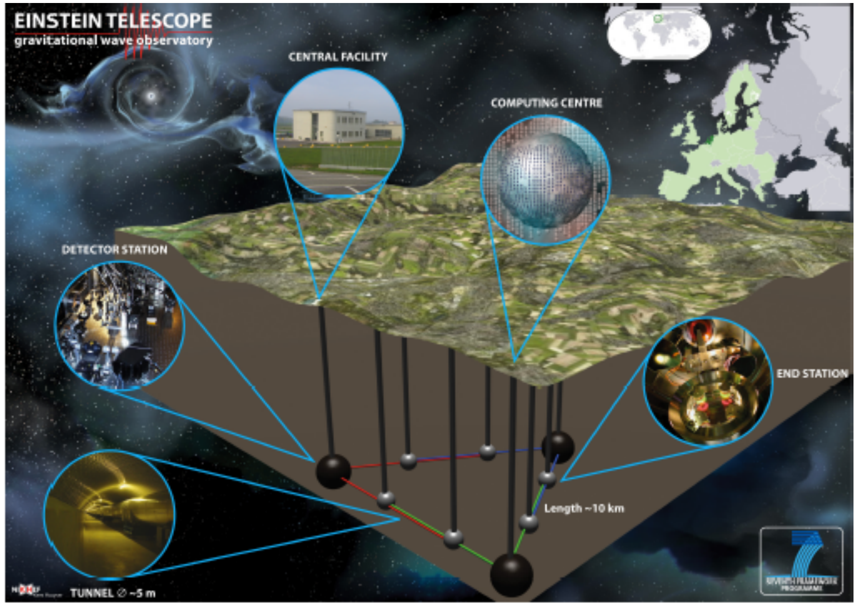
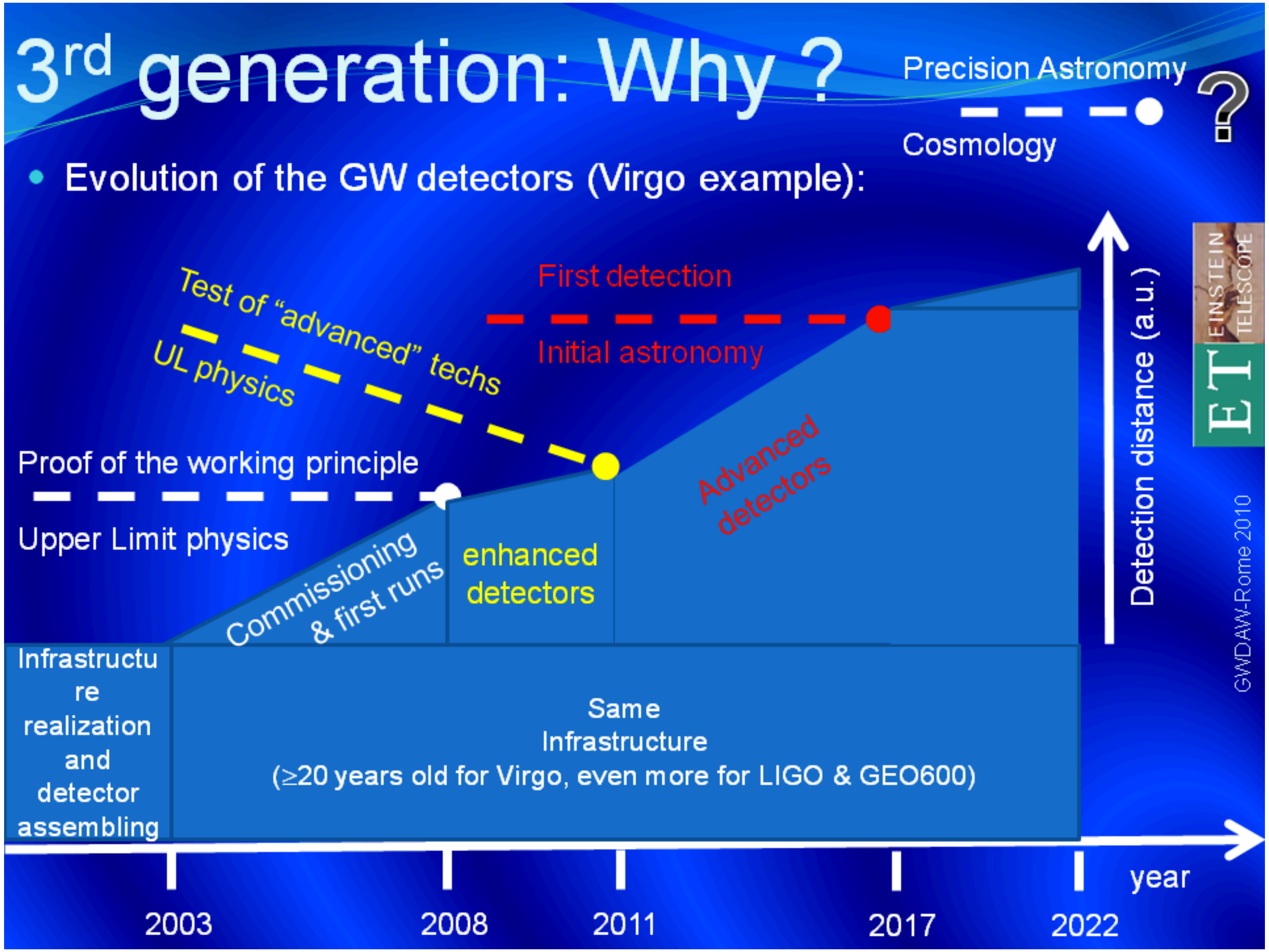
Astrophysics and Cosmology with Einstein Telescope



Tania Regimbau, OCA

GreCo Seminar, IAP, October 2nd 2011

GW Astronomy



3rd generation: Why ?

- Evolution of the GW detectors (Virgo example):

ET Science Team

- ET Design Document

http://www.et-gw.eu/etdsdocument

- ET Working Group on Astrophysical issues (Sathyaprakash)

http://www.et-gw.eu/wp-4

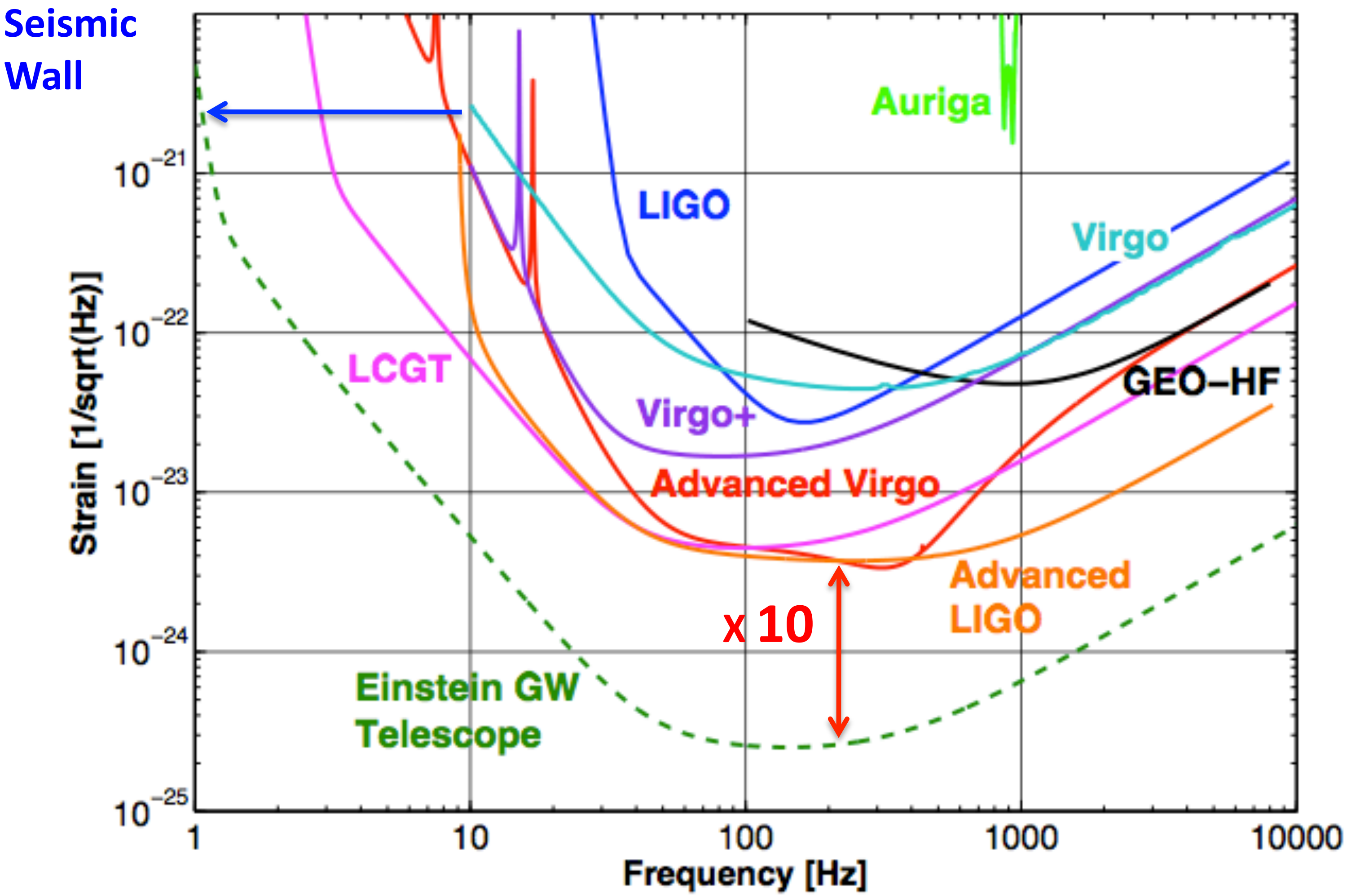
- participants :

European Gravitational Observatory, Instituto Nazionale di Fisica Nucleare, Max-Planck-Gesellschaft zur Förderung der Wissenschaften, Centre National de la Recherche Scientifique, University of Birmingham, University of Glasgow, NIKHEF, Cardiff University

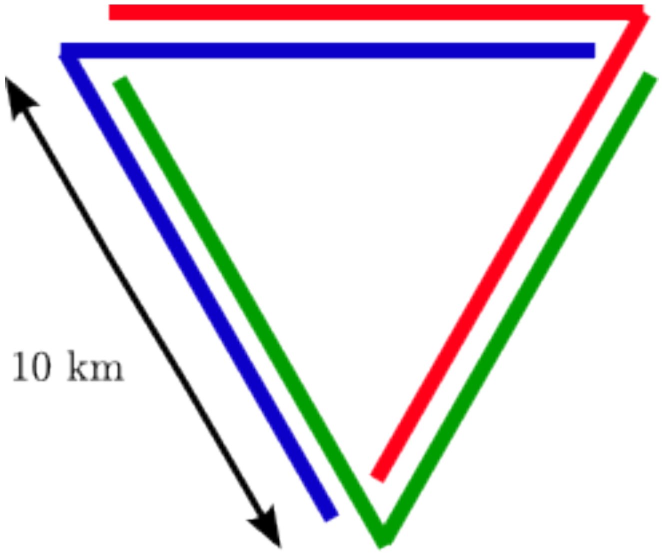
Einstein Telescope

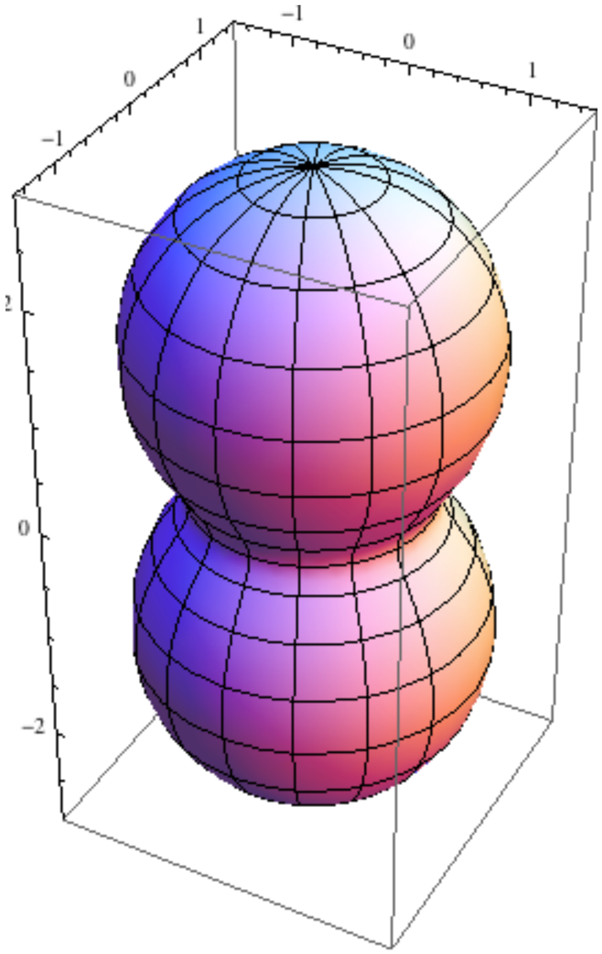
- third generation european interferometer (~ 2025)
- undergound to reduce seismic noise
- cryogenic, non diffractive optics
- a total of 30 km beam tube
- sensitivity 10 times better than advanced detectors
- broad frequency range from 1 Hz to 10 kHz

Sensitivity



Triangular configuration





- ✓ provide redundancy
- ✓ generate null stream
- ✓ measure both polarizations
- ✓ all sky sensitivity

Predicted Sources

➢ Burst sources

- core-collapse to NS or BHs, supernovae
- initial instabilities (oscillation modes, bar modes)
- soft gamma repeater flares

➢ Continuous waves

- pulsars, R modes
- low-mass X-ray binaries

➢ Compact binaries & IMBH captures

➢Stochastic background

- cosmological (inflation, cosmic strings, phase transition, pre-big bang)
- astrophysical (compact binaries, supernovae, core-collapse, magnetars…)

