# Ears Wide Open

## Observing the Universe with 3rd Generation Ground-Based Detectors

B.S. Sathyaprakash

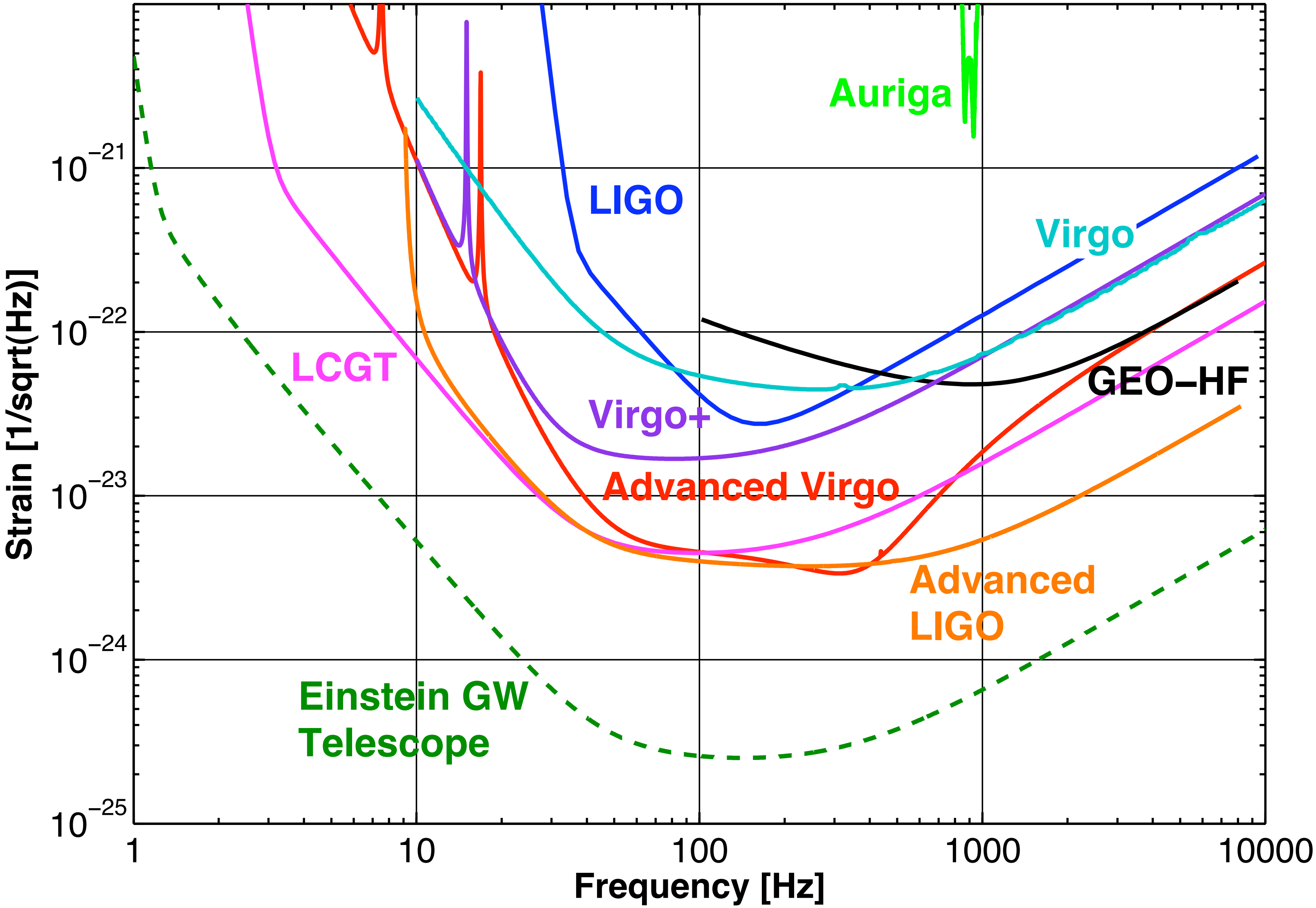
Credits: Einstein Telescope Science Team

# Science with GW

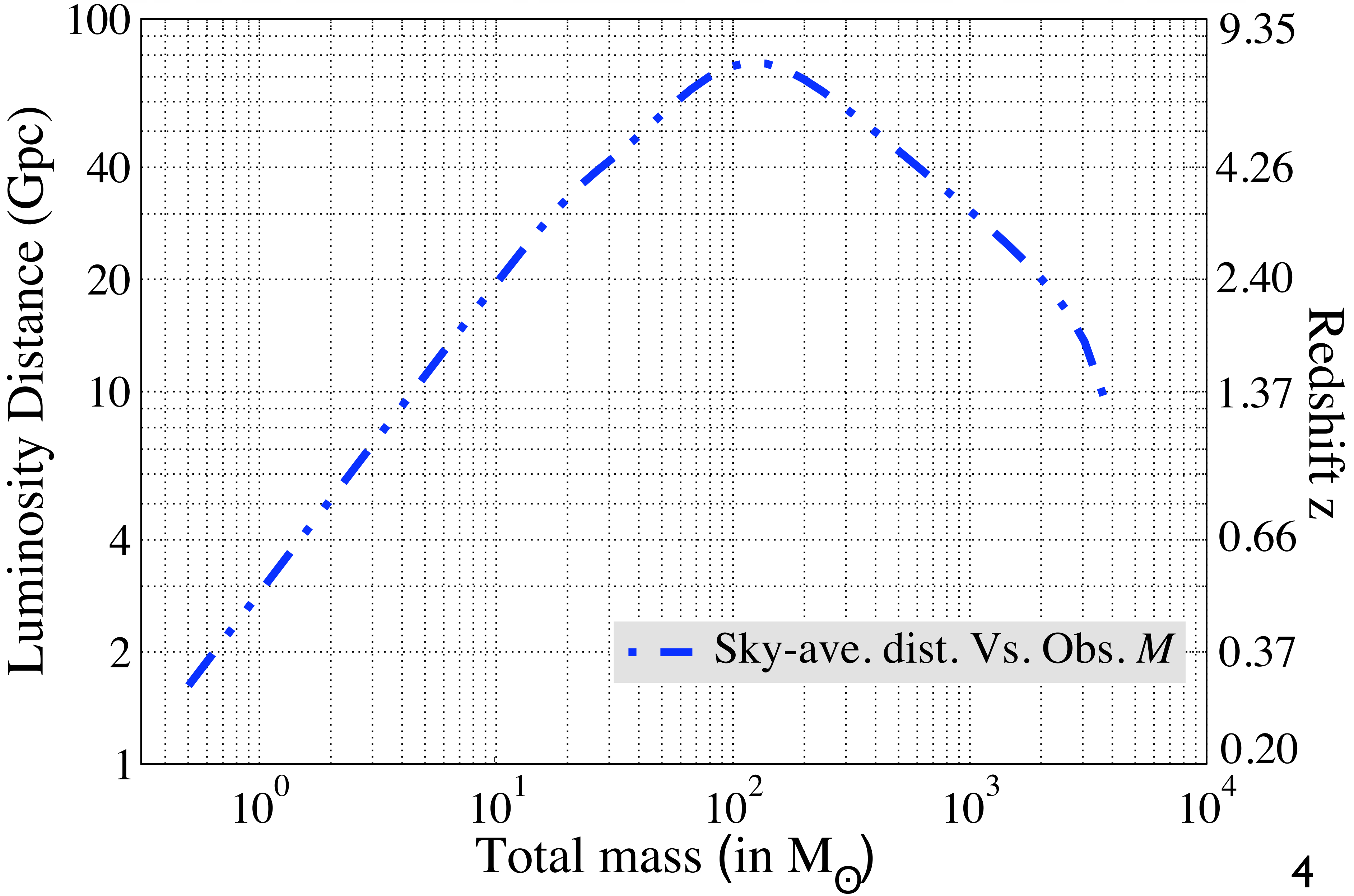
Talks on Thu by Hendry and Mours

- Was Einstein right?
  - 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?
- Unsolved problems in 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 phase transitions took place in the early Universe?
- Fundamental questions
  - What were the physical conditions at the big bang?
  - What is dark energy?
  - Are there really ten spatial dimensions?

