Astrophysical Results from LIGO Scientific Collaboration and Virgo

GW Data Analysis

- Let’s play a game
  - www.blackholehunter.org

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

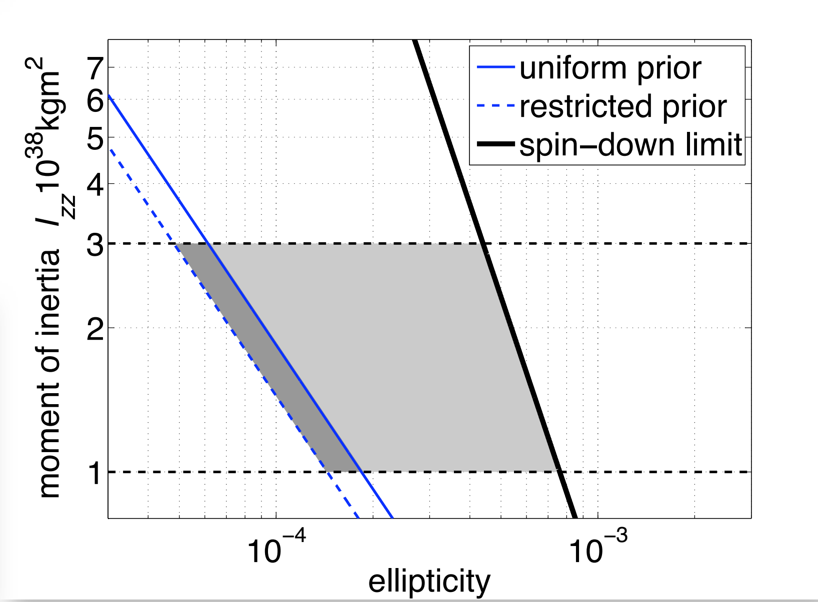
spin-down rate, $\dot{\nu} \approx -3.7\times10^{-10}\,\mathrm{Hz\,s^{-1}}$

$$\dot{E} = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4\times10^{31}\,\mathrm{W}$$

$$h_0^{\mathrm{sd}} = 8.06\times10^{-19}\, I_{38} r_{\mathrm{kpc}}^{-1} (|\dot{\nu}|/\nu)^{1/2}$$

- We have searched for gravitational waves in data from the fifth science run of LIGO detectors
- The search did not find any gravitational waves
- Lack of GW at S5 sensitivity means a limit on ellipticity a factor 4 better than spin-down upper limit - less than 4% of energy in GW

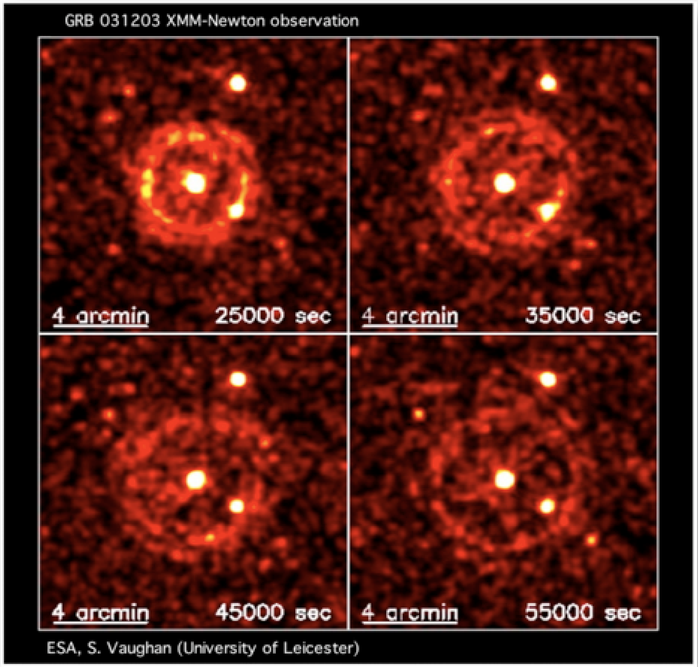
$$h_0^{95\%} = 3.4\times10^{-25}. \quad \varepsilon = 1.8\times10^{-4}$$

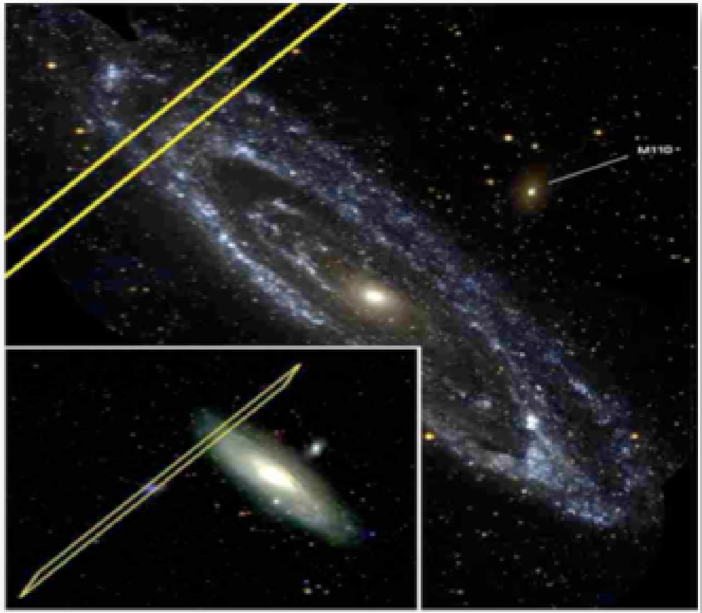


Origin of GRB 070201 from LIGO Observations

LSC, Astrophys. J. **681,** (2008) 1419

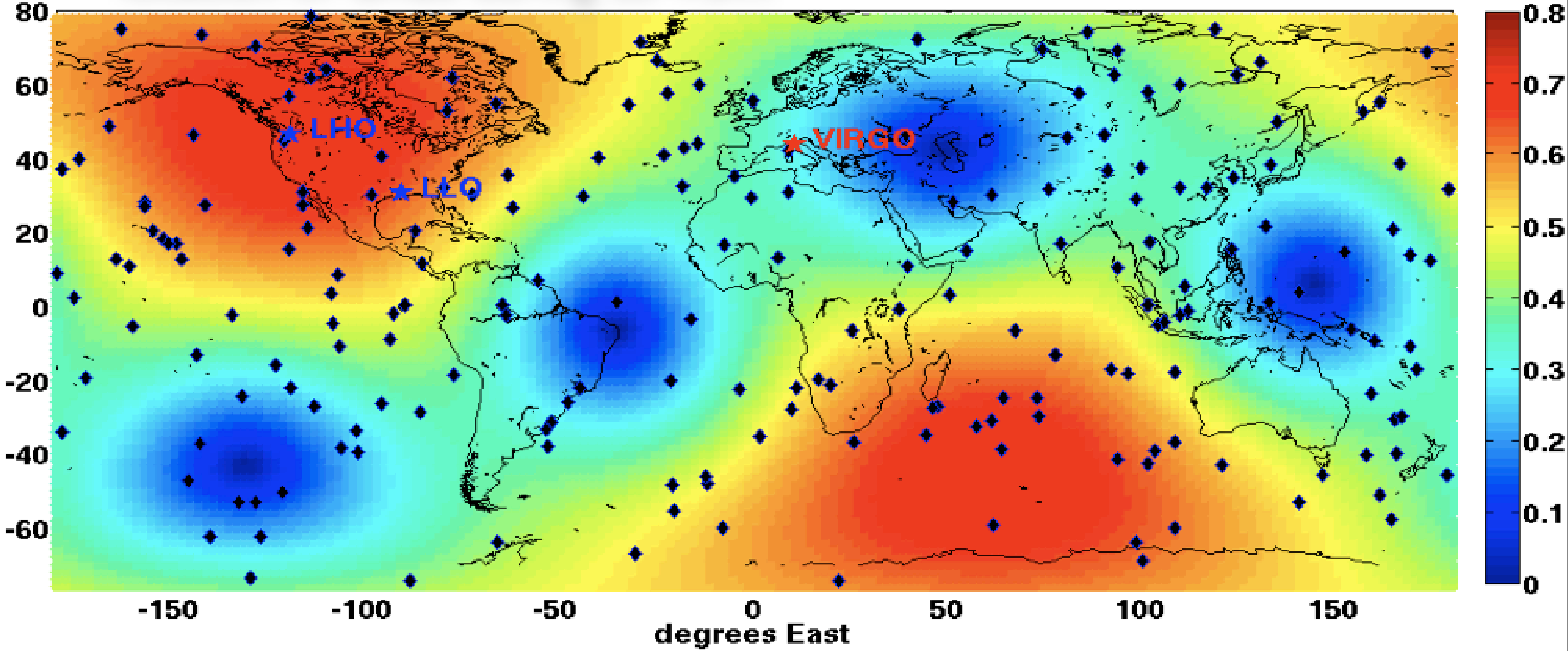
- LSC searched for binary inspirals and did not find any events: results in ApJ 681 1419 2008
- Null inspiral search result excludes binary progenitor in M31
- Soft Gamma-ray Repeater (SGR) models predict energy release <= 10^{46} ergs.
- SGR not excluded by GW limits





Search for GRBs during all of S5

- Nov 2005 - Oct 2007: 212 GRBs
- LSC-Virgo searched for 137 GRBs with 2 or more LIGO-Virgo detectors: Null result
- ~25% with redshift, ~10% short duration
- Polarization-averaged antenna response of LIGO-Hanford, dots show location of GRBs during S5-VSR1



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LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

Stochastic background

- Metric fluctuations carry energy:

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

- Characterize by frequency dependence:

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

- Describe in terms of strain power spectrum

$$\boxed{S(f) = \frac{3H_0^2}{10\pi^2} \frac{\Omega_{GW}(f)}{f^3}}$$

- Strain scale:

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

Searching for a Stochastic Background

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm gw}}{d\ln f}$$

- Nucleosynthesis upper-limit

$$\int \frac{df}{f}\Omega_{\rm gw}(f) \lesssim 1.5 \times 10^{-5}.$$

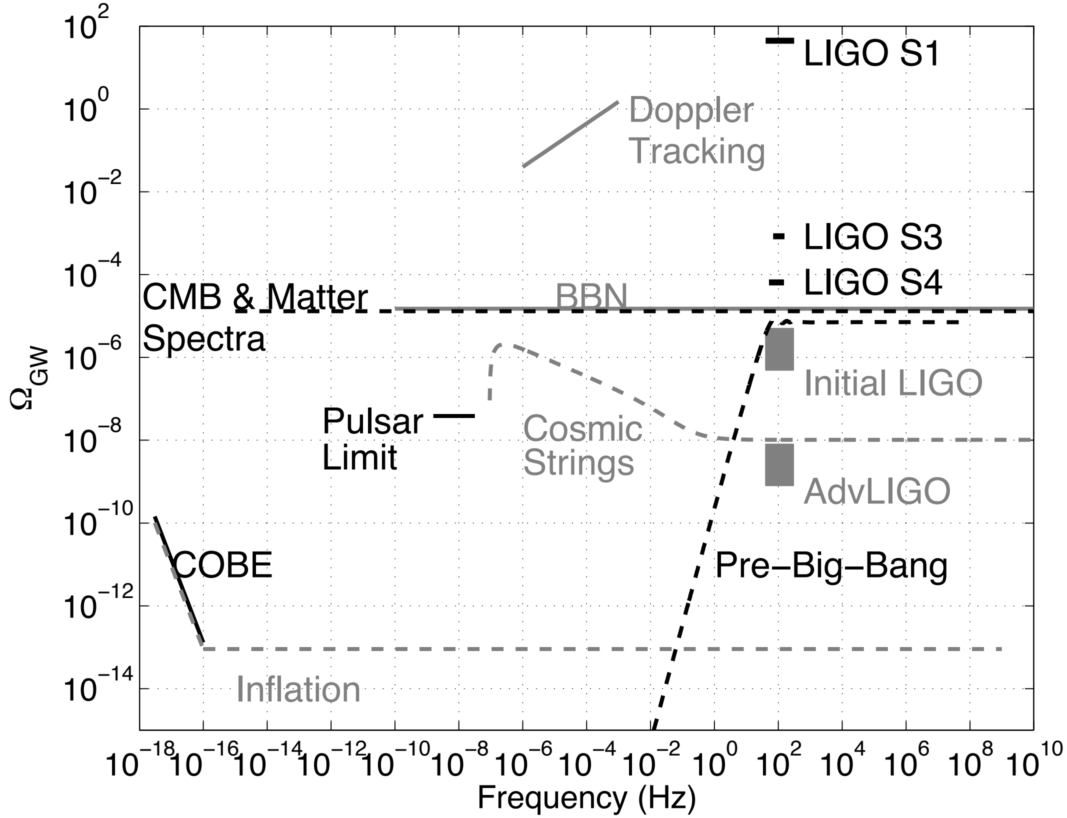
- Upper limit from LIGO data from the 4th Science run

$$\Omega_{\rm gw}(f) < 6.5 \times 10^{-5}$$

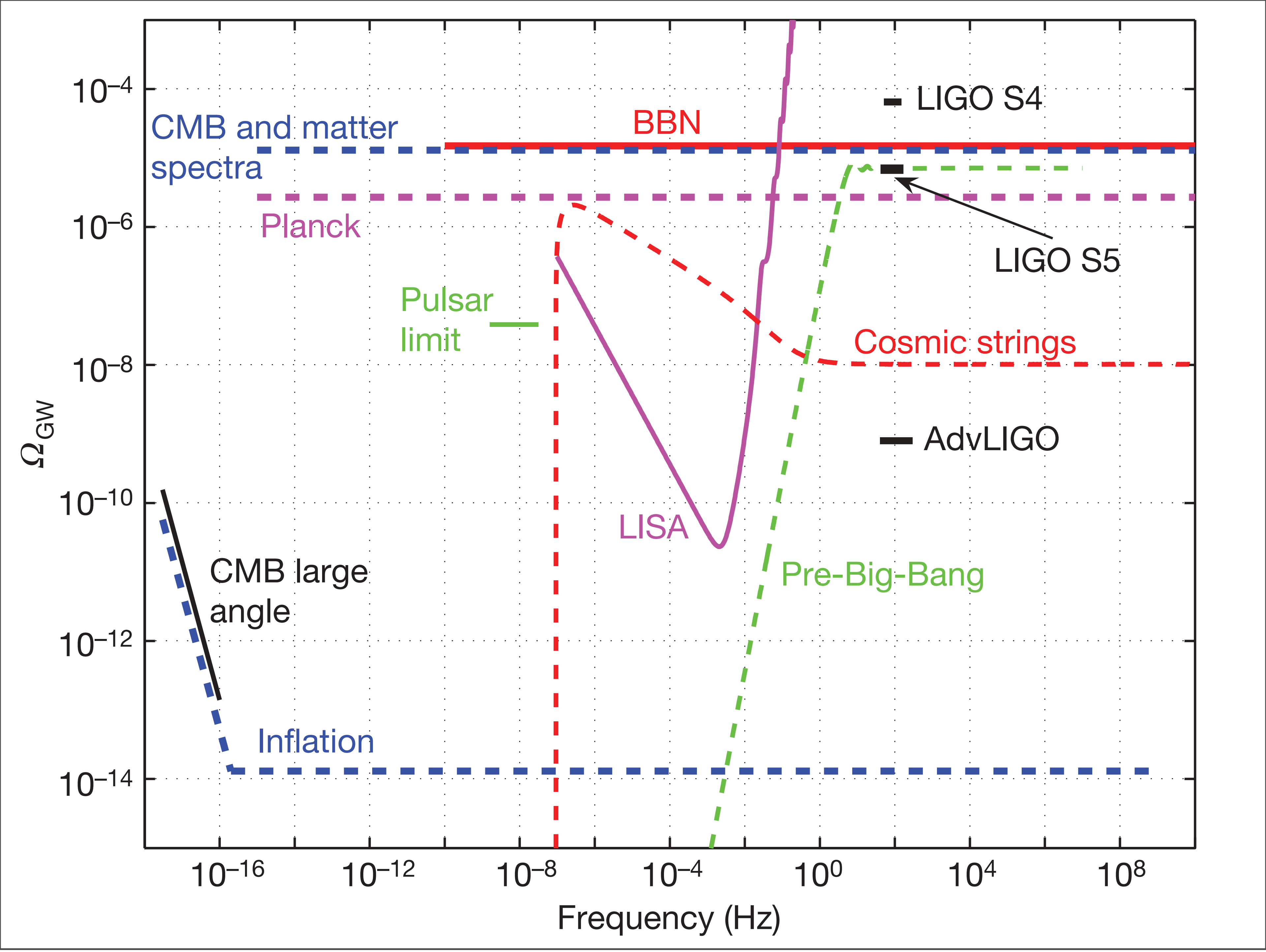
- Data from the 5th science run has improved this better than the nucleosynthesis limit

$$\Omega_{\rm GW} < 6.9 \times 10^{-6}$$

LSC, Astrophys. J. 659 (2007) 918



CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD



10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
Ω_{GW}
10^{-16}
10^{-12}
10^{-8}
10^{-4}
10^{0}
10^{4}
10^{8}
Frequency (Hz)
CMB and matter spectra
BBN
LIGO S4
LIGO S5
Planck
Pulsar limit
Cosmic strings
AdvLIGO
LISA
CMB large angle
Pre-Big-Bang
Inflation

Astrophysics, Fundamental Physics and Cosmology from GW Observations

B.S. Sathyaprakash
Cardiff University, Cardiff, United Kingdom
ISAPP School, Pisa, Italy, September 27-29, 2010

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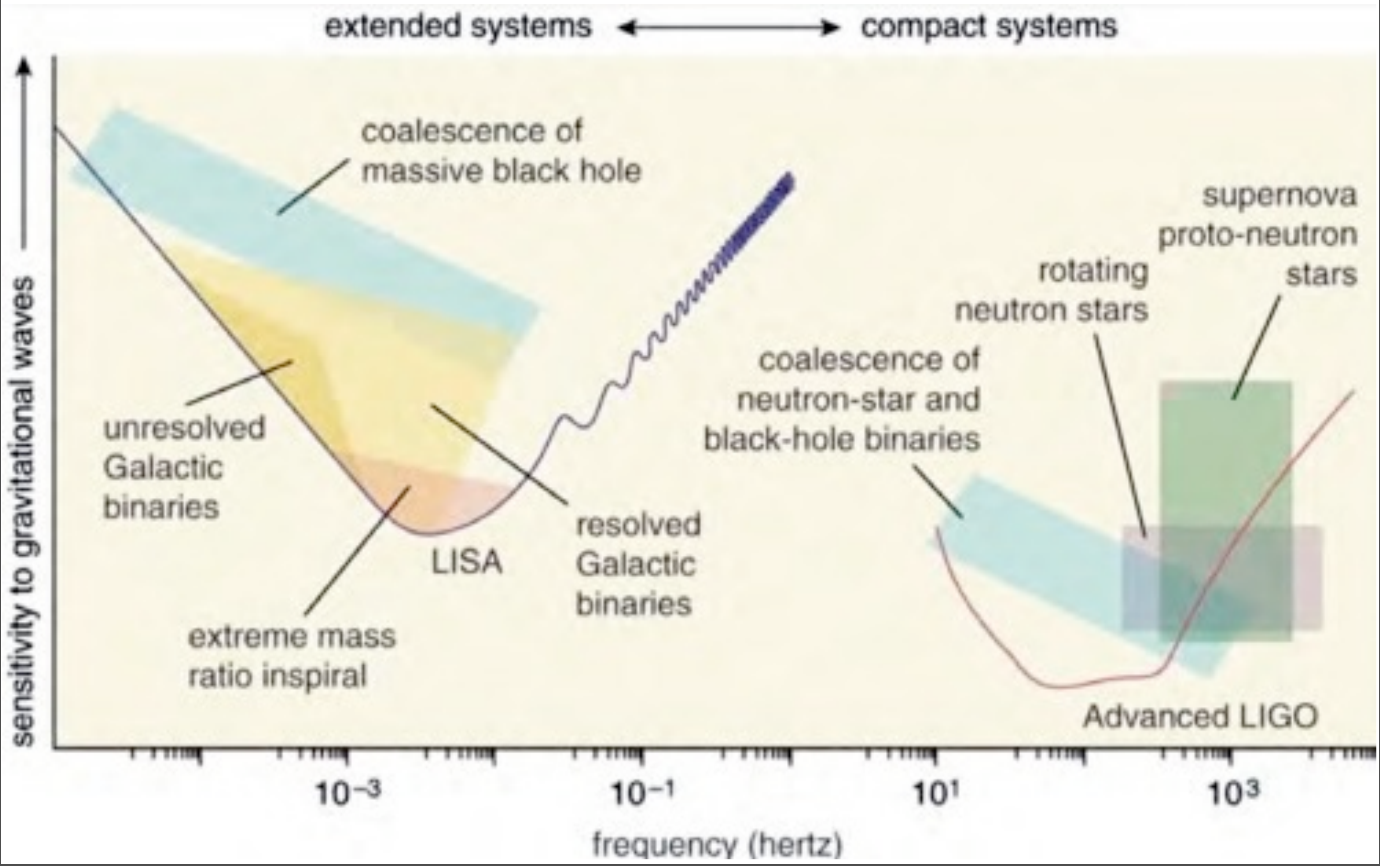
Summary of Sources