Fundamental Physics

- wave generation formula beyond the quadrupole approximation

- number of polarizations

- GW speed and mass of graviton (string theory)

- Brans-Dicke scalar field coupling parameter

- Uniqueness theorem: GR Kerr metric unique end point of gravitational collapse

- No-hair theorem : BH completely characterized by mass and spin

- EOS (supra-)nuclear matter

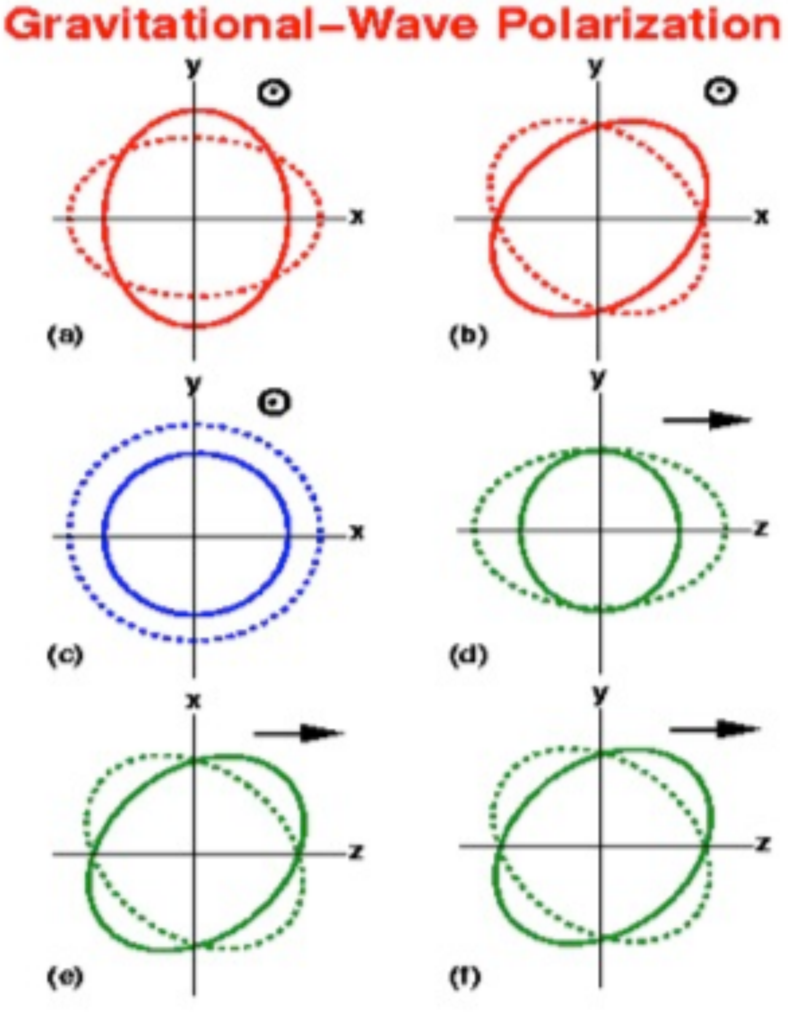
Measuring Polarization

- Einstein General Relativity :
 2 transversal polarizations

- scalar tensor theories :
could have 4 extra polarizations
+ 1 transversal
+3 longitudinal

- ET can resolve both polarizations assuming GR

- a network of detectors, by comparing their measurements, can rule out a whole class of alternative theories.



Bound on the Mass of Graviton

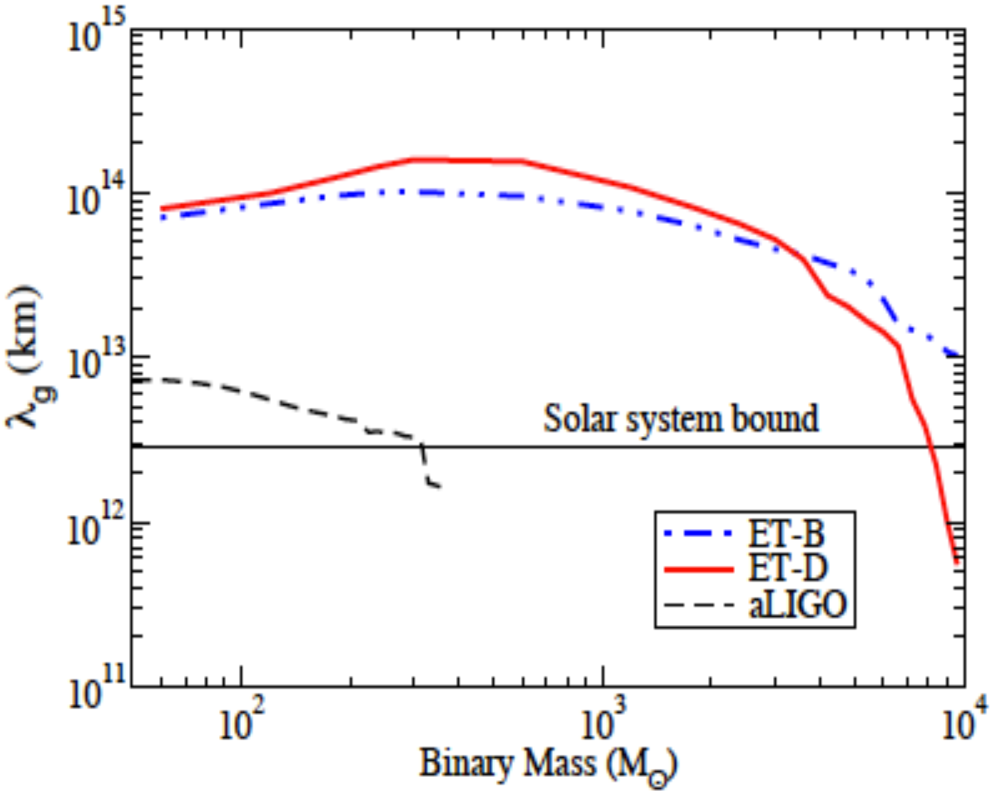
- use measurement of the phase of compact binaries to put a bound on the Compton wavelength and then on the mass of the graviton

- massive gravitons create a distorsion in the observed phasing because of the shifted time of arrival of the waves emitted at different wavelength (and thus having different speed!)

$$\Psi_{eff}(f) = \Psi(f) - \beta f^{-1} + \phi_g + \tau_g f$$
$$\beta = \pi D / \lambda_g^2 (1+z)$$

- ET bound 2 orders of magnitude better than actual limits

Arun and Will 2009



Bound on Brans-Dicke scalar field coupling parameter

- ➢additional scalar field couples to both matter and tensor field of GR
- ➢coupling dimensionless parameter:

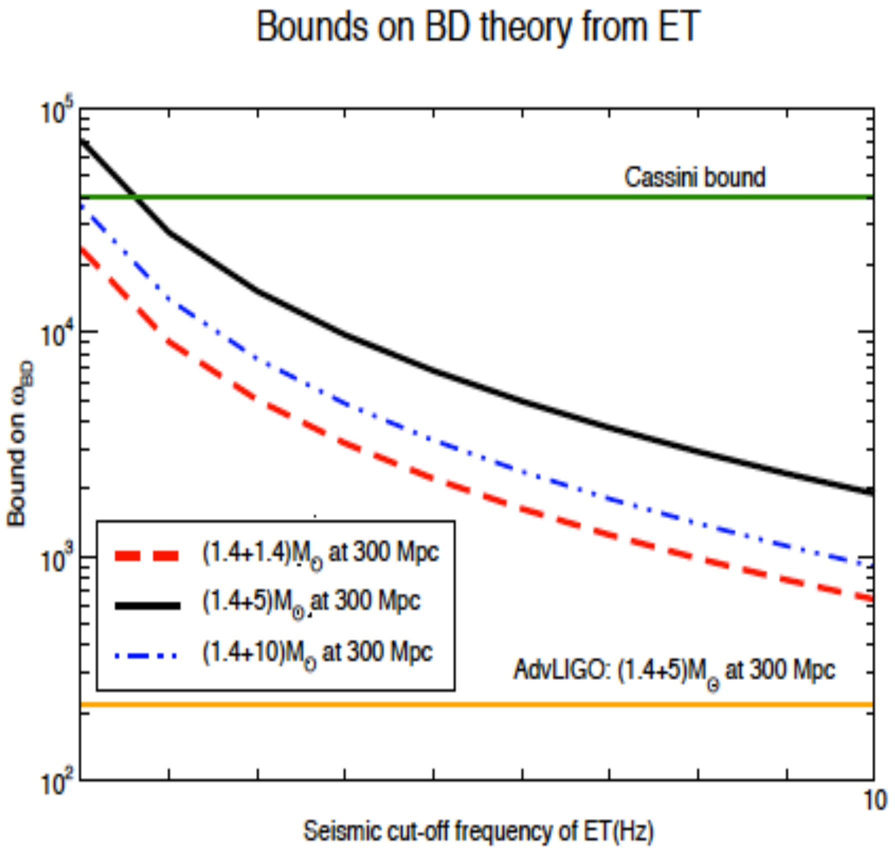
$\varpi_{BD} \to \infty$ for Einstein GR

- ➢ dipolar gravitational radiation

- ➢phasing formula in BD theory is the same as in GR except for an additional dipolar term proportional to ϖ_{BD}^{-1}

- ➢ET constrains by 1 order of magnitude more than actual limits

Arun 2011



Testing BH no hair theorem

- distorted Kerr black holes are unstable and emit gravitational radiation

- Einstein GR : superposition of damped sinusoid

$$\omega_{lm} = M^{-1} F_{lm}(j) \text{ and } \tau_{lm} = M G_{lm}(j), \text{ with } j = M^{-2} J$$

- Measuring the frequency and the damping time of the different modes provide independant measurement of the mass and the spin

- Test no hair theorem with consistency checks between different mode frequencies and damping times.

- The amplitude of the modes carry additional information about what caused the deformity

Cosmology

- Constraints on cosmological parameters
- dark energy EOS
- BH seeds and formation of Galaxies
- Star formation history
- Early stages of the Universe

Cosmography with Compact Binaries

- ET expects to see ~1 million of NS-NS a year up to z~2

- standard candles : well modelled waveforms

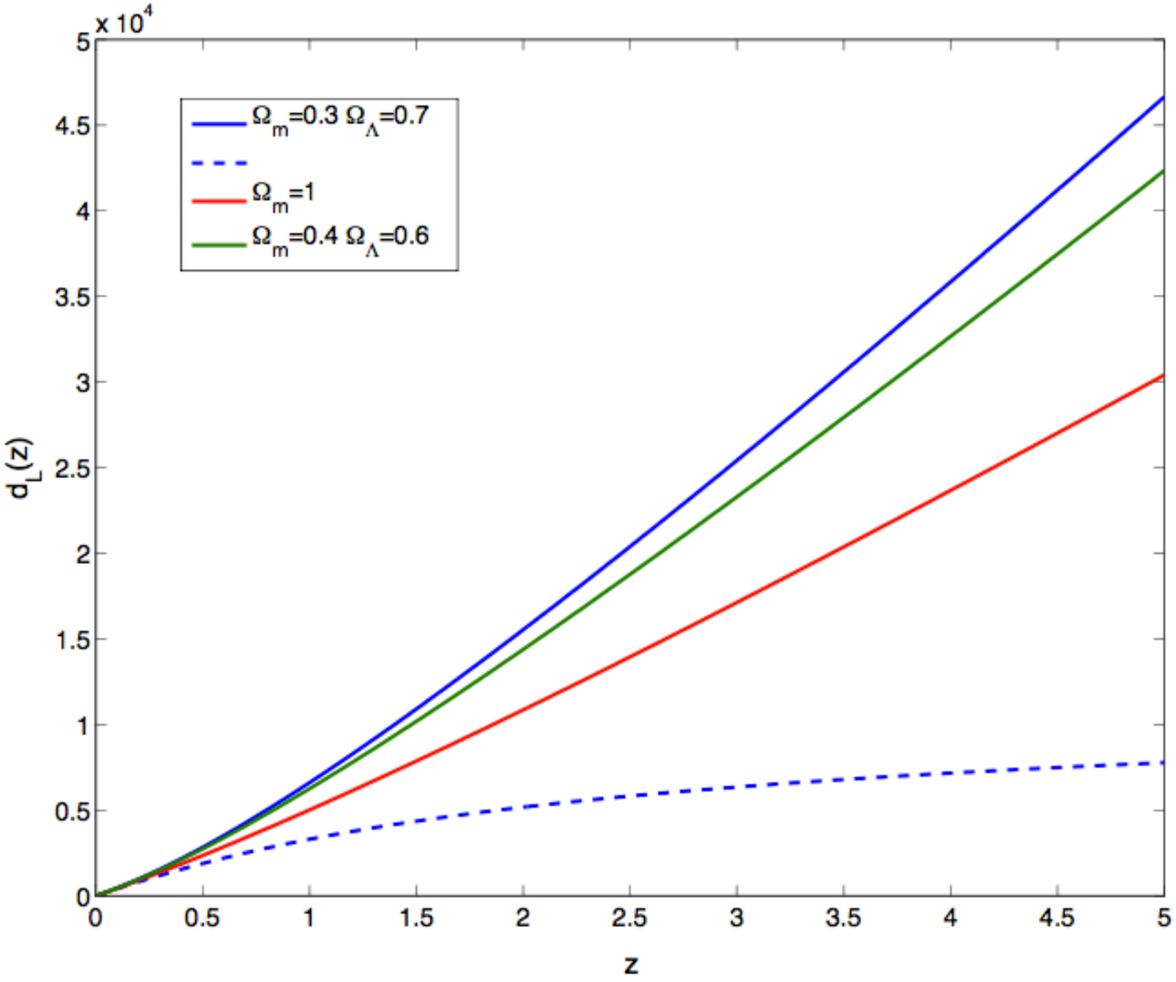
- self calibrated (No cosmic distance ladder required): the distance luminosity is measured directly from the amplitude and the phase

$$D_L = \sqrt{\frac{L}{4\pi F}} = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}}}$$