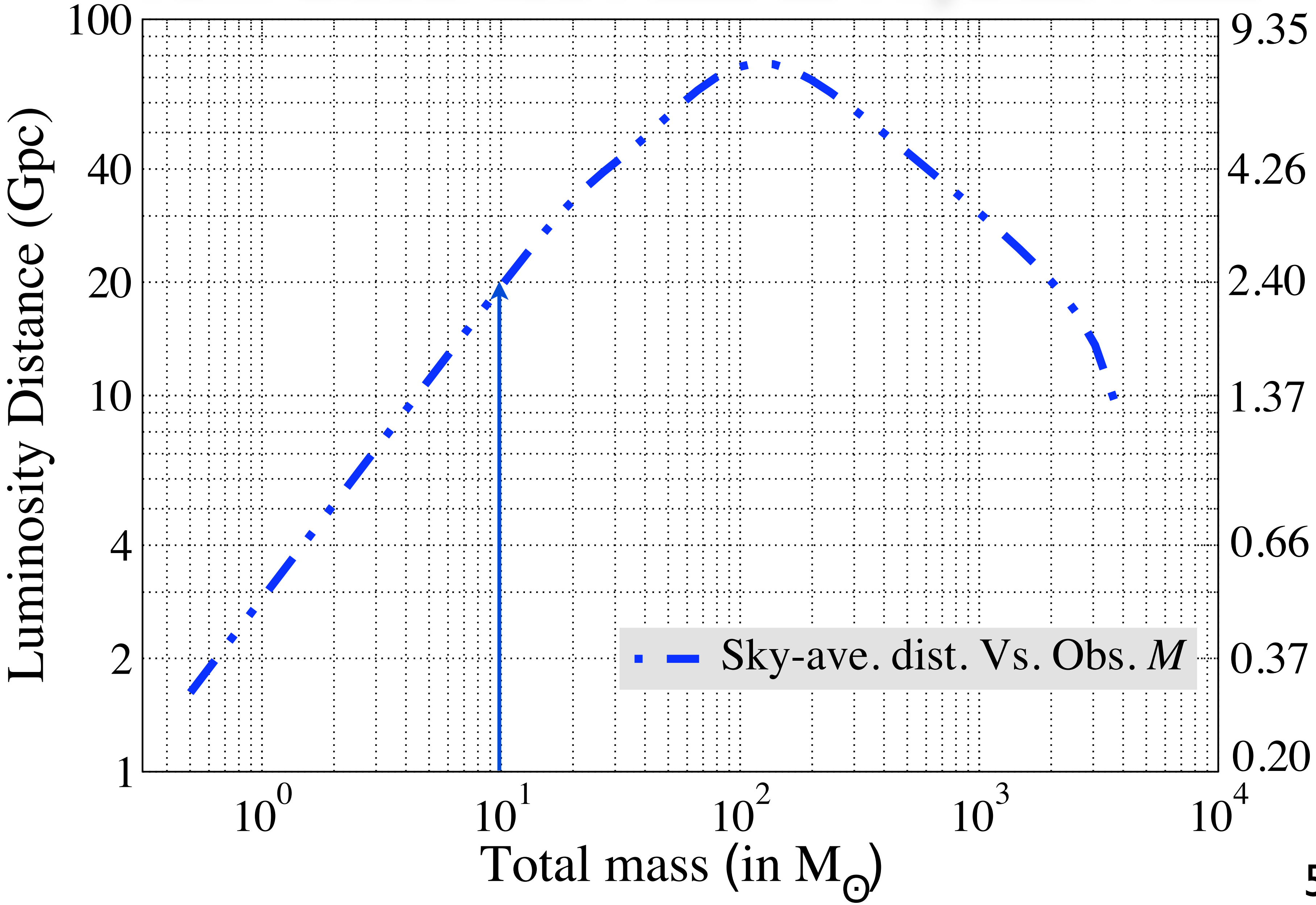
# Expected Future Sensitivities



# ET's Distance Reach Vs Observed Mass



# From Observed Mass to Physical Mass



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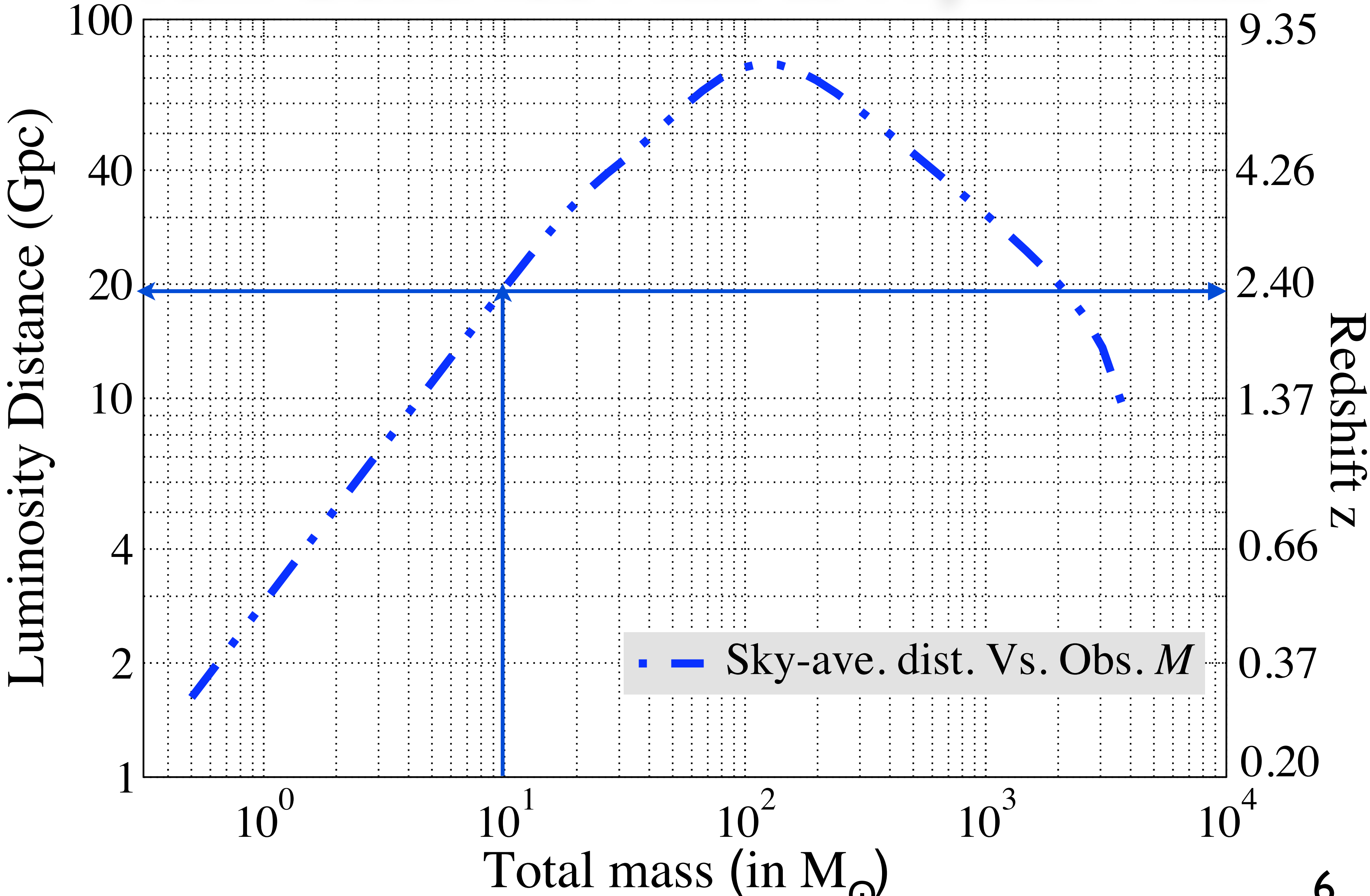
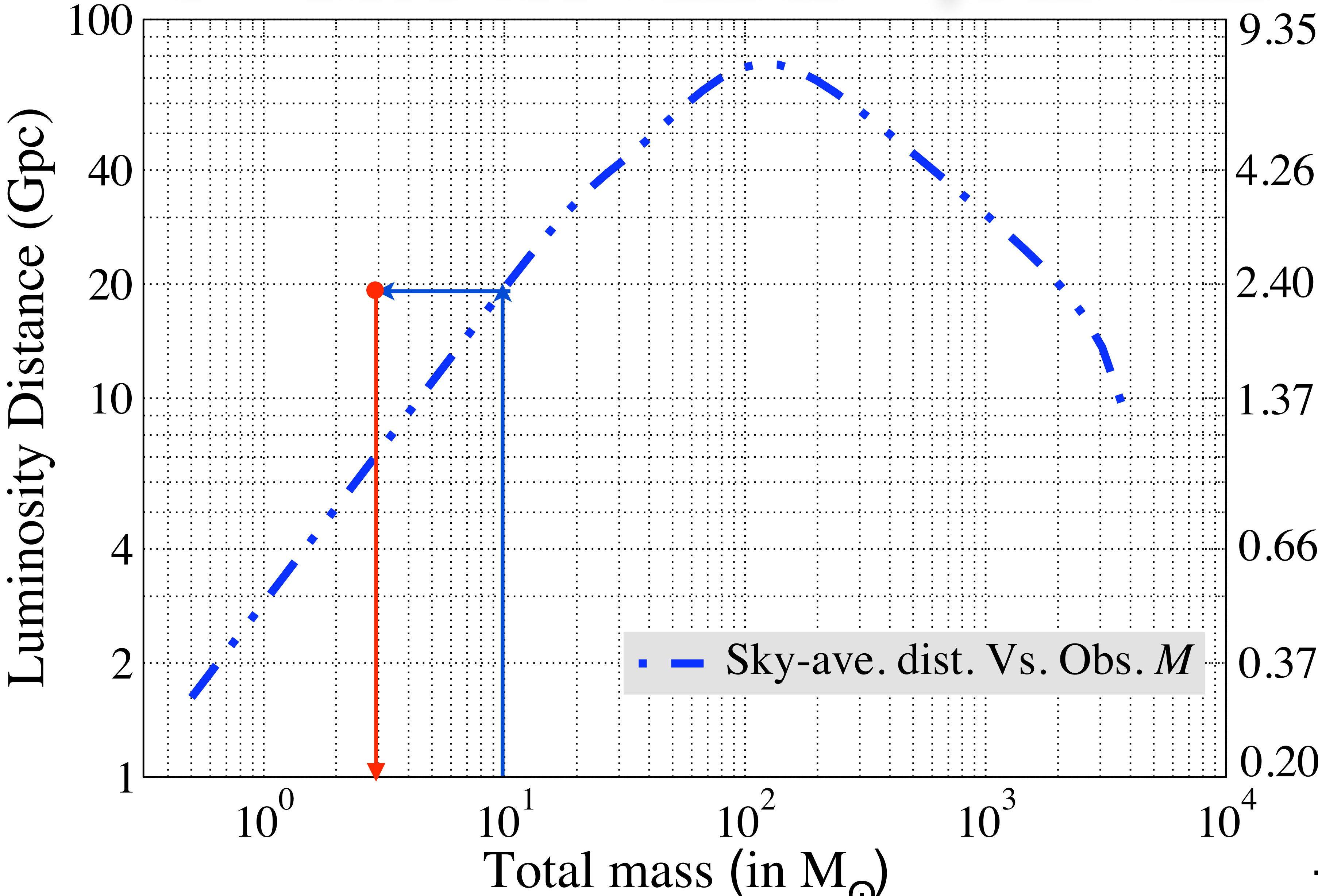
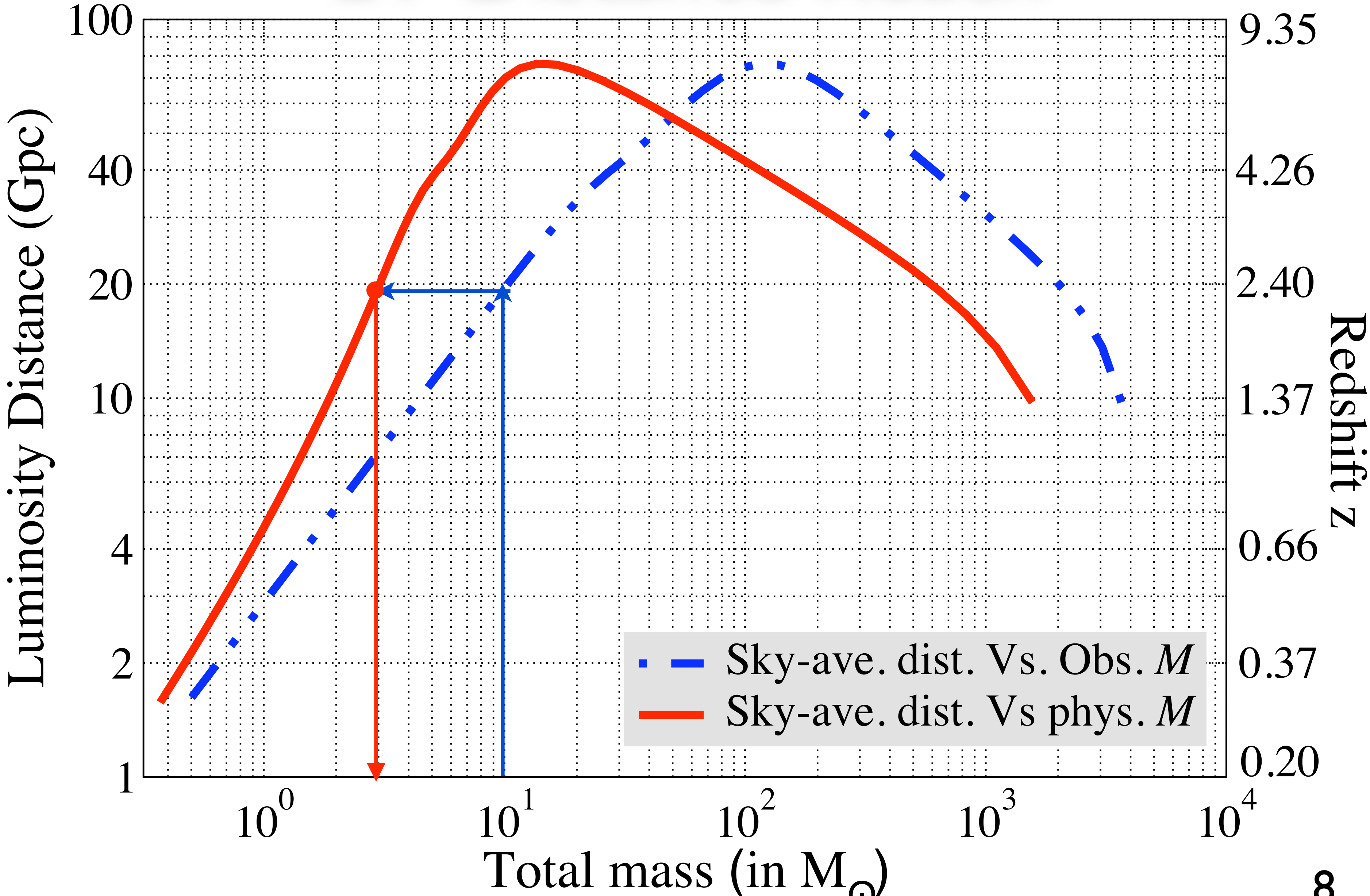


# From Observed Mass to Physical Mass



# ET Distance Reach



# Expected Annual Coalescence Rates

- Rates quoted are mean of the distribution; In a 95% confidence interval, rates uncertain by 3 orders of magnitude
- Rates are quoted for
  - Binary Neutron Stars (BNS)
  - Binary Black Boles (BBH)
  - Neutron Star-Black Hole binaries (NS-BH)

| | BNS | NS-BH | BBH |
|---|---|---|---|
| Initial LIGO (2002-06) | 0.02 | 0.006 | 0.009 |
| Advanced LIGO x12 sensitivity (2014+) | 40 | 10 | 20 |
| Einstein Telescope | Millions | 100,000 | Millions |

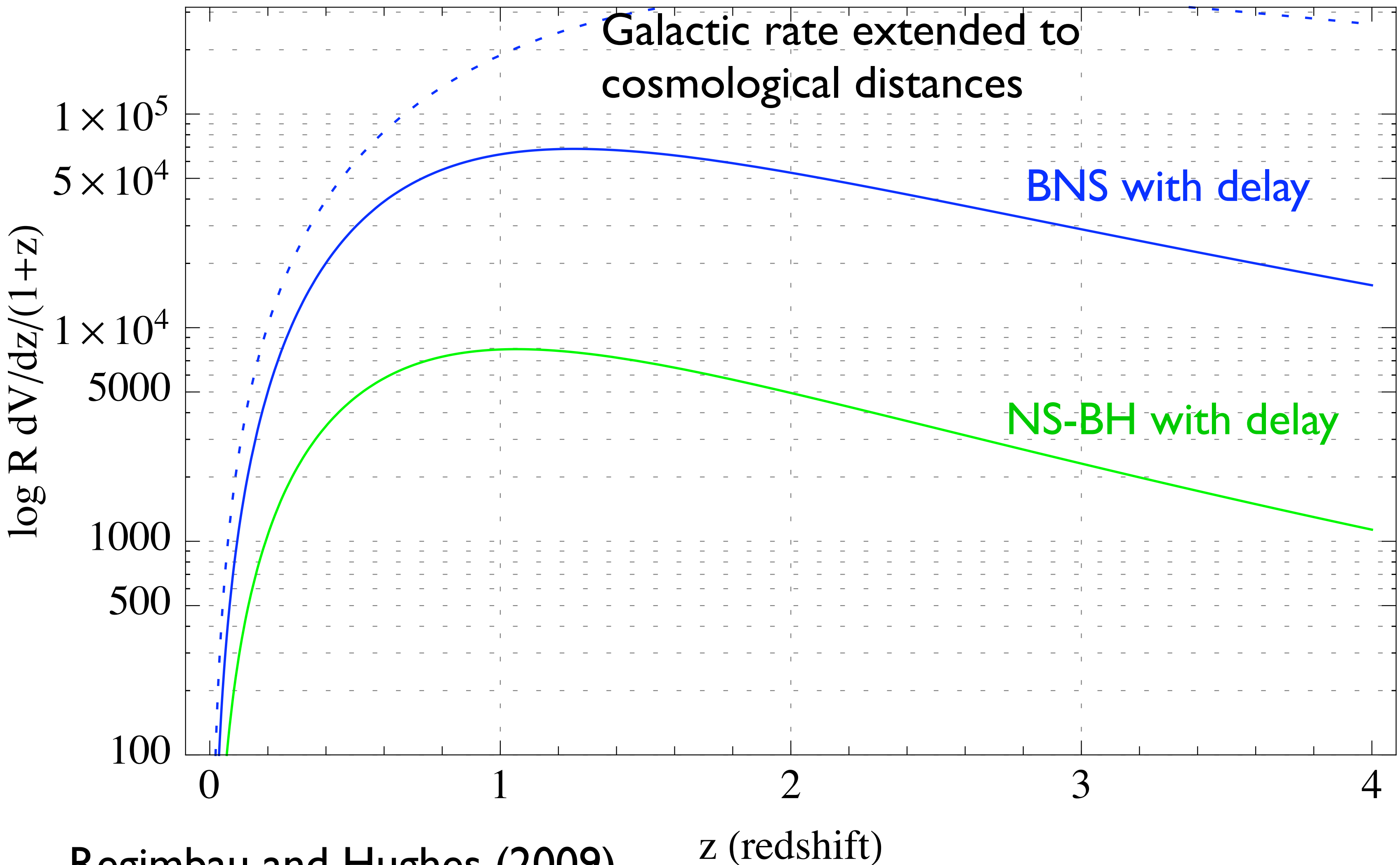
# Astrophysics

# Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs are believed to be triggered by merging NS-NS and NS-BH
- 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
  - 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