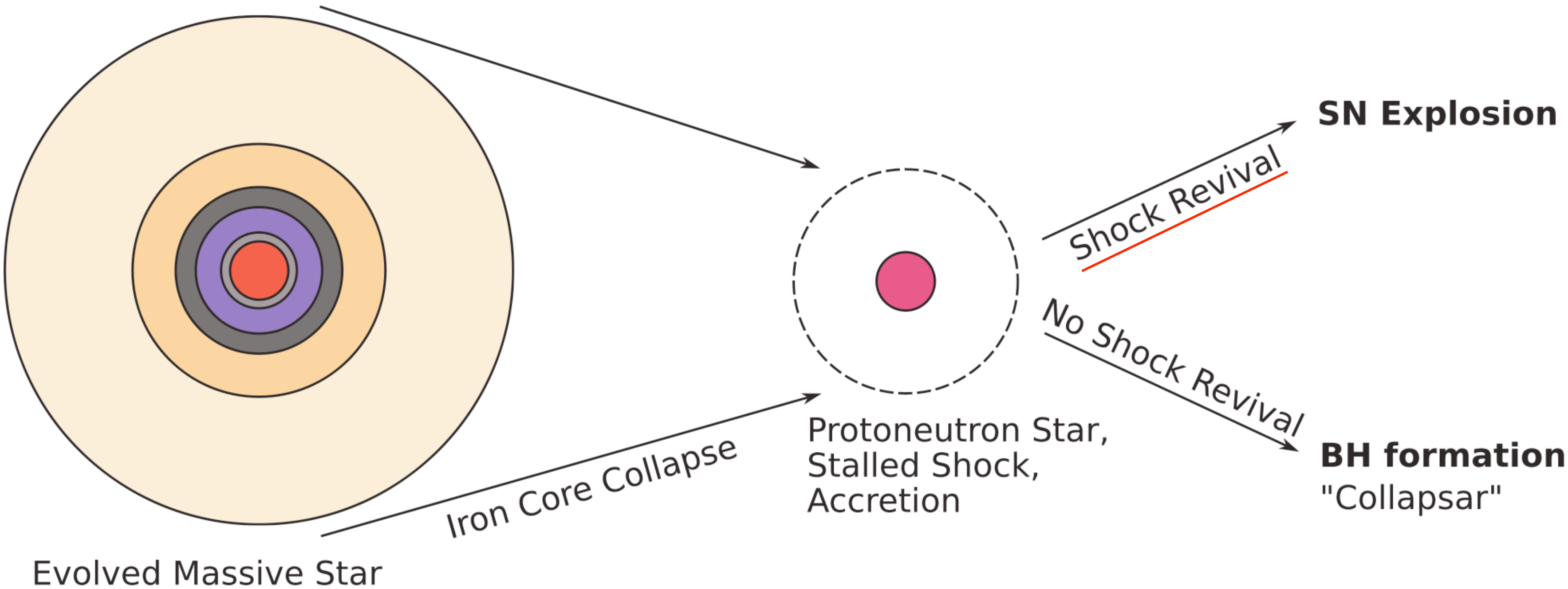
Astrophysics

- 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

Supernovae

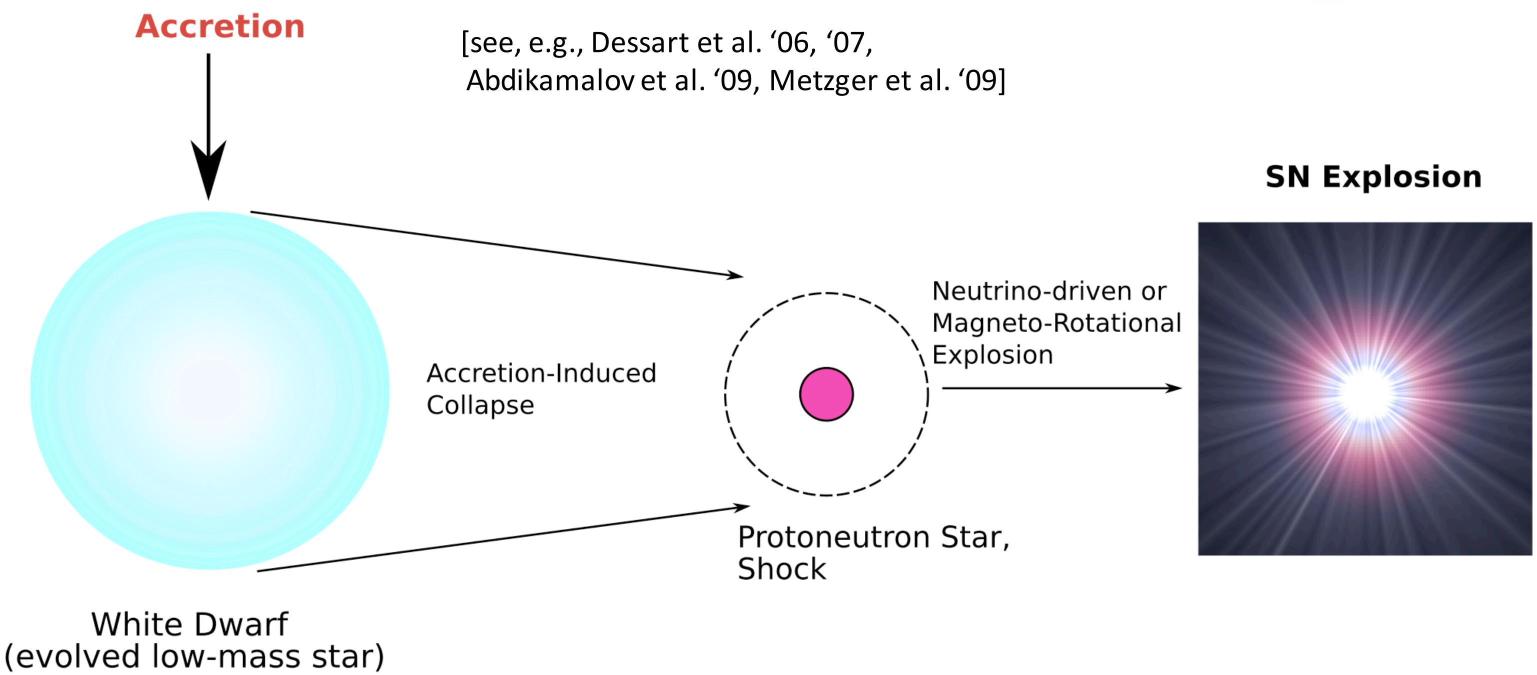
- Standard candles of astronomy
  - Our knowledge of the expansion rate of the Universe at redshift of $z=1$ comes from SNe
- Produce dust and affect evolution of galaxies
  - Heavy elements are only produced in SNe
- They are precursors to formation of neutron stars and black holes
  - The most compact 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

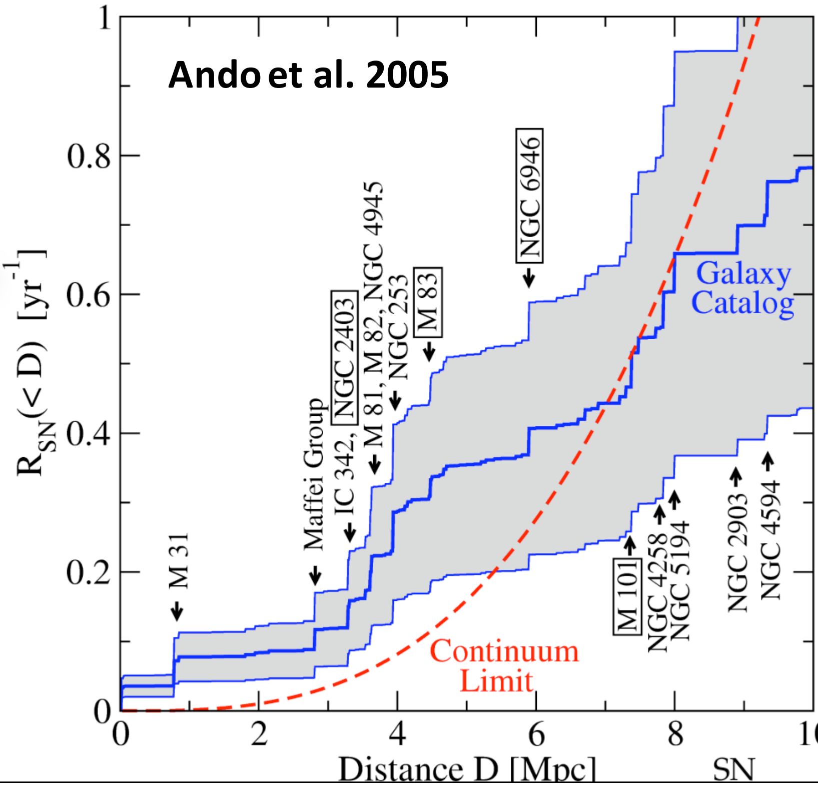
Accretion Induced Collapse

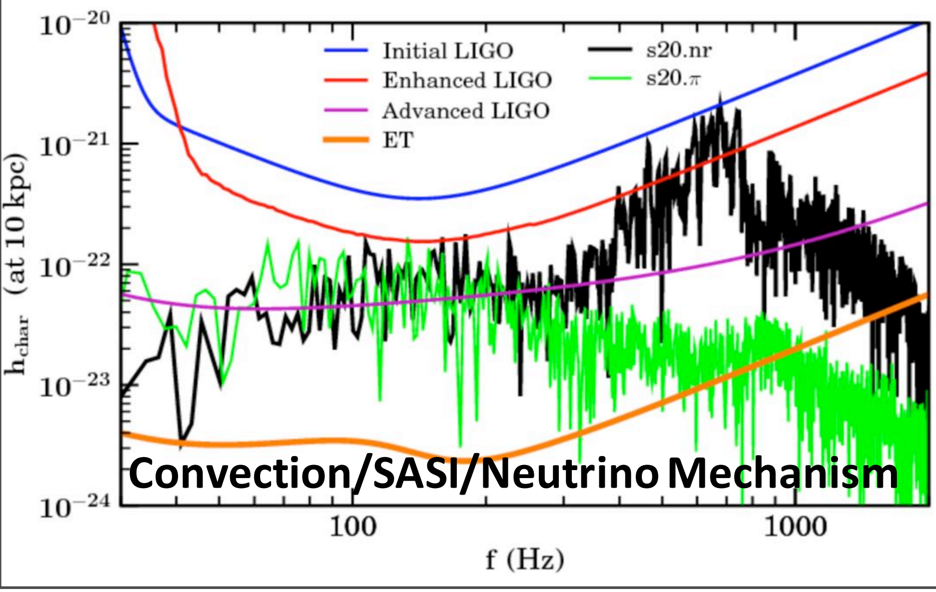


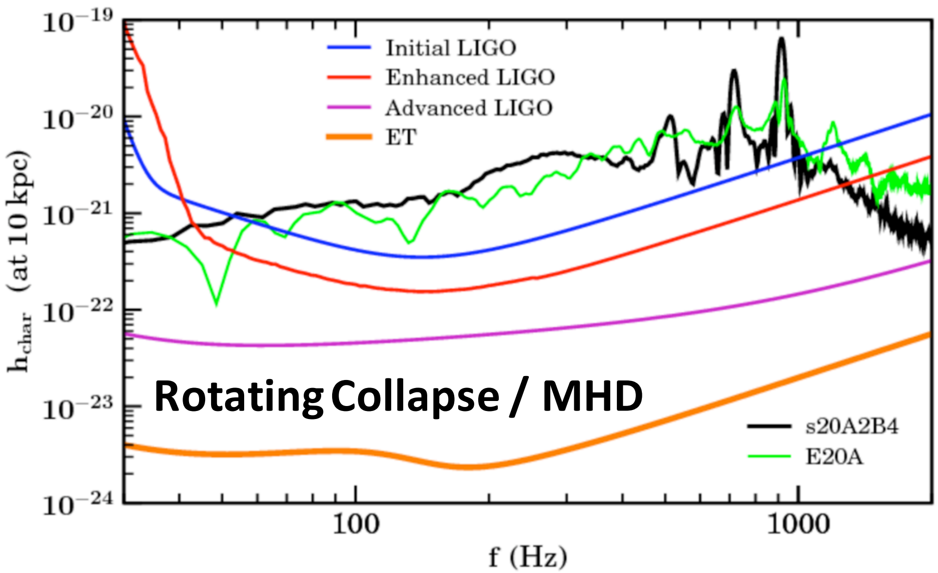
- Collapse of accreting, probably rotating White Dwarfs
  - Neutrino-driven or magneto-rotational explosion
- Explosion probably weak, sub-luminous
  - Might not be seen in optical
- Potential birth site of magnetars - highly (10^{15}- 10^{16} G) magnetized neutron stars

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

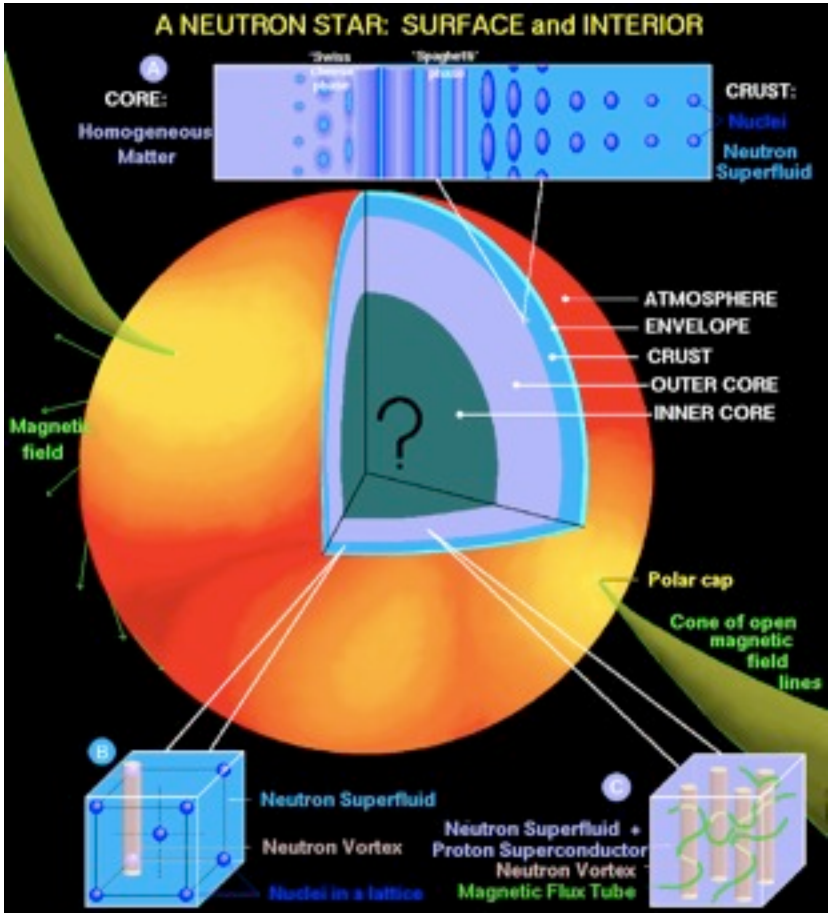




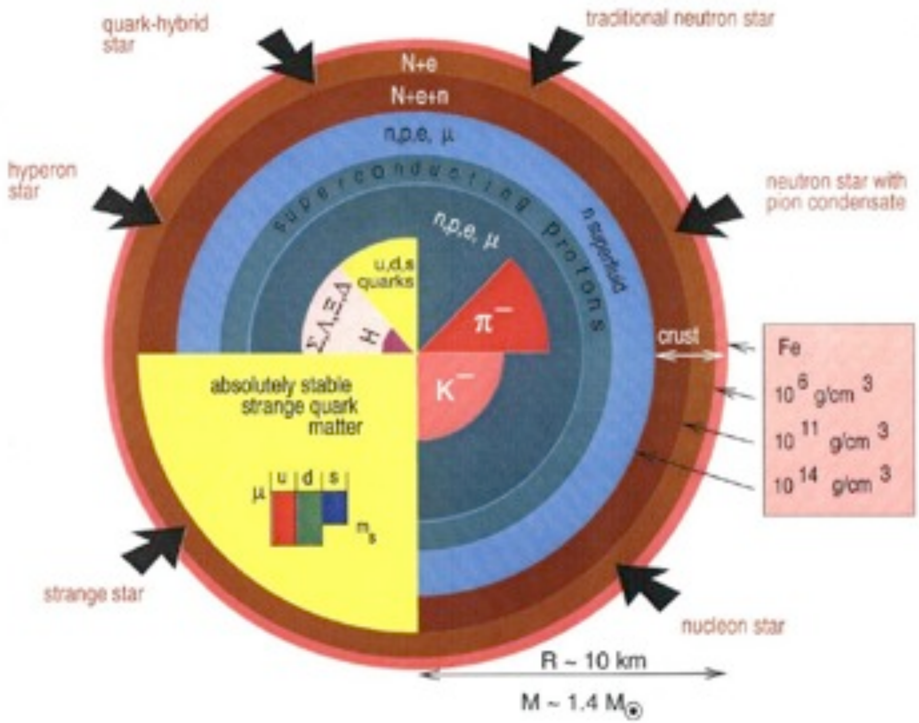


Neutron Stars

- Great interest in detecting radiation: physics of such stars is poorly understood.
- After 35 years still don't know what makes pulsars pulse or glitch.
- Interior properties not understood: equation of state, superfluidity, superconductivity, solid core, source of magnetic field.
- May not even be neutron stars: could be made of strange matter!



An extreme challenge



- Neutron star modelling involves the very extremes of physics:
  - Rapid (differential) rotation
  - General relativity
  - Superfluidity
  - Strong magnetic fields
  - Crust-core interface
    - Exotic nuclear physics
    - Strange quarks, hyperons

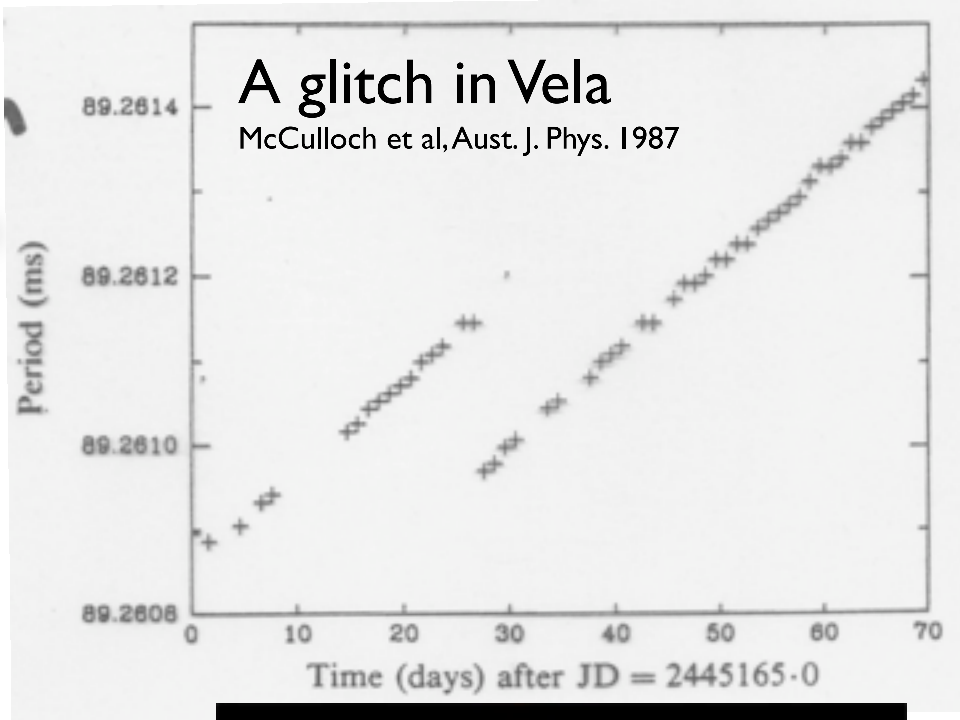
Pulsar Glitches

- 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

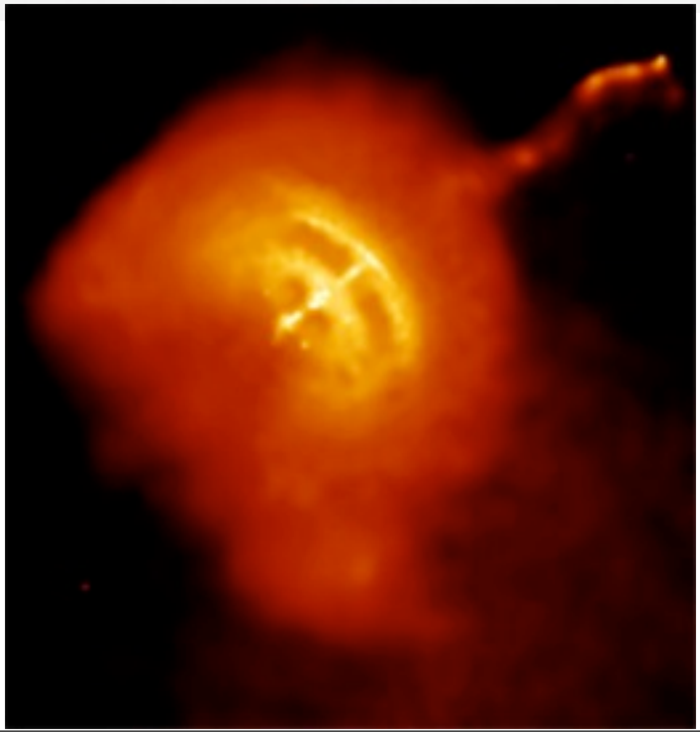
$$\Delta J \sim I_* \Delta\Omega \qquad \Delta E = \Delta J \Omega_{\rm lag}$$

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

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

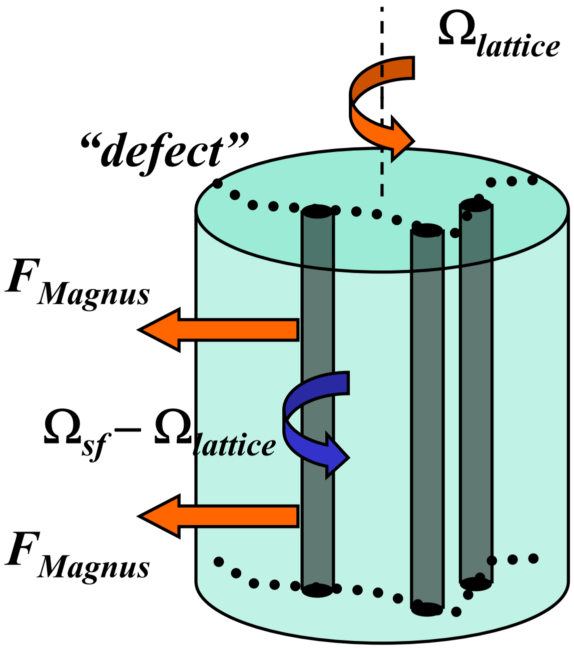


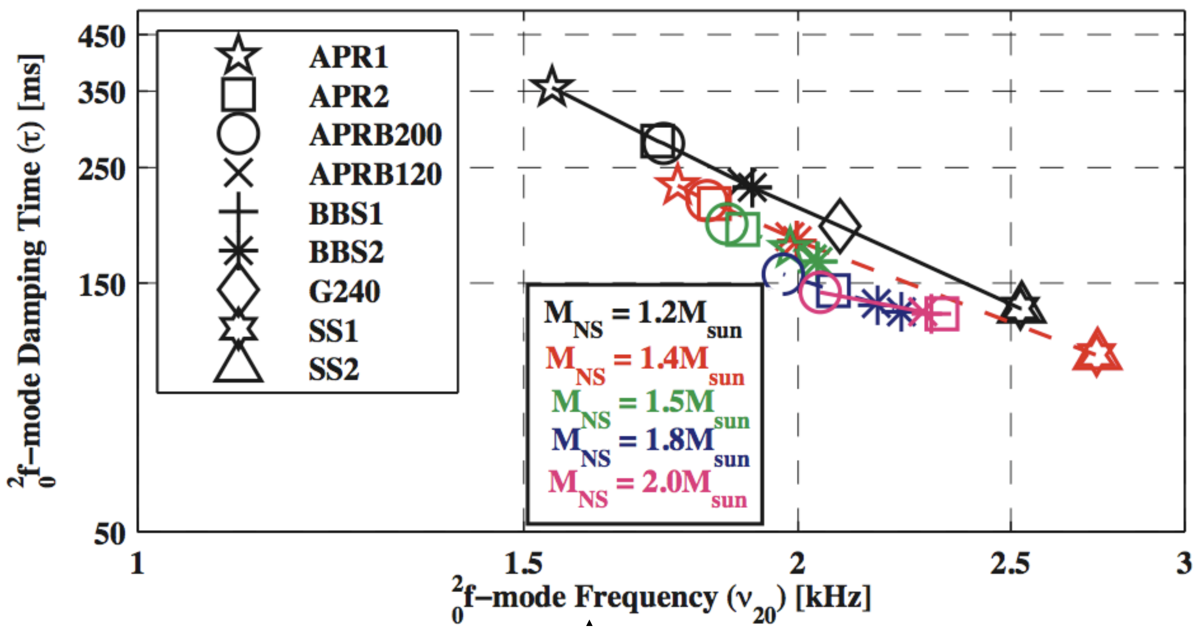
A composite Vela image



NS Normal Mode Oscillations

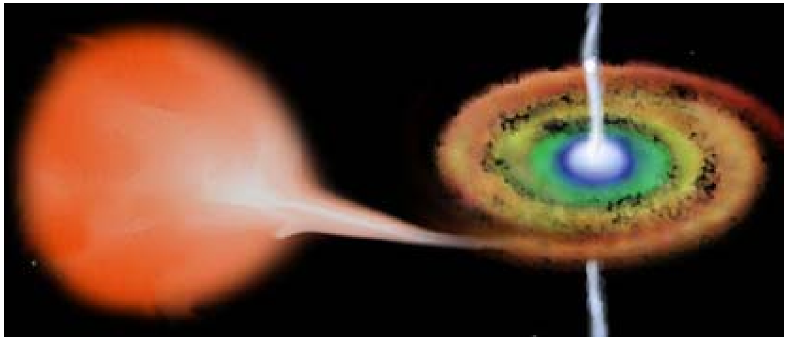
- Sudden jolt due to a glitch, and superfluid vortex unpinning, could cause oscillations of the core, emitting gravitational waves
  - These normal mode oscillations have characteristic frequencies and damping times that depend on the equation-of-state
- Detecting and measuring normal modes could reveal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