- can extract intrinsic parameters and provide accurate distance estimates *with fLow=1-3 Hz, the inspiral signal can be observed for several days*

- determine redshift through EM observations (GRB, host galaxy) or statistical estimates

Cosmology with Compact Binaries

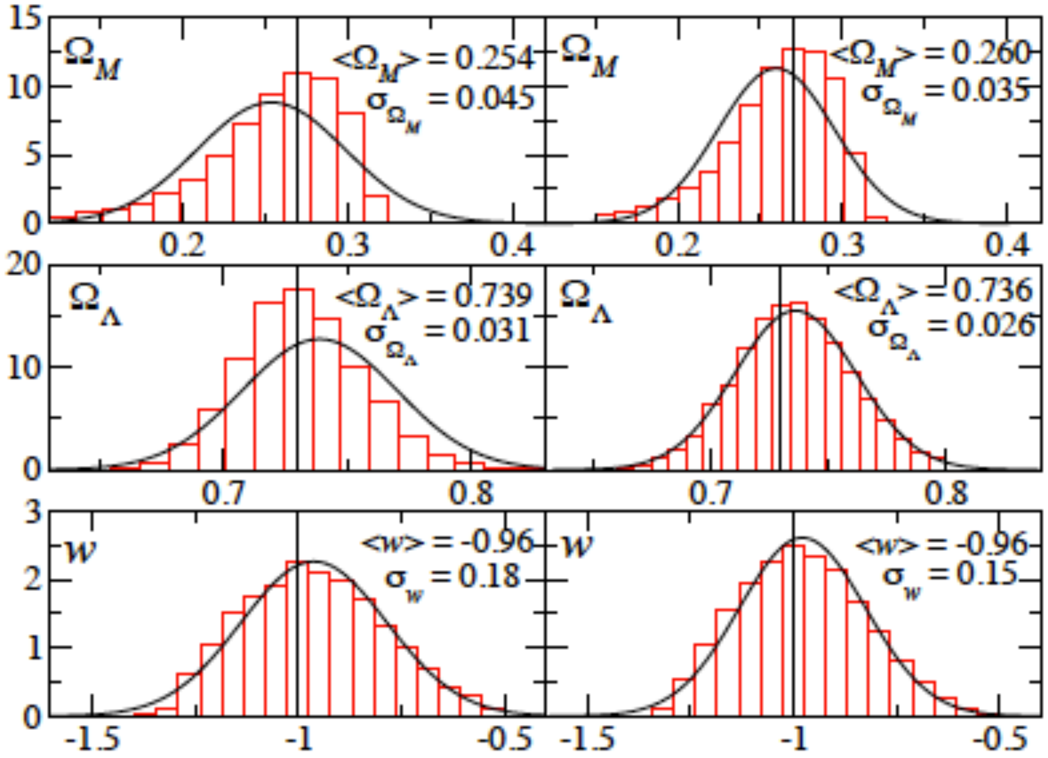


Cosmology with Compact Binaries

$$\frac{\sigma_{\Omega M}}{\Omega_M} = 18\%$$

$$\frac{\sigma_{\Omega\Lambda}}{\Omega_\Lambda} = 4.2\%$$

$$\frac{\sigma_w}{w} = 18\%$$



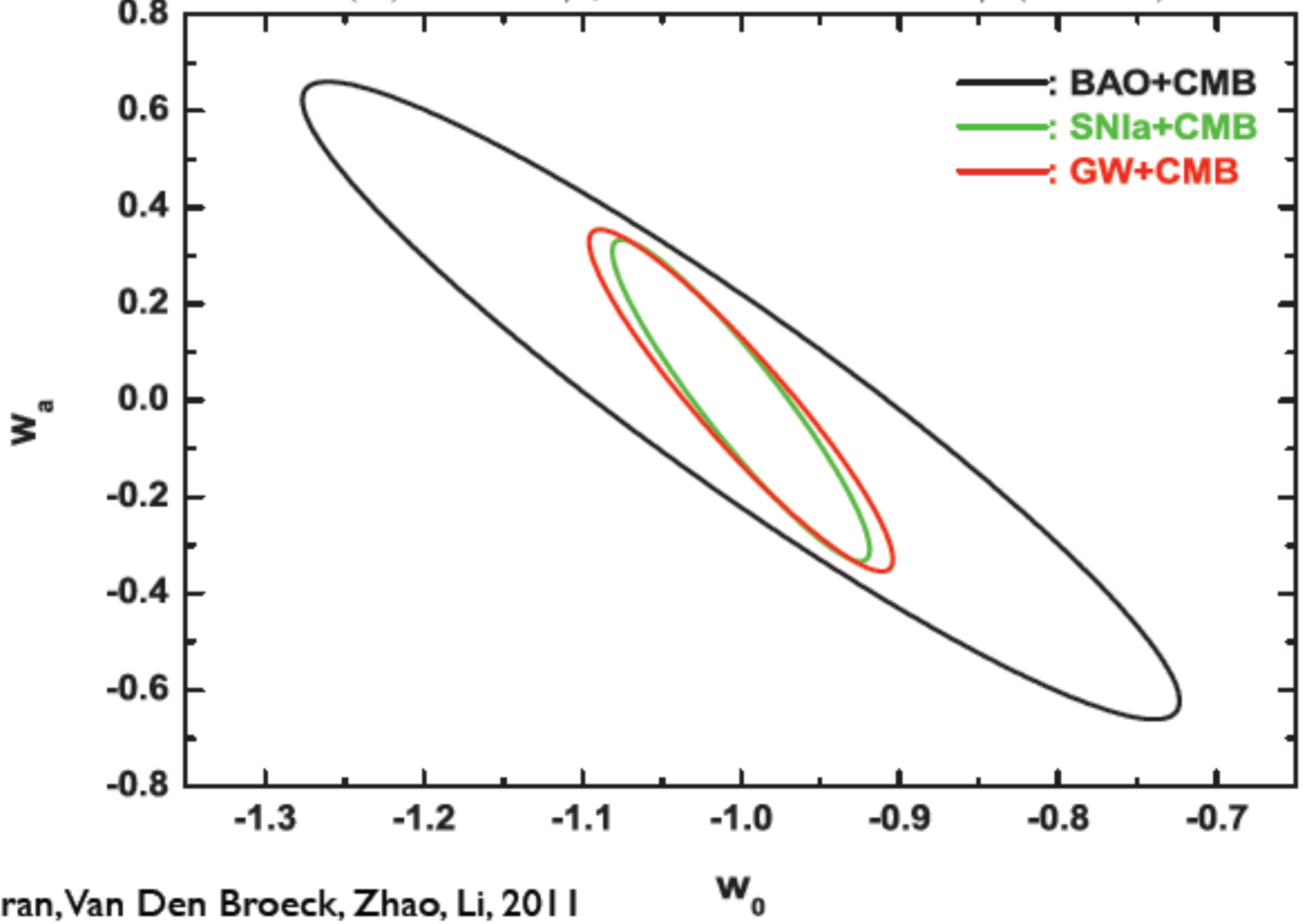
$$\frac{\sigma_{\Omega M}}{\Omega_M} = 14\%$$

$$\frac{\sigma_{\Omega\Lambda}}{\Omega_\Lambda} = 3.5\%$$

$$\frac{\sigma_w}{w} = 15\%$$

Cosmology with Compact Binaries

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



Baskaran, Van Den Broeck, Zhao, Li, 2011

Seed of Super-Massive BH

- SMBH found in the centres of many galaxies grow **hierarchically** from initial seeds through the processes of accretion and following mergers between their host DM halos

Light seed scenario : BH seeds of 100 M_s form at z ~20 from the collapse of pop III stars

Heavy seed scenario : BH of 10^5 M_s form from direct collapse of dust clouds

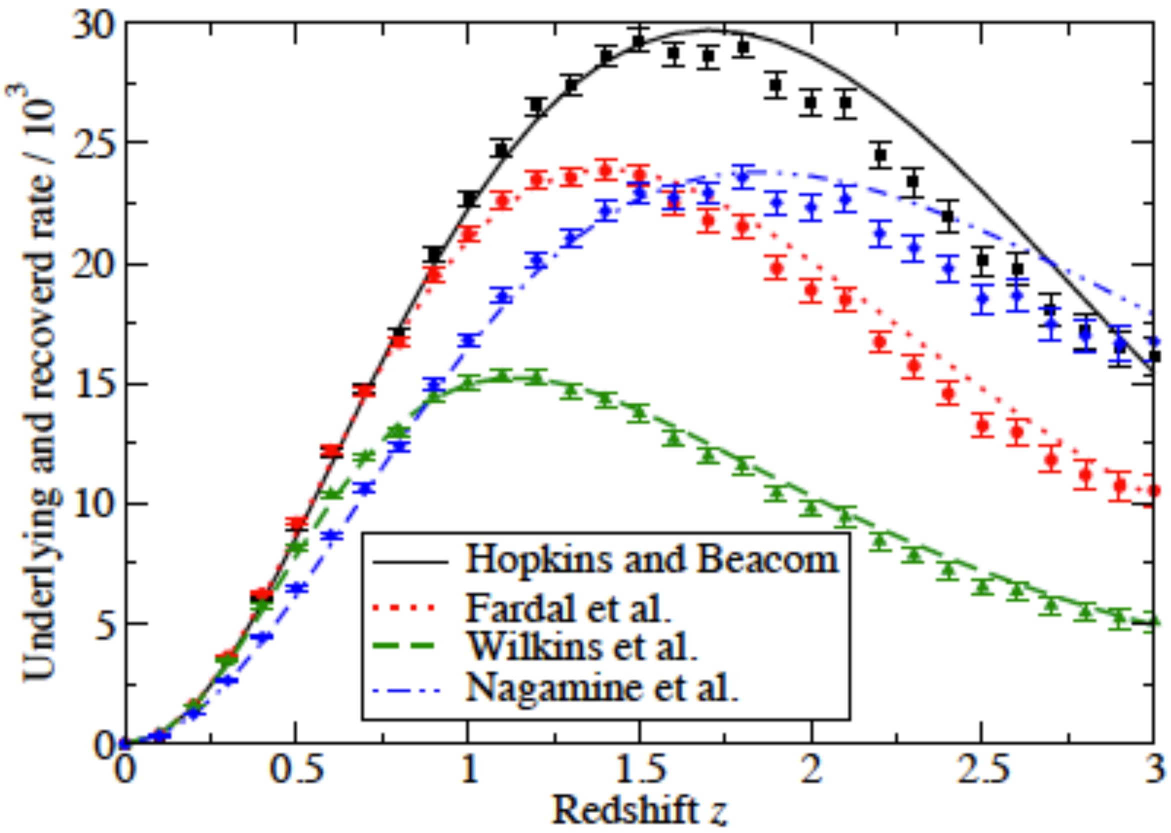
- ET sensitive to the merger of BH binaries with masses in 10-100 M_s
(between a few and a few tens of seed BH mergers over three years)

- could directly observe the first epoch of mergers between light seeds

- complement LISA (>10^3 M_s)

- unique way to test light seed scenario against heavy seed scenario :
a single detection with ET would rule out heavy seed scenario