# Probing Star Formation Rate

$$dM/dt_{MW} \simeq \dot{\rho}_{MW}/n_{mw} = 3M_{\odot}\ \mathrm{yr}^{-1}$$

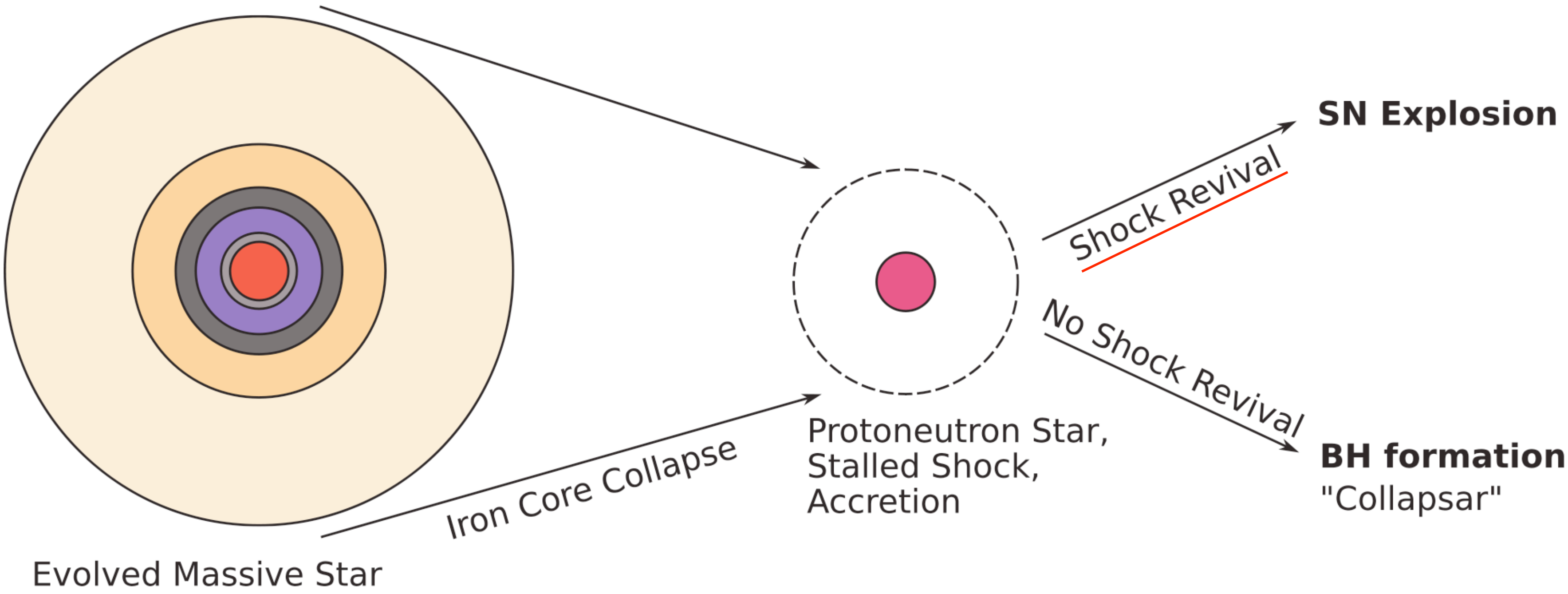



Regimbau and Hughes (2009)

# 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?

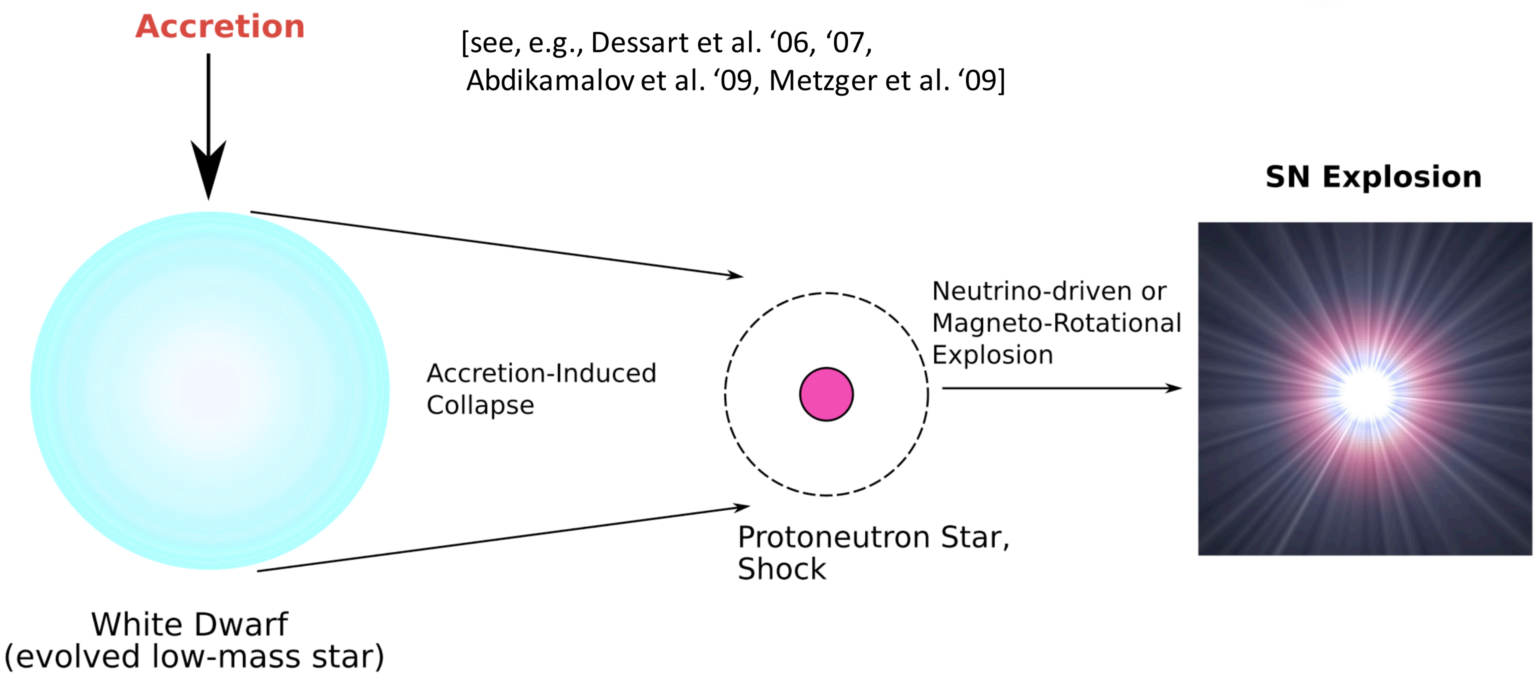
# Core Collapse SNe




- 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

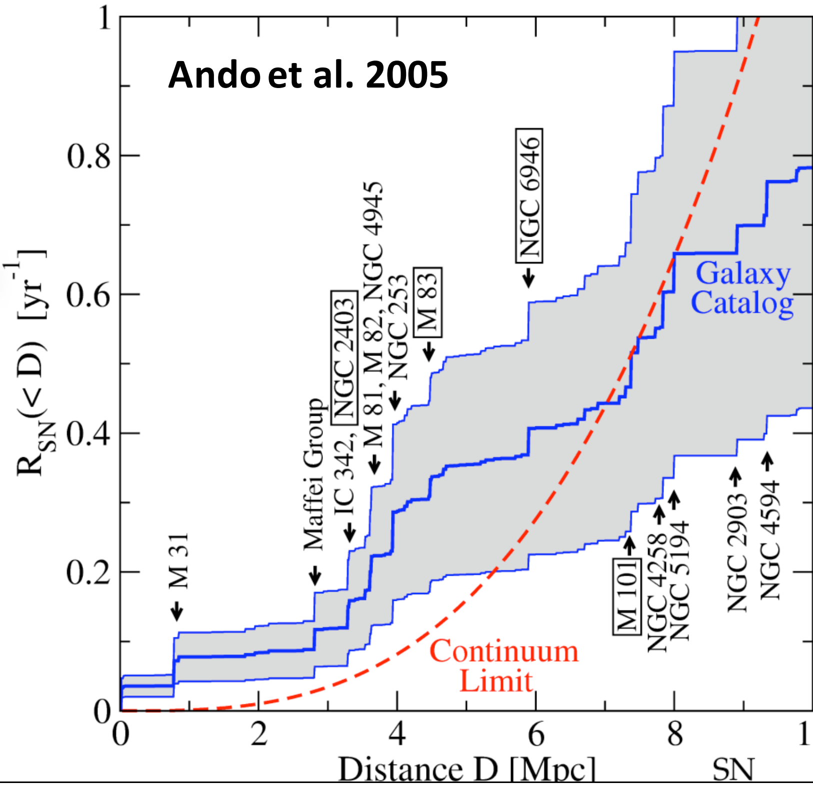
[see, e.g., Dessart et al. '06, '07, Abdikamalov et al. '09, Metzger et al. '09]

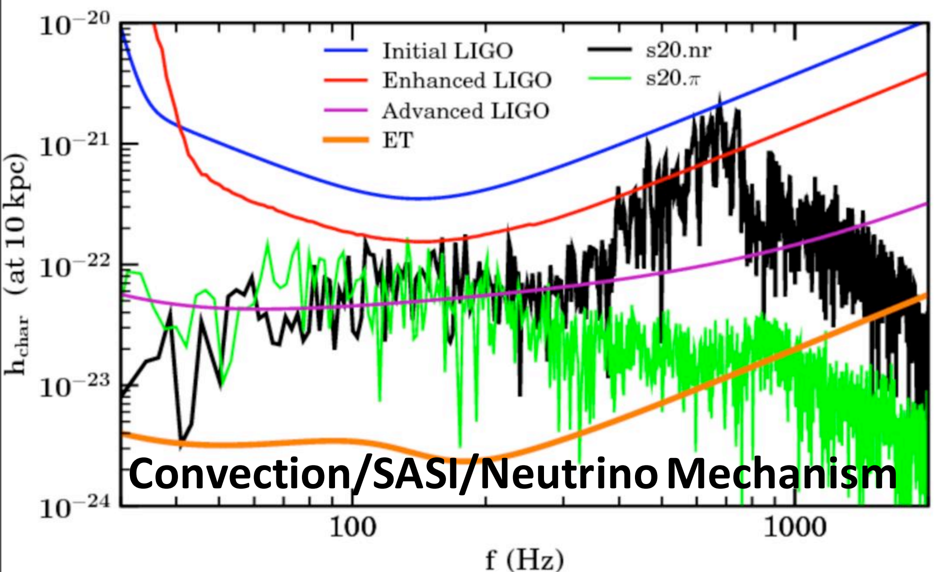


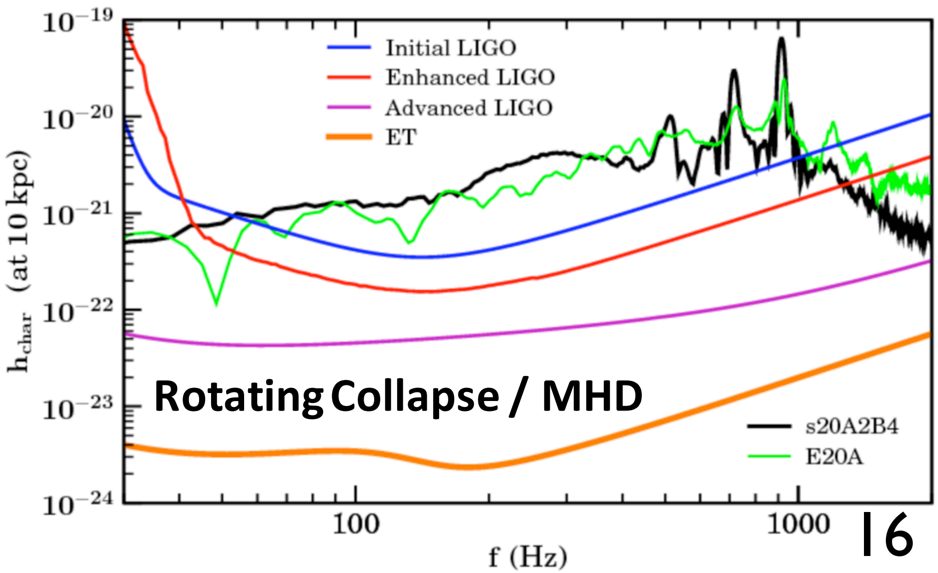

- Collapse of accreting, probably rotating White Dwarfs
  - Neutrino-driven or magneto-rotational explosion
- Explosion probably weak, sub-luminous
  - Might not be seen in optical
- Potential birth site of magnetars - highly ($10^{15}$- $10^{16}$ G) magnetized neutron stars

# 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 neutrino masses
- Plots show the spectra of SNe at 10 Kpc for two different models



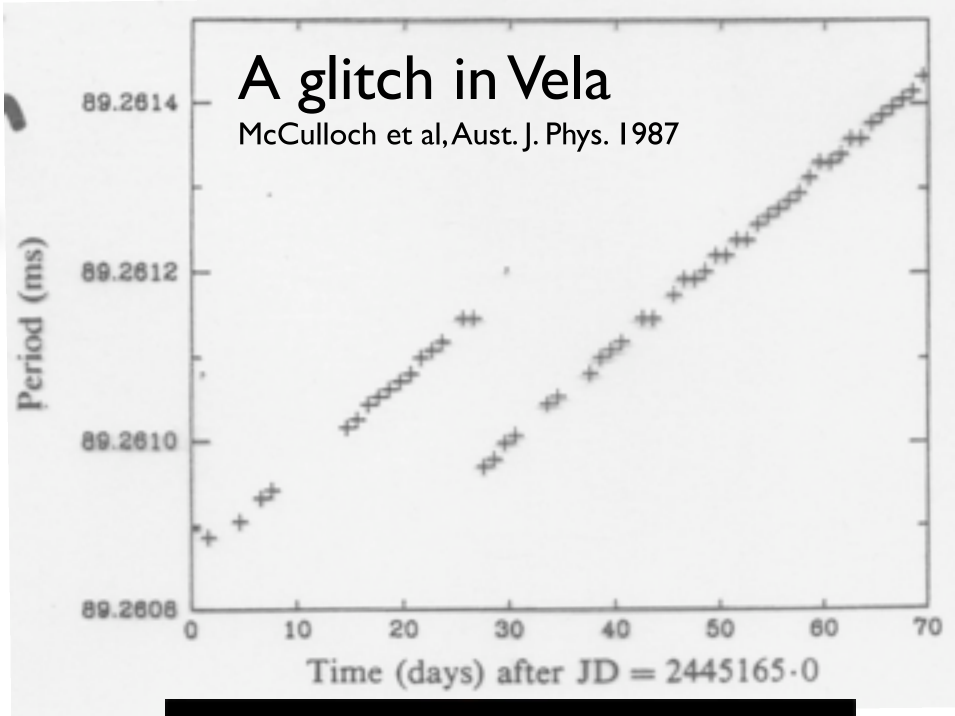
# Pulsar Glitches

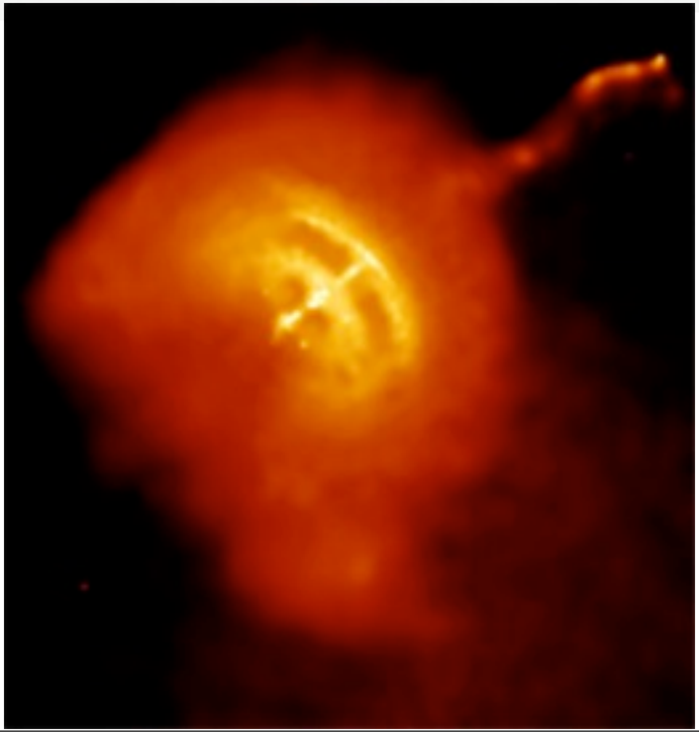
- Pulsars have fairly stable rotation rates:
  - However, observe the secular increase in pulse period
- Glitches are sudden dips in the rotation period
  - Vela shows glitches once every few years
- Could be the result of transfer of angular momentum from core to crust
  - At some critical lag rotation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