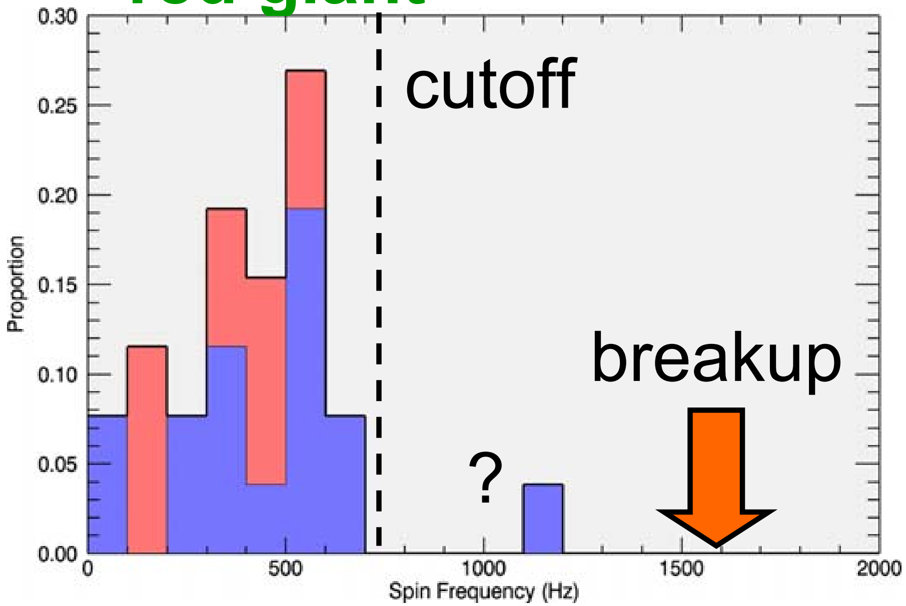
Accreting Neutron Stars

- 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



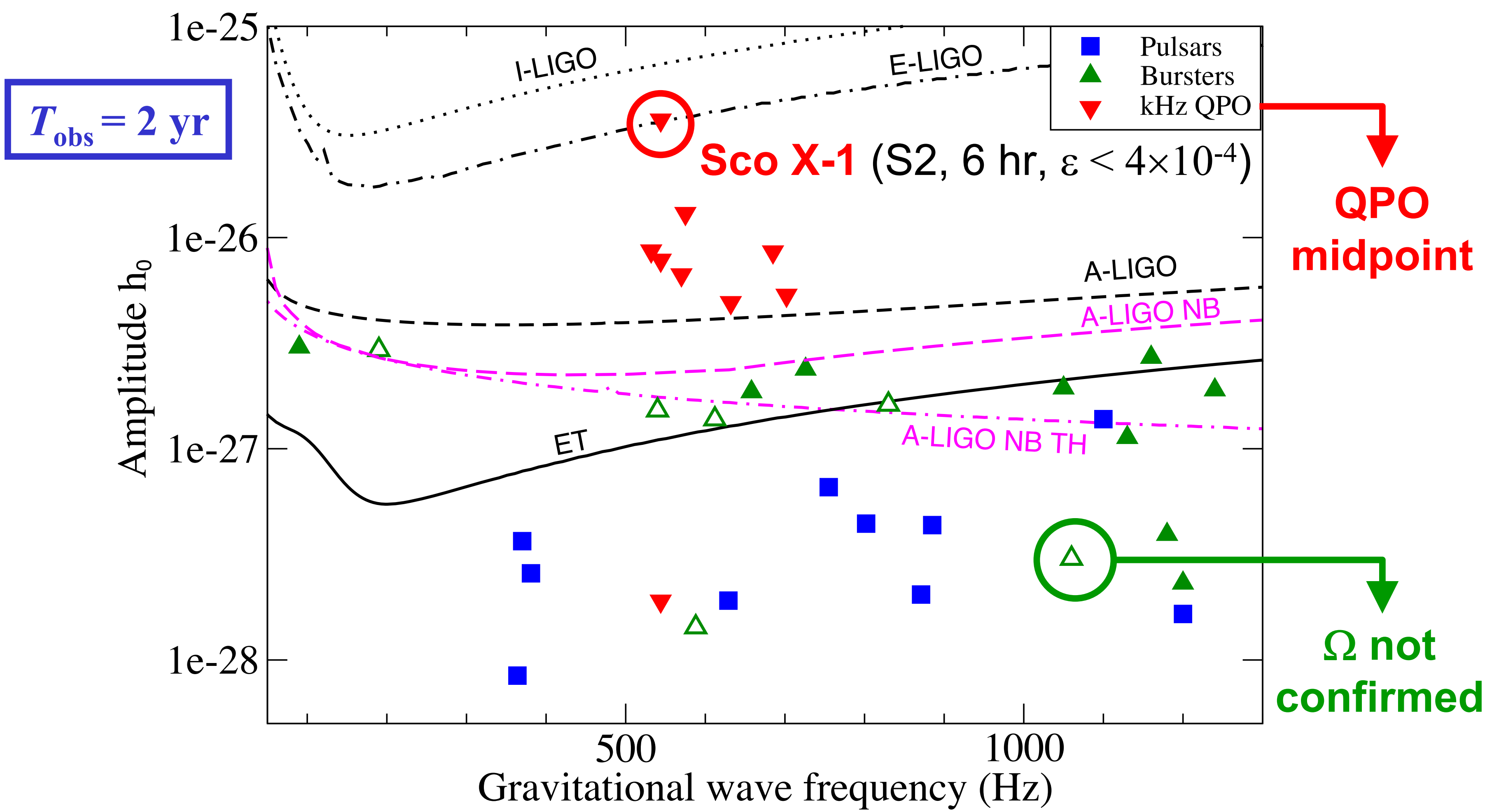
$< 1M_{\mathrm{Sun}}$ red giant

NS



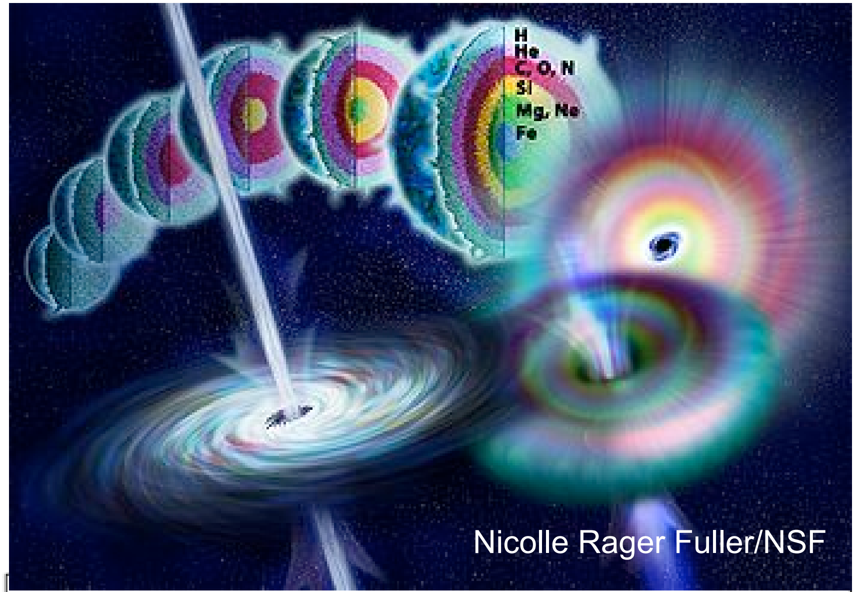
pulses & burst oscillations

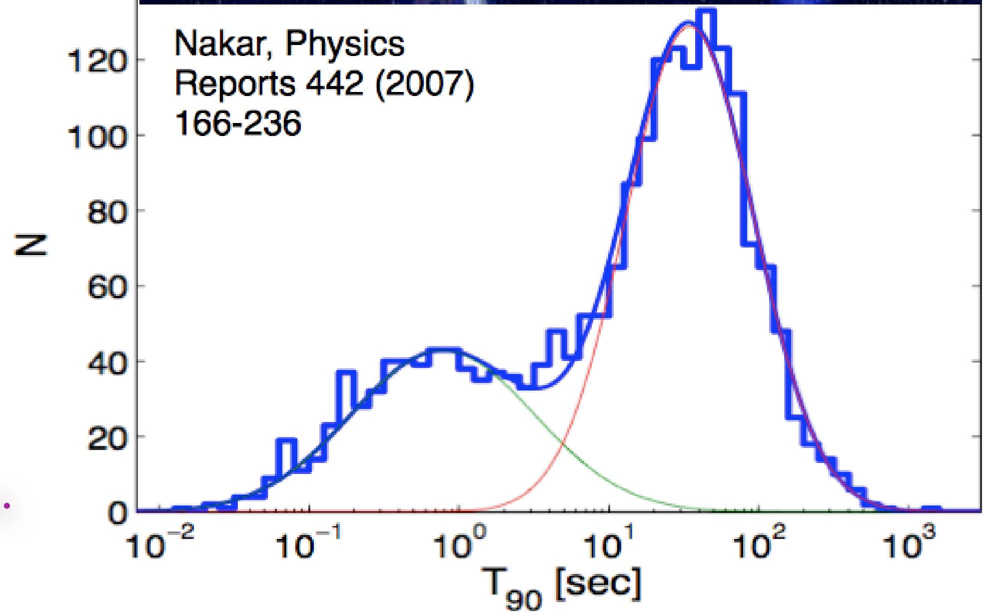
Sensitivity to Accreting NS



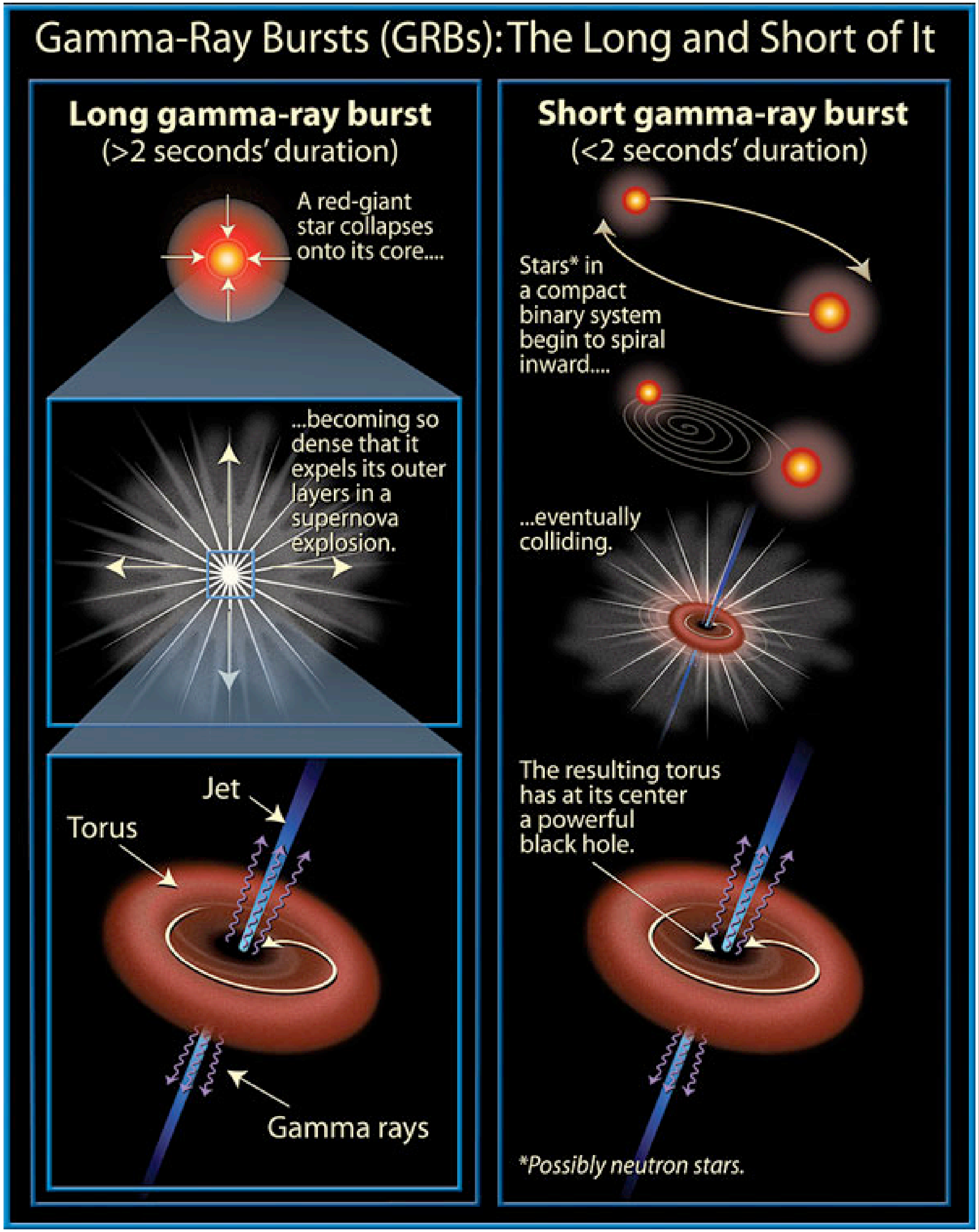
GRB Progenitors

- 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.





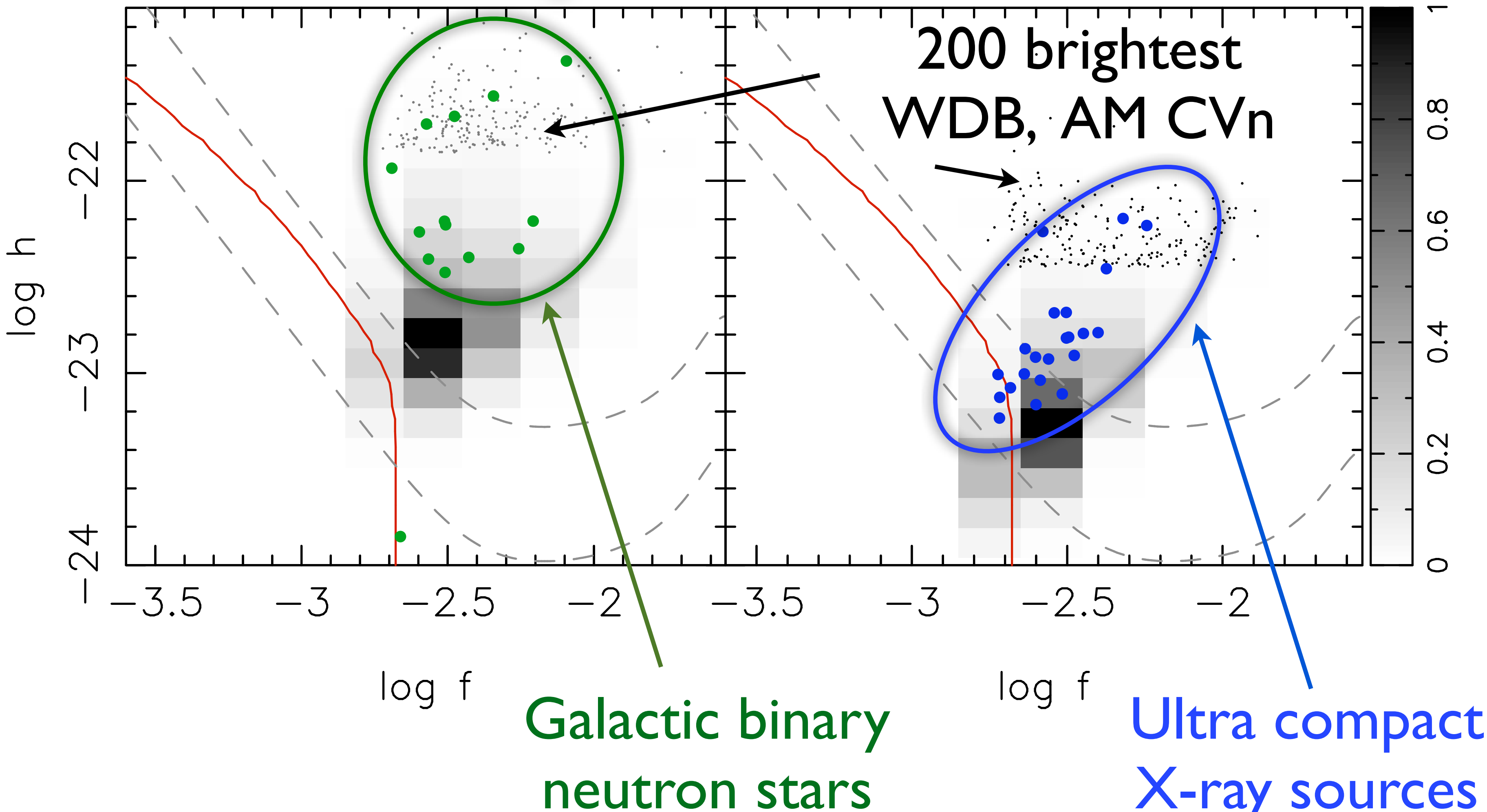
- Long GRBs
  - Core-collapse SNe, GW emission not well understood
    - Could emit burst of GW
- Short GRBs
  - Could be the end state of the evolution of compact binaries
    - BNS, NS-BH
- GRBs in ET
  - Short-hard GRBs might be detectable at redshift z=2
  - An ET network could measure the binary orientation, masses, spins, and help build better models
  - Should be possible to shed light on GRB progenitors



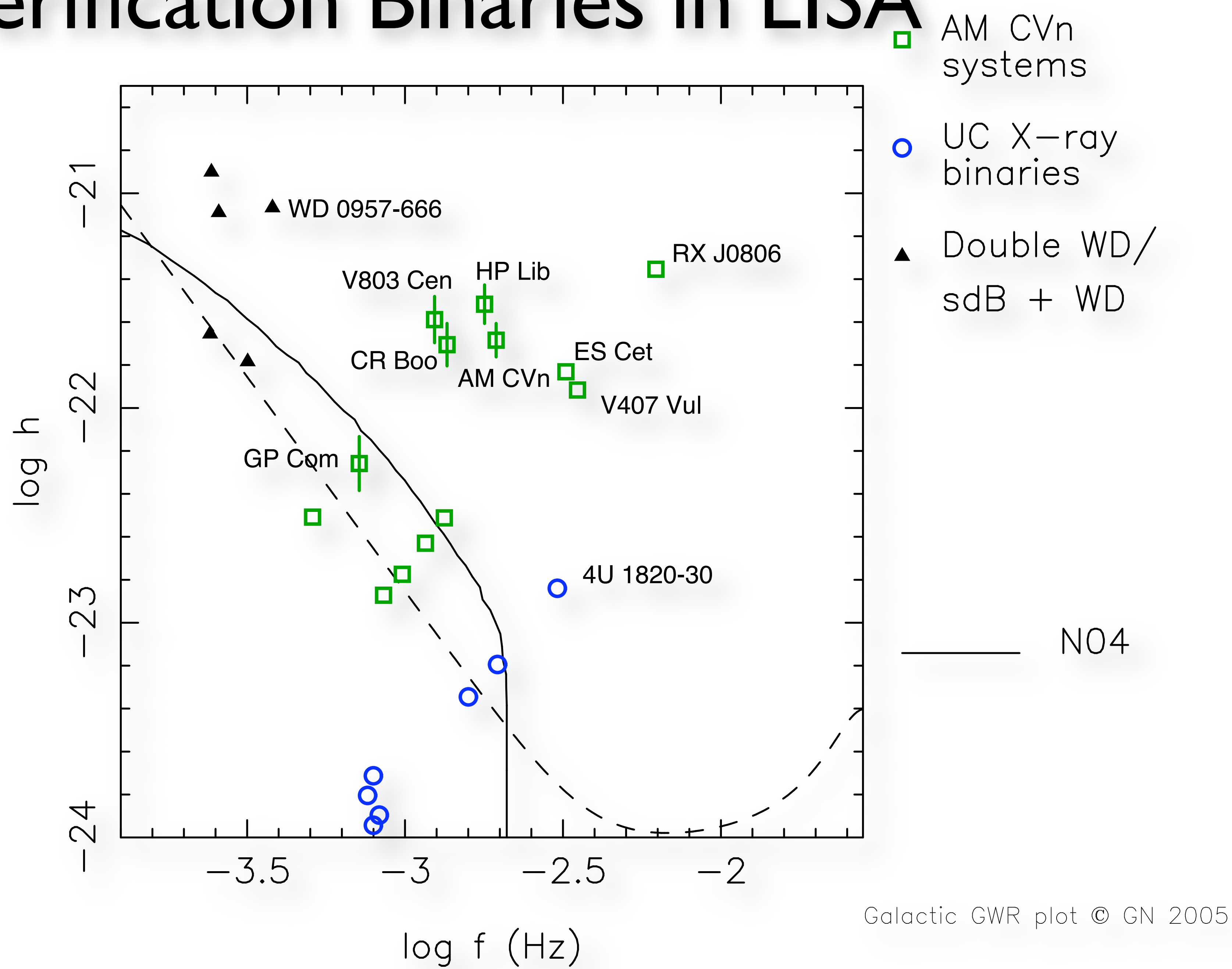
Astrophysics

- What is the population of white dwarfs in our galaxy?
  - What is their mass function, are there white dwarfs that are very close to Chandrasekhar limit?
- Do massive black hole mergers produce detectable EM afterglows?
- At what rate do massive black holes form and merger throughout the Universe?
  - How does this rate evolve with red-shift?
- How frequently do intermediate and stellar-mass black holes infall into massive black holes?
  - What is the merger history of massive black holes at galactic nuclei

White Dwarf Binaries and AM CVn Systems in LISA



Verification Binaries in LISA



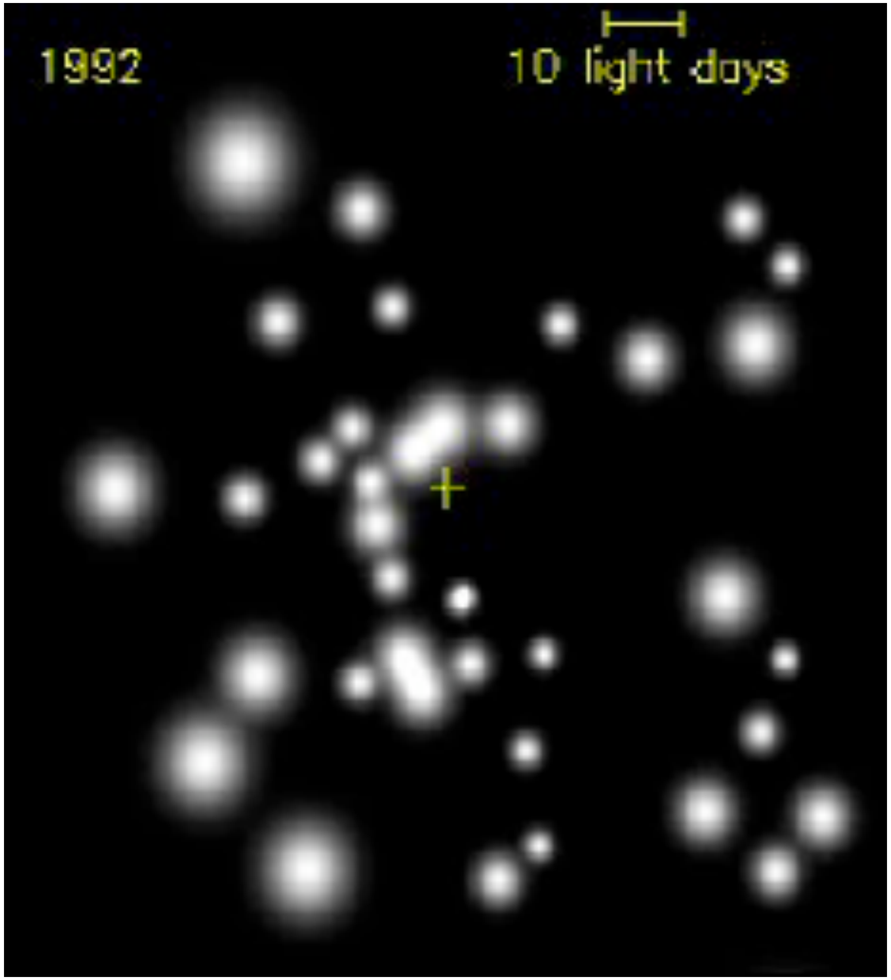
Black hole seeds

How to supermassive black holes form and evolve?