Star Formation History

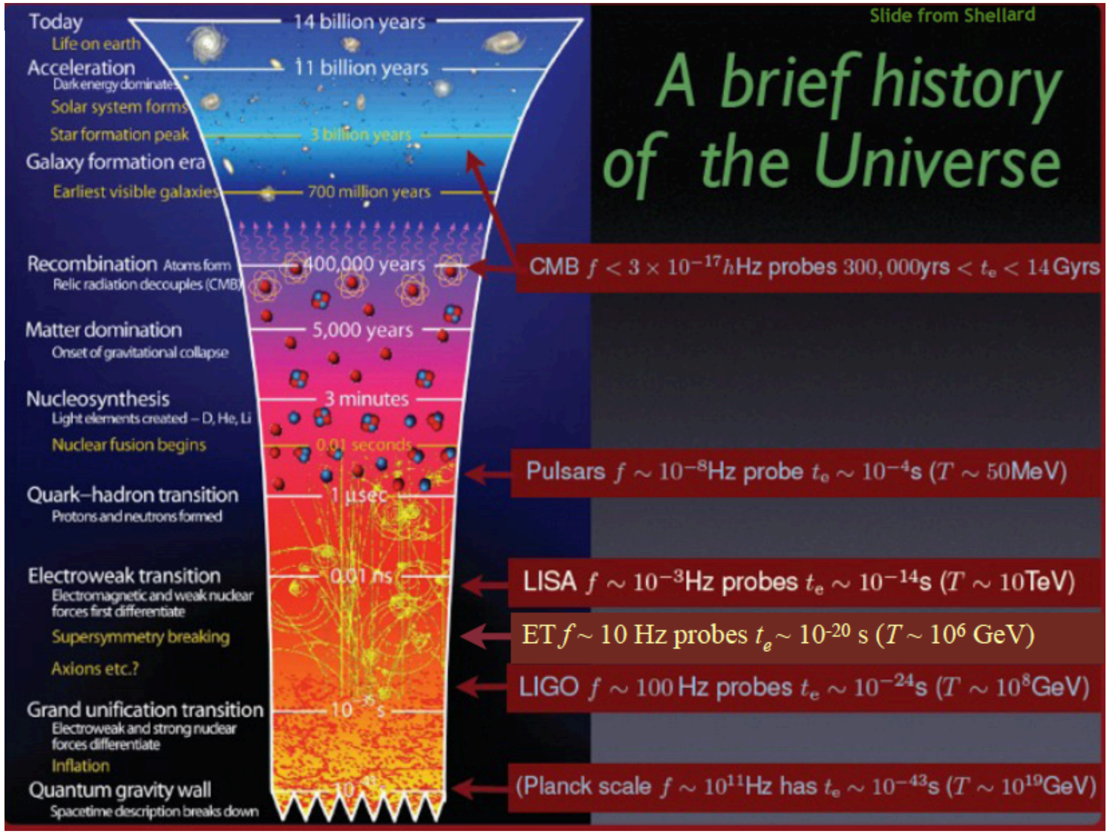


Stochastic Backgrounds

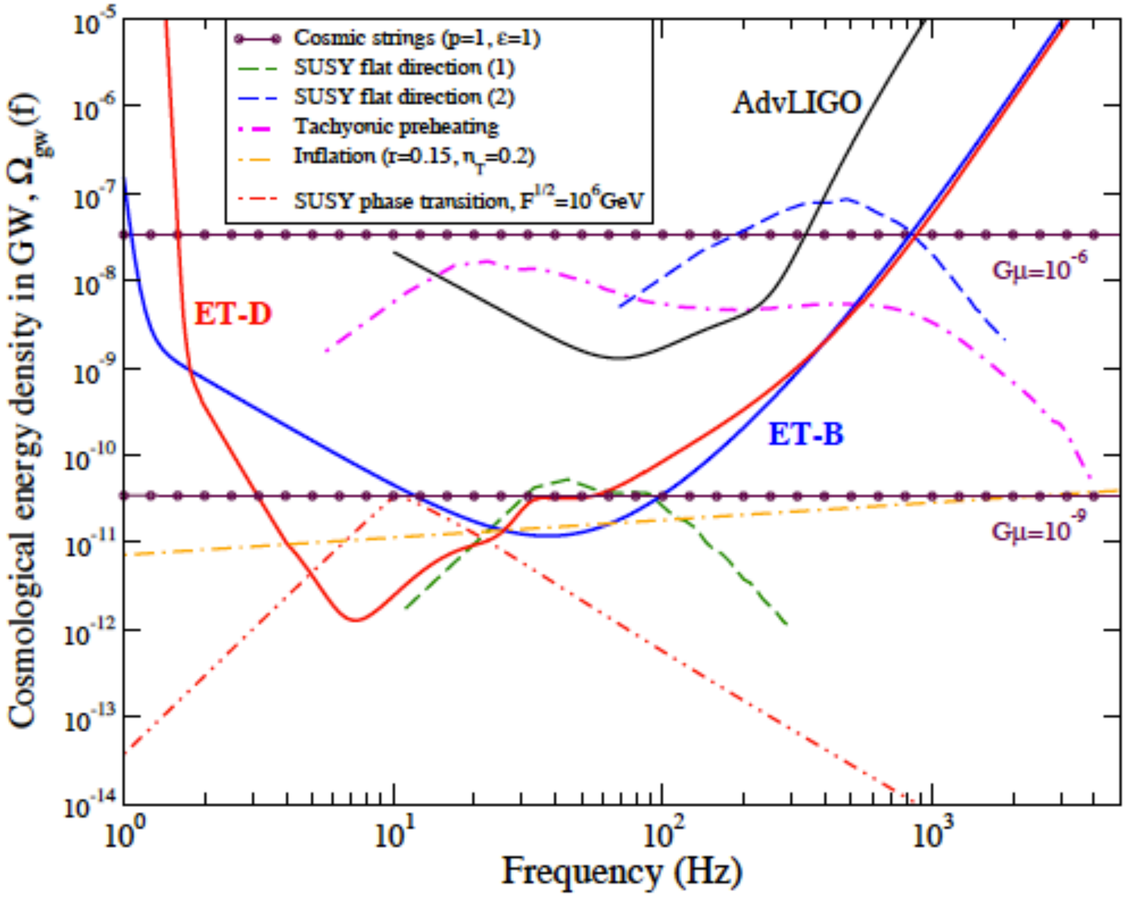
A stochastic background of gravitational waves has resulted from the superposition of a large number of unresolved sources since the Big Bang.

- **Cosmological:**
signature of the early Universe
inflation, cosmic strings,
phase transitions…

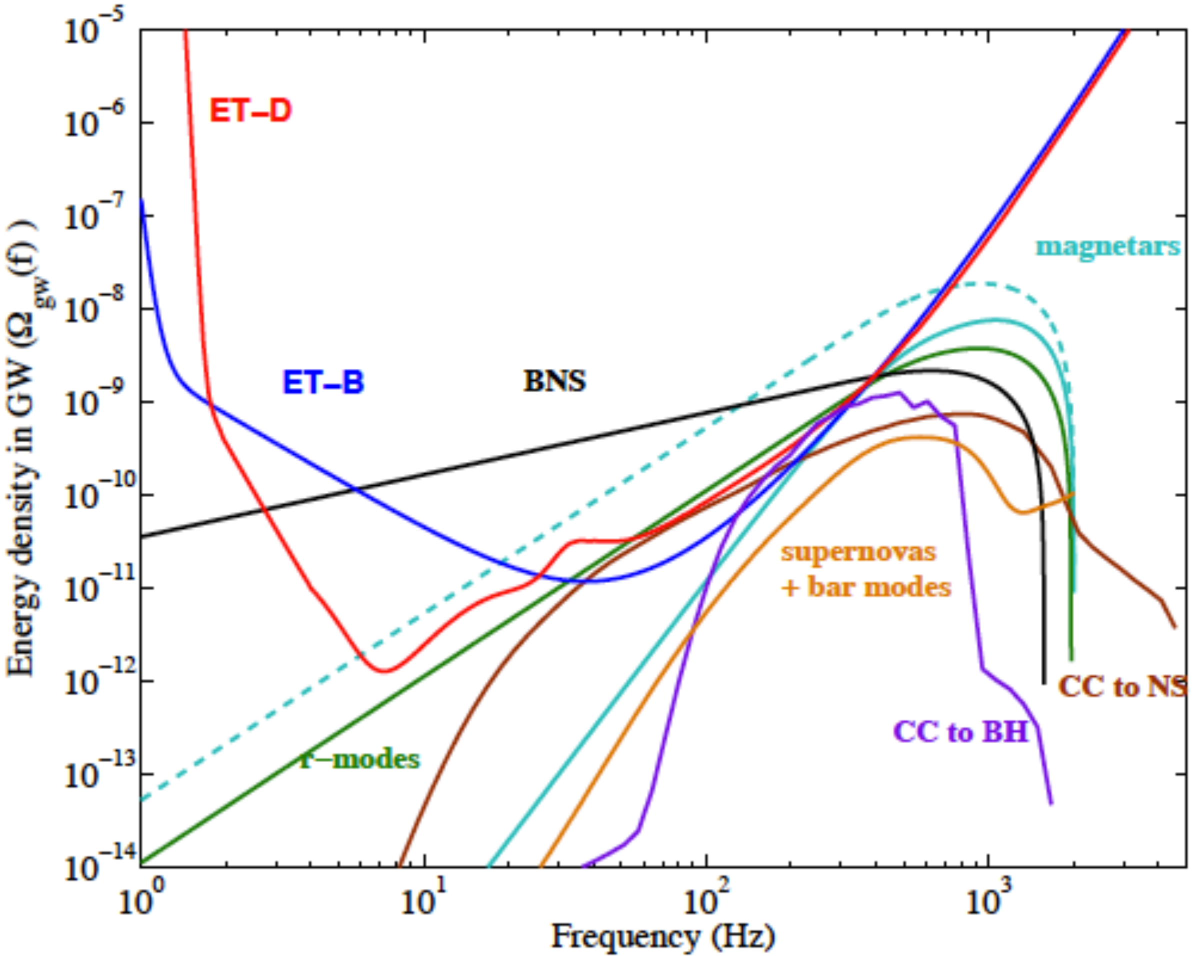
- **Astrophysical:**
Sources from the beginning of stellar activity



Cosmological Stochastic Backgrounds



Astrophysical Stochastic Backgrounds



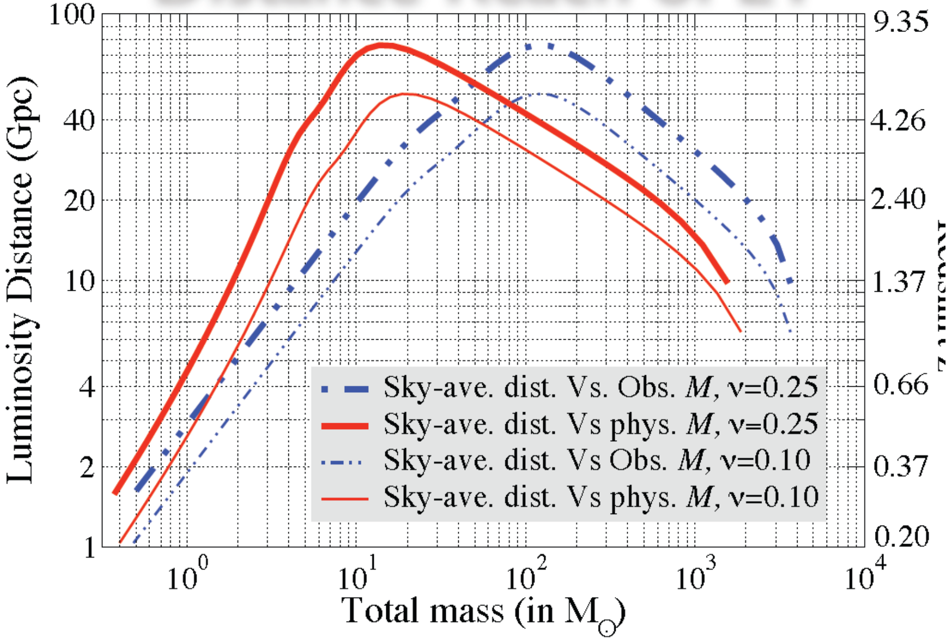
Astrophysics and Multimessenger Astronomy

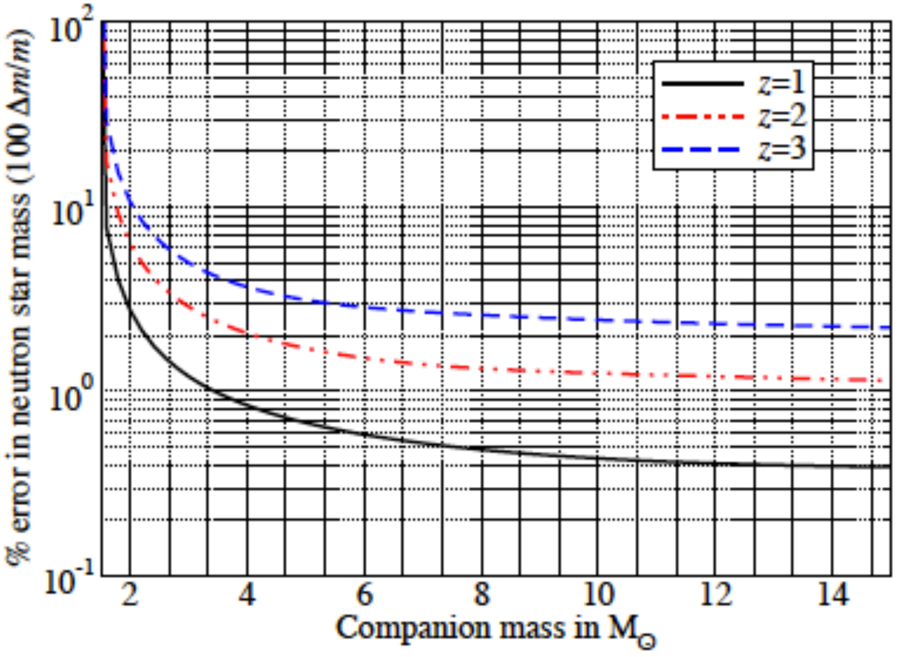
- mass function of NS and BH
- NS equation of state
- NS initial conditions : rotation, magnetic field, temperature
- Mechanism limiting LMXR spin period
- Gamma-ray burst progenitors
- Cause of pulsar glitches and magnetar flares
- Supernova: physical phenomena, asymmetry, **shock revival**

…….

NS and BH mass function

Distance Reach of ET





NS Equation of State

EoS signature can be found in any GW emission involving NS:

- quadrupolar emission from axysymmetric rotating NS

-> measure ellipticity

- quasi normal modes (glitches)