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

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

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

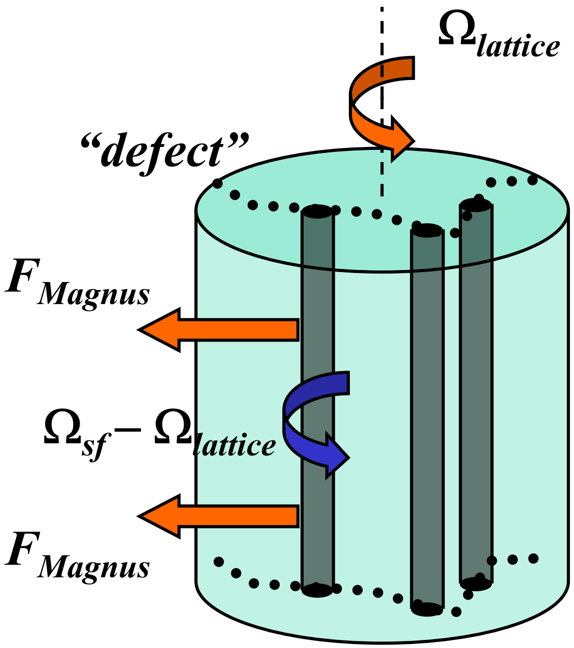


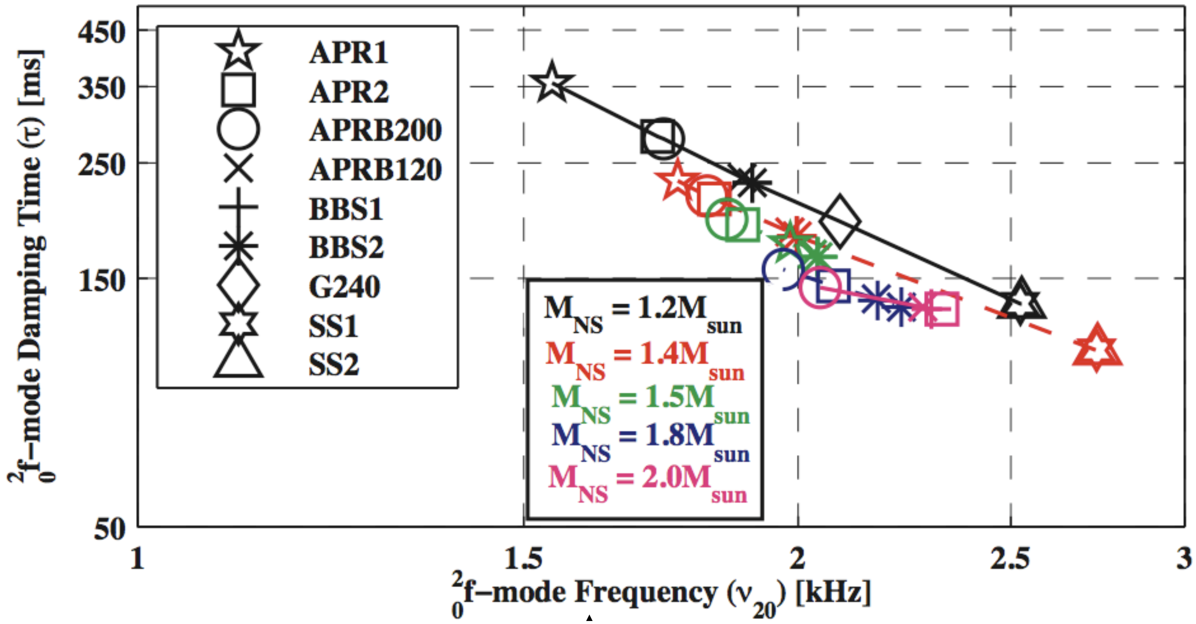



A composite Vela image

# NS Normal Mode Oscillations

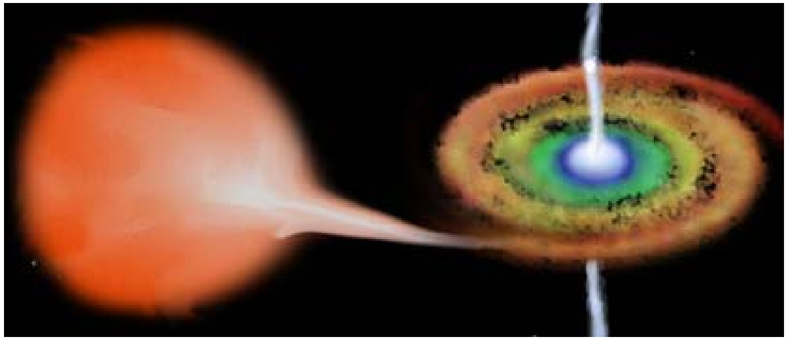
- Sudden jolt due to a glitch, and superfluid vortex unpinning, could cause oscillations of the core, emitting gravitational waves
  - These normal mode oscillations have characteristic frequencies and damping times that depend on the equation-of-state
- Detecting and measuring normal modes could reveal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