Are black holes the end state of gravitational collapse?

Is no-hair theorem valid?

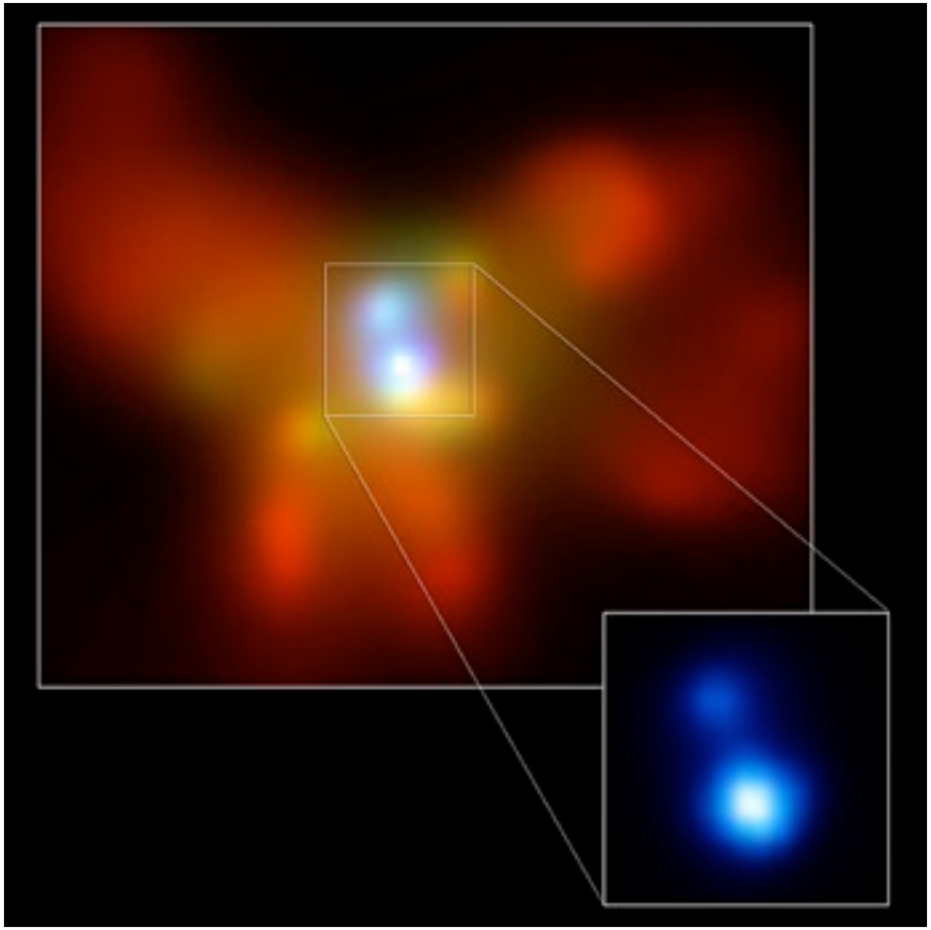
Sagittarius A: A Galactic SMBH



Super-massive black hole mergers

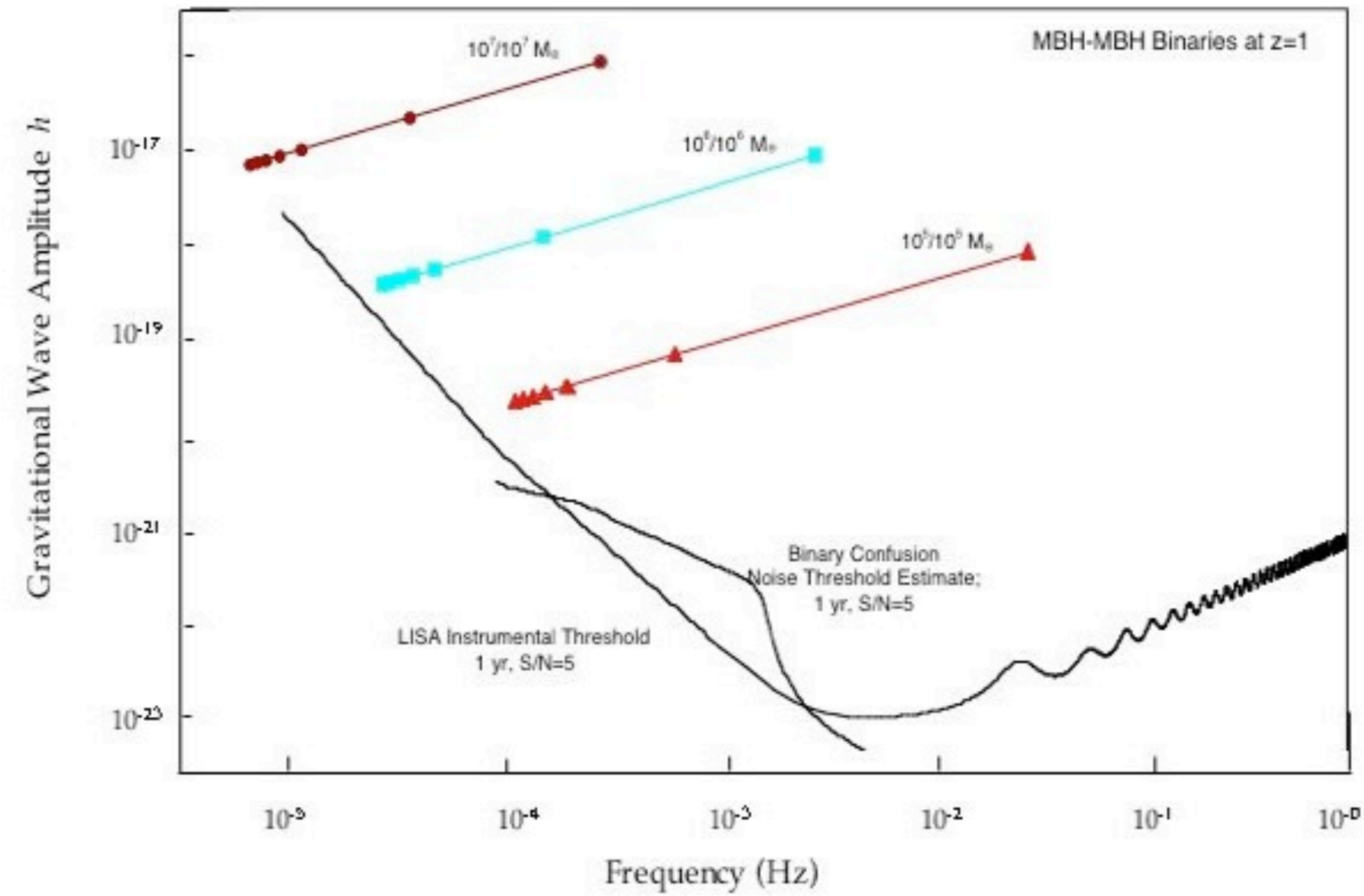
SMBH binary in NGC 6240

NGC6240, Kamossa et al



- X-ray observations have revealed that the nucleus of NGC 6240 contains an SMBH binary that will coalesce within the Hubble time
- The high visibility of the signal means we can see SMBH binaries anywhere in the Universe
- We can catch the signal at early times to predict the precise time and position of the coalescence event, allowing the event to be observed simultaneously by other telescopes.

Visibility of SMBH binary mergers



Cutler and Vecchio

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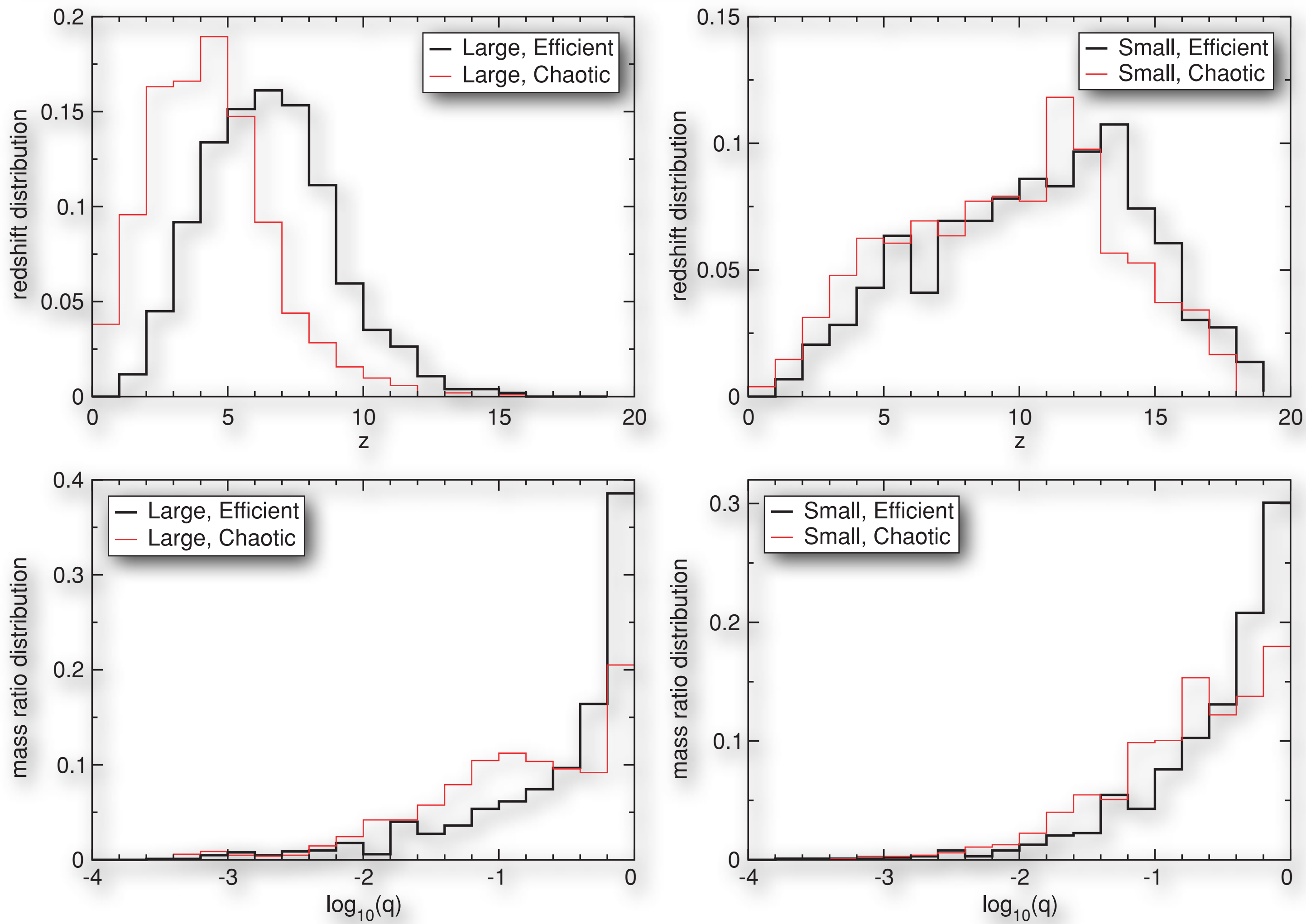
Massive black holes in LISA

- When and where do supermassive black holes form and grow?
- What is the mass function of supermassive black holes?
- What can we find in the environment around black holes?
  - Population of smaller black holes, neutron stars, white dwarfs?

Models of Black Hole Seeds and Their Evolution

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



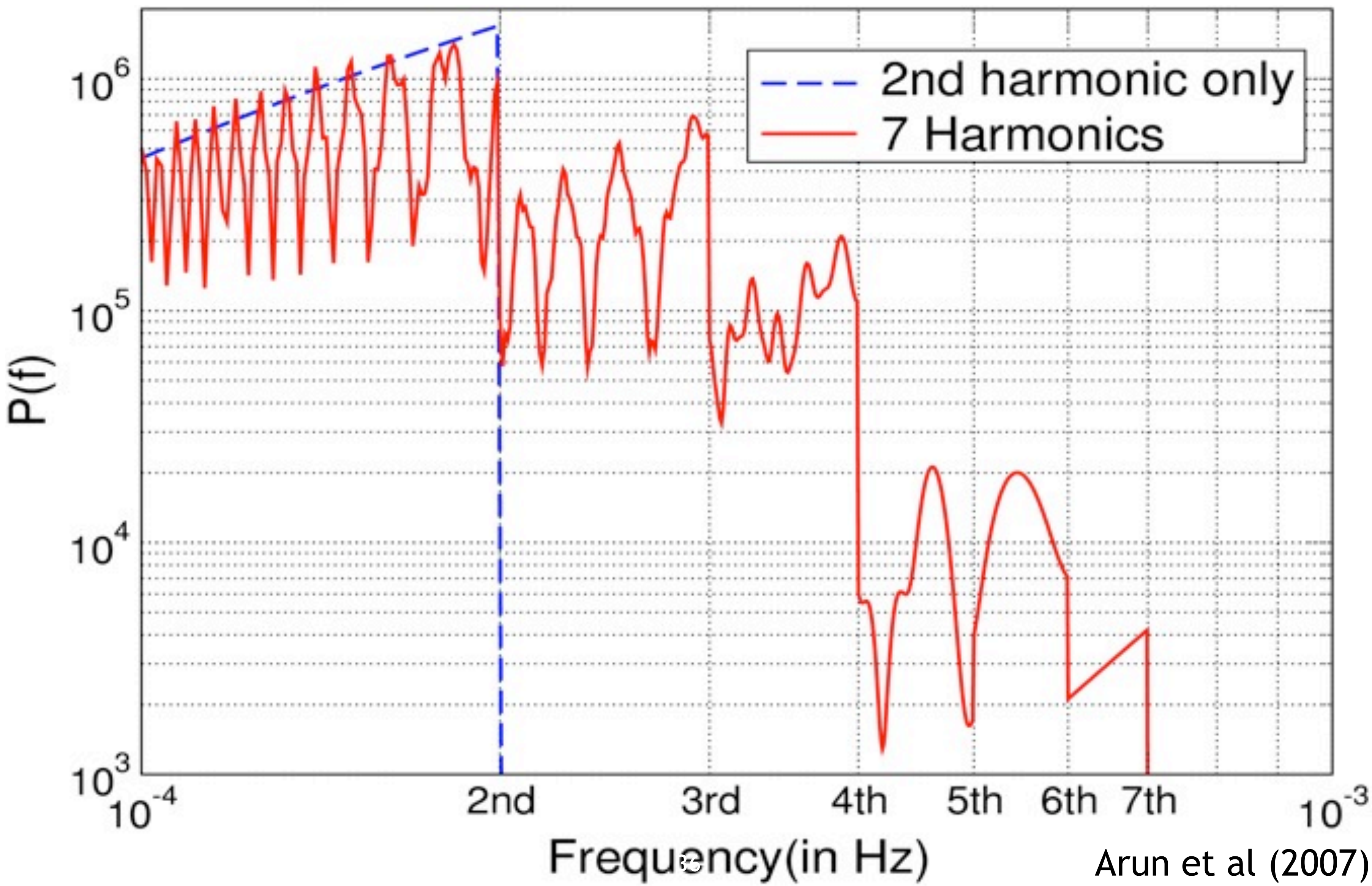
Expected Detection of SMBBH Mergers in LISA

- Numbers for the 6-link model are followed, within parenthesis, by those for the baseline (i.e., 4-link) LISA noise model
- LISA should detect and verify the nature of black hole seeds

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

Model	N	$N_{\rm det}$	$N_{10\% D_{\rm L}}$	$N_{10\,\rm deg^2}$	$N_{10\,\rm deg^2,10\% D_{\rm L}}$	$N_{1\rm deg^2}$	$N_{1\rm deg^2,1\% D_{\rm L}}$
SE	80	33 (25)	21 (8.0)	8.2 (1.5)	7.9 (1.1)	2.2 (0.6)	1.7 (0.1)
SC	75	34 (27)	17 (4.4)	6.1 (0.4)	5.5 (0.4)	1.3 (0.1)	1.3 (0.1)
LE	24	23 (22)	21 (7.7)	10 (0.8)	10 (0.7)	2.2 (0.1)	1.2 (0.05)
LC	22	21 (19)	14 (4.3)	6.5 (0.5)	5.4 (0.5)	1.8 (0.04)	1.0 (0.1)

Signal as seen in LISA

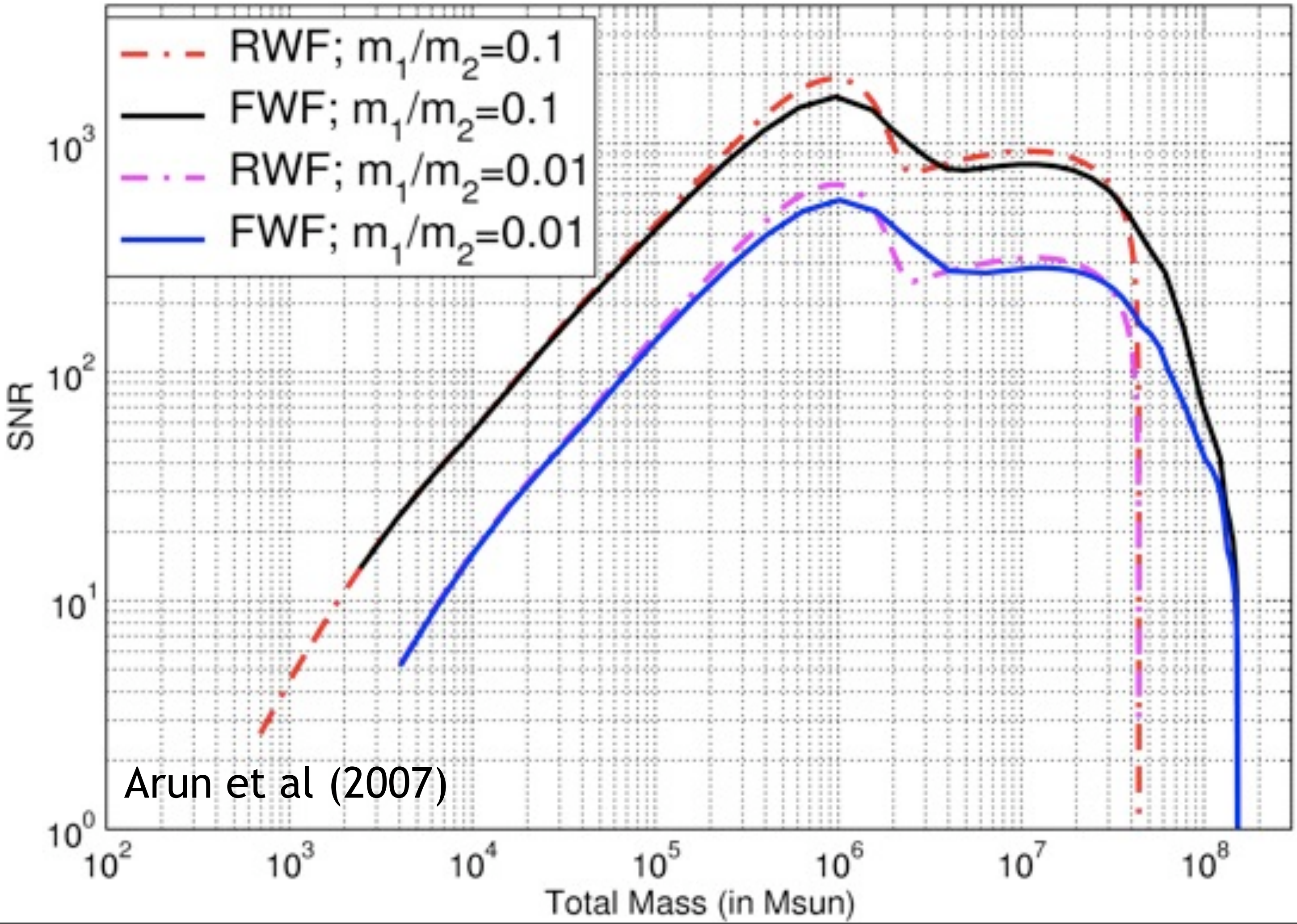


Arun et al (2007)

Mass reach of LISA

RWF=Restricted Waveform: only the dominant harmonic

FWF=Full Waveform: all harmonics up to 7 times the orbital frequency

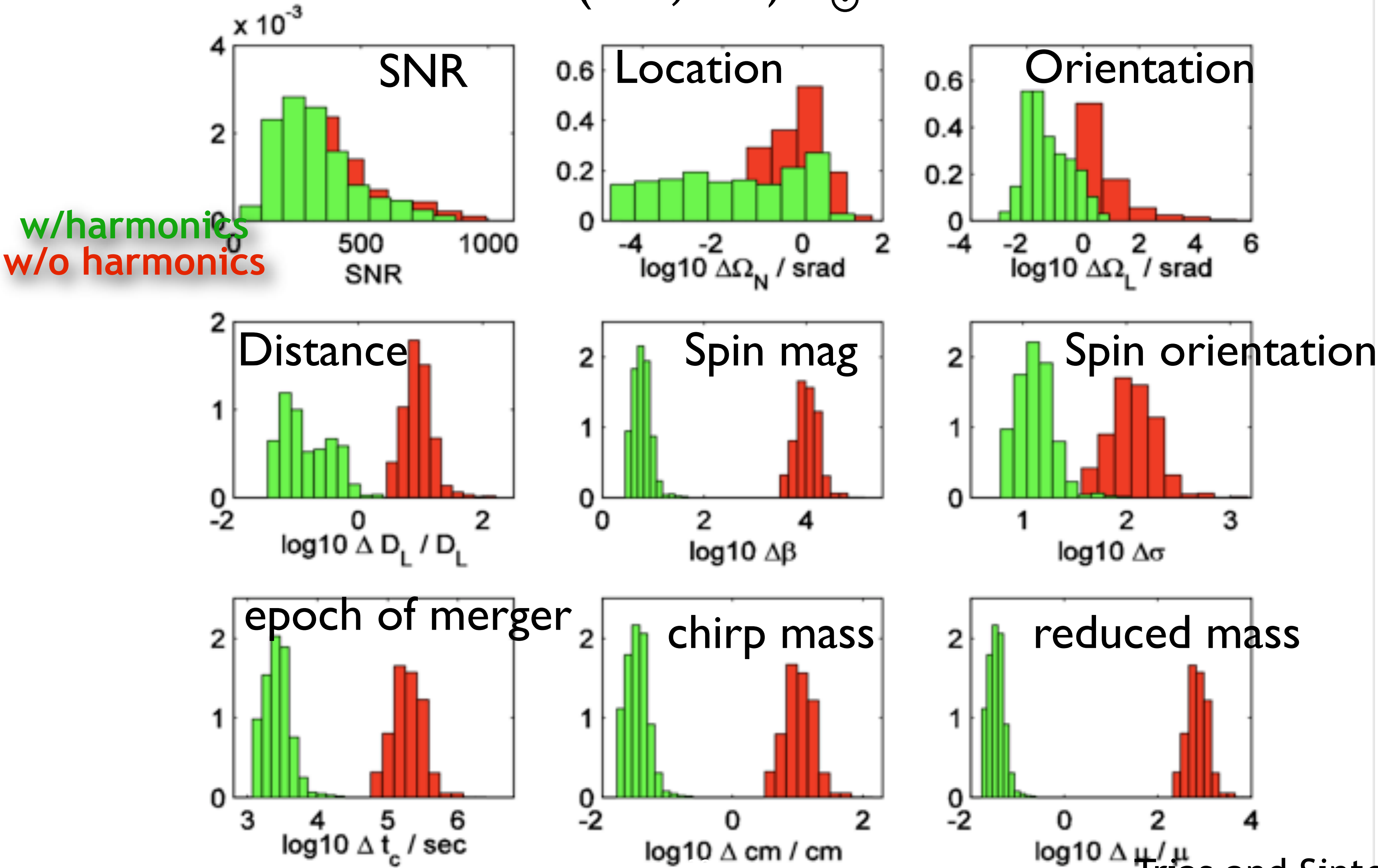


LISA's ability in measuring the Source

- Because of LISA's superb visibility to supermassive black holes the parameters of the binary can be measured to phenomenal accuracy: The parameters we are interested in are:
    - The epoch when the binary merges, chirp-mass and reduced mass of the binary, spin-parameters, the sky location, luminosity distance, orientation of the binary with respect to the line of sight.