-> measure mass and radius from frequency and damping time

- compact binary merger

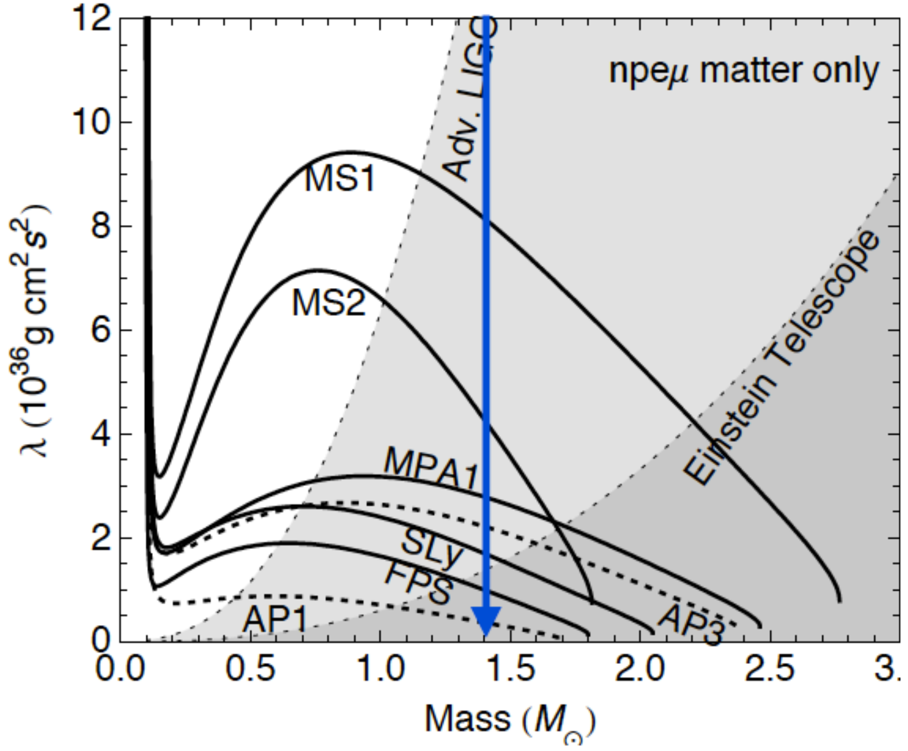
-> from post merger oscillations

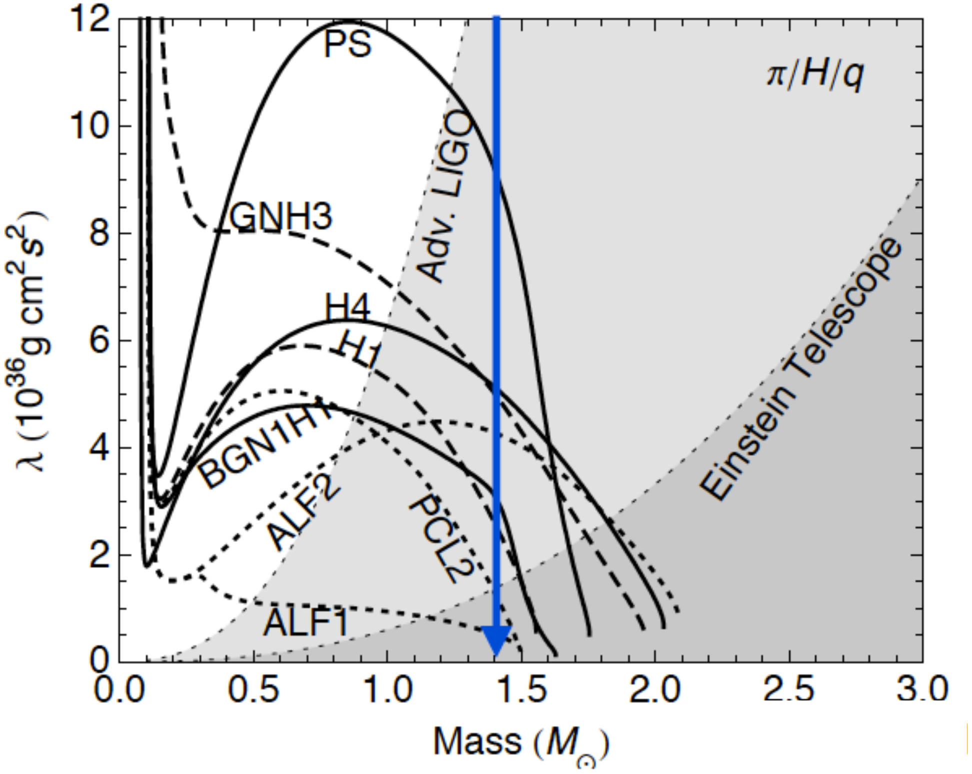
-> measure tidal effects in the inspiral waveform (can lead to disruption of the NS before merger)

- r and bar modes

NS Equation of State

Hinderer et al. PhysRevD, 81, 123016

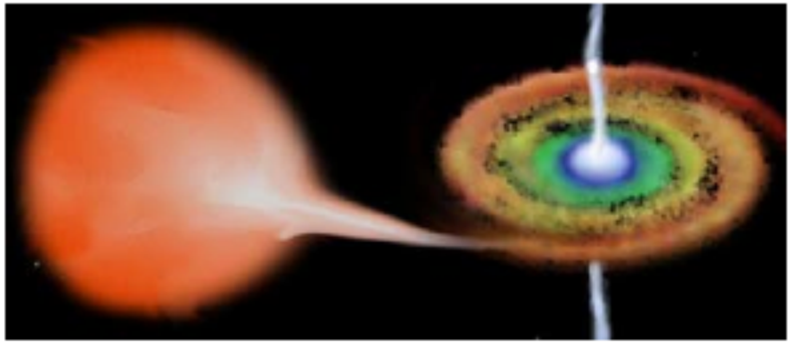


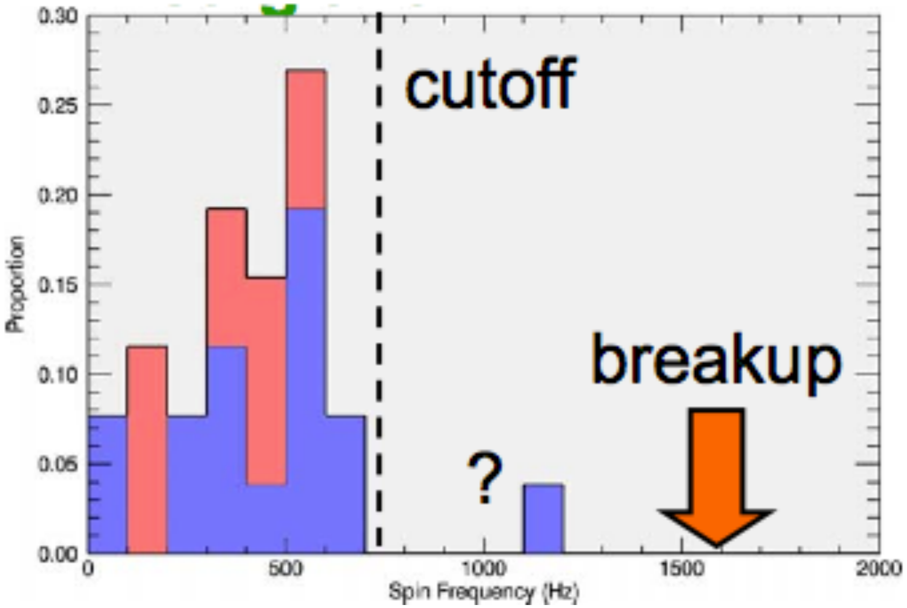


Period of LMXB

from Sathyaprakash

- NS in a binary system, being reaccelerated by accretion from red giant companion
- Spin frequency stalled at about 700 Hz (> break up speed)
- GW back reaction torque could balance accretion torque (mountains, R modes ?)
- if induced by montains, needs ellipticity >10^{-8}



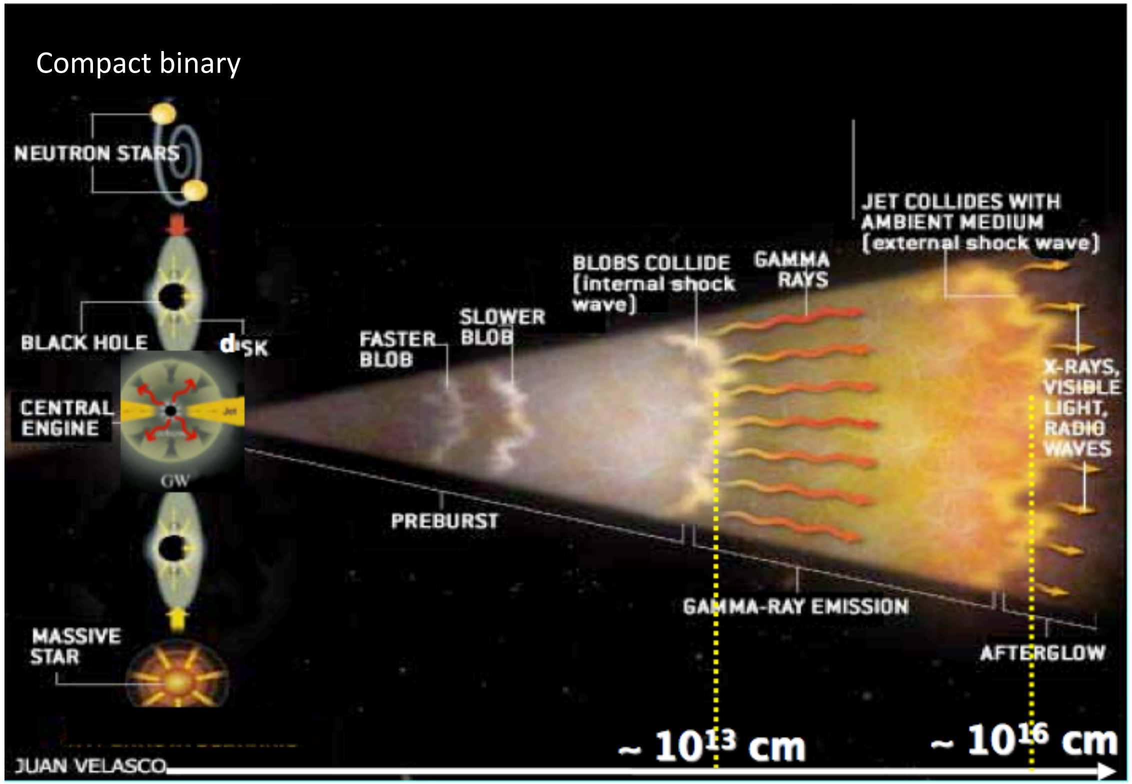


Progenitors of GRB

Fireball Model : *« For both long and short bursts, GRB powered by the formation of a central fast rotating BH plus an accretion disk »*

short GRB =
Binary coalescence
NS-NS or NS-BH (+~15% of SGR)

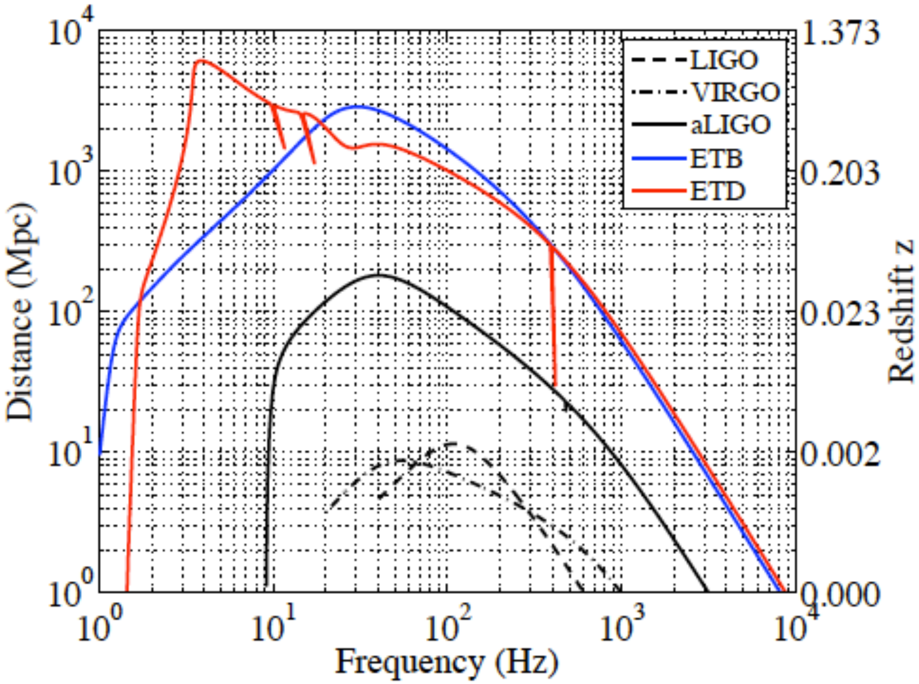
long GRB =
core-collapse to BH
or to ms magnetar
(hypernova/prompt CC)



GRB progenitors : distance reach

$E_{GW}^{iso} = \varepsilon mc^2 \sim 10^{53}\,\mathrm{erg}$

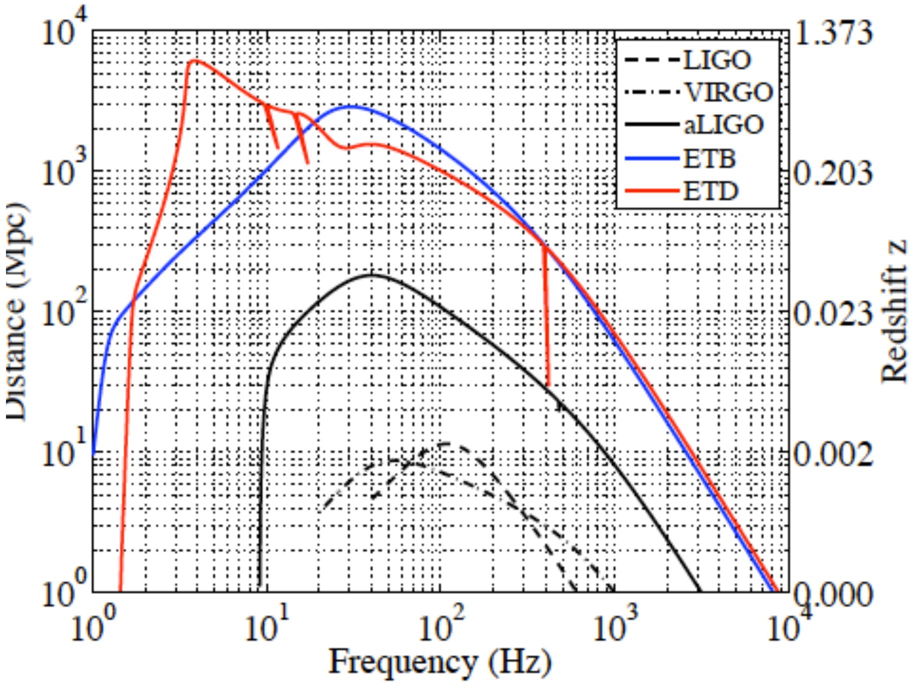
$\varepsilon = 5\%\ (0.1 - 20\%)$



Long GRB : model of CC

$E_{GW}^{iso} = 10^{46}\,\mathrm{erg}$

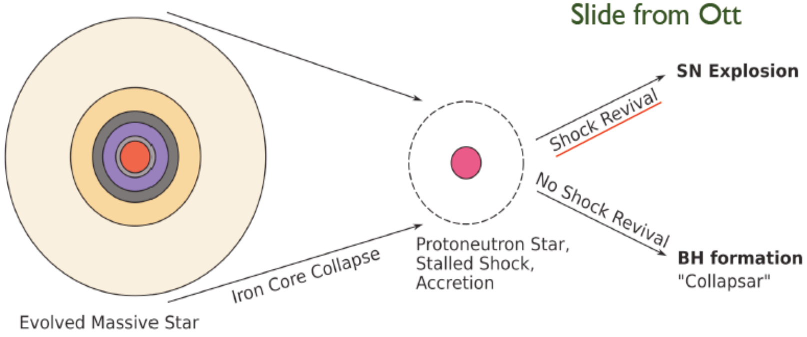
$\varepsilon = 10^{-6}\%$



SH-GRB : model of magnetar
(NS-NS or NS-BH coalescence : z>2-5)