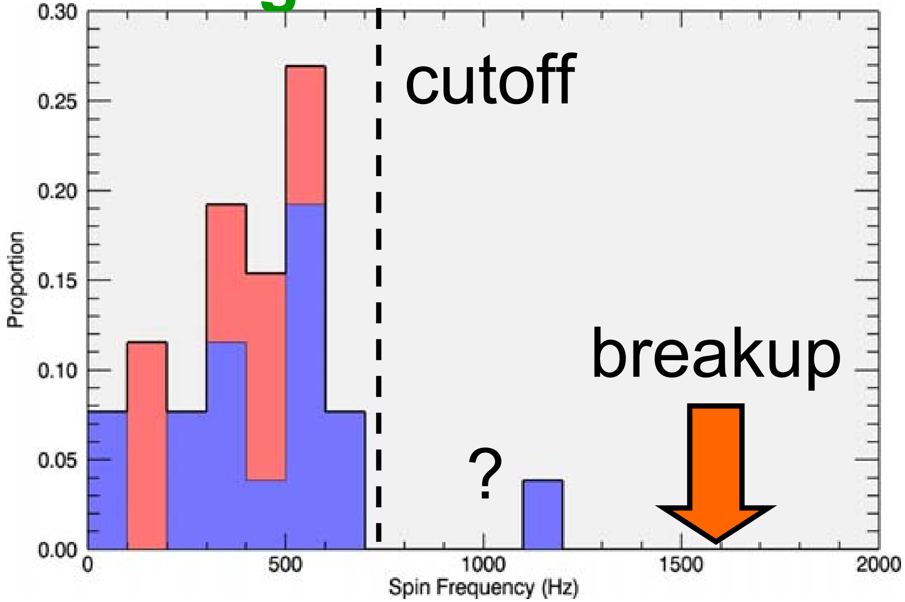
# Accreting Neutron Stars

- 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



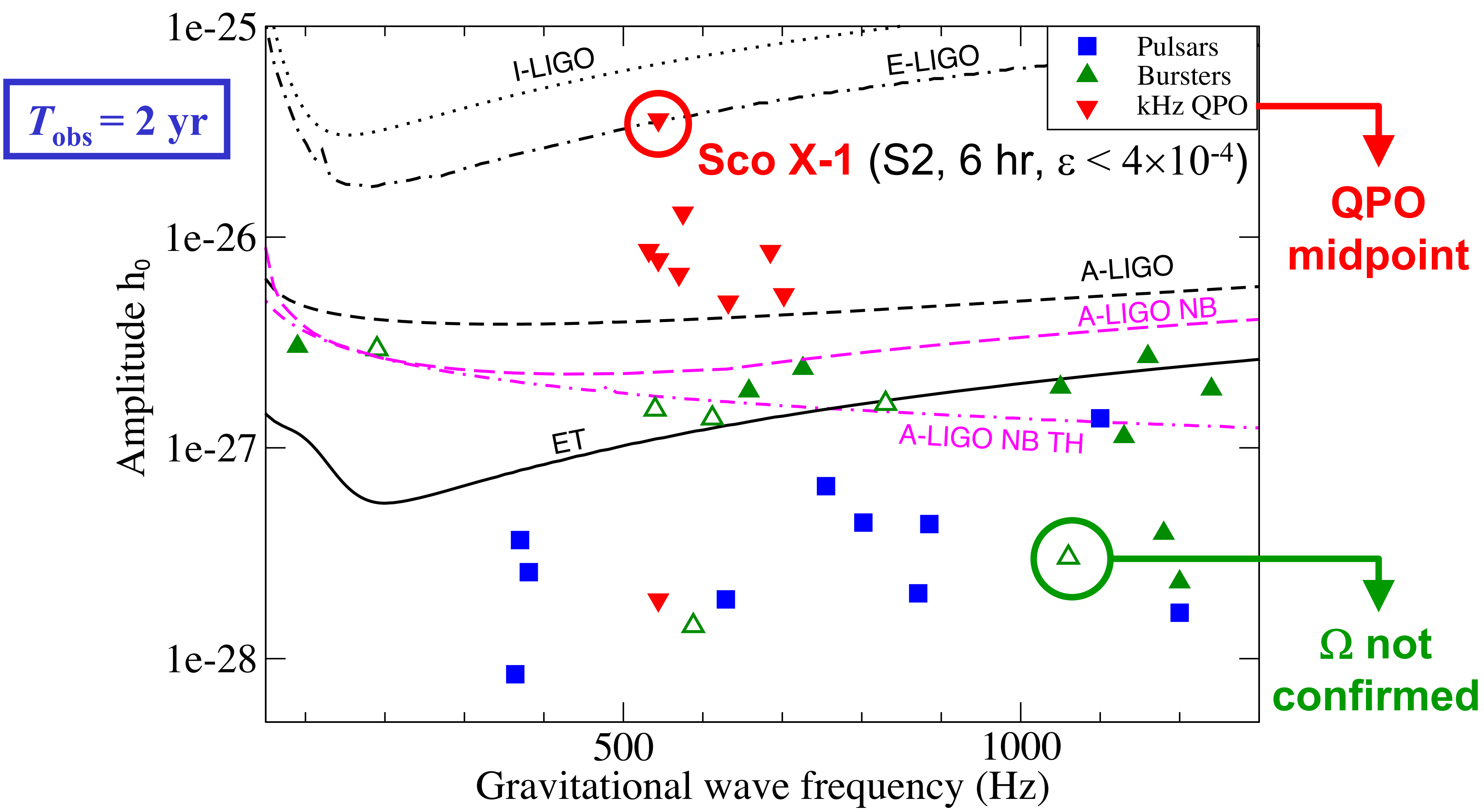
$< 1 M_{Sun}$ **red giant**

**NS**



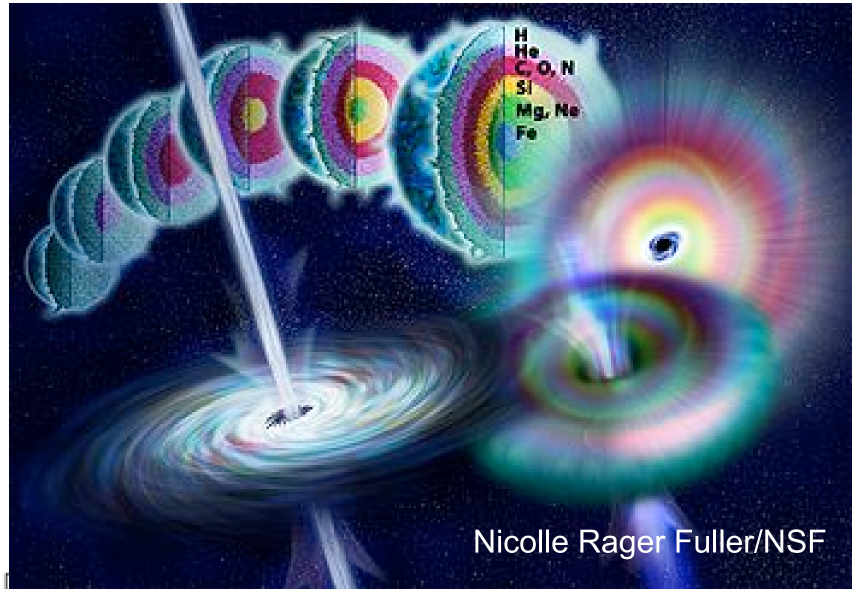

**pulses** & **burst oscillations**

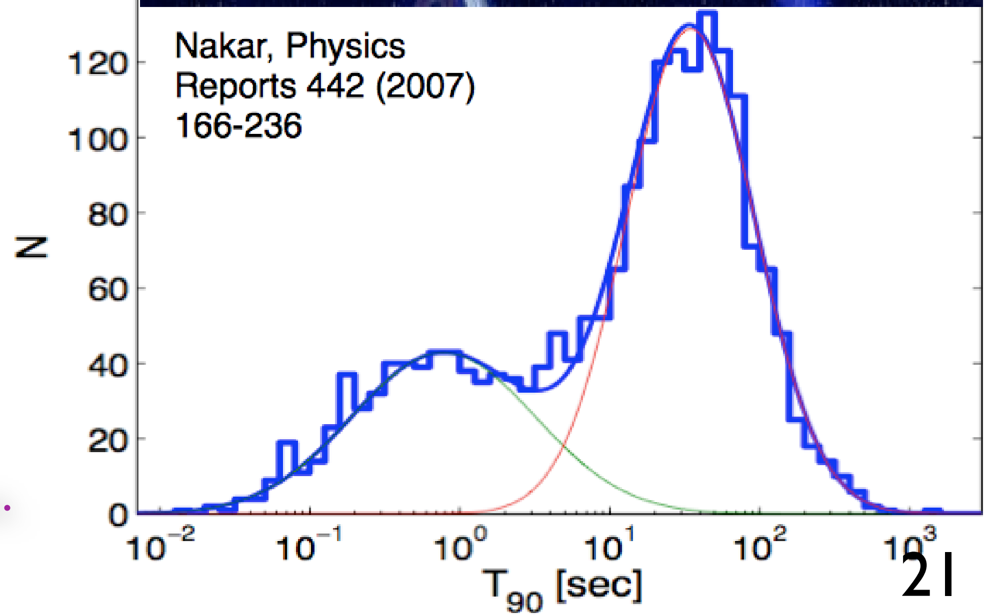
# Sensitivity to Accreting NS



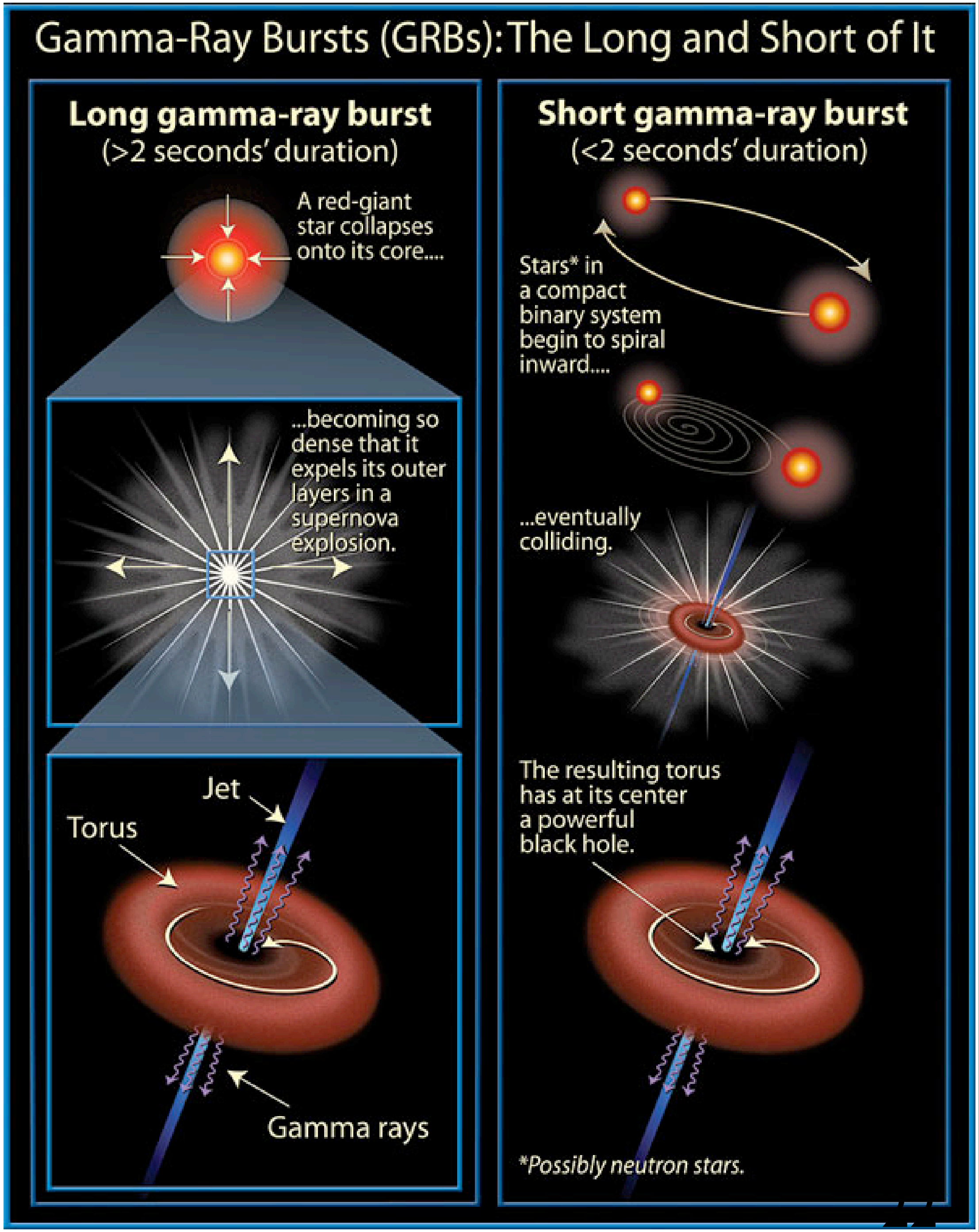
# GRB Progenitors

- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations
  - Short GRBs
    - Duration: $T_{90} < 2$ s
    - Mean redshift of 0.5
  - Long GRBs
    - Duration $T_{90} > 2$ s
    - Higher z, track Star Form. Rate.



- 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
- GRBs in ET
  - Short-hard GRBs might be detectable at redshift $z=2$
  - An ET network could measure the binary orientation, masses, spins, and help build better models
  - Should be possible to shed light on GRB progenitors

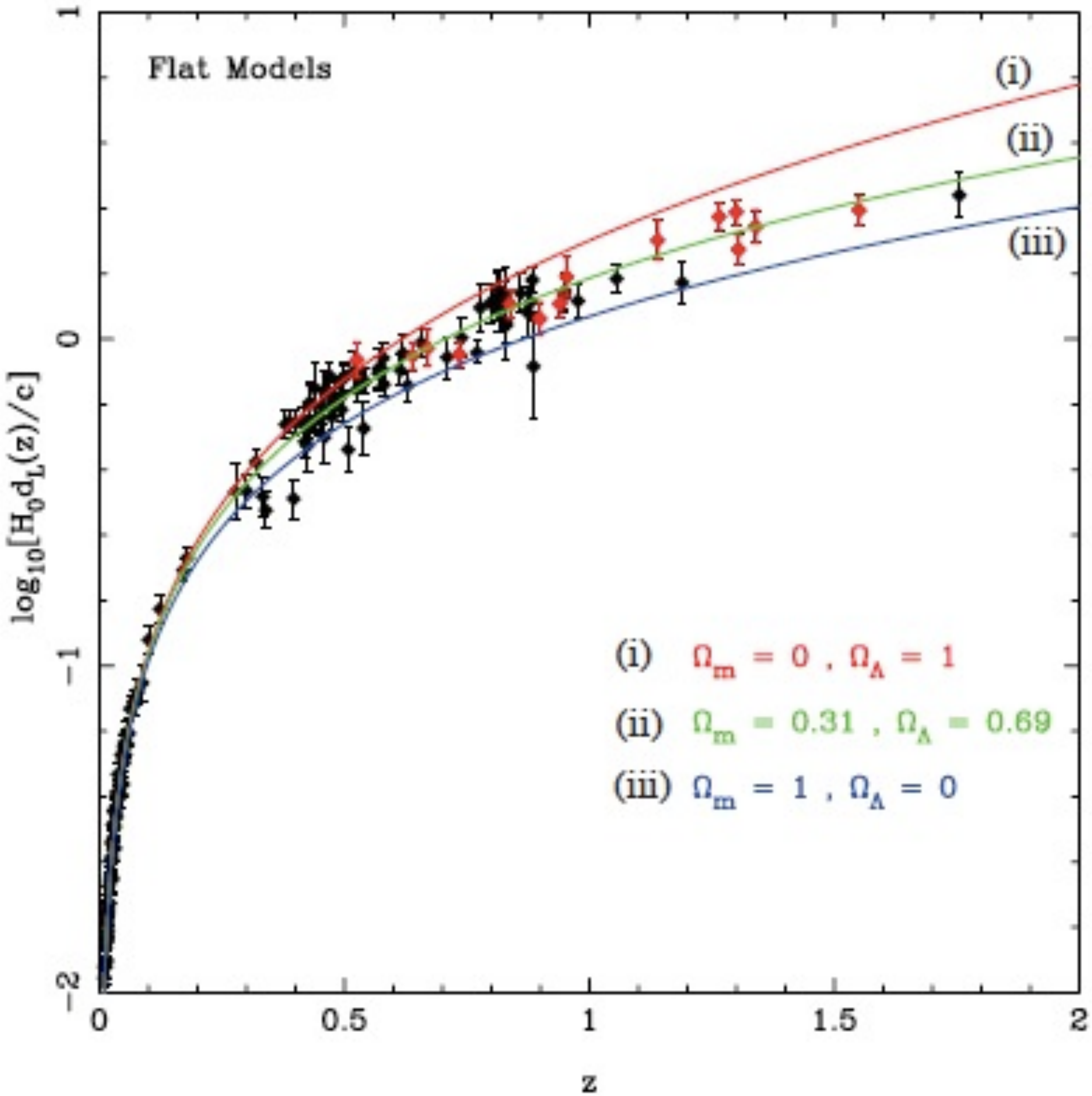


# Cosmology

# Cosmology

- Cosmography
  - 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 BH
  - Hierarchical growth of central engines of BH
- Dipole anisotropy in the Hubble parameter
  - The Hubble parameter will be "slightly" different in different directions due to the local flow of the Milkyway
- 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

# Luminosity Distance Vs Redshift



# Cosmological parameters

- Luminosity distance Vs. red shift depends on a number of cosmological parameters $H_0$, $\Omega_M$, $\Omega_b$, $\Omega_\Lambda$, $w$, etc.

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

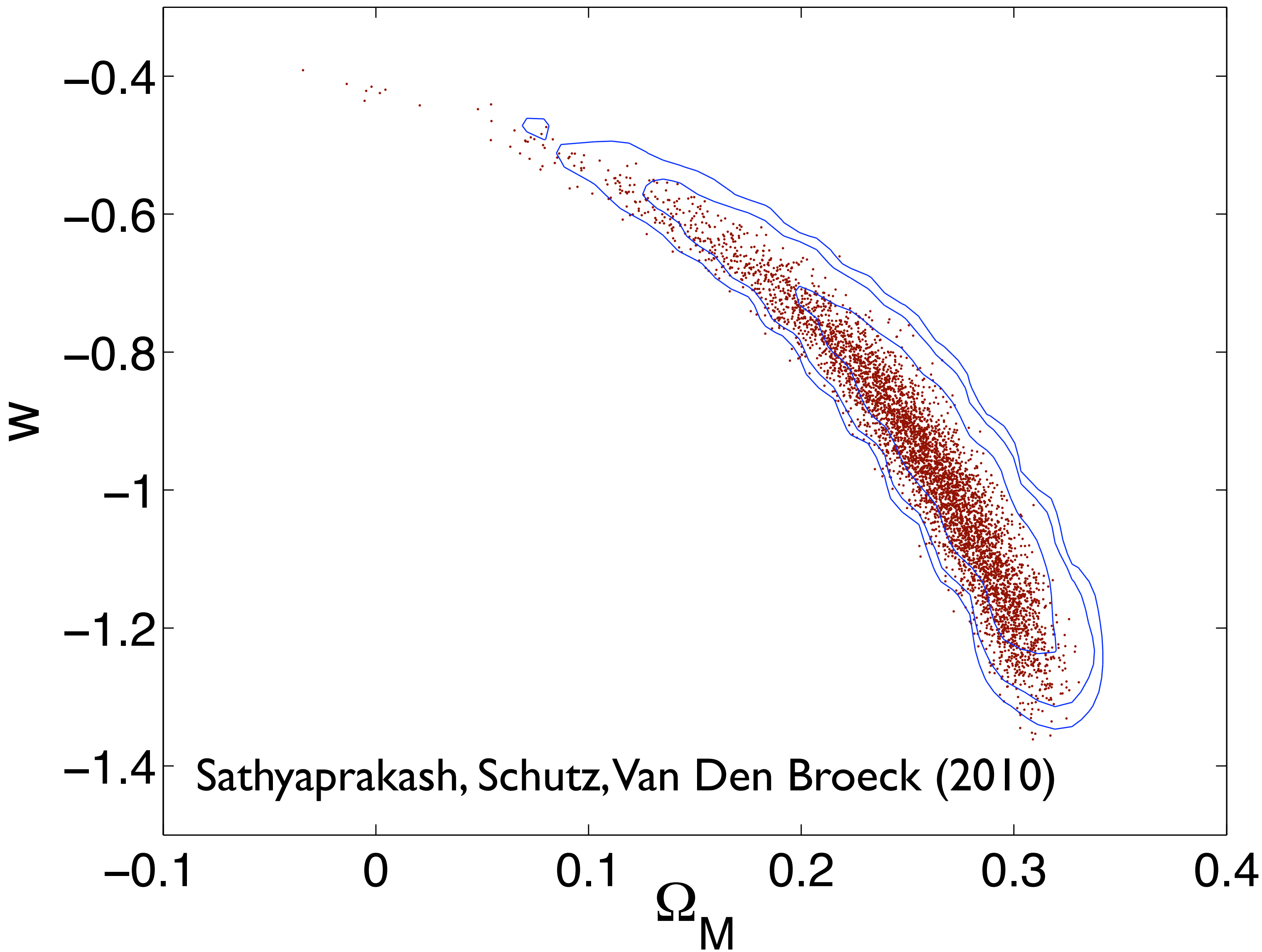
- Einstein Telescope will detect 1000's of compact binary mergers for which the source can be identified (e.g. GRB) and red-shift measured.
- A fit to such observations can determine the cosmological parameters to better than a few percent.

