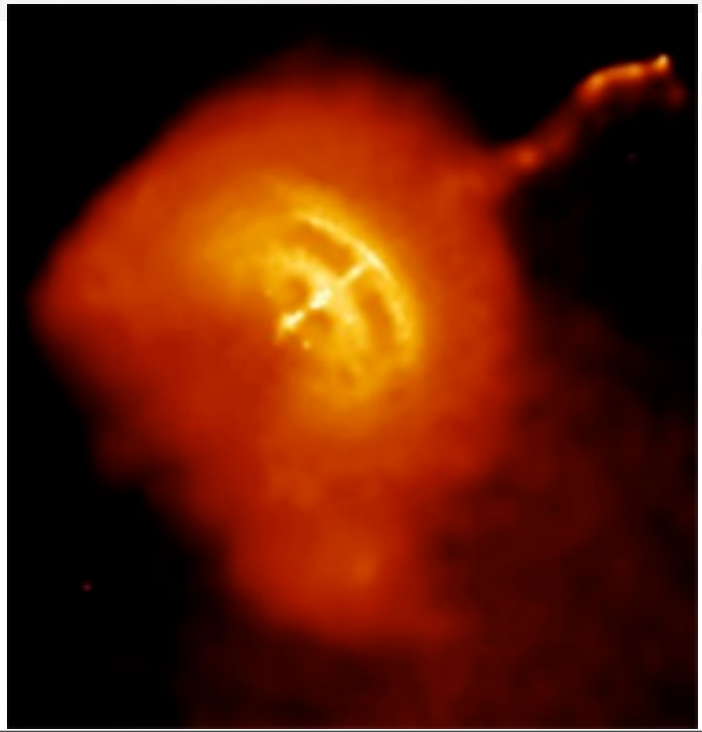
- Pulsars have fairly stable rotation rates:
  - However, observe the secular increase in pulse period
- Glitches are sudden dips in the rotation period
  - Vela shows glitches once every few years
- Could be the result of transfer of angular momentum from core to crust
  - At some critical lag rotation rate of superfluid core couples to the curst, imparting energy to the crust