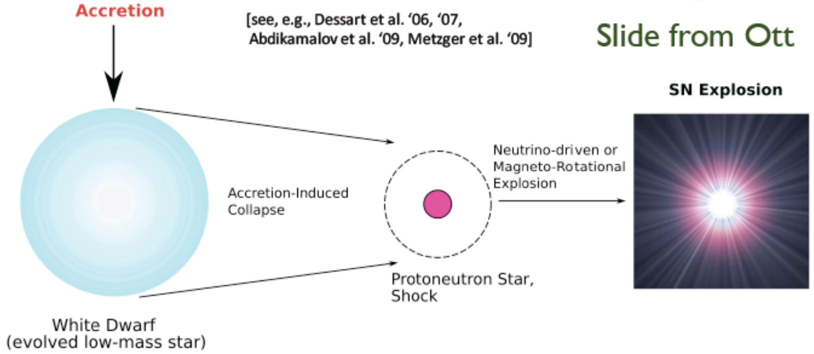
Core-Collapse Supernova

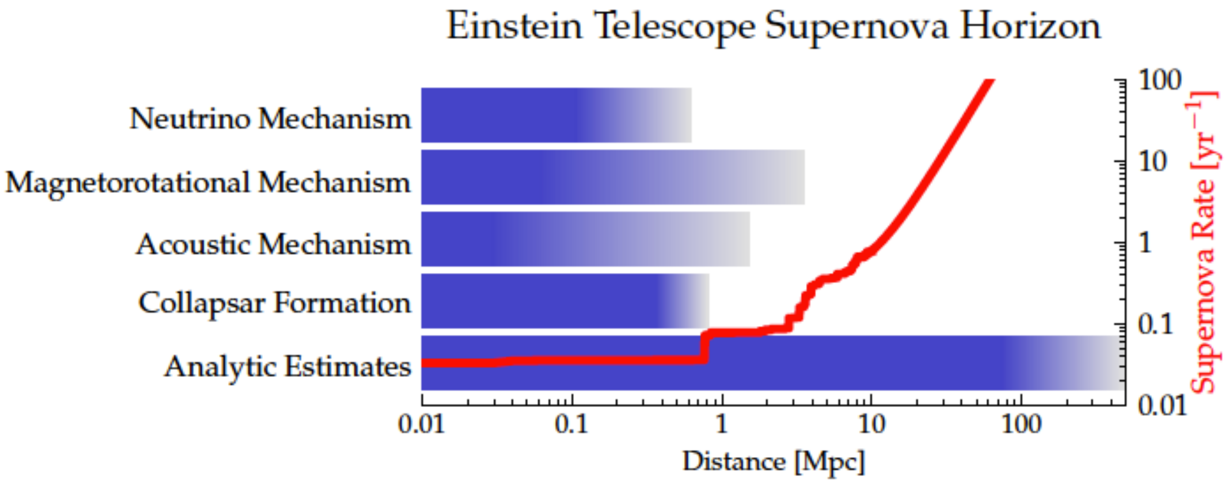
Slide from Ott



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

Slide from Ott




Einstein Telescope Supernova Horizon

ET Mock Data and Science Challenge

- ➢ produce population of sources realistically distributed redshift, sky position, orientation, polarization, mass etc…

- ➢ develop sophisticated DA techniques able to do accurate parameter estimation, and put constraints on fundamental physics, astrophysics and cosmology

- ➢ first challenge : population of BNS up to a redshift of z~6

Simulation of BNS inspirals

- **coalescence time** (Poisson process):

$$p(\Delta t) \propto \exp(-\Delta t / \lambda) \text{ with } \lambda = \left[\int_{z_{\min}}^{z_{\max}} \frac{dR_c^o}{dz}(z)\, dz \right]^{-1}$$

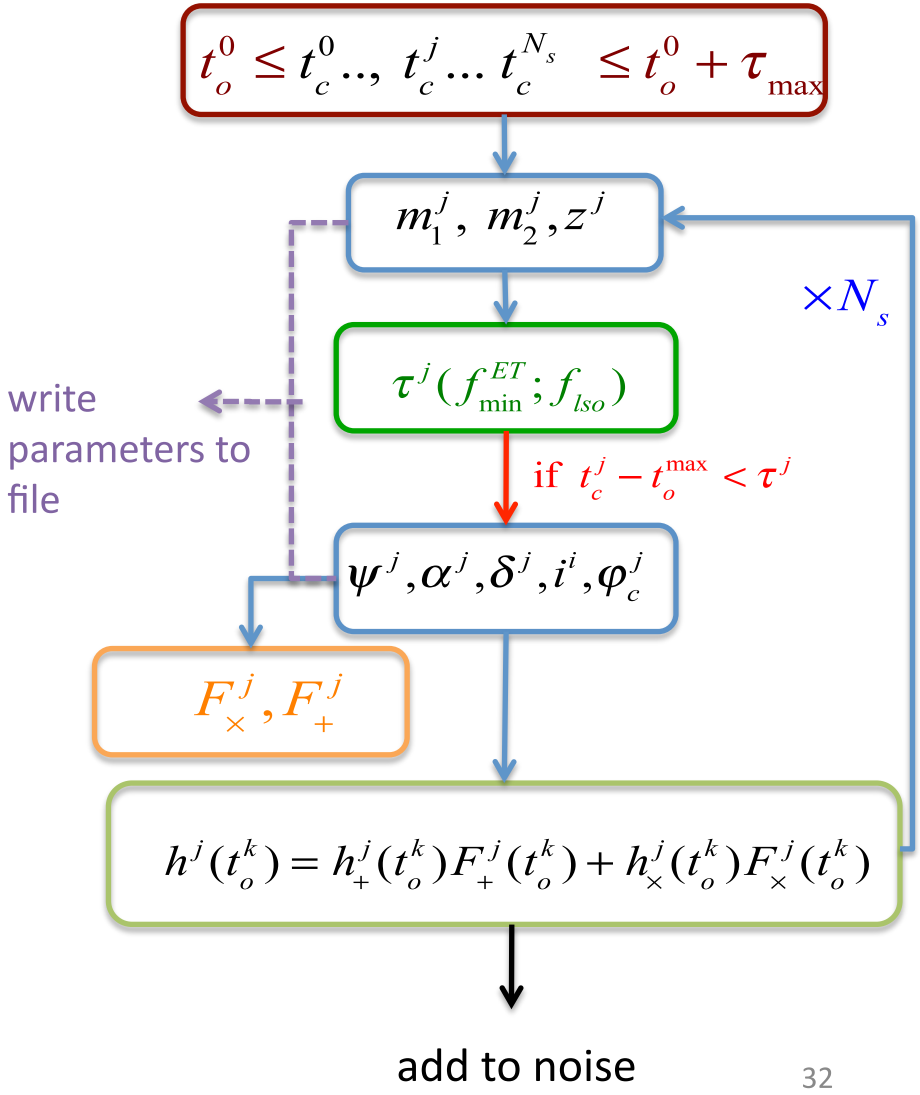
- **redshift:**

$$p(z) \propto \frac{dR_c^o}{dz}(z)$$

- **masses**: Gaussian distribution

$$N(\mu = 1.4; \sigma = 0.5) \text{ in } [1.2 - 3]\ (\mathrm{M}_\odot)$$

- **position in the sky:** uniform distribution
- **orientation:** uniform distribution
- **phase at LSO:** uniform distribution



$t_o^0 \le t_c^0 .., t_c^j ... t_c^{N_s} \le t_o^0 + \tau_{\max}$

m_1^j, m_2^j, z^j

$\times N_s$

$\tau^j(f_{\min}^{ET}; f_{lso})$

write parameters to file

if $t_c^j - t_o^{\max} < \tau^j$

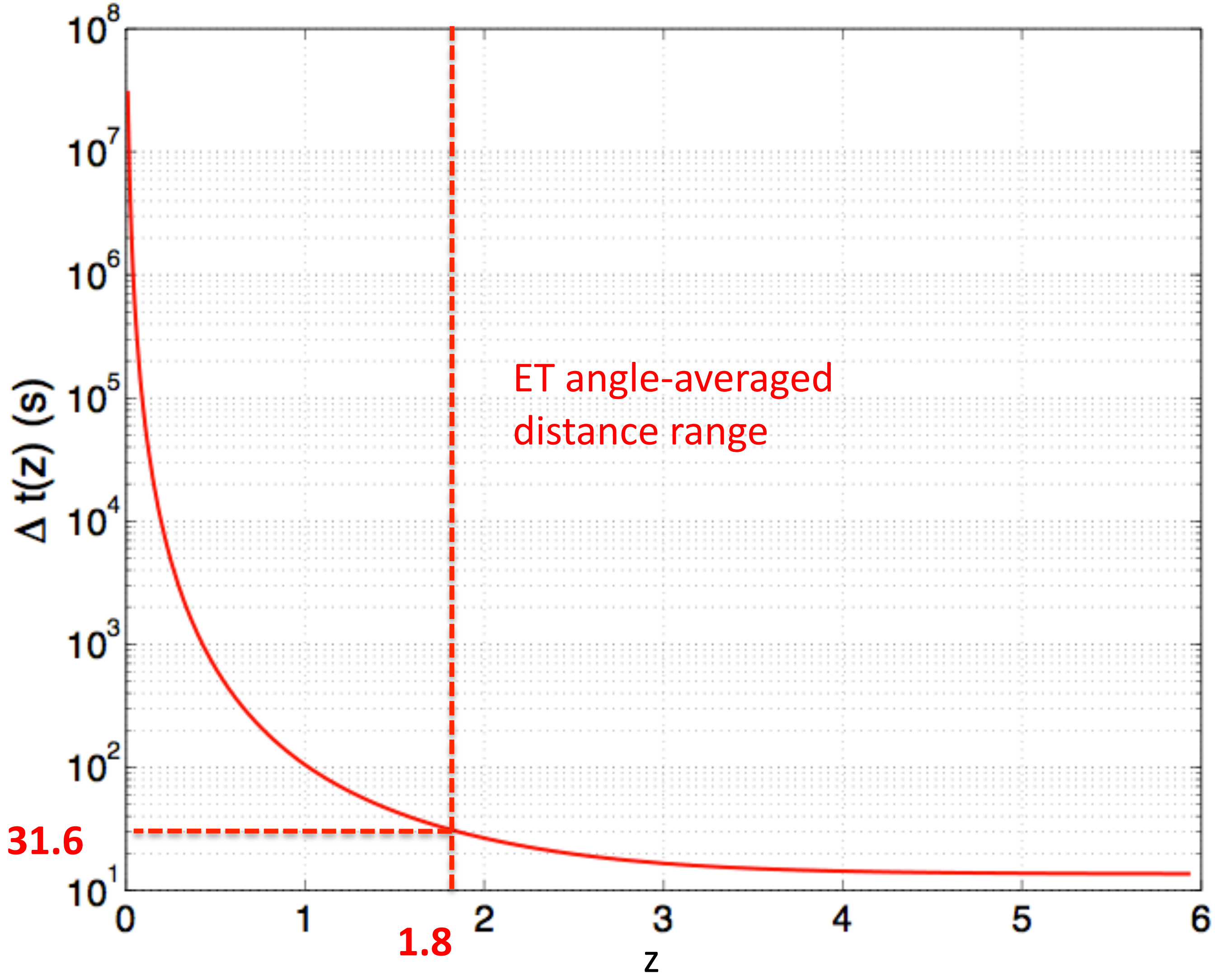
$\psi^j, \alpha^j, \delta^j, i^i, \varphi_c^j$