Schutz 86

# Gravity's Standard Sirens

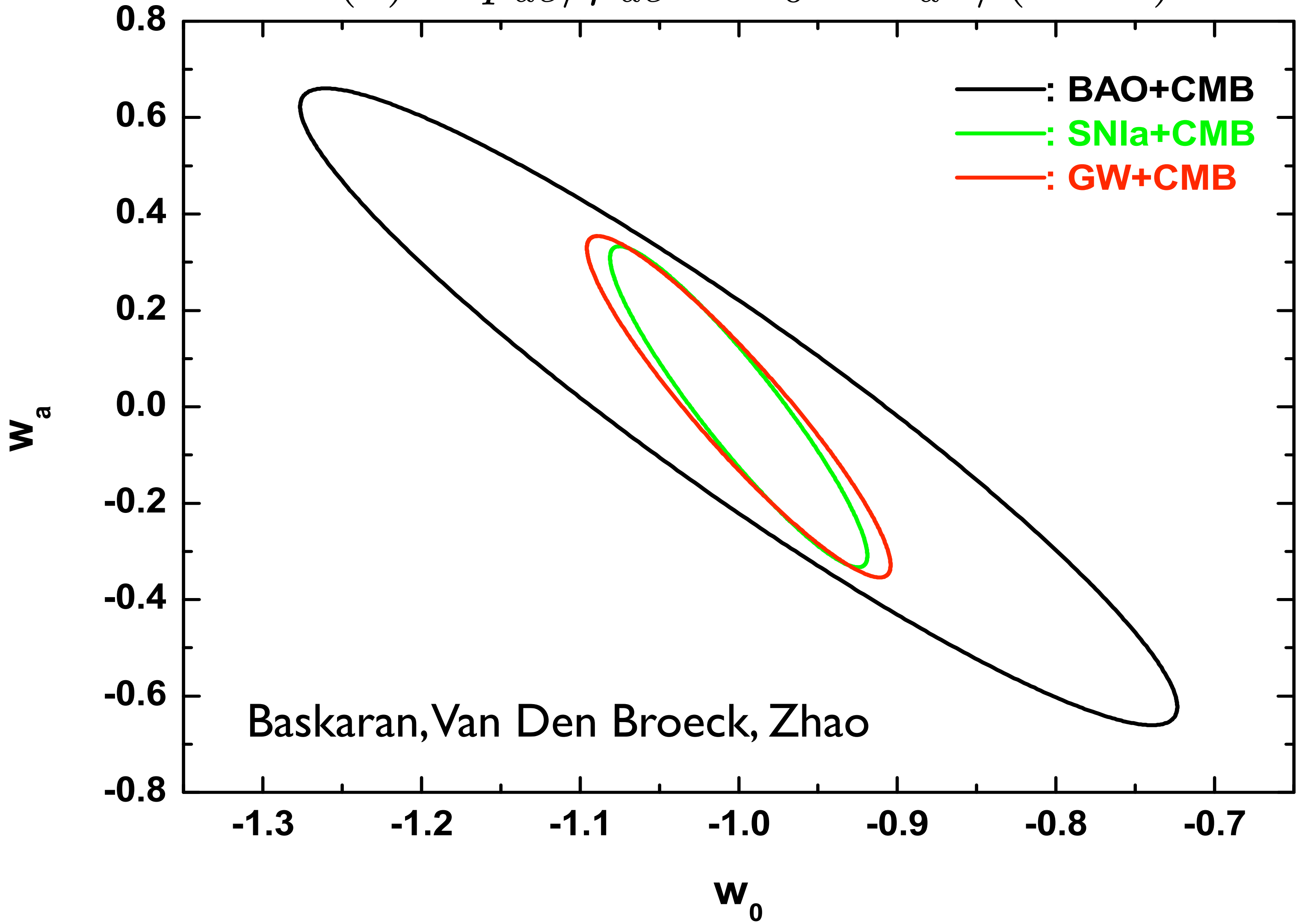
- To measure the luminosity distance to a source we need its apparent and absolute luminosities
- Gravitational wave observations of compact binary inspirals can measure both
  - Apparent luminosity this is GW strain in our detector $h \propto \frac{\mathcal{M}^{5/6}}{D_{\mathrm{L}}}$
  - Absolute luminosity this rate at which frequency changes
- Therefore, binary black hole inspirals are self-calibrating standard sirens
- However, GW observations alone cannot determine the red-shift to a source
- Joint gravitational-wave and optical observations can facilitate a new cosmological tool

# Measuring Dark Energy and Dark Matter

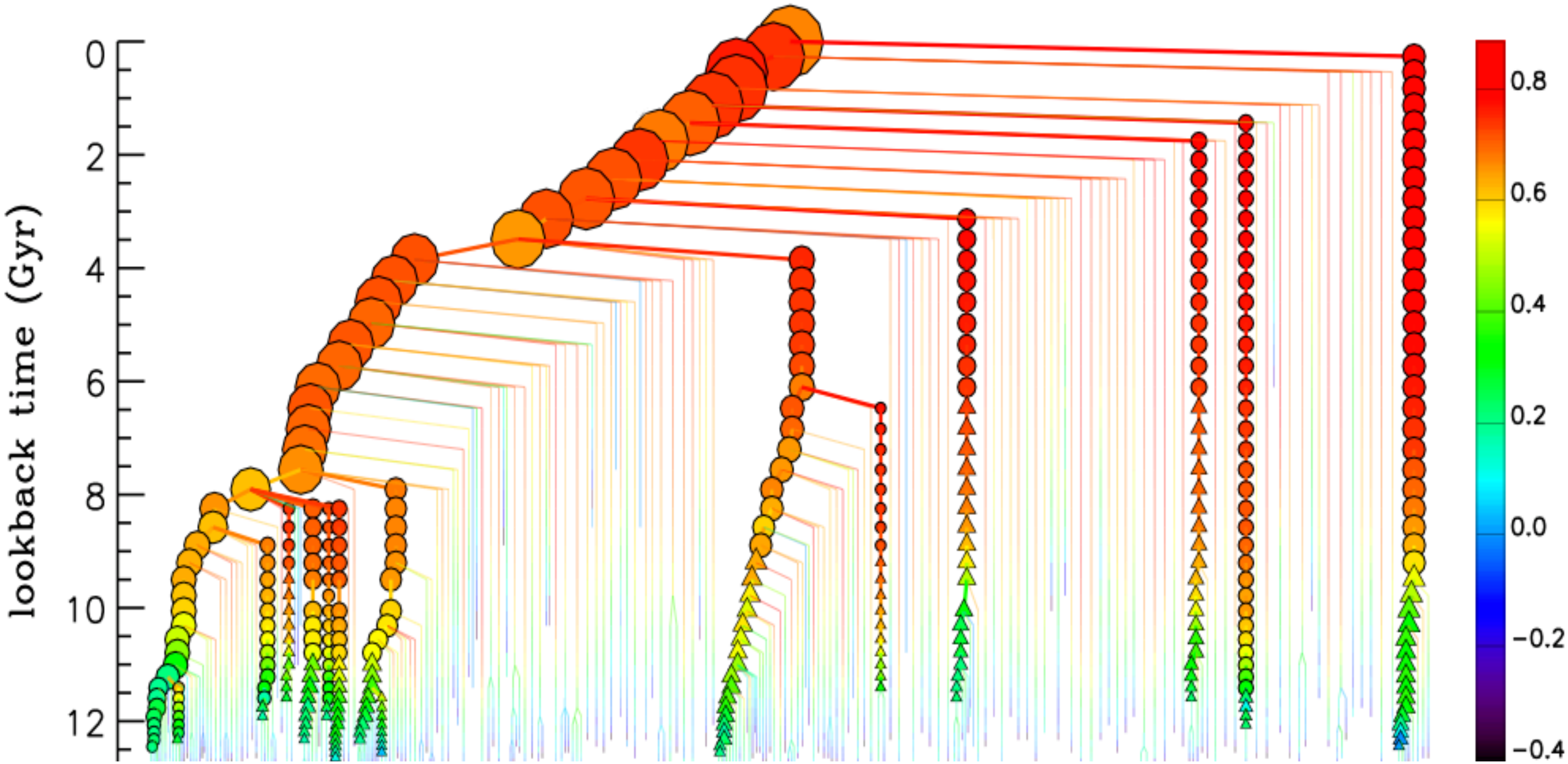


# Measuring w and its variation

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



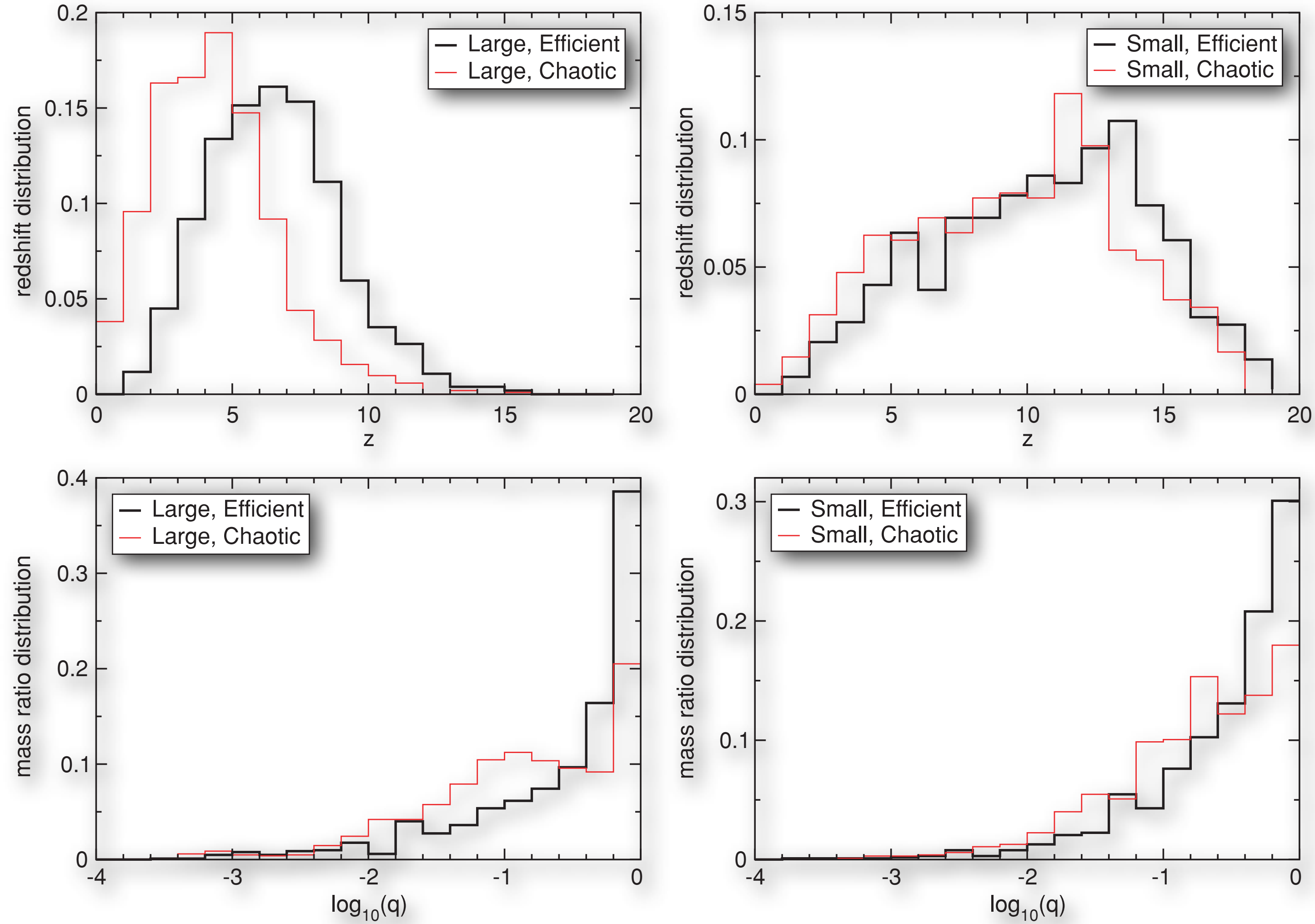
# Hierarchical Growth of Black Holes in Galactic Nuclei



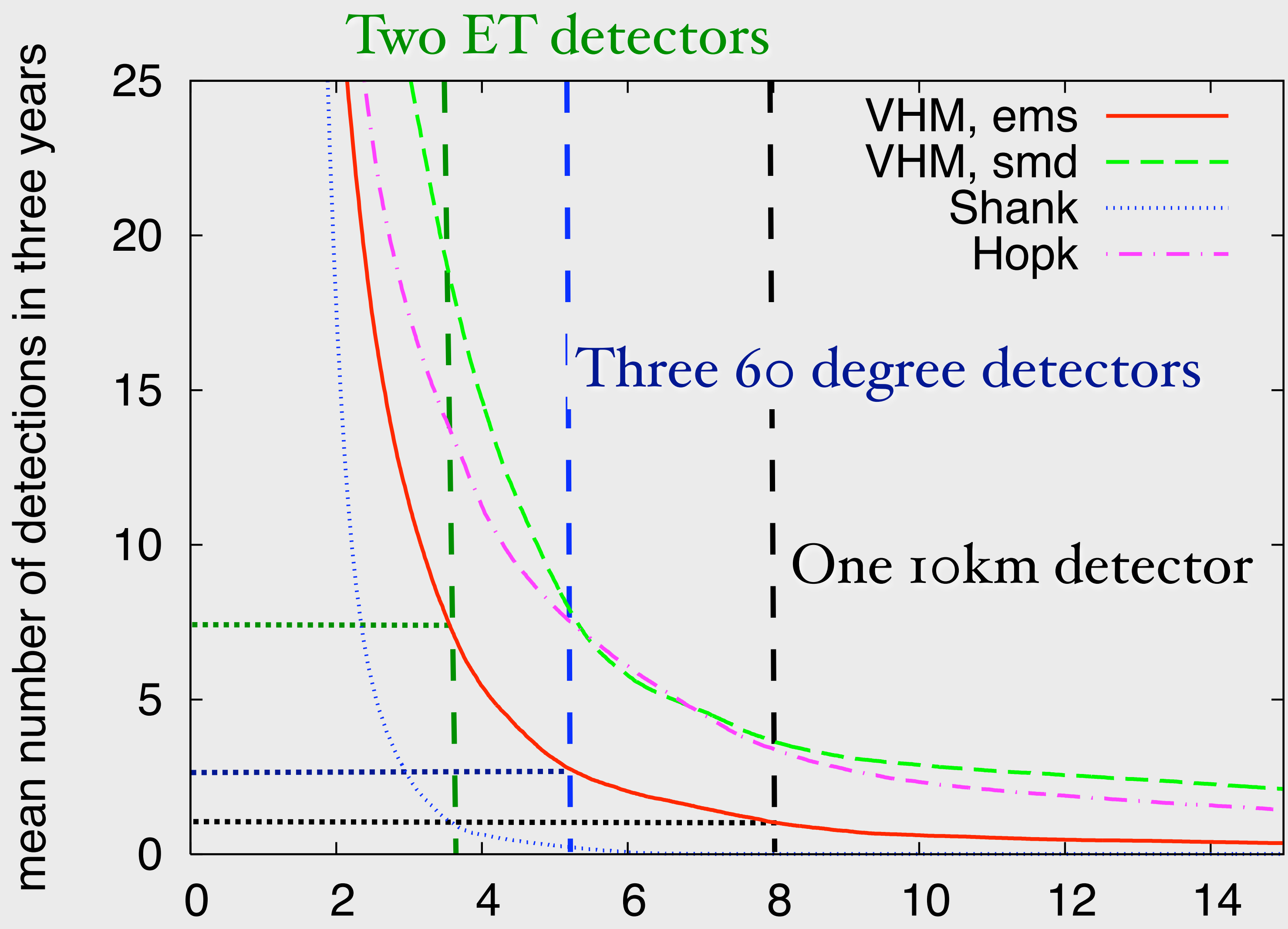

- Initially small black holes may grow by hierarchical merger
  - ET could observe seed black holes if they are of order 1000 solar mass