$$\Delta J \sim I_* \Delta\Omega \qquad \Delta E = \Delta J \Omega_{\rm lag}$$

$$\Delta\Omega/\Omega \sim 10^{-6}$$

$$\Delta E \sim 10^{-13}\text{-}10^{-11} M_\odot c^2$$

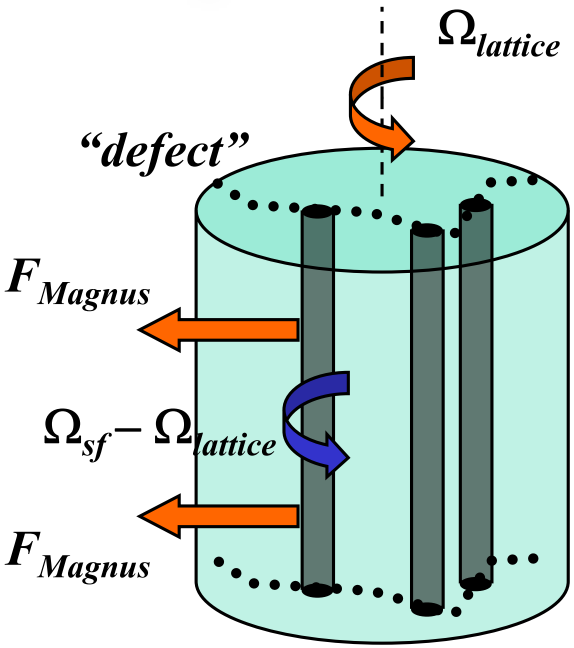


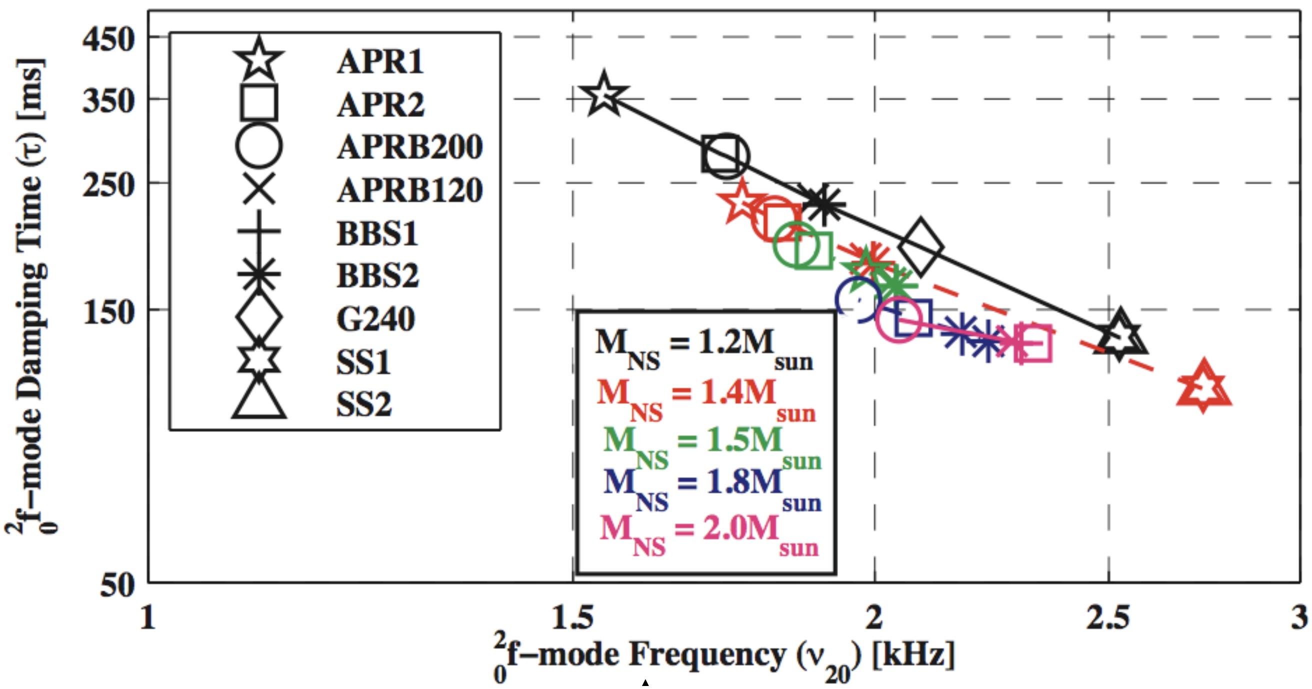


A composite Vela image

NS Normal Mode Oscillations

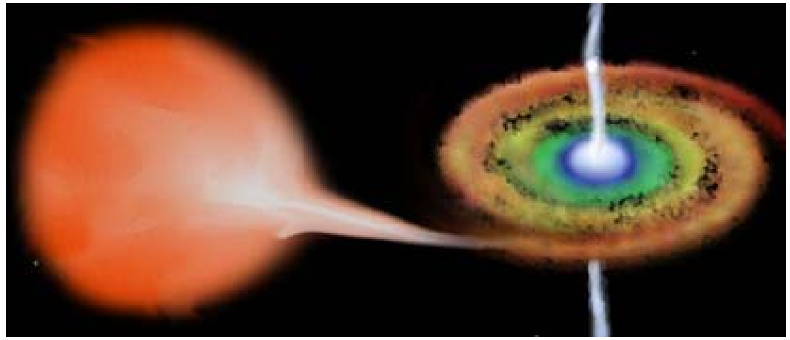
- Sudden jolt due to a glitch, and superfluid vortex unpinning, could cause oscillations of the core, emitting gravitational waves
  - These normal mode oscillations have characteristic frequencies and damping times that depend on the equation-of-state
- Detecting and measuring normal modes could reveal the equation-of-state of neutron stars and their internal structure





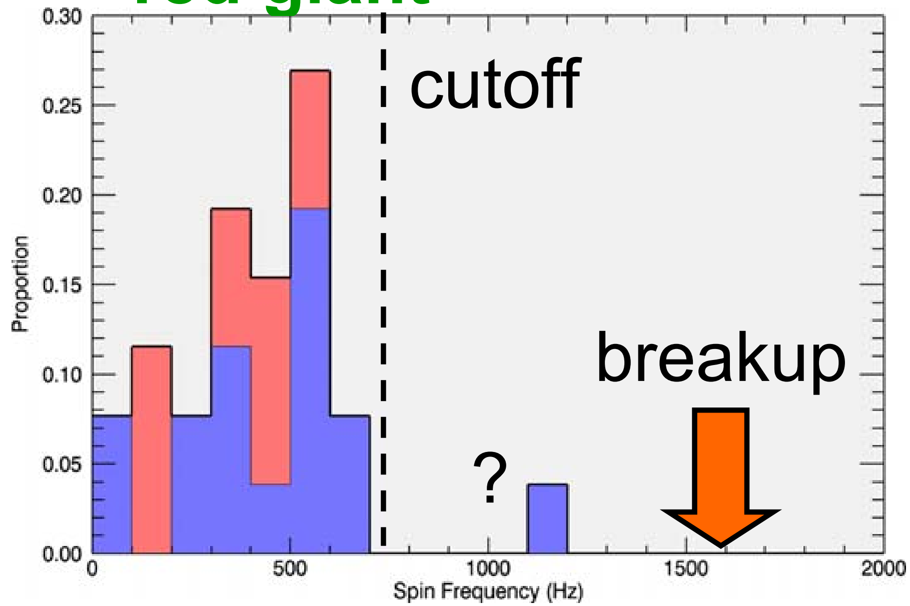
Accreting Neutron Stars

- Spin frequencies of accreting NS seems to be stalled below 700 Hz
  - Well below the break-up speed
- What could be the reason for this stall?
  - Balance of accretion torque with GW back reaction torque
- Could be explained if ellipticity is ~ 10^{-8}
  - Could be induced by mountains or relativistic instabilities, e.g. r-modes



$< 1M_{Sun}$ red giant

NS



pulses & burst oscillations

Summary of Science with ET

- Fundamental Physics
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Is Einstein theory the correct theory of gravity?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Astrophysics
  - What is the nature of gravitational collapse?
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - How did massive black holes at galactic nuclei form and evolve?
  - What is dark energy?
  - What phase transitions took place in the early Universe?
  - What were the physical conditions at the big bang?