$F_\times^j, F_+^j$

$h^j(t_o^k) = h_+^j(t_o^k) F_+^j(t_o^k) + h_\times^j(t_o^k) F_\times^j(t_o^k)$

add to noise

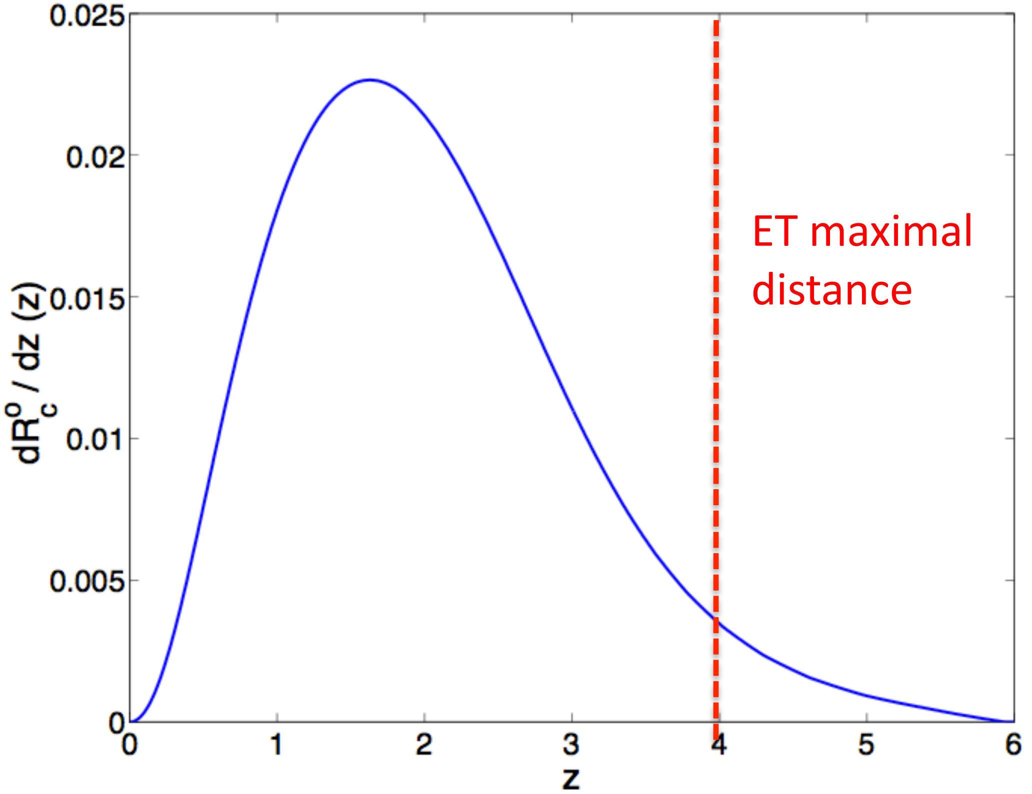
Time between coalescences



Coalescence Rate

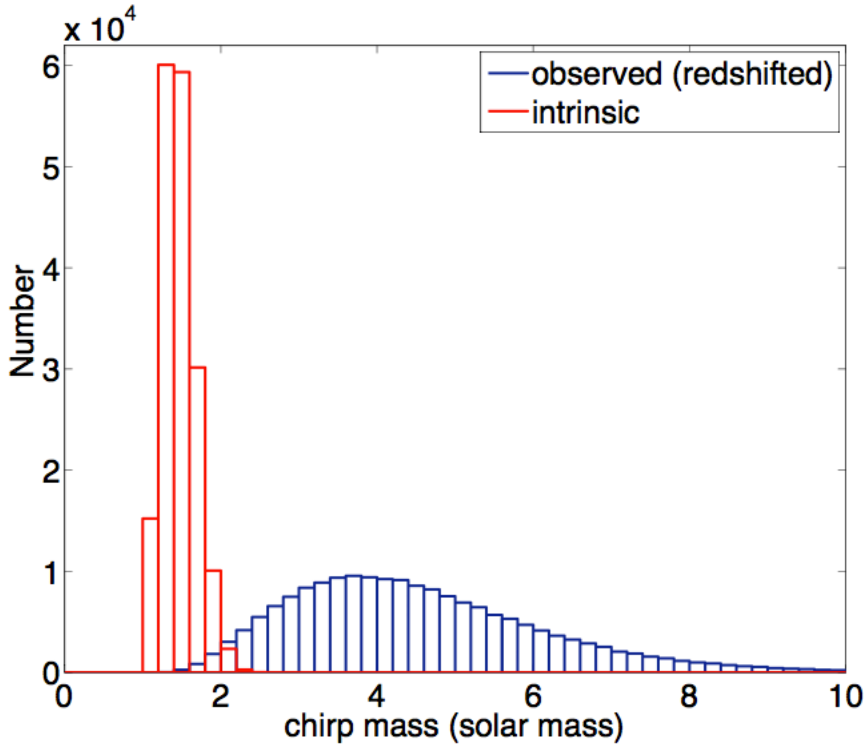
$$\frac{dR_c^o}{dz}(z) = \dot{\rho}_c^o(z)\frac{dV}{dz}(z) \quad \text{with } \dot{\rho}_c^o(z) \propto \int \frac{\dot{\rho}_*(z_f)}{1+z_f} P(t_d)\,dt_d$$

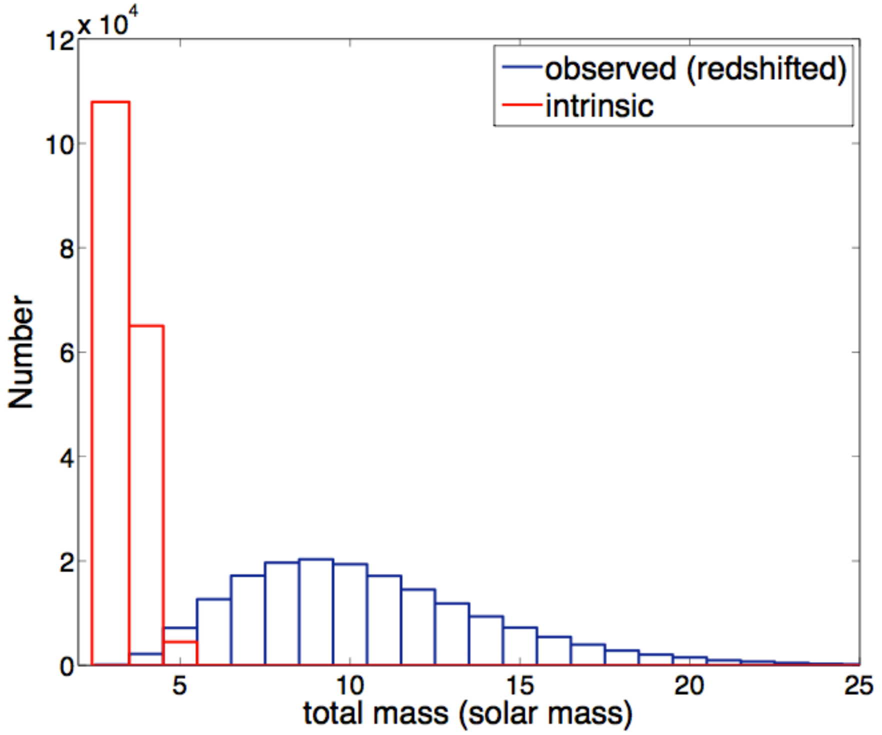
- $H_0 = 0.7,\ \Omega_m = 0.3,\ \Omega_\Lambda = 0.7$
- SFR : Hopkins & Beacom 2006
- delay: $P(t_d) \propto 1/t_d$ with t_d>20 Myr
- local rate: $\dot{\rho}_c^o(0) = 1\ \text{Myr}^{-1}\text{Mpc}^{-3}$ *



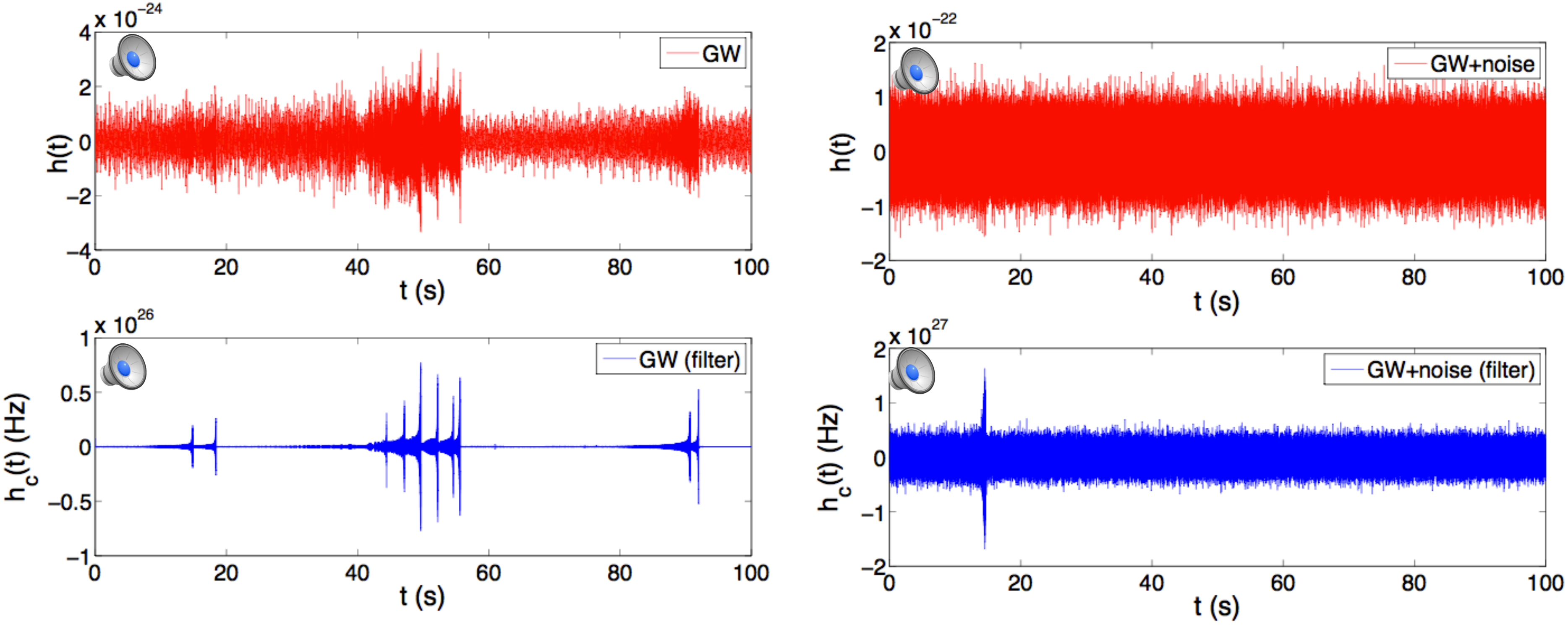
* 'realistic' rate from the LIGO rate paper

Chirp mass/Total mass

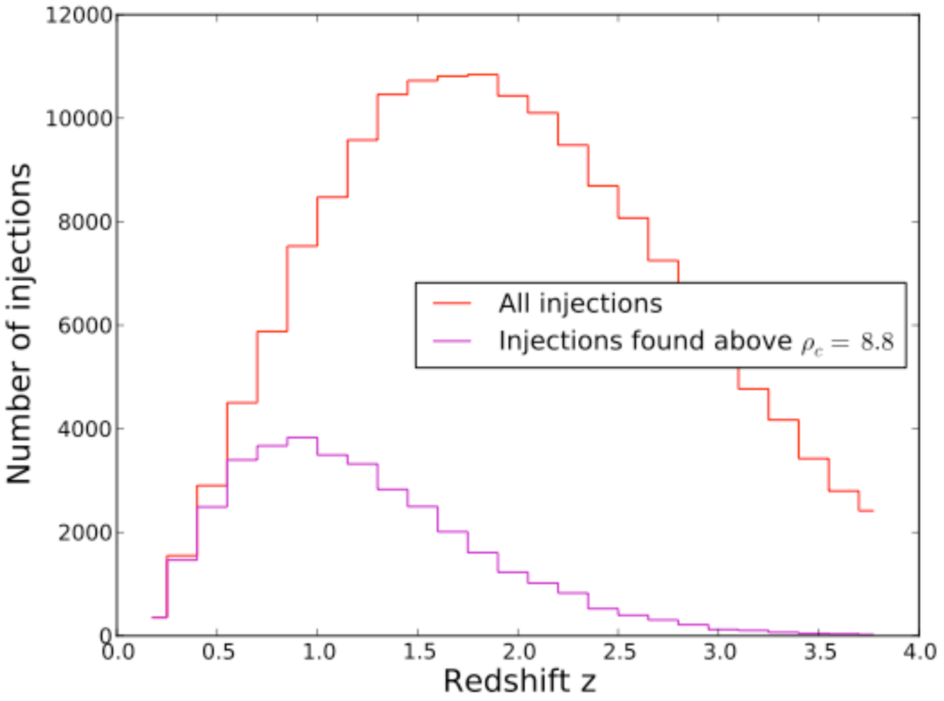


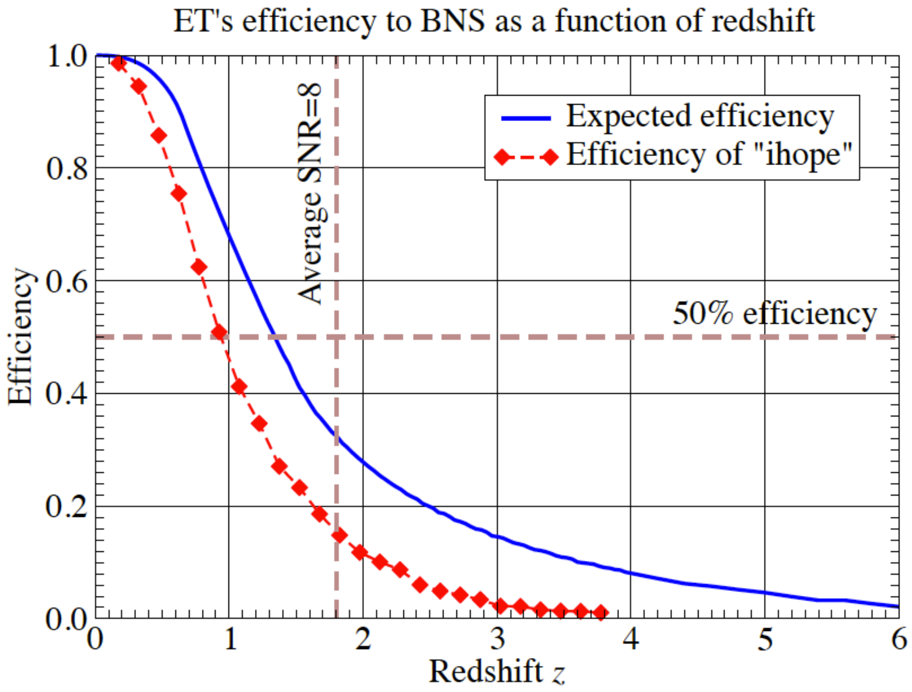


GW Signal

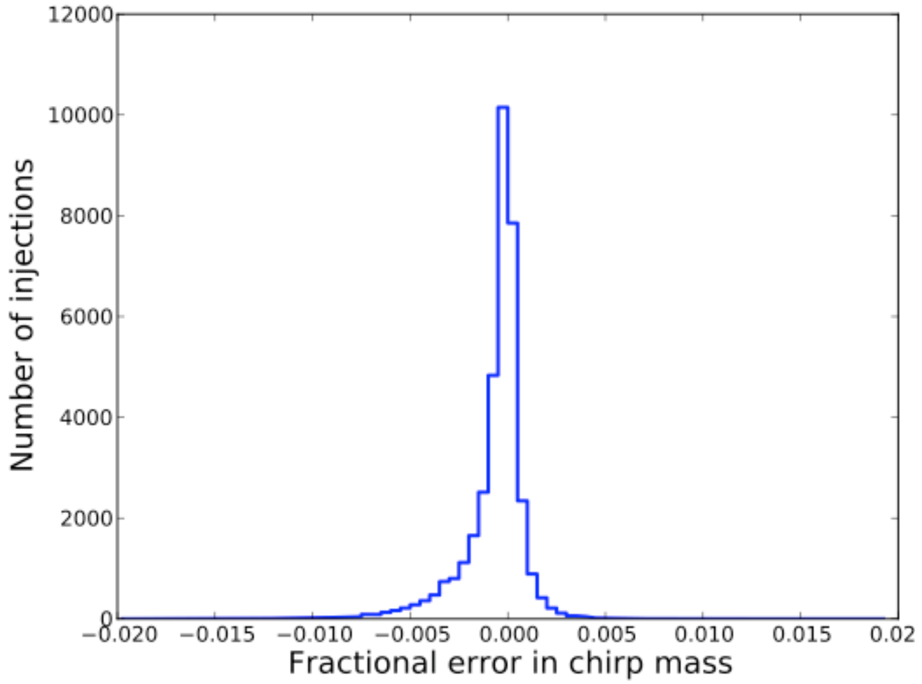

x 10^−24
4
2
0
−2
−4
h(t)
0
20
40
60
80
100
t (s)
GW
x 10^−22
2
1
0
−1
−2
h(t)
0
20
40
60
80
100
t (s)
GW+noise
x 10^26
1
0.5
0
−0.5
−1
h_c(t) (Hz)
0
20
40
60
80
100
t (s)
GW (filter)
x 10^27
2
1
0
−1
−2
h_c(t) (Hz)
0
20
40
60
80
100
t (s)
GW+noise (filter)