# Probing Demography of Black Hole Seeds

Class. Quantum Grav. **26** (2009) 094027 K G Arun *et al*



# IMBH Event Rates in ET



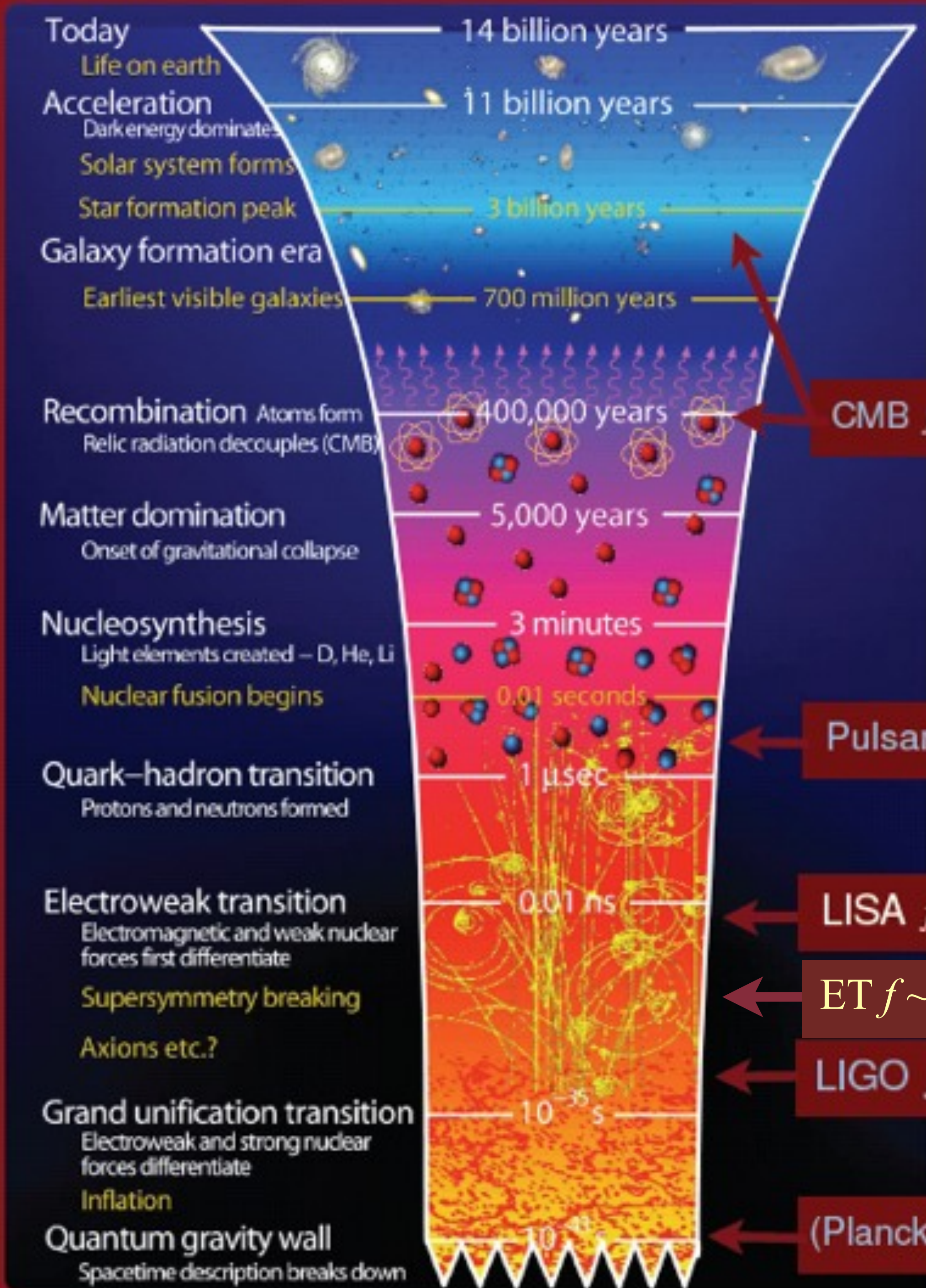

Gair et al 2009

# Stochastic Backgrounds

- Primordial background
  - Quantum fluctuations produce a background GW that is amplified by the background gravitational field
- Phase transitions in the Early Universe
  - Cosmic strings - kinks can form and "break" producing a burst of gravitational waves
- Astrophysical background
  - A population of Galactic white-dwarf binaries produces a background above instrumental noise in LISA

Slide from Shellard

# A brief history of the Universe




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

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

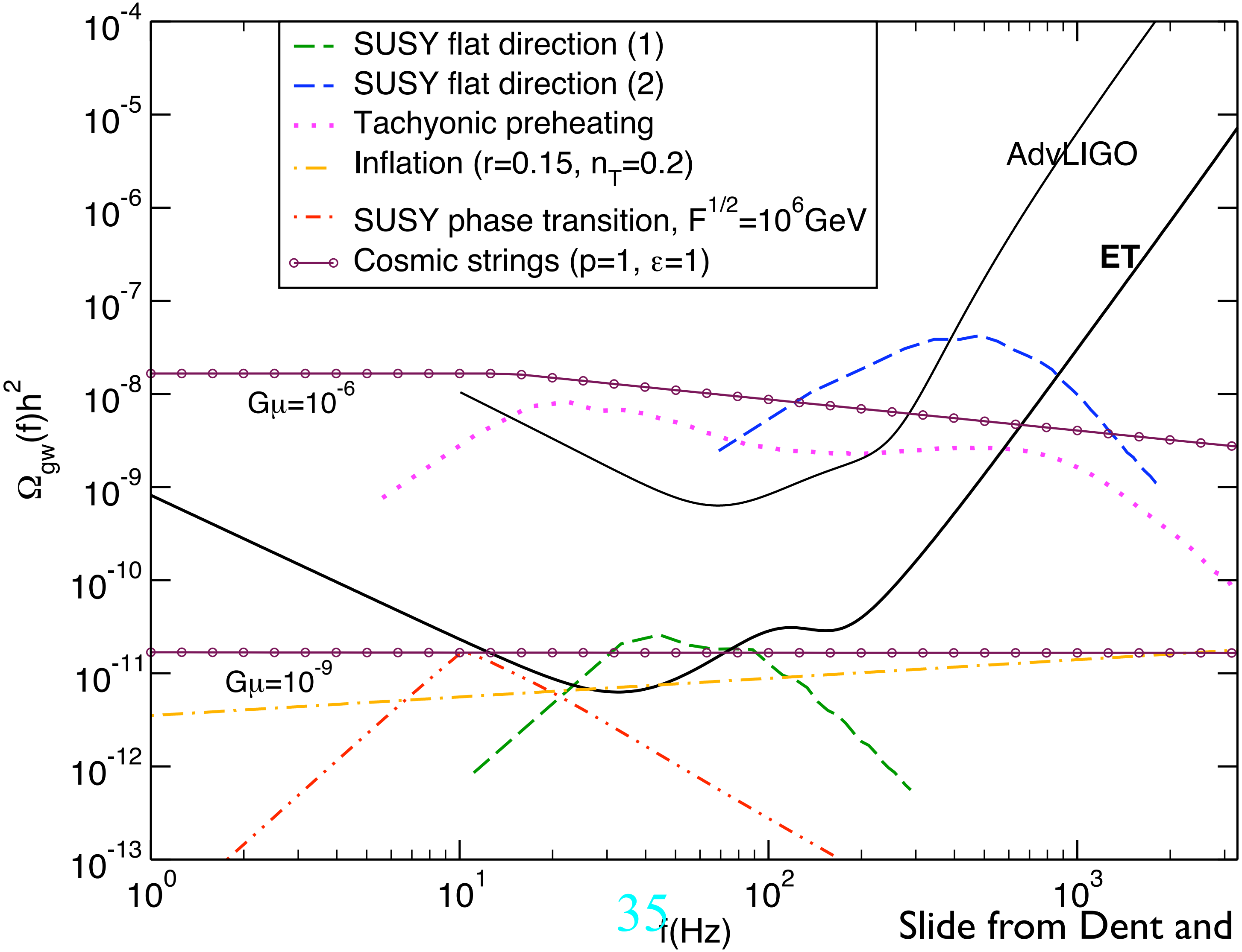
LISA $f \sim 10^{-3}$Hz probes $t_e \sim 10^{-14}$s ($T \sim 10$TeV)

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)

# Landscape of Stochastic GW in ET




Slide from Dent and Regimbau

# Fundamental Physics

# Fundamental Physics

- Properties of gravitational waves
  - Testing GR beyond the quadrupole formula
    - Binary pulsars consistent with quadrupole formula but they cannot measure the properties of GW
  - How many polarizations?
    - 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
- EoS of dark energy
  - GW from inspiralling binaries are standard 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?
- Merger dynamics of spinning black hole binaries

# Do Gravitons Have Mass?

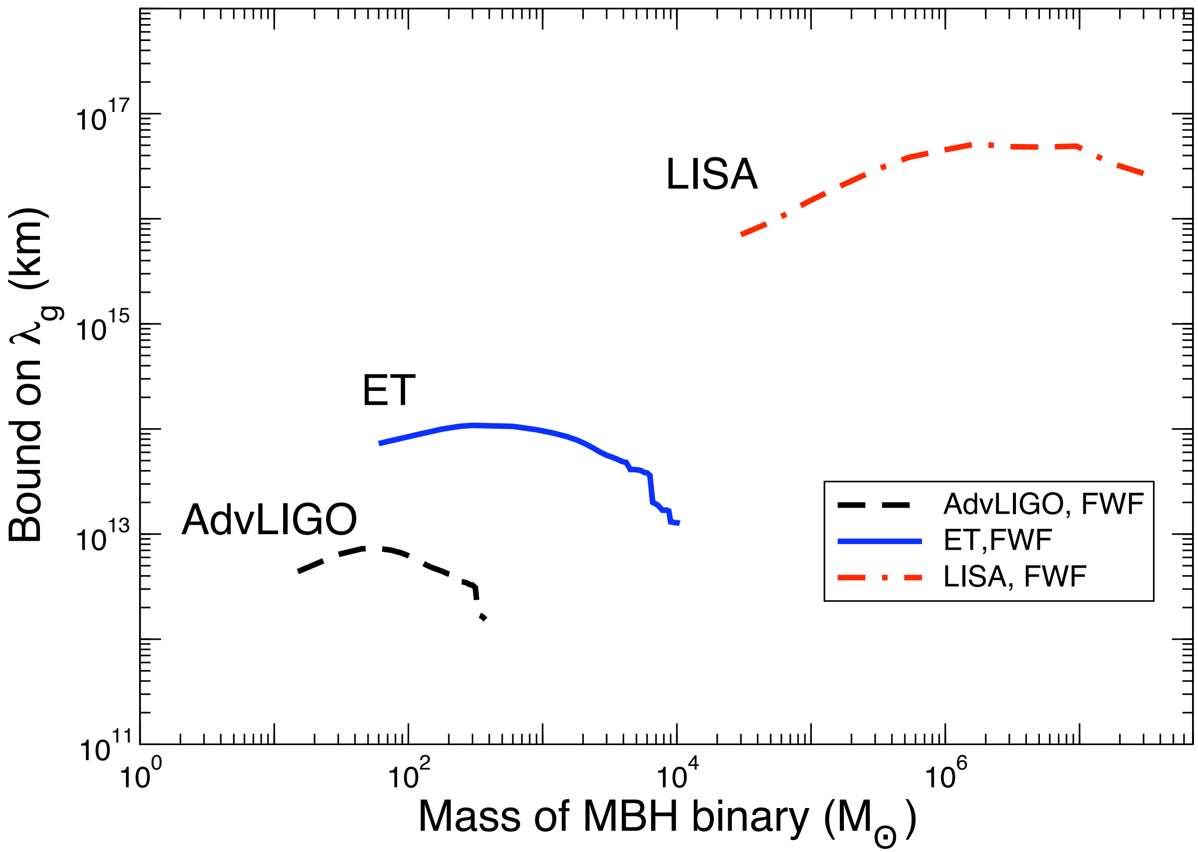
- Coincident observation of a supernova and the associated gravitational radiation can be used to constrain the speed of gravitational waves to a fantastic degree:
- If $\Delta t$ is the time difference in the arrival times of GW and optical radiation and $D$ is the distance to the source then the fractional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

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

- Should also be possible to constrain the mass of the graviton as they alter GW phasing of inspiral waveform due to dispersion of gravitational waves; no EM counterpart needed