Parameter measurement distributions

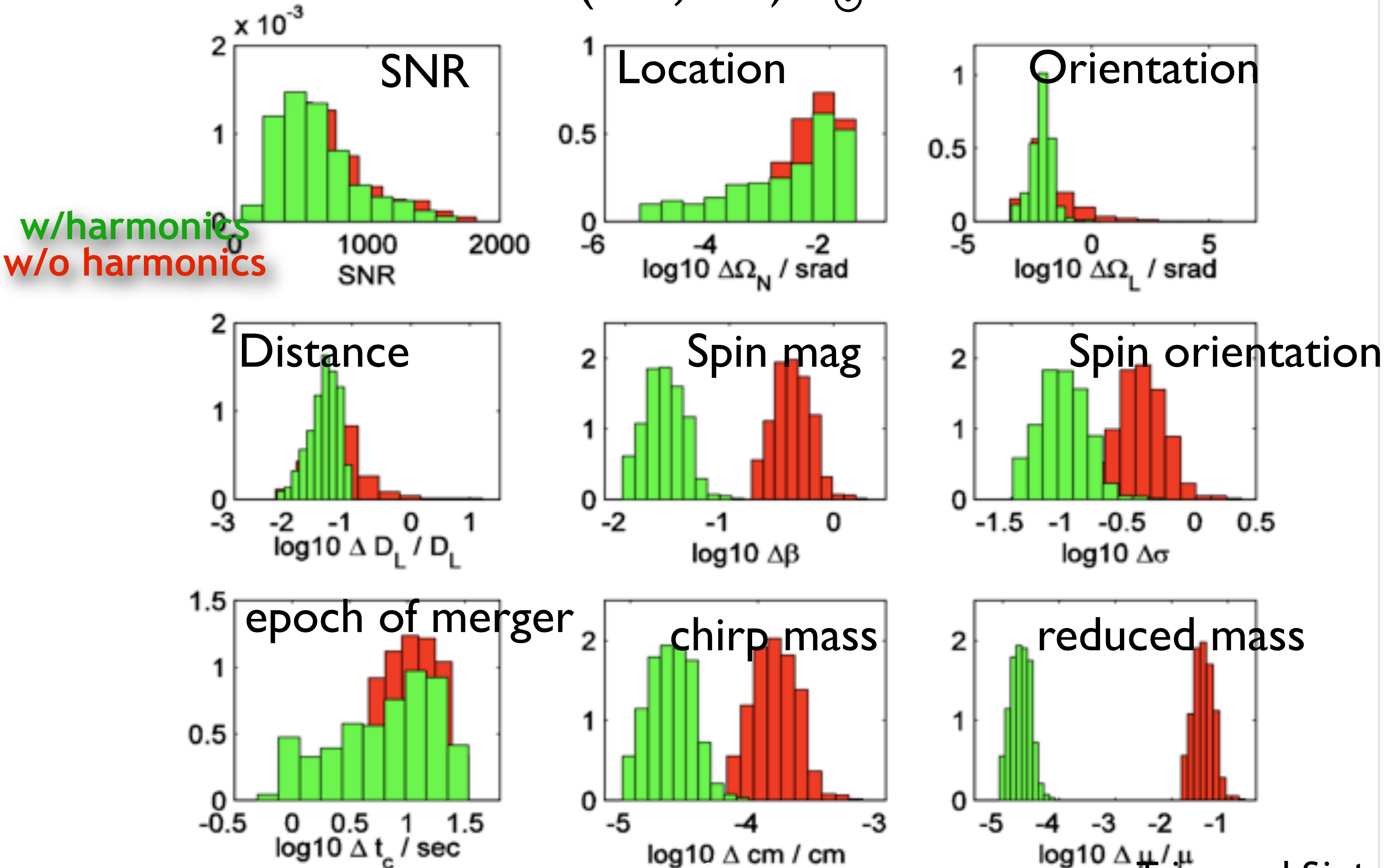
$(10^6, 10^6)M_\odot$



Trias and Sintes

Parameter measurement distributions

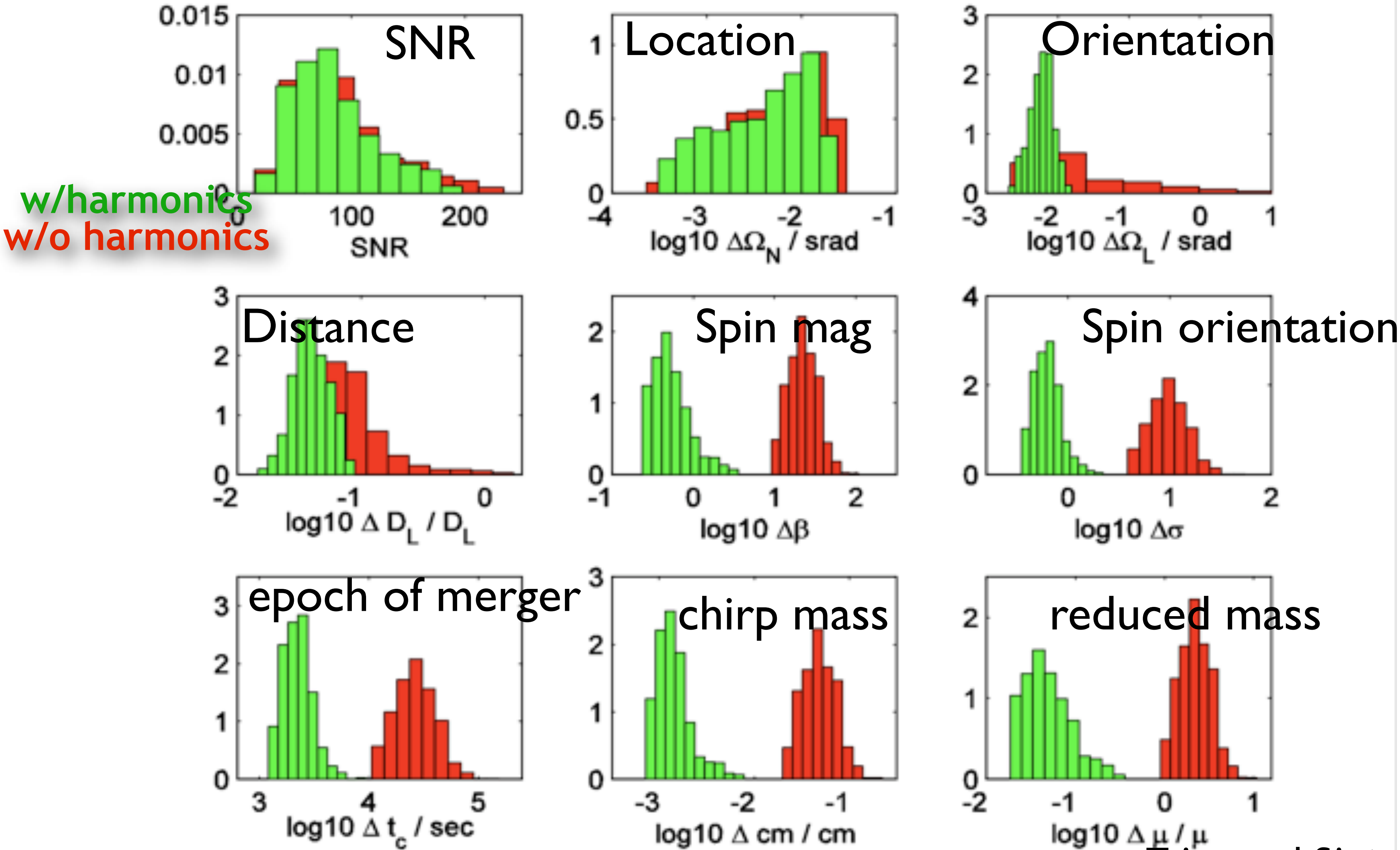
$(10^5, 10^5)M_\odot$



Trias and Sintes

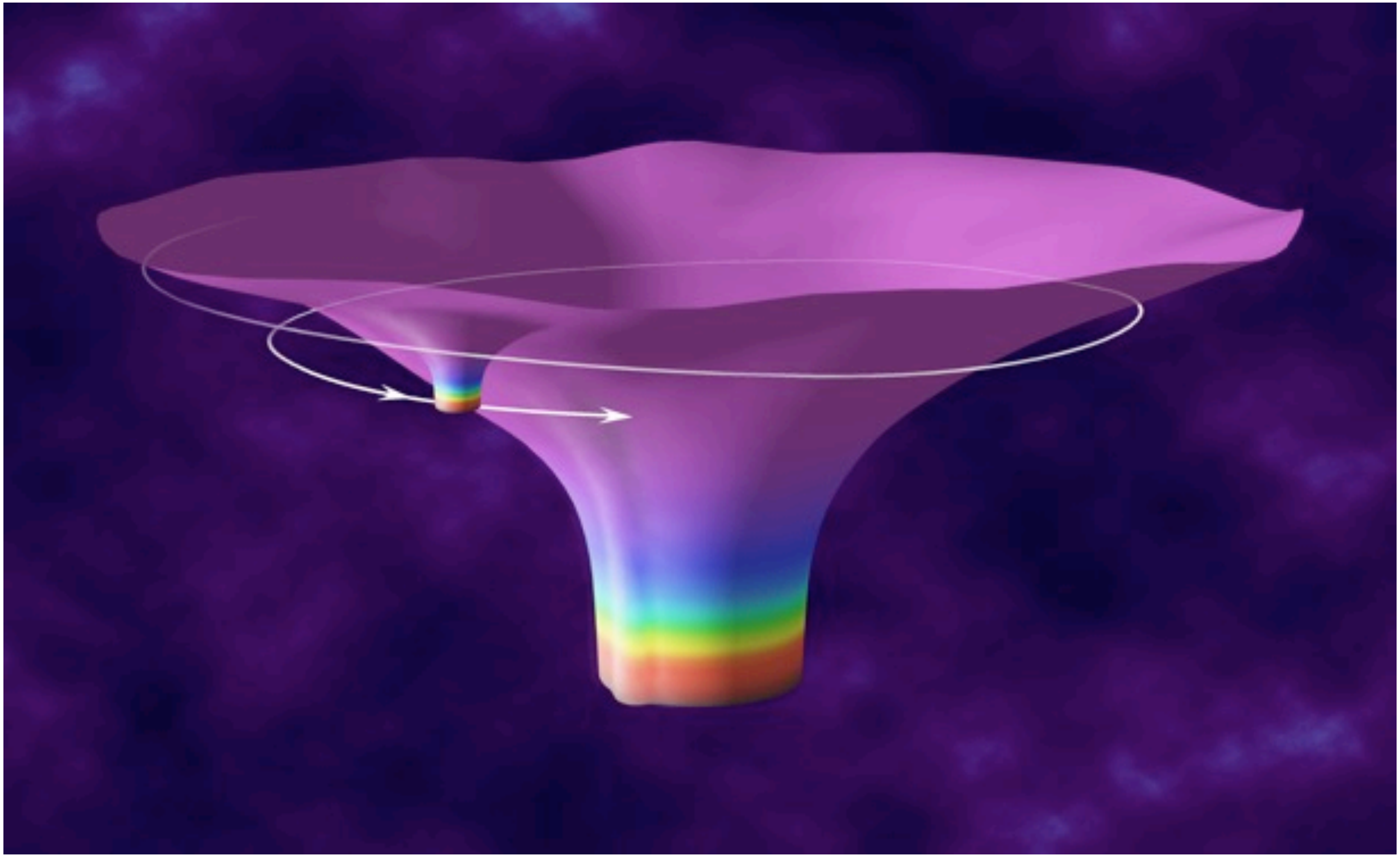
Parameter measurement distributions

$(10^5, 10^7)M_\odot$



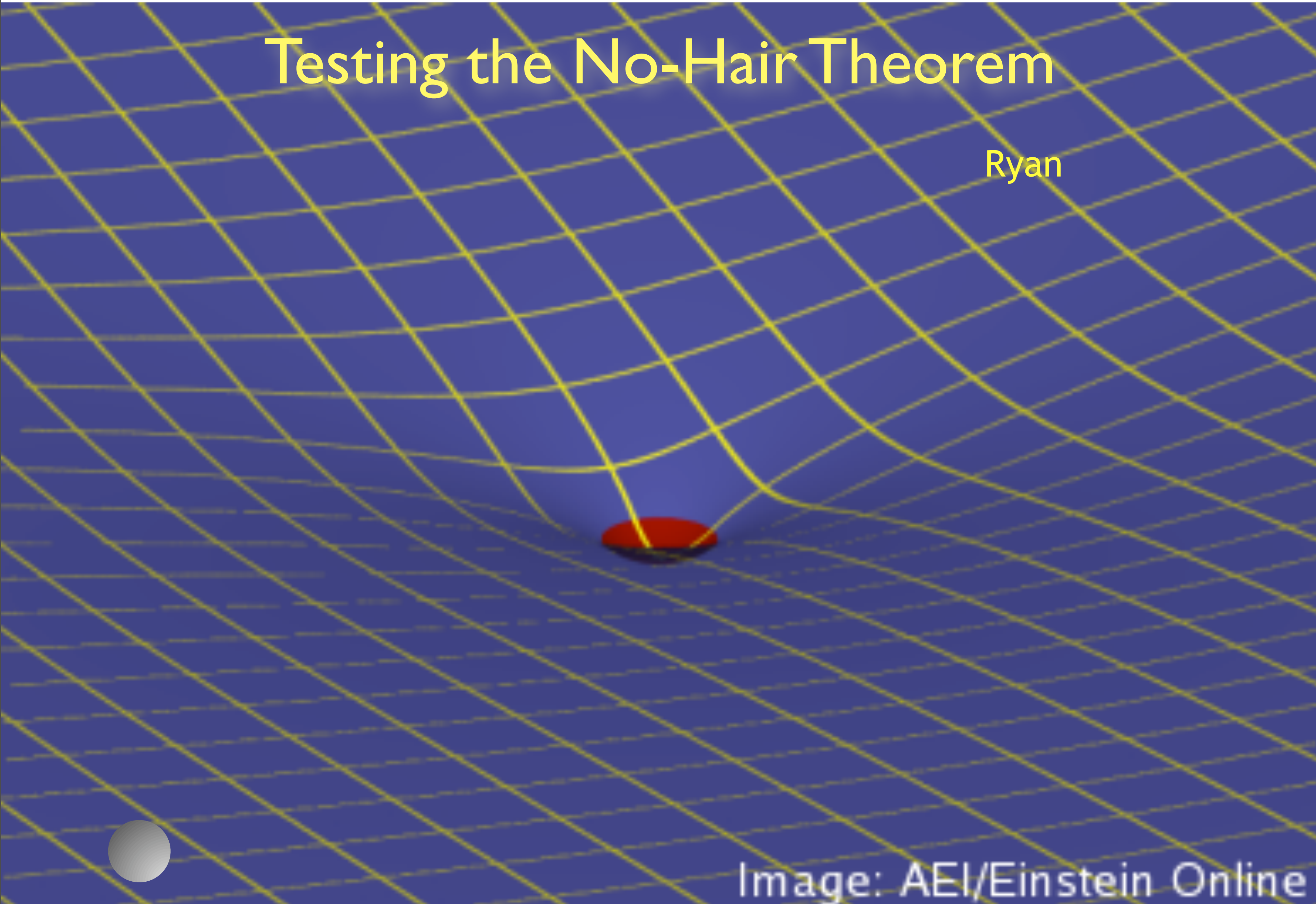
Trias and Sintes

Capture of Small Black Holes by Intermediate-Mass Black Holes



Testing the No-Hair Theorem

Ryan



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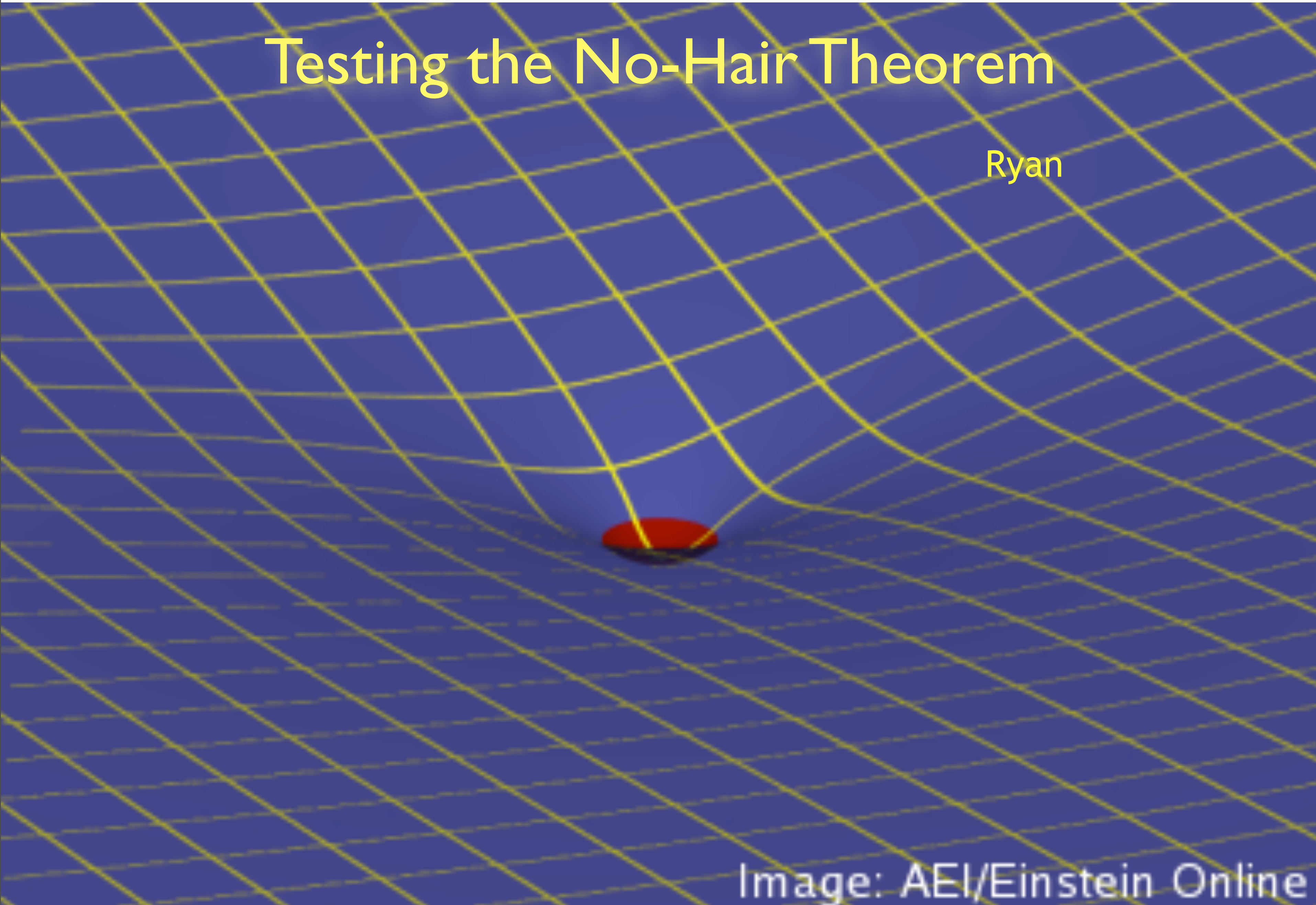
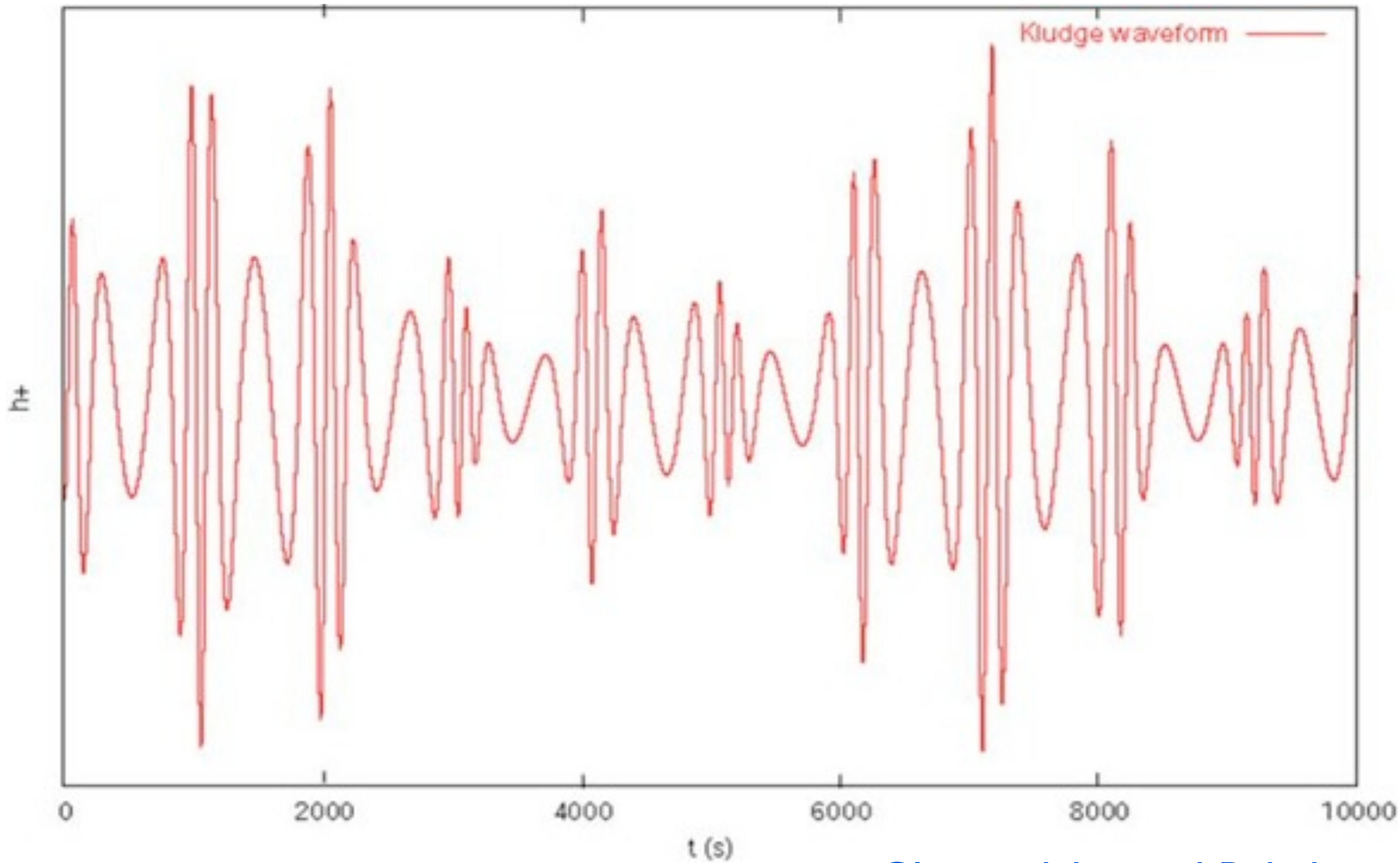