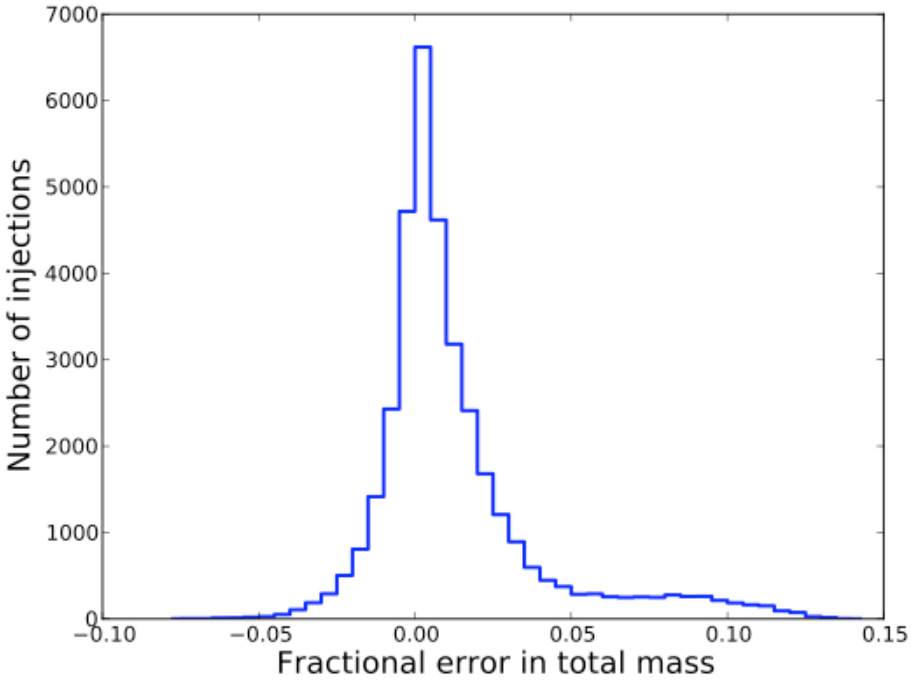
Efficiency of CBC analysis





CBC parameter recovery





- Chirp mass accuracy < 0.5%
- Total mass accuracy few% for most injections

Null stream

- sum of 3 detector outputs **contains no GW signal!**

$$s_I(t) = n_I(t) + d_I^{ij} h_{ij}(t) \text{ with}$$

$$d_I^{ij} = \frac{1}{2}(l_J^i \otimes l_J^j - l_K^i \otimes l_K^j)$$

$$s(t) = \sum_{I=1}^{3} s_I(t) = \sum_{I=1}^{3} n_I(t) + h_{ij}(t) \underbrace{\sum_{I=1}^{3} d_I^{ij}}_{=0} = \sum_{I=1}^{3} n_I(t)$$

- estimate of individual single-interferometer PSD

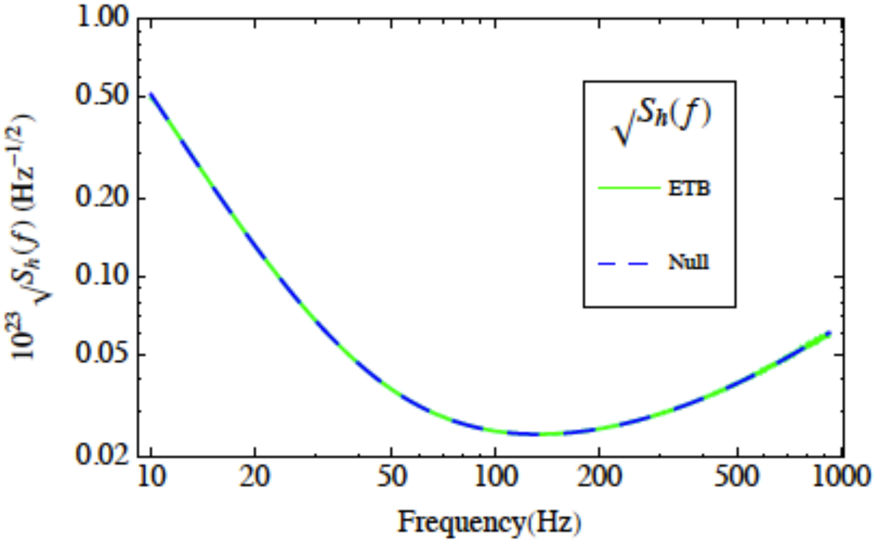
$$\hat{S}_{n,I}(f) \simeq \frac{1}{3} S_{n,null}(f)$$

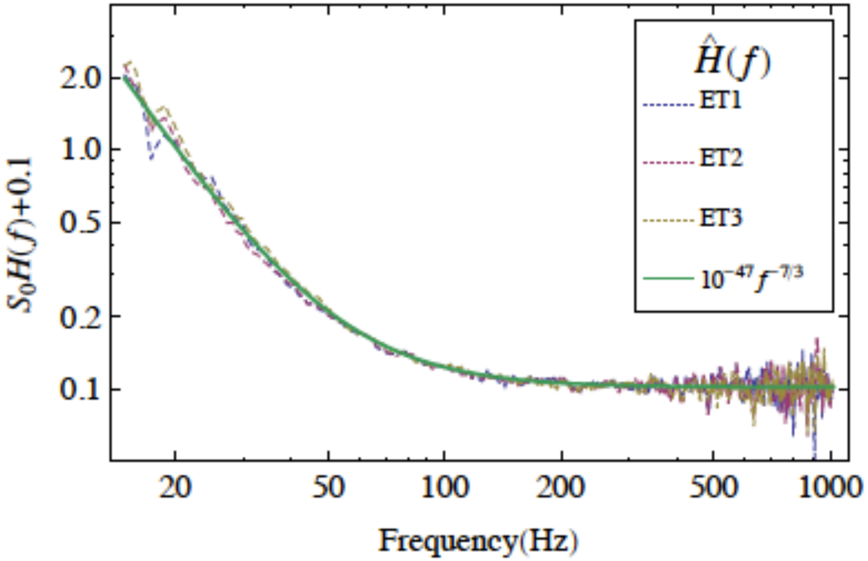
- residual consistent with the median PSD of the injected population of GW signal

$$S_{n,BNS}(f) \propto f^{-7/3}$$

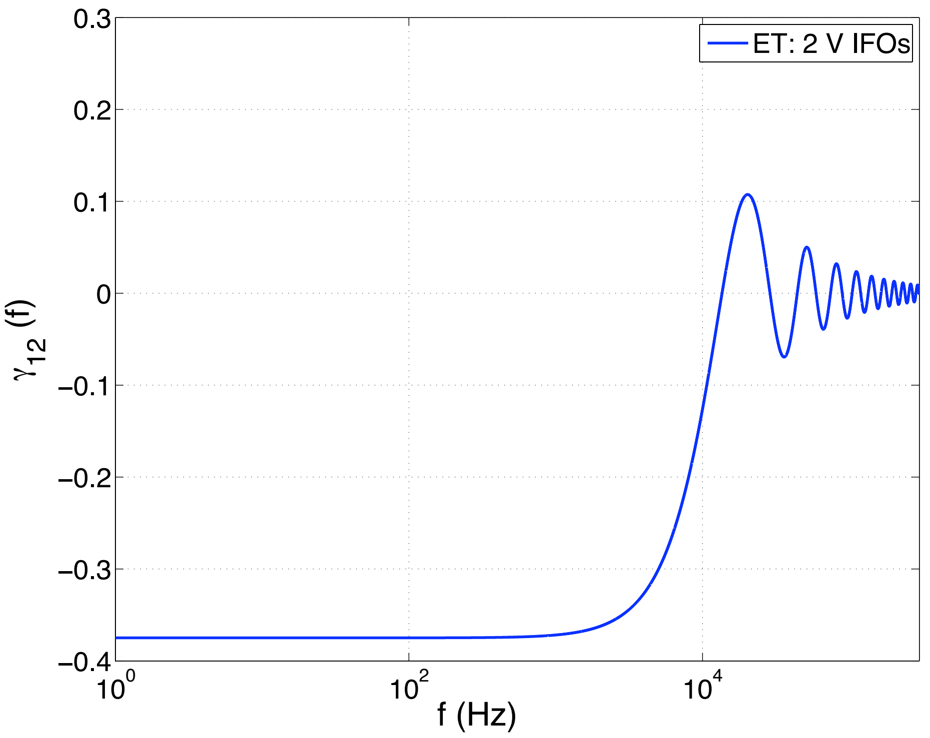
$$\hat{H}(f) = S_{n,I}(f) - \frac{1}{3} S_{n,null}(f) \propto f^{-\alpha}$$

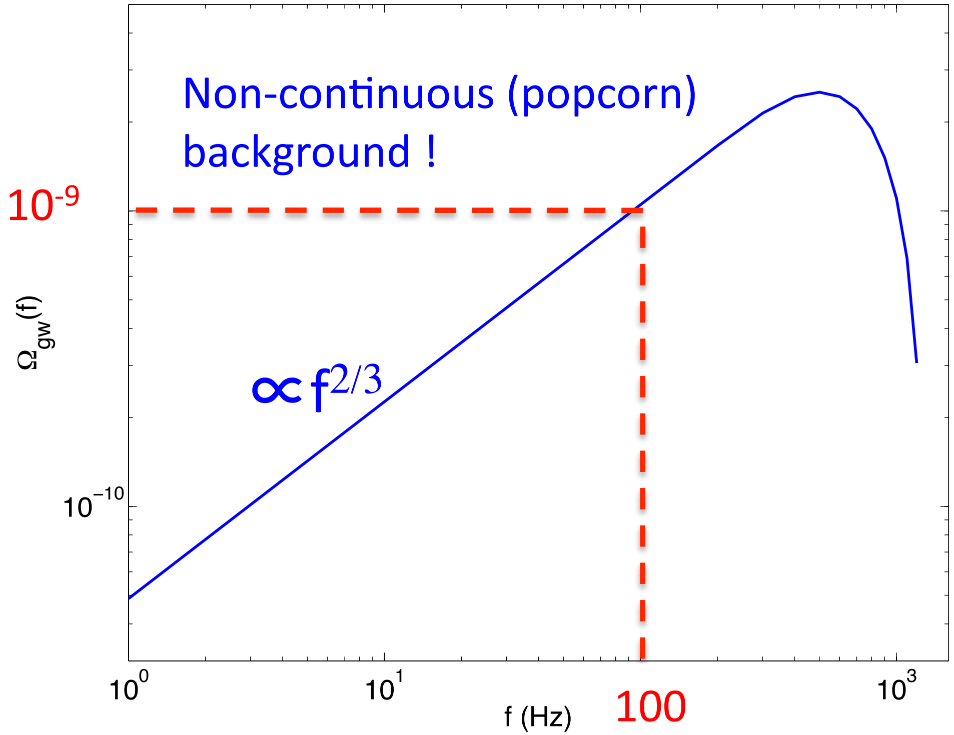
$$\alpha \sim -7/3$$





Stochastic analysis





	E1-E2	E2-E3	E1-E3
W_{est} @100 Hz	9.8 10^{-10}	9.9 10^{-10}	9.3 10^{-10}
error	1.3 10^{-11}	1.3 10^{-11}	1.3 10^{-11}

ET MD & Science Challenge

Overall Goal:

- Focus on ET **Science** Challenge rather than Data Challenge
- New data to be produced and released by December 2011
- Aim to publish results by May 2012 and present at GWPAW (June)

Injected Sources:

Data will contain populations of BNS, NS-BH and BBH inspirals with some chosen model for each and an occasional burst from a SN.

Science Challenges:

- Estimate the rate of different populations as a function of redshift
- Assuming standard cosmology, measure mass functions of NS & BH
- Detect and estimate the spectrum of SN
- Estimate the background produced by compact binary populations
- Estimate cosmological parameters without GRB counterparts

(McLeod&Hogan 2008, Messenger&Read 2011, Regimbau&Bulik in preparation)

For more information about ET Science Challenge:

regimbau@oca.eu

paper in preparation :

A Science Challenge for the proposed Einstein GW Telescope,
T. Regimbau, ,B. Sathyaprakash, T. Dent, C. Robinson, D. Meacher, C. Rodriguez, C. Van Den Broeck, T.G.F. Li, W. Del Pozzo, S. Giampanis (2011)

Summary

- Einstein Telescope will detect a wide variety of sources, and address a large range of problems in astrophysics but also fundamental physics and cosmology

- In particular, coalescing compact binaries that could be detected up to very large distances can be used to test GR, put constraints on the NS and BH mass functions, the NS EoS, the star formation history, the progenitors of GRBs, the cosmological parameters and the nature of dark energy (DE) …

- Science Challenge to address the ET science potential