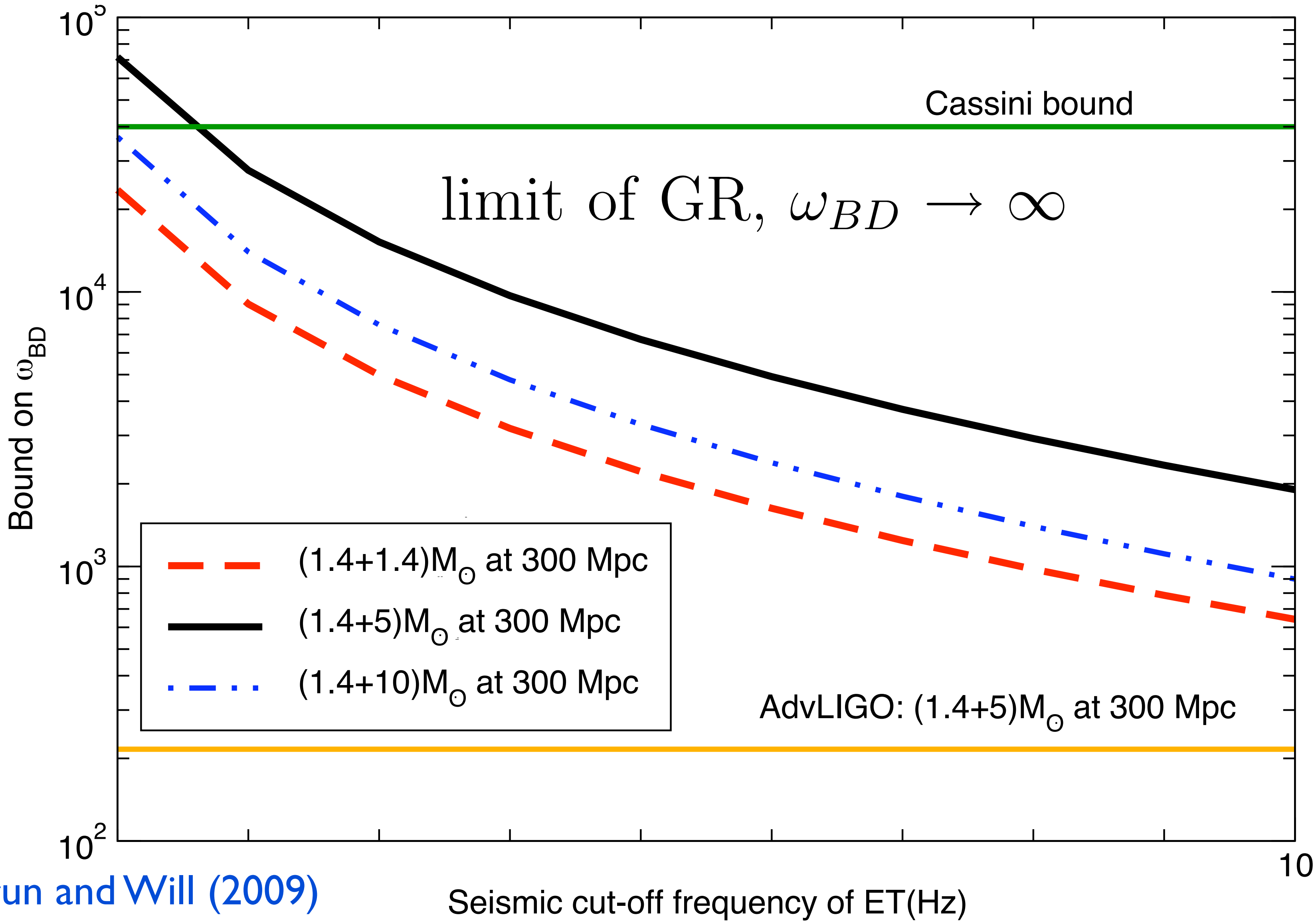
# Bound on $\lambda_g$ as a function of total mass

- Limits based on GW observations will be five orders-of-magnitude better than solar system limits
- Still not as good as (model-dependent) limits based on dynamics of galaxy clusters




Will (1998); Berti, Buonanno and Will (2006); Arun and Will (2009)

# Bounds on Brans-Dickie Theory from ET

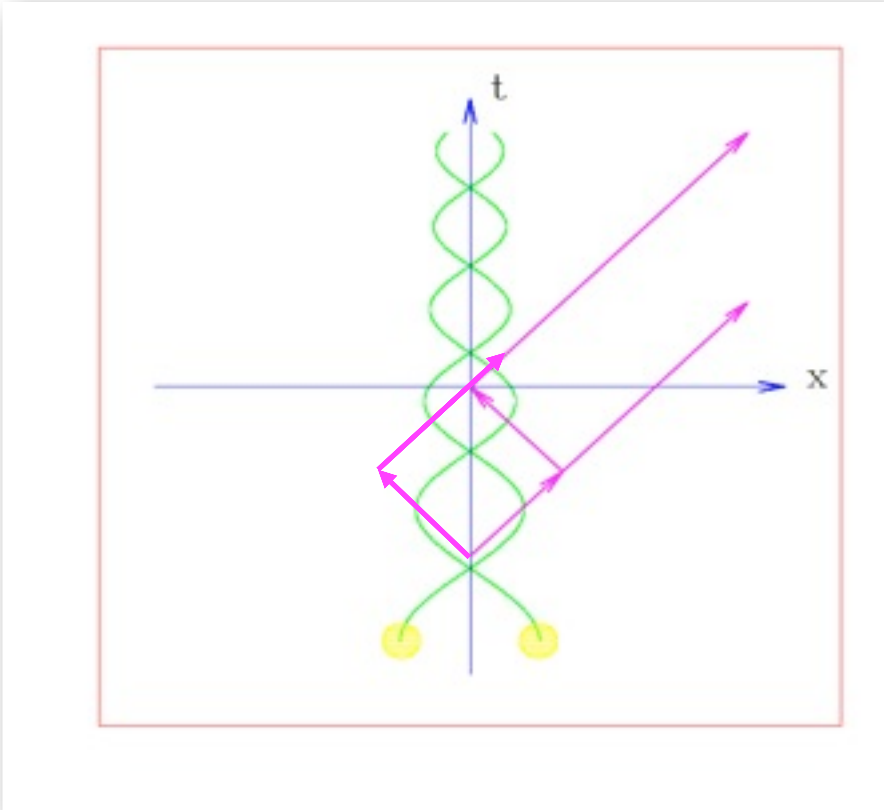



Arun and Will (2009)

# 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 dependent one can check to see if GR is the correct theory

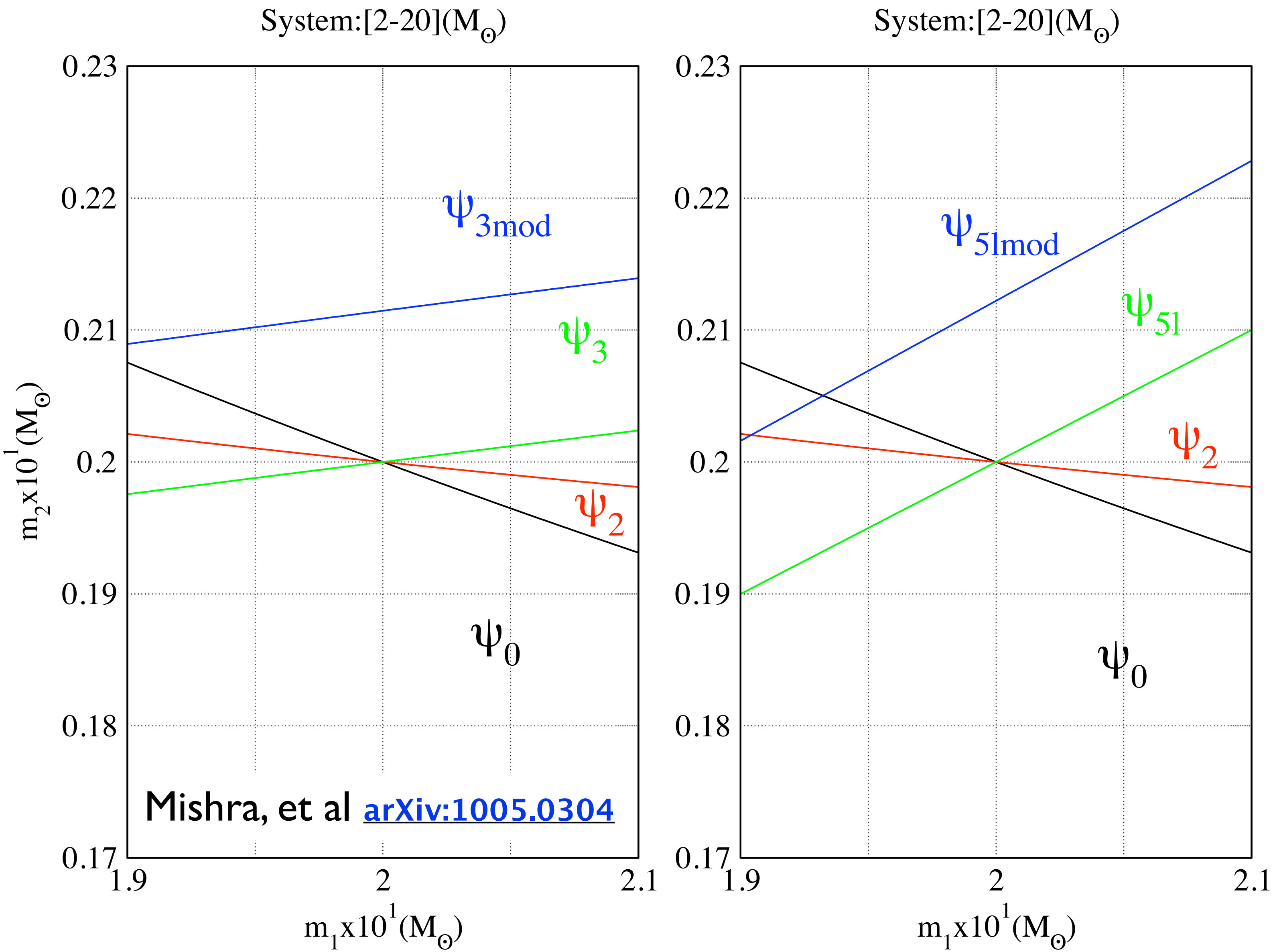
Gravitational wave tails




Blanchet and Schaefer (1994)

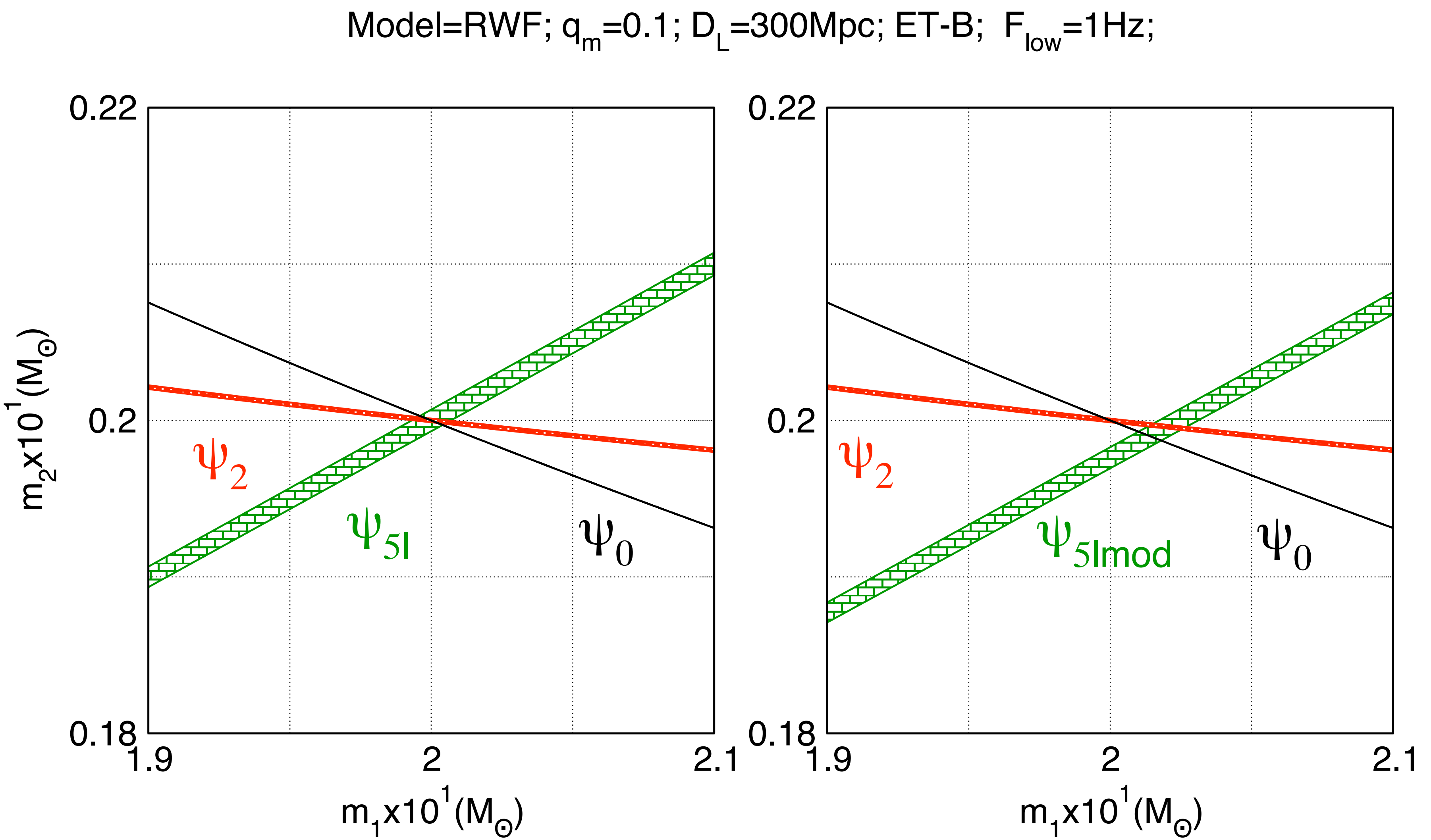
# What will we see if GR is not the correct theory?

Effect of changing the coefficients $\psi_3$ and $\psi_{51}$ by 5% on the test.




Mishra, et al arXiv:1005.0304

# How well can ET measure non-linear effects?




Mishra, et al arXiv:1005.0304

# Ongoing 3G Research

- Trade studies
  - Optimization with respect to low frequency sensitivity, detector location and optical topology
    - How well can we localize the source, measure orientation and polarization, ...
    - What physics does the low frequency window enable?
- ET mock data challenge
  - There will be far too many sources
    - How good are current algorithms in digging signals out of noise and extracting the science from ET observations?
  - A month's worth of mock data to be released soon

# Credits

- Patrick Sutton
- Christian Ott
- Jonathan Gair
- Chris Van Den Broeck
- Sukanta Bose
- Richard O'Shaughnessy
- Tania Regimbau
- Thomas Dent
- James Clark
- Gareth Jones
- Alberto Vecchio
- John Veitch
- Craig Robinson
- Andrew Melatos
- Eric Chassande-Mottin
- Pau Amaro-Seoane
- Nils Andersson
- K.G. Arun
- Lucia Santamaria
- Kostas Kokkotas
- Mark Hannam
- Sascha Husa
- Badri Krishan
- Joceylyn Read
- Luciano Rezzolla
-