Gravitational Capture and Testing Uniqueness of Black Hole Space-times

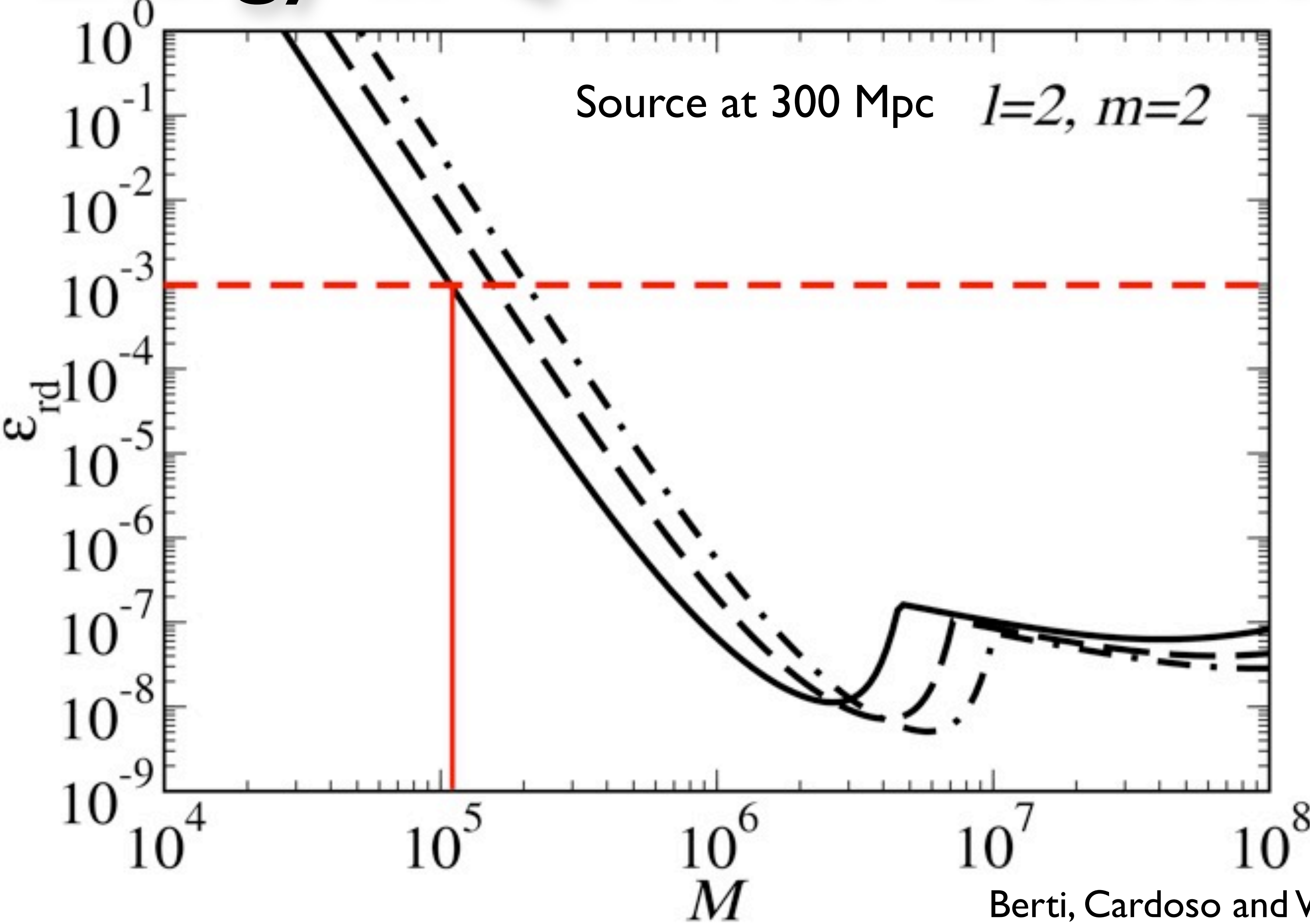


Glampedakis and Babak

Black hole quasi-normal modes

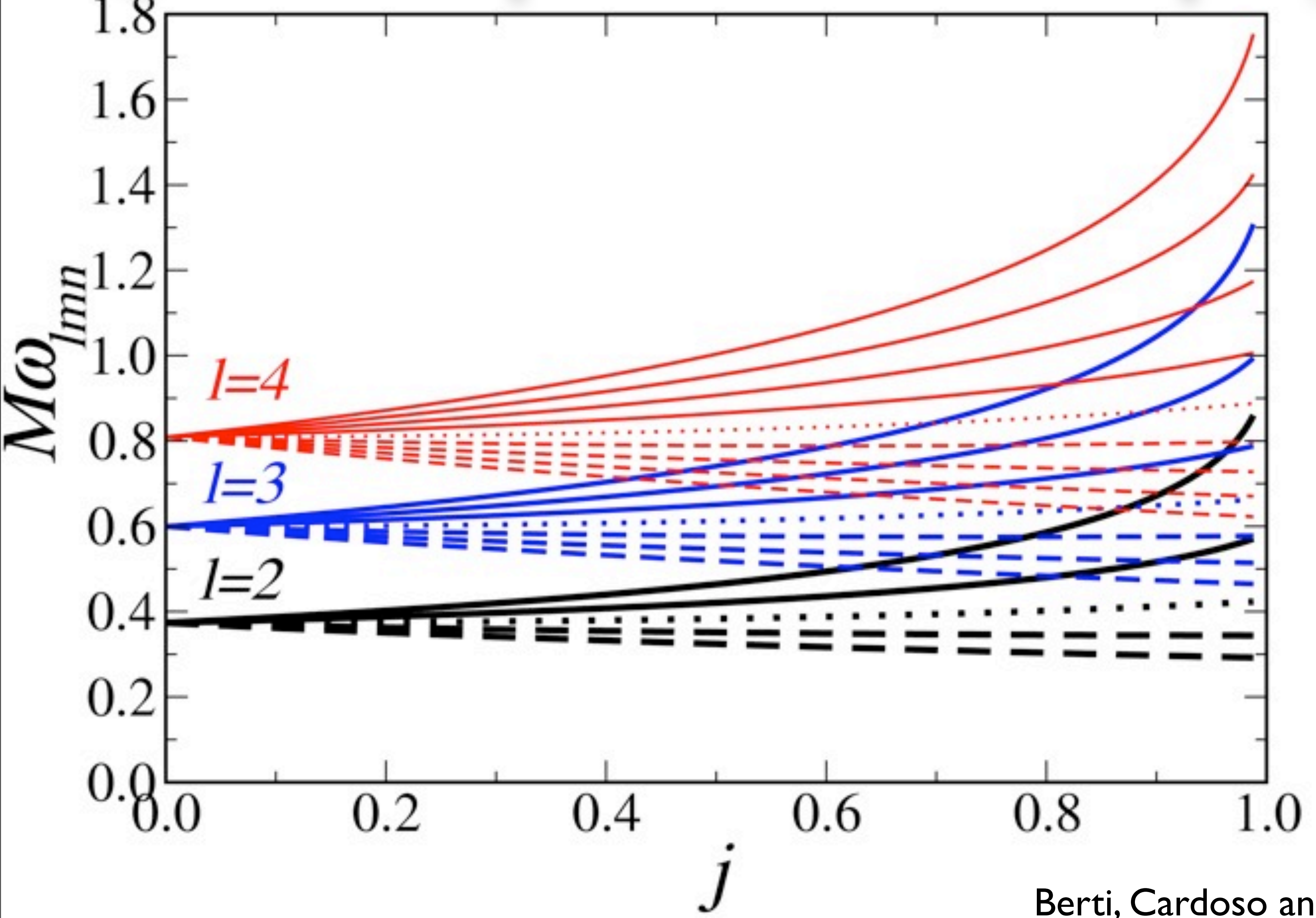
- Damped sinusoids with characteristic frequencies and decay times
  - In general relativity frequencies f_{lmn} and decay times t_{lmn} all depend only on the mass M and spin q of the black hole
- Measuring two or modes unambiguously, would severely constrain general relativity
  - If modes depend on other parameters (e.g., the structure of the central object), then test of the consistency between different mode frequencies and damping times would fail
- LISA should be able to observe formation of black holes out to red-shifts of several

Energy in QNM for Detection



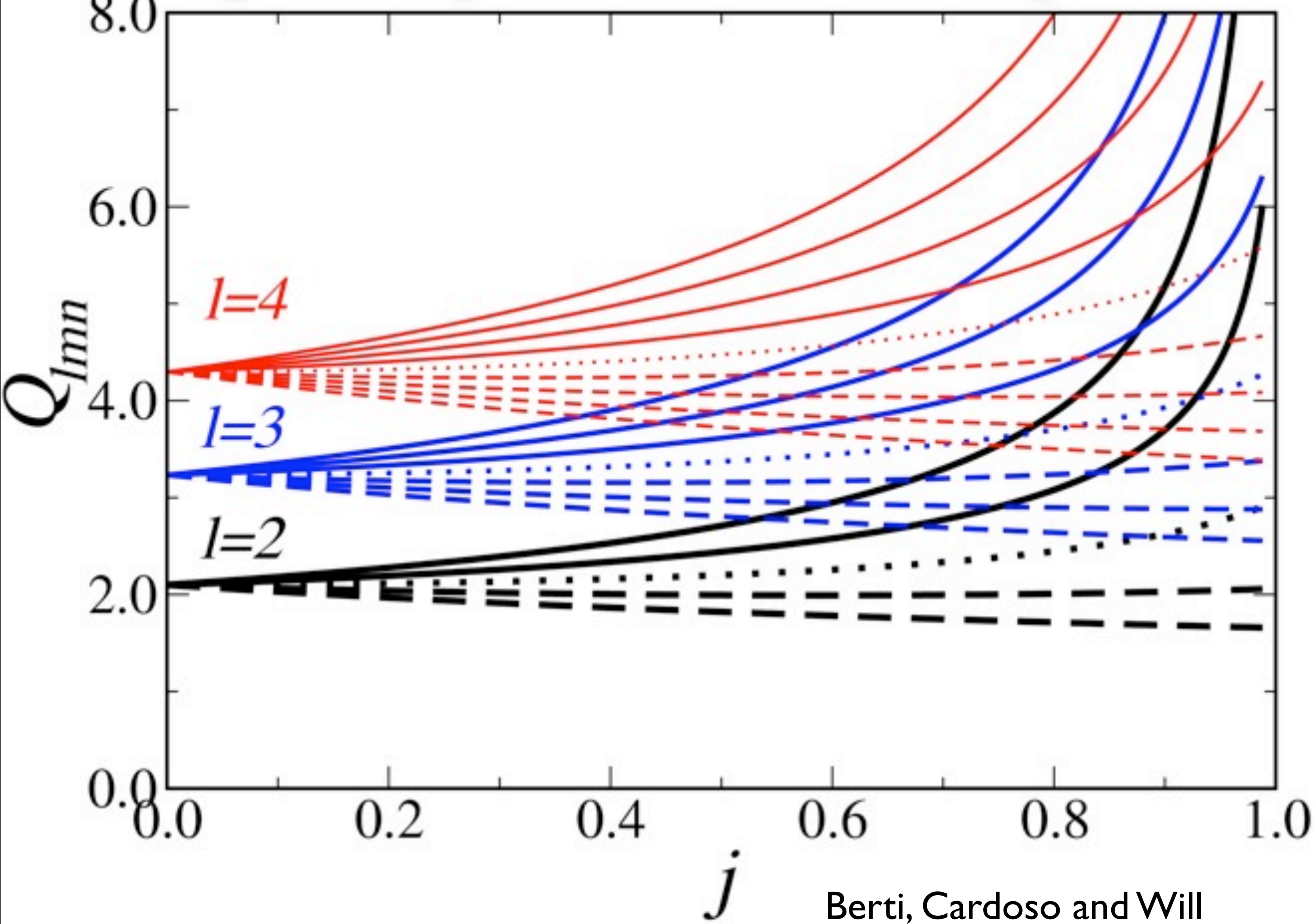
Berti, Cardoso and Will

QNM Frequencies Vs. BH Spin j



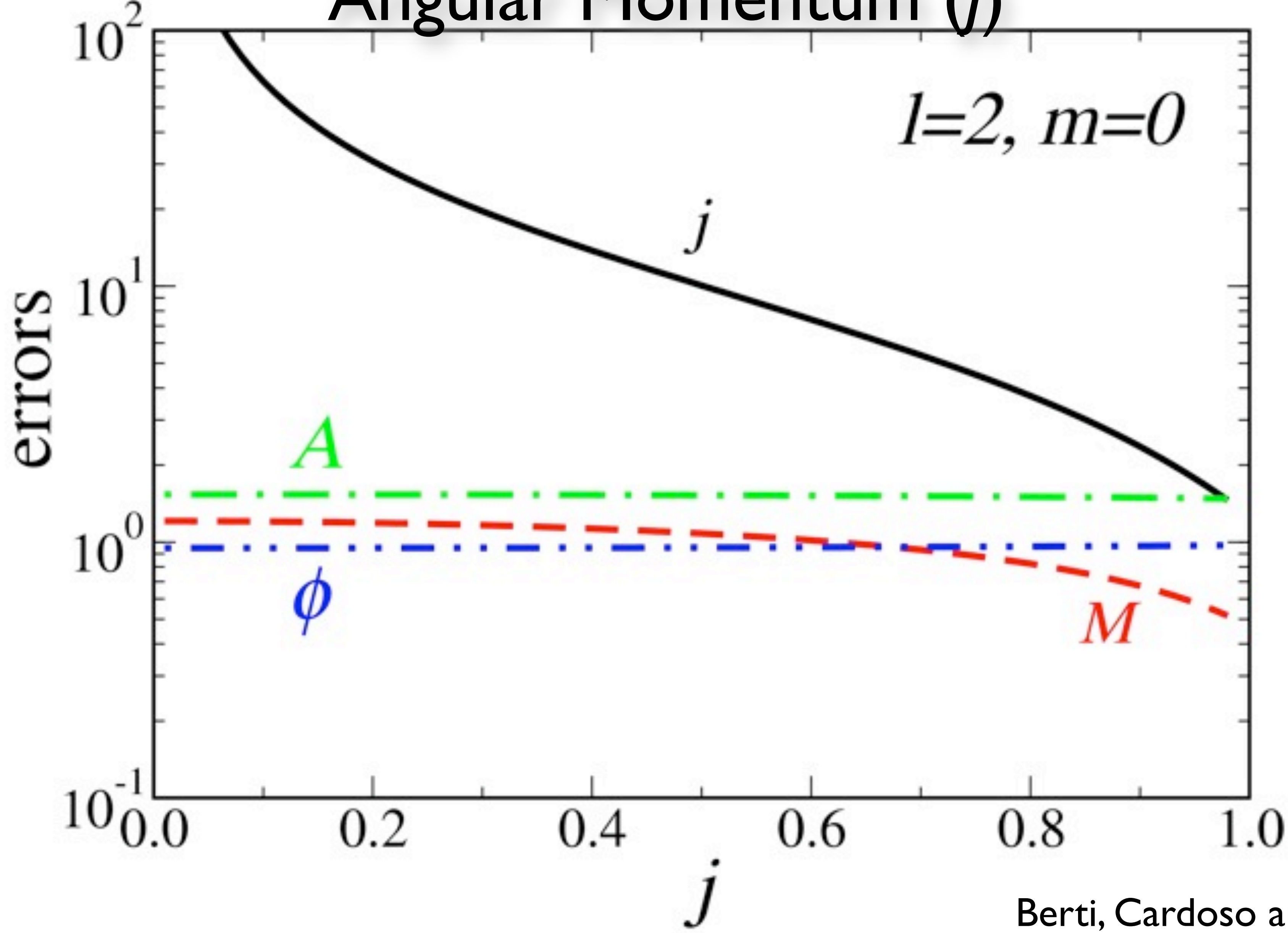
Berti, Cardoso and Will

Quality Factor of QNMs



Berti, Cardoso and Will

Error (x SNR) in Amplitude (A), Mass (M), Angular Momentum (j)



Berti, Cardoso and Will

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

Cosmological parameters

- Luminosity distance Vs. red shift depends on a number of cosmological parameters H_0, Ω_{M}, Ω_{b}, Ω_{Λ}, w, etc.

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

- 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.

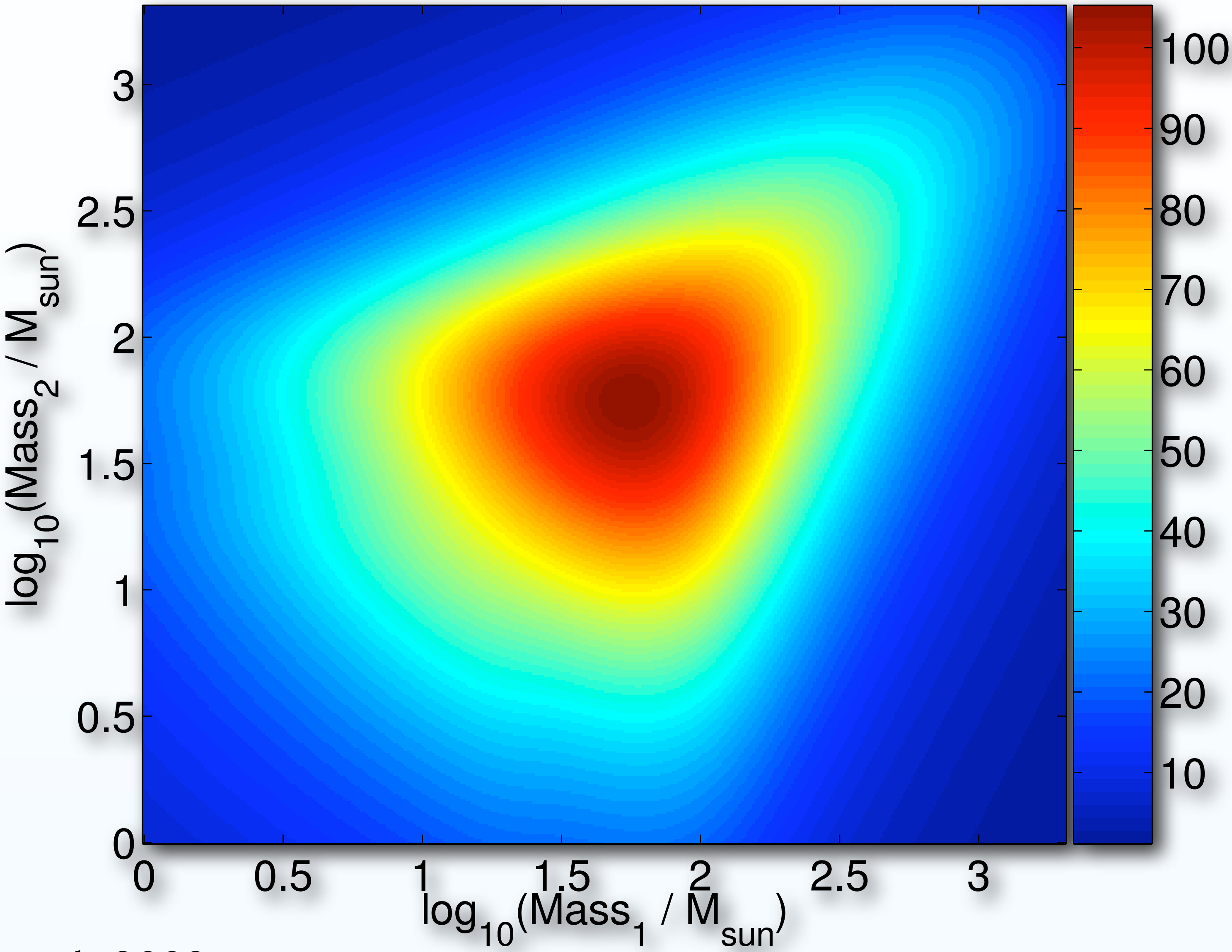
Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_{\mathrm{L}}}$
  - 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

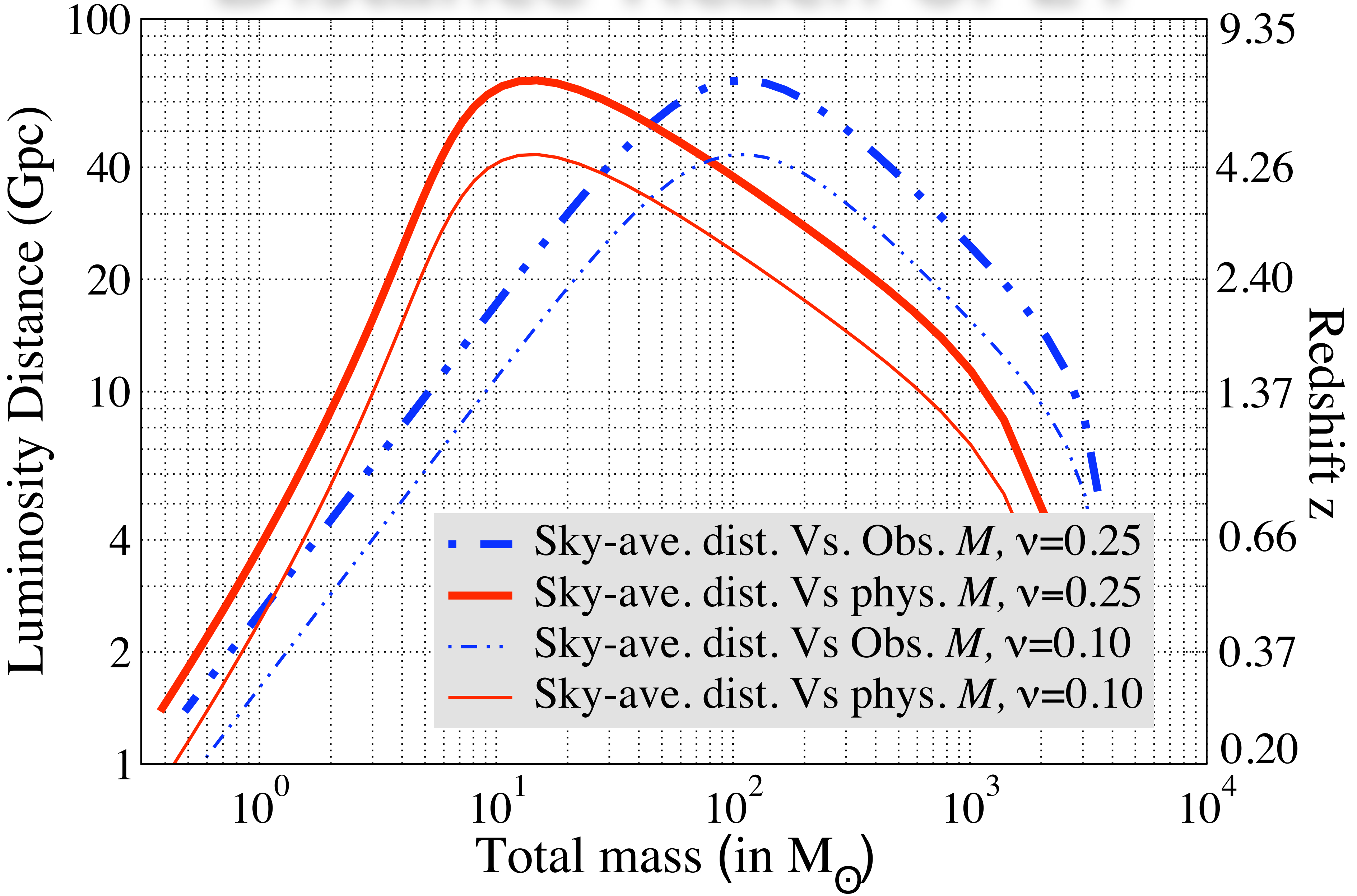
ET and Cosmology

SNR in ET for coalescences at z=0.5

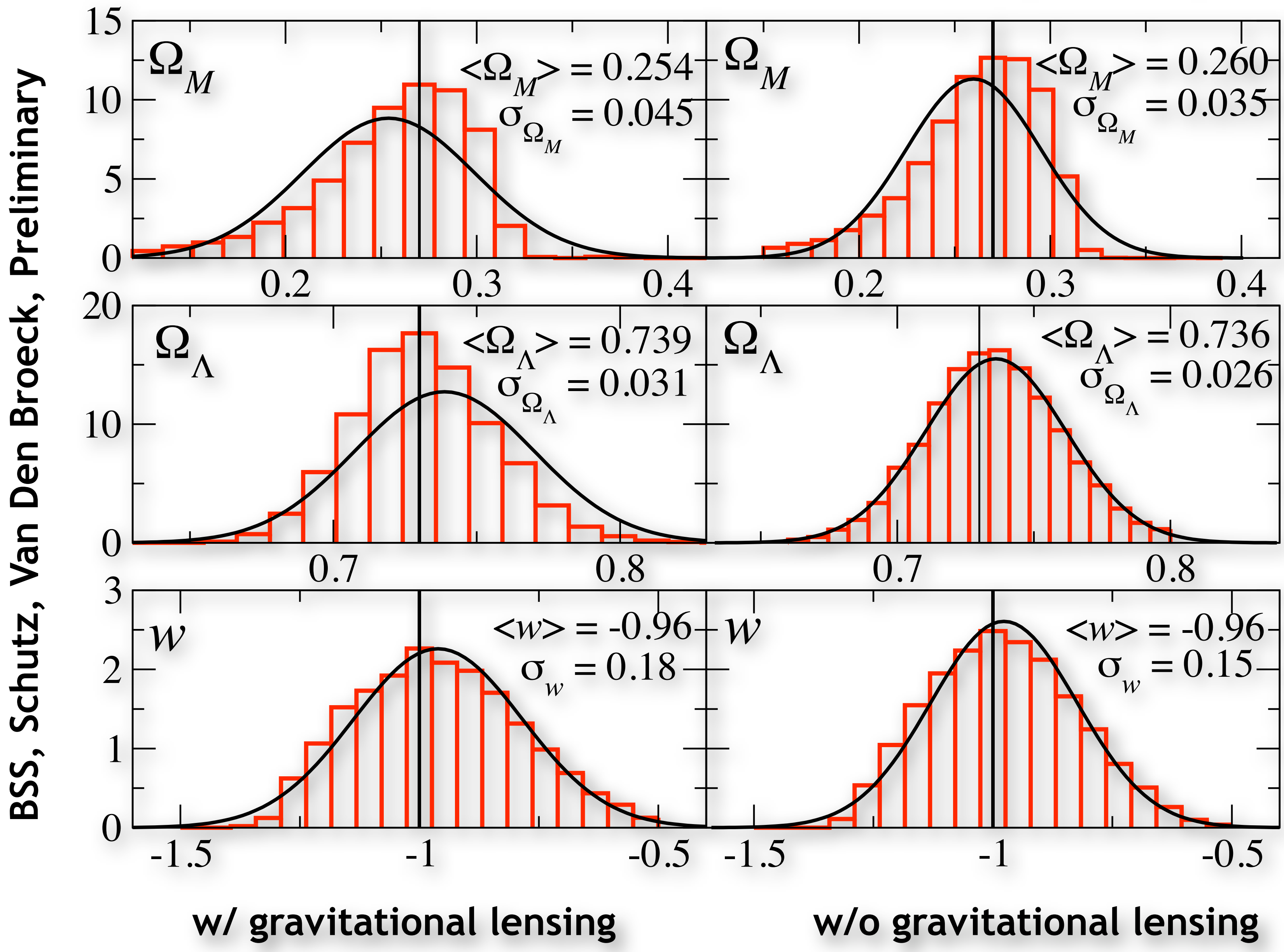


Bose et al, 2009

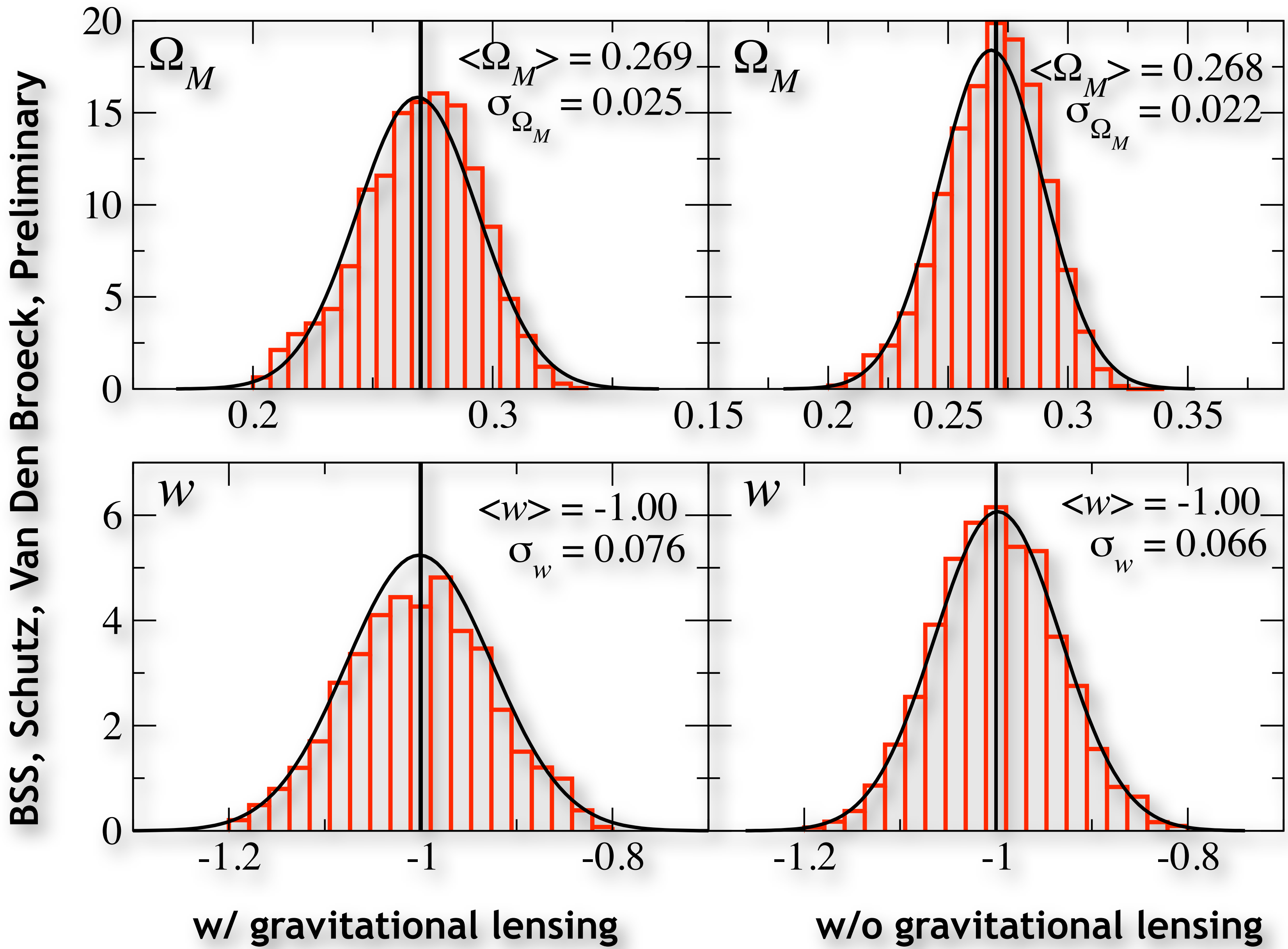
Distance Reach of ET



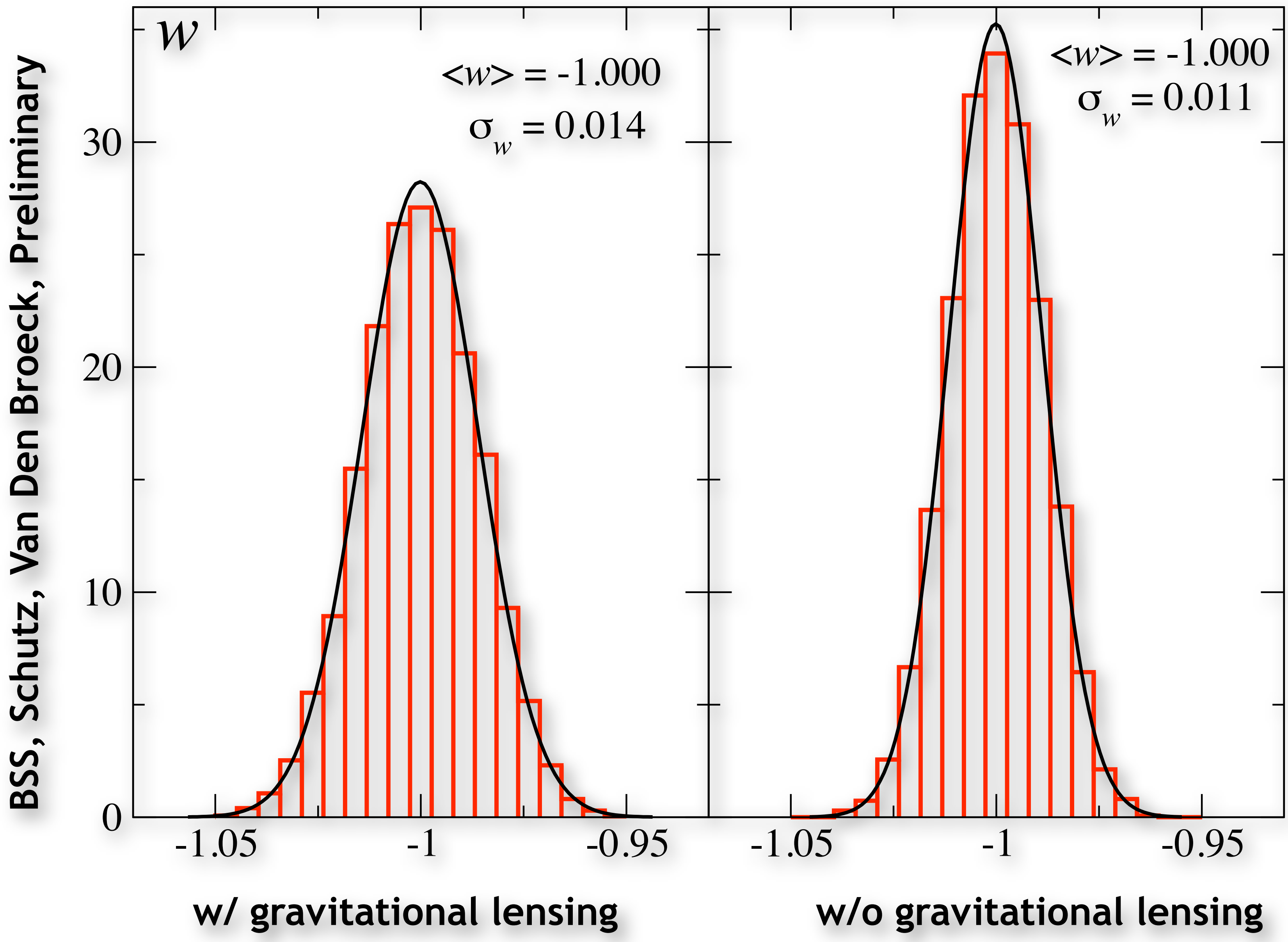
Measurement of *DM*, *DE*, *w*



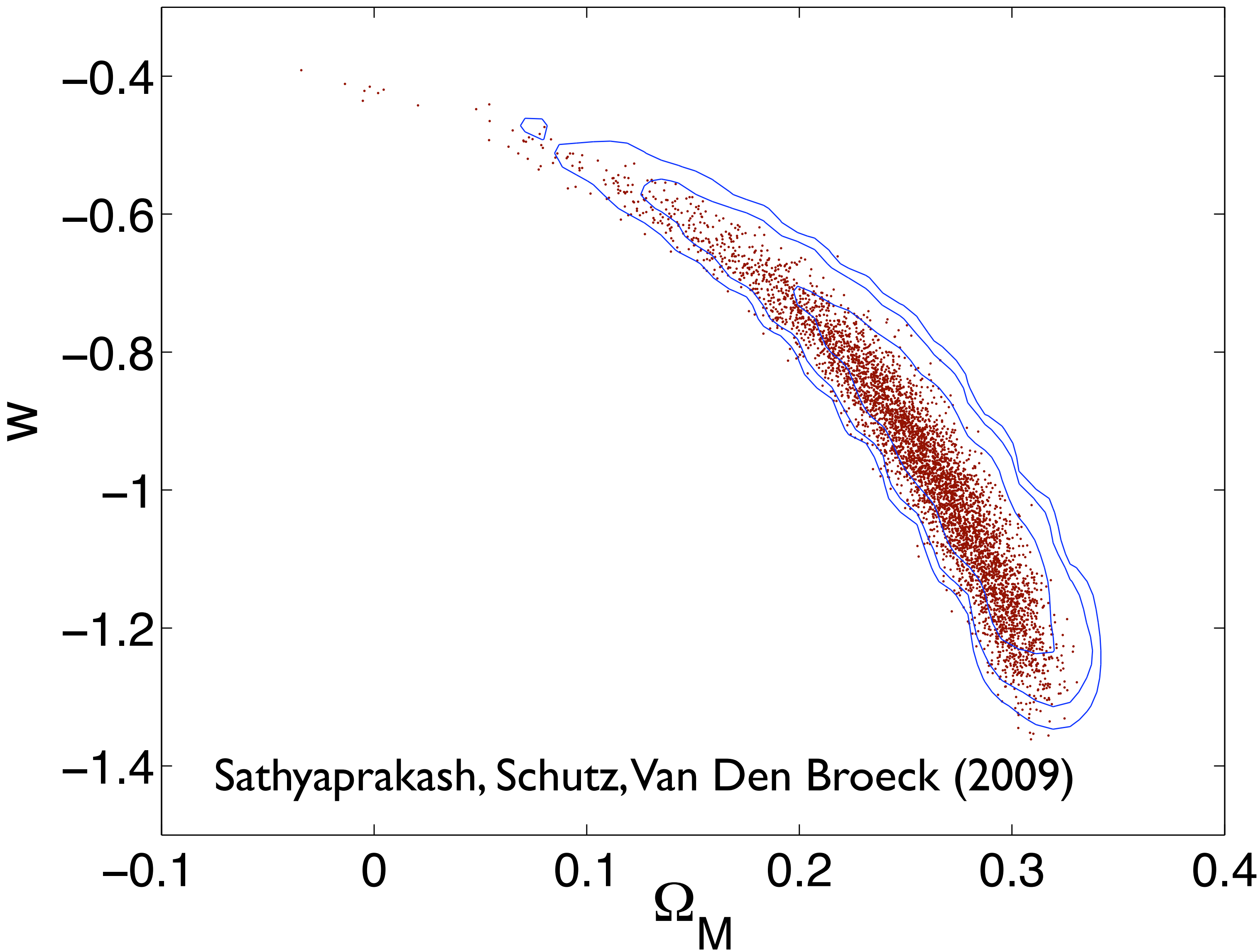
Measurement of *DM* and *w*



Measurement of *w*



Measuring Dark Energy and Dark Matter



LISA's ability to measure cosmological parameters

Measuring w with LISA

$\Delta \ln D_L$ (10^{-2})	$\Delta\Omega_S$ (10^{-6} str)	$\Delta \ln \mathcal{M}$ (10^{-6})	$\Delta\delta$ (10^{-6})	Δt_C (sec)	$\mathbf{N}_{\text{clusters}}$	Δw
1.2	12	6.0	31	1.7	**0.25**	0.068
0.88	4.3	4.6	23	1.2	**0.088**	0.050
1.1	110	4.7	21	1.7	**2.2**	0.062
0.58	13	3.5	16	1.1	**0.27**	0.033
0.25	170	3.3	12	2.6	**3.5**	⋯
0.17	26	2.7	9.7	1.1	**0.53**	0.0096
0.74	150	3.1	15	1.2	**3.1**	⋯
0.19	13	2.5	12	0.58	**0.27**	0.011
15	84	2.3	8.0	2.1	**1.7**	0.82
0.11	8.1	1.7	7.9	0.69	**0.17**	0.0062
0.42	220	3.9	15	2.9	**4.5**	⋯
0.24	65	3.0	11	1.6	**1.3**	0.014
0.58	410	3.5	13	1.1	**8.4**	⋯
0.45	300	2.9	10	0.74	**6.1**	⋯

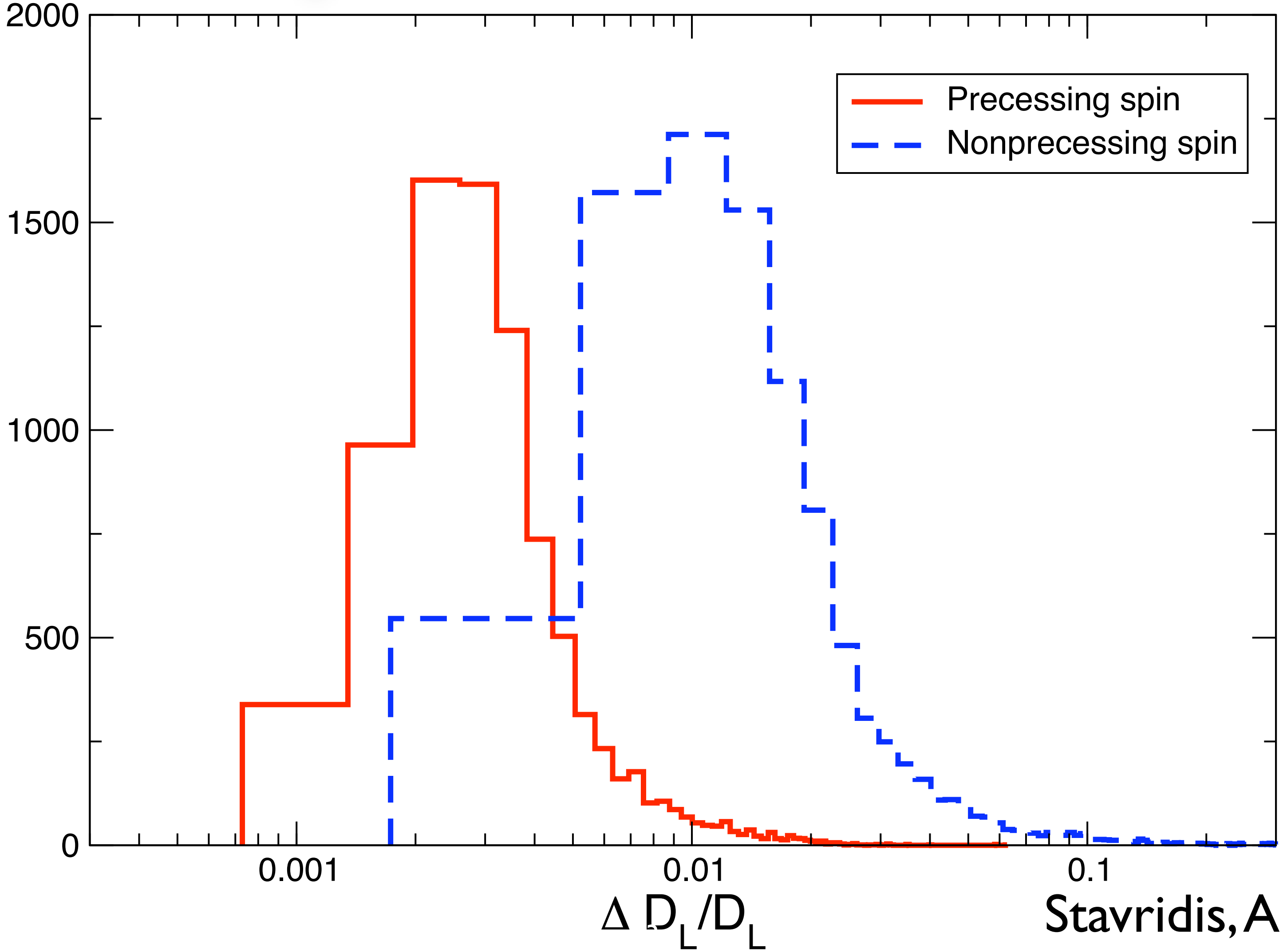
$$(m_1, m_2) = (10^5, 10^6)M_\odot$$

A lighter system

$\Delta \ln D_L$ (10^{-2})	$\Delta\Omega_S$ $(10^{-6}$ str$)$	$\Delta \ln \mathcal{M}$ (10^{-6})	$\Delta\delta$ (10^{-6})	Δt_C (sec)	$\mathbf{N}_{\text{clusters}}$	Δw
1.3	21	5.5	13	3.2	**0.43**	0.073
1.0	8.4	4.2	9.1	2.1	**0.17**	0.056
1.1	120	4.2	9.2	2.5	**2.4**	0.062
0.70	25	3.3	6.5	1.7	**0.51**	0.039
0.33	170	3.4	5.8	2.7	**3.5**	⋯
0.25	53	2.6	4.2	1.6	**1.1**	0.014
0.78	160	3.0	6.8	1.7	**3.3**	⋯
0.26	27	2.3	5.0	1.0	**0.55**	0.015
15	87	2.4	3.8	2.2	**1.8**	1.0
0.19	25	2.0	3.9	1.3	**0.51**	0.011
0.47	240	4.1	7.2	3.1	**4.9**	⋯
0.32	110	2.9	4.8	2.1	**2.2**	0.018
0.57	420	3.1	6.1	1.6	**8.6**	⋯
0.50	350	2.5	4.2	1.1	**7.1**	⋯

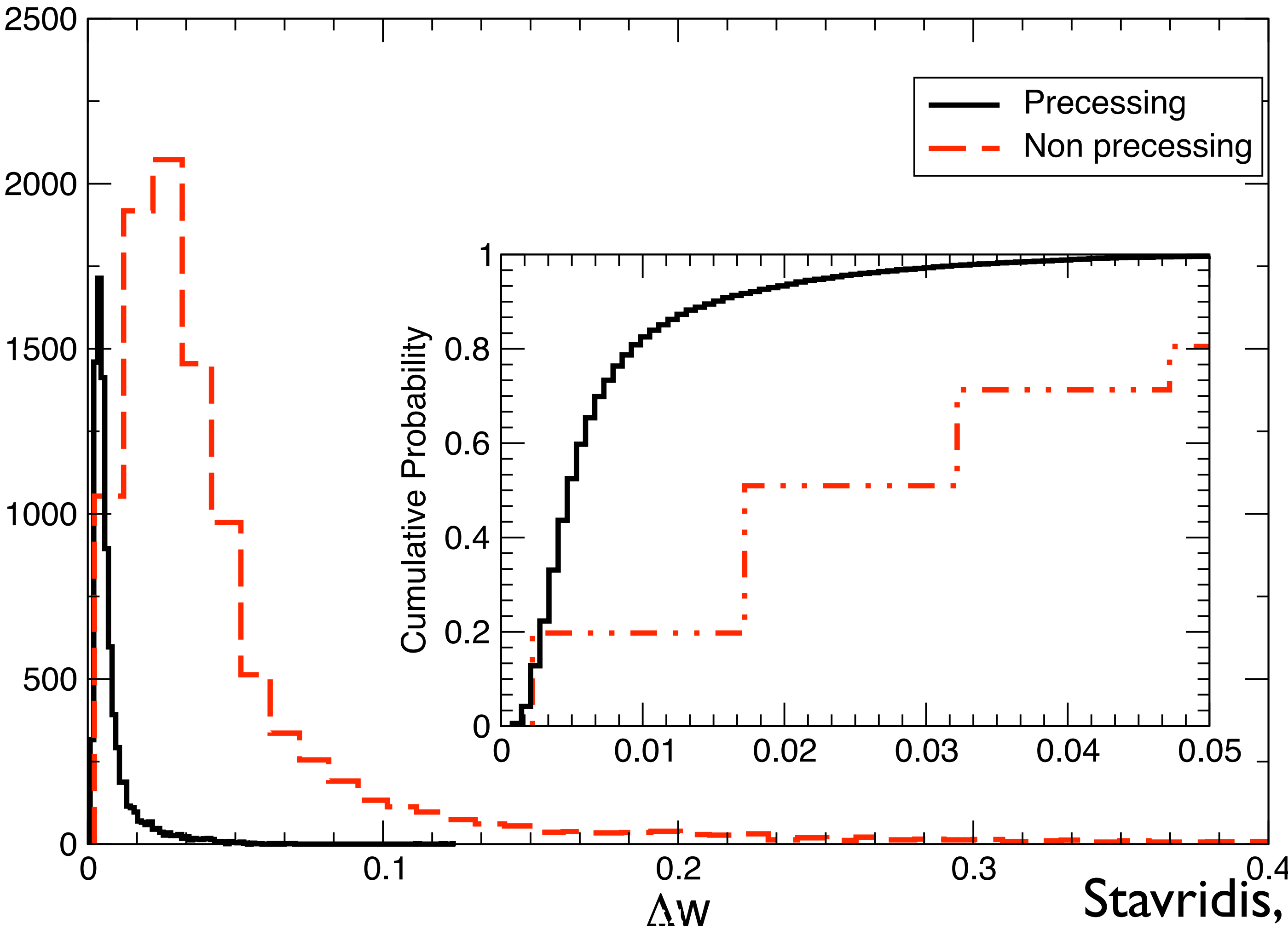
$$(m_1, m_2) = (6.45 \times 10^4, 1.29 \times 10^6)M_\odot$$

Spin-Precession: More accurate Luminosity Distance Measurement



Stavridis, Arun, Will

Spin-Precession: Improvement in Dark Energy Measurement



Stavridis, Arun, Will

Fundamental Physics

- Properties of gravitational waves
  - Testing the wave generation formula 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 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

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

- Can be used to set limits on the mass of the graviton - no strong motivation for massive graviton theory due to vDVZ discontinuity, but might be avoided

Will (1994, 98)

Massive Graviton: Dispersion as Waves Propagate

- A massive graviton induces dispersion in the waves

$$hf \gg m_{\rm g}c^2 \qquad\qquad \frac{v_{\rm g}^2}{c^2} = 1 - \frac{m_{\rm g}^2 c^4}{E^2},$$

$$v_{\rm g}/c \approx 1 - \tfrac{1}{2}(c/\lambda_{\rm g} f)^2, \text{ where } \lambda_{\rm g} = h/m_{\rm g}c$$

- Arrival times are altered due to a massive graviton - frequency-dependent effect

$$t_a = (1+Z)\left[t_e + \frac{D}{2\lambda_g^2 f_e^2}\right]$$

Will (1994, 98)

Bound on λ_g as a function of total mass

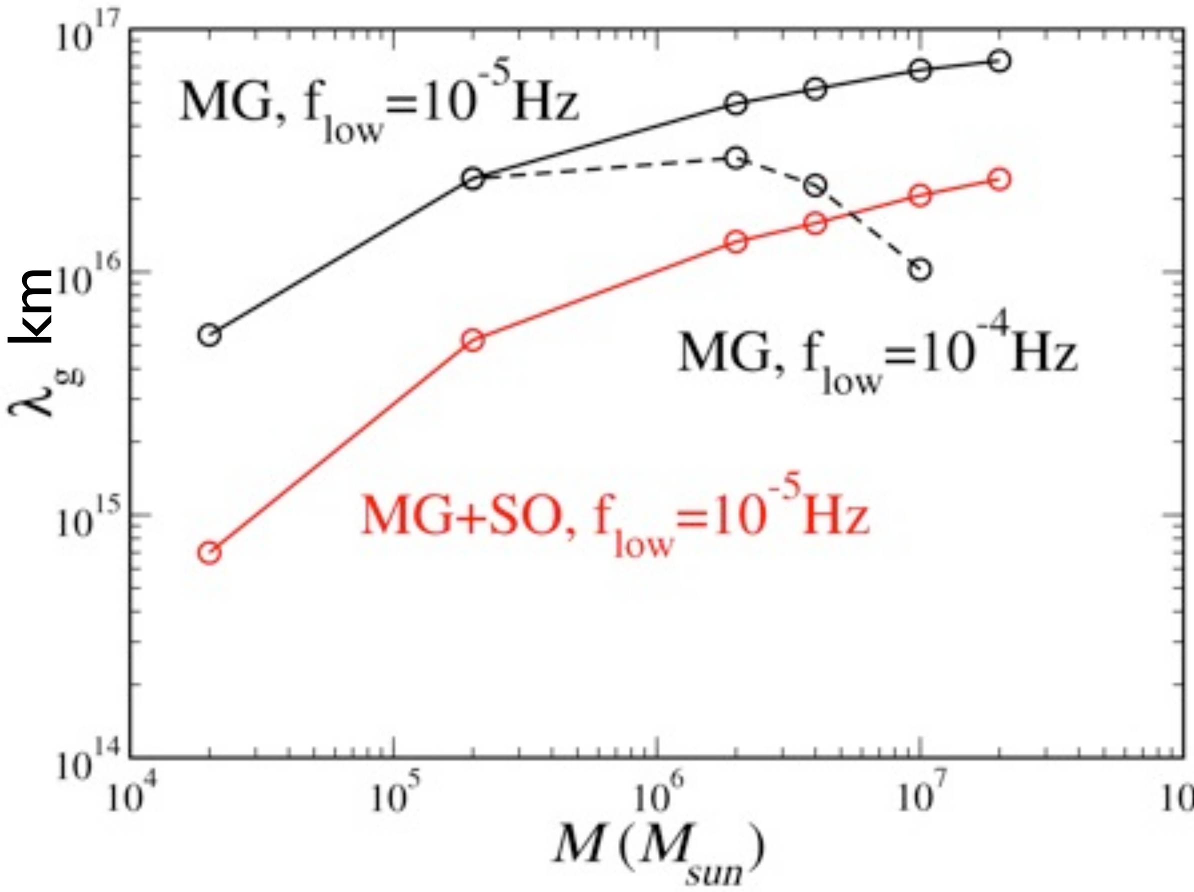
- Limits based on GW observations will be five orders-of-magnitude better than solar system limits

$$V(r) = \frac{GM}{r}\exp(-r/\lambda_{\rm g}),$$

$$\lambda_{\rm g} > 2.8 \times 10^{12}\ {\rm km}$$

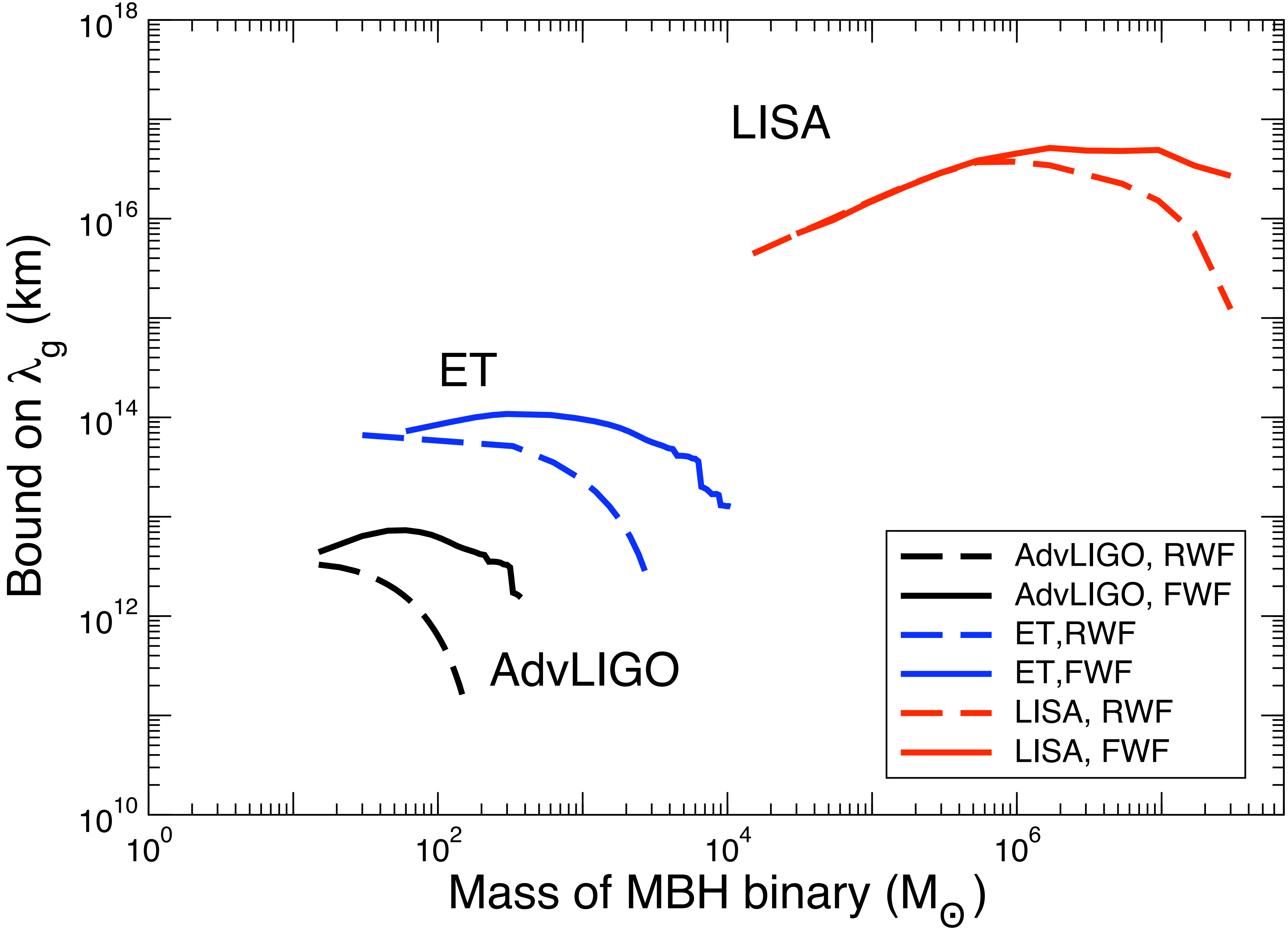
- Still not as good as (model-dependent) limits based on dynamics of galaxy clusters $\lambda_{\rm g} > 6 \times 10^{19}\ {\rm km}$

1m = 0.2 μeV



Berti, Buonanno and Will (2006)

Arun and Will (2009)

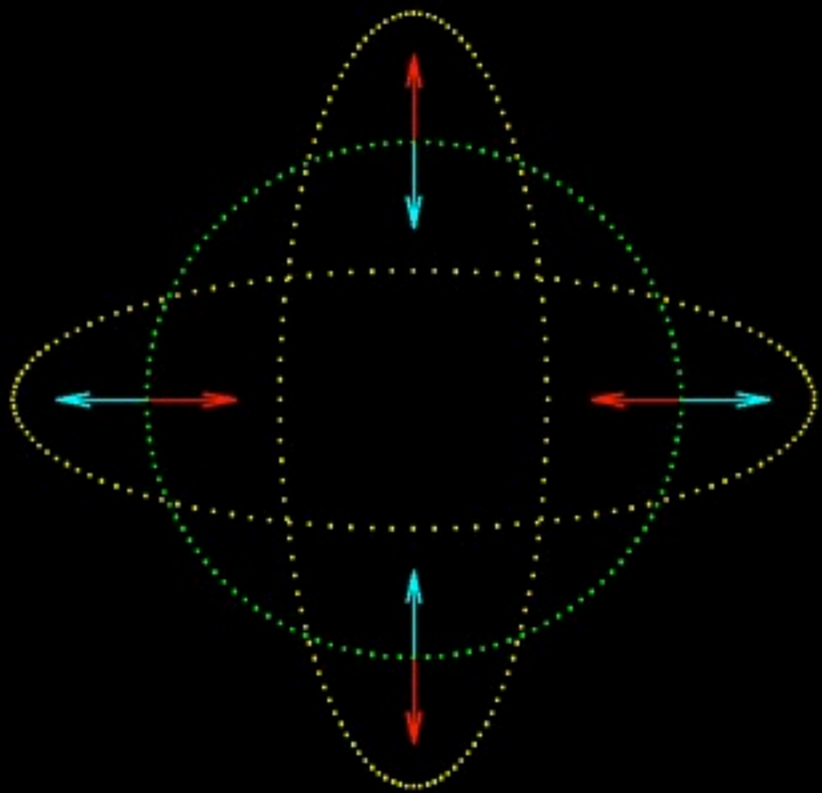


Counting the Polarization States

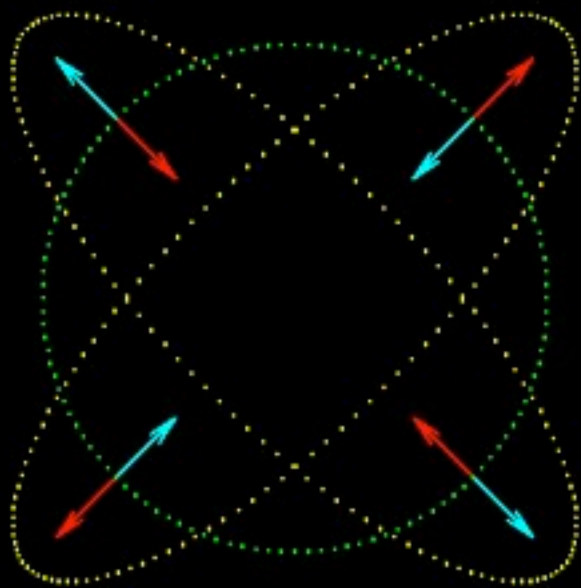
Only two states in GR: h_+ and $h_\times$

Counting the Polarization States

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



Plus polarization

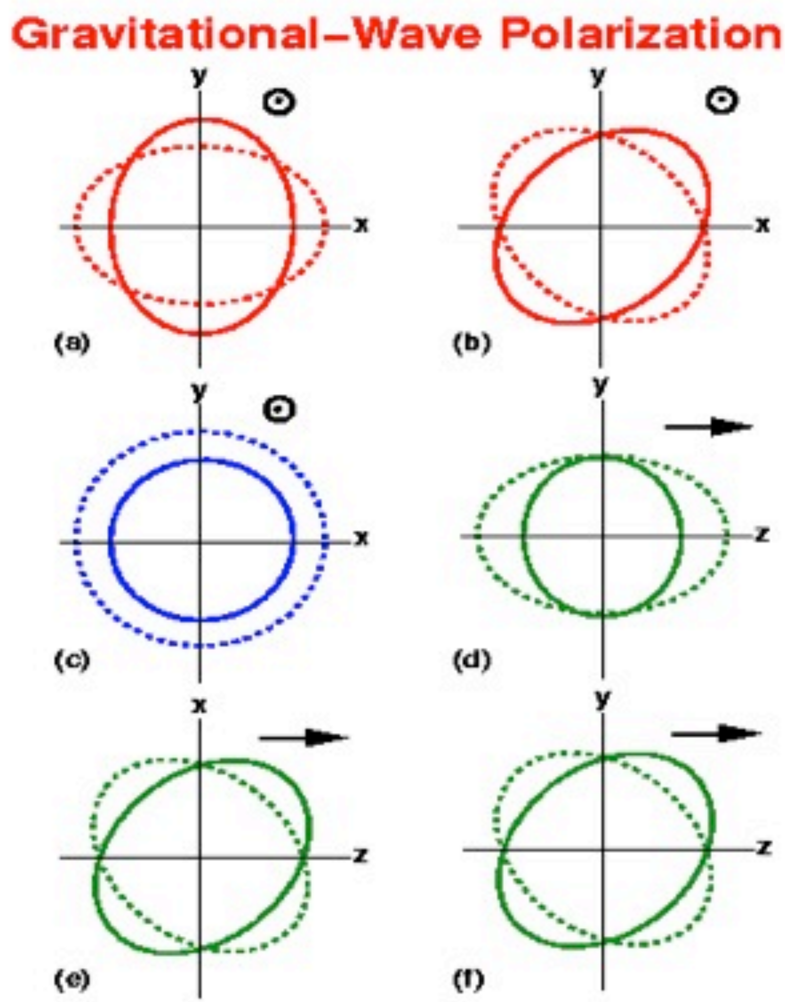


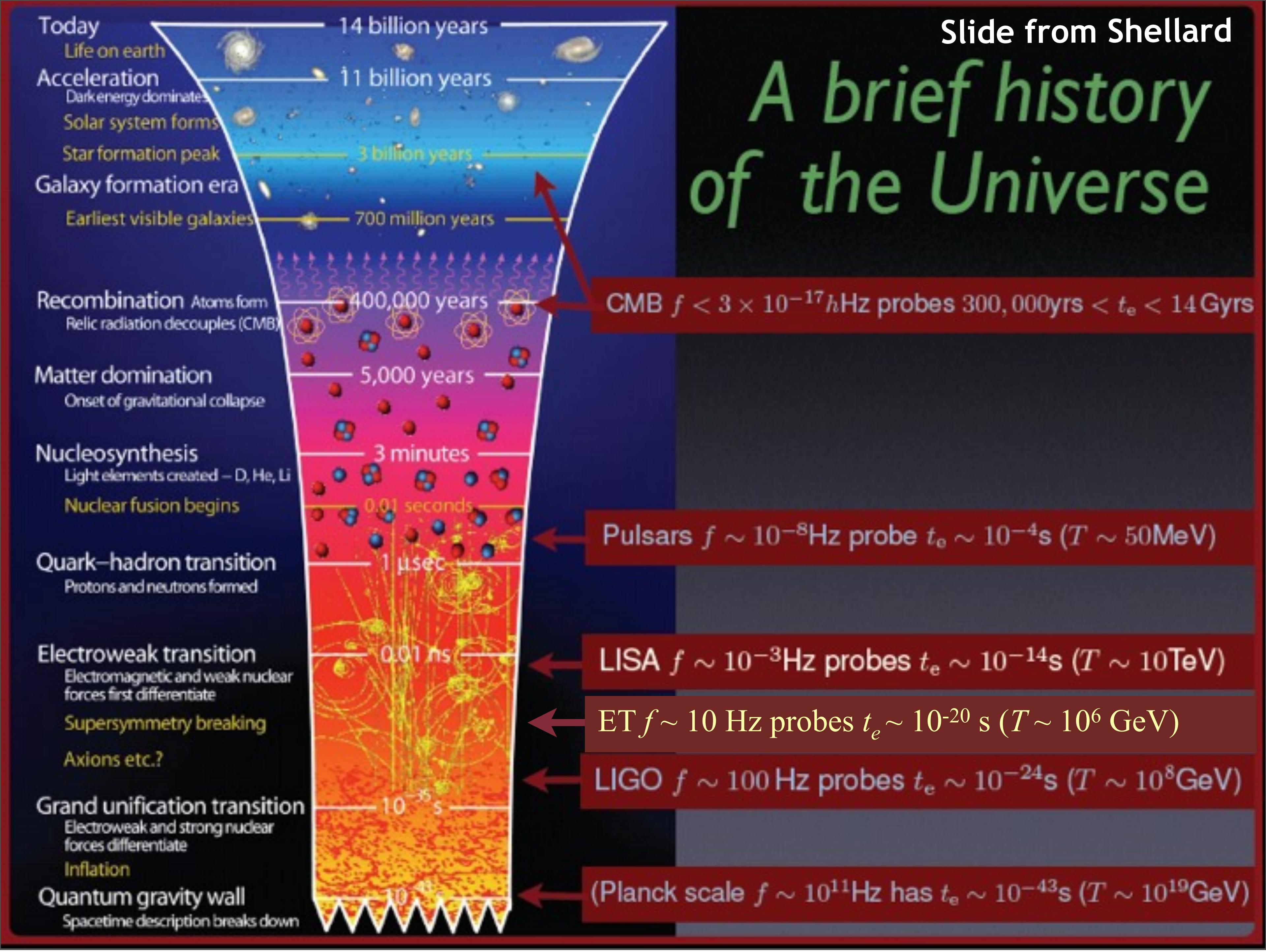
Cross polarization

Polarization States in a Scalar-Tensor Theory

- Polarization tests are qualitative tests
- A single measurement is good enough to rule the theory out
- In Einstein's theory there are only two polarization states - the plus and the cross polarizations
- In a scalar-tensor theory of gravity, there are six different polarization modes

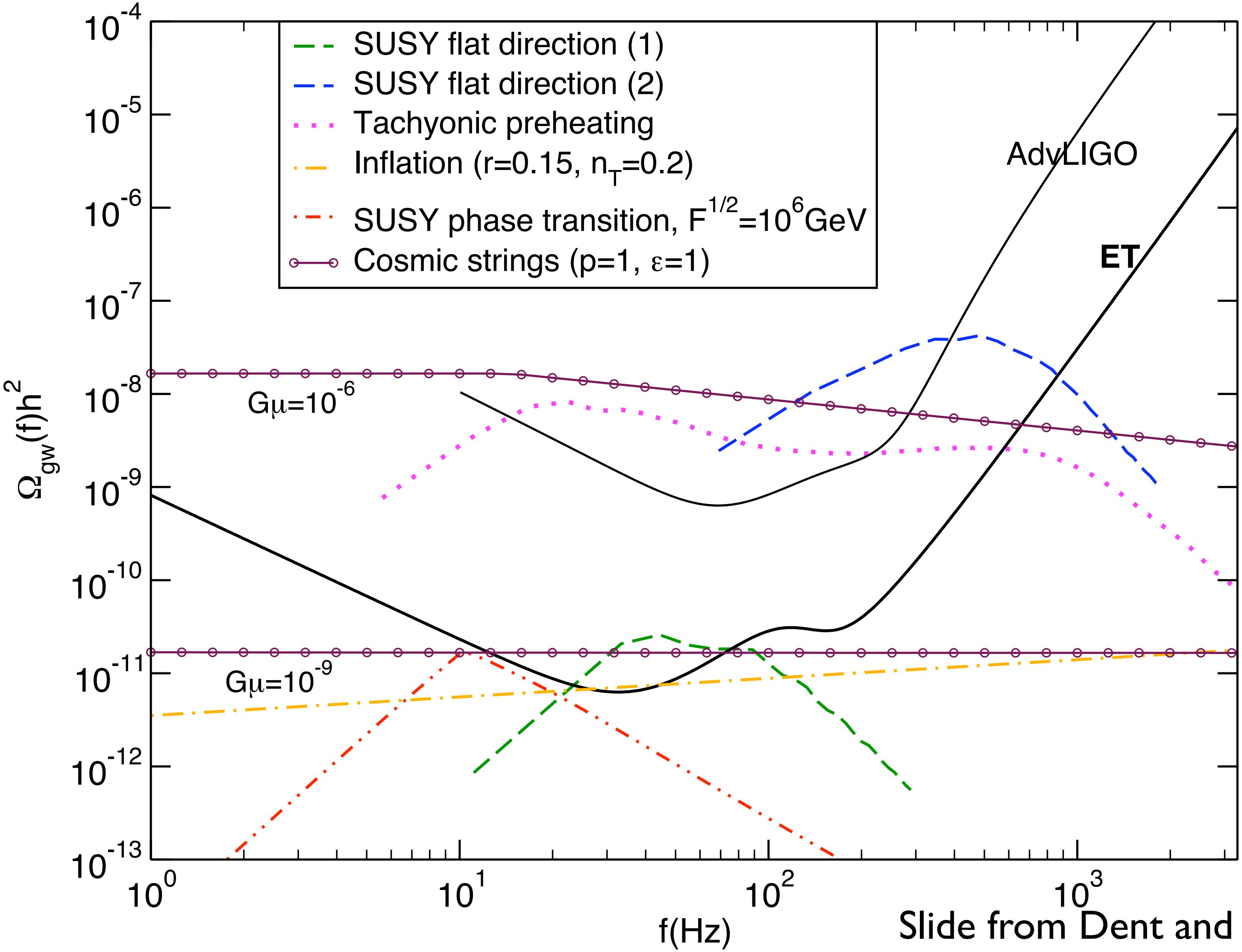
Cliff Will, Living Rev. in Relativity





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
10^{-43} s
CMB $f < 3 \times 10^{-17} h$Hz probes $300,000\text{yrs} < t_e < 14\,\text{Gyrs}$
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

What can gravitational waves reveal about the Universe?

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - 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
  - How did massive black holes at galactic nuclei form and evolve?
  - Were there phase transitions 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?