Multi-messenger cosmology in the ET era: Some recent results

Chris Van Den Broeck

NIKHEF

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Overview

- If progenitors of short-hard gamma ray bursts (GRBs) are mergers of binary neutron stars (or of neutron star - black hole binaries) then they would be powerful "standard sirens" for doing cosmology with ET *(Sathyaprakash, Schutz, CVDB, arXiv:0906.4151)*

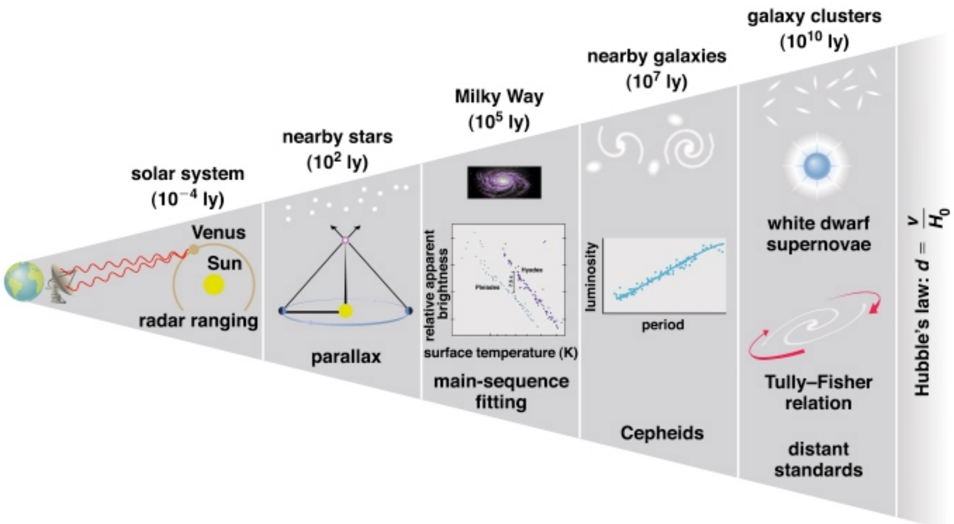
More recently:

- Drop 3 simplifying assumptions in earlier work:
  - All "useful sources" are seen face-on (tight beaming of GRB)
  - Distribution of sources uniform in (co-moving) volume
  - Not all parameters can be measured at once, so some assumed known with near-perfect accuracy from previous measurements

(W. Zhao, D. Baskaran, T. Li, CVDB, in preparation)

Cosmography with binary inspirals

- Standard candle in cosmology: source for which intrinsic luminosity approximately known; can be used to measure distance
- If redshift also known, exploit $d_L(z)$ relationship to probe geometry of the Universe
- Example: Type Ia supernovae



- Problem: need for calibration using closer-by sources

"Cosmic distance ladder"

Cosmography with binary inspirals

- Schutz '86: Use GW signals from binary inspirals:

$$A(t) = \frac{[\mathcal{M}_c(m_1, m_2)]^{5/3}}{D_\mathrm{L}} f(\theta, \phi, \psi, \iota) \, [F(t)]^{2/3}$$

  - Amplitude depends on masses, position/orientation, distance
  - Masses obtained separately from *phasing*
  - *If position/orientation can be obtained, can get distance without recourse to other sources!*

  "Standard sirens"

- LISA:
  - Use binary supermassive black holes
  - Position/orientation from Doppler modulation of the signal due to probes' motion around Sun
- Ground-based:
  - Use inspirals involving at least one neutron star → EM counterpart

Cosmography with binary inspirals

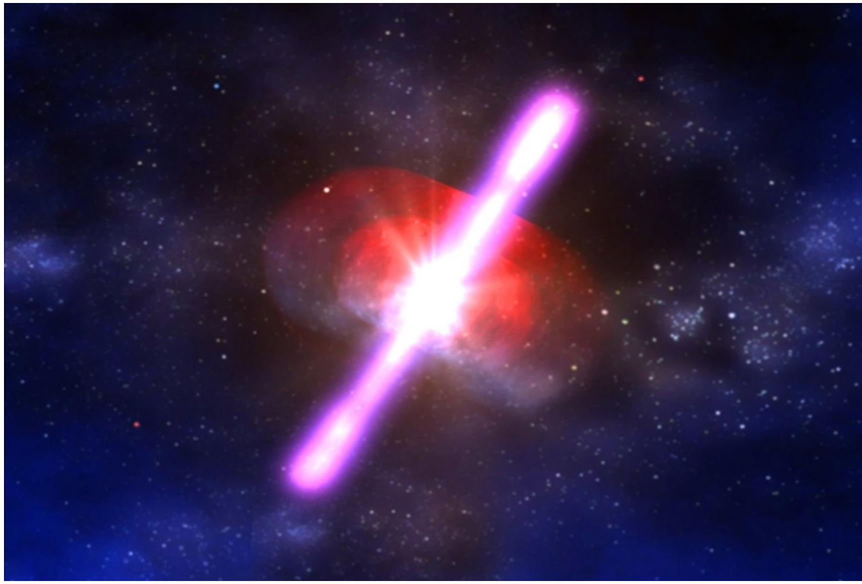
- Binary neutron stars believed to cause *short, hard gamma ray bursts*
  - Get sky position
  - Network of GW detectors (even if co-located): information on orientation of binary

→ $(\theta,\varphi,\psi,\iota)$

→ Distance information from GW signal

  - Identify host galaxy: get redshift

→ Probe $d_L(z)$



- Advanced LIGO
  - Hubble constant to a few percent

Nissanke et al., arXiv:0904.1017

- Einstein Telescope
  - Hubble constant
  - Density of matter, dark energy
  - Dark energy equation-of-state

Sathyaprakash, Schutz, CVDB, arXiv:0906.4151

Dark energy and its evolution

- SNIa measurements: expansion of the Universe appears to be accelerating
  - GR incorrect at large length scales?
  - Cosmological constant?
  - New field, "dark energy", with
    - positive density
    - negative pressure

- Dark energy equation-of-state (EOS):

$$w = p_{de}/\rho_{de} \quad < 0$$

  - If w = -1 then cosmological constant, but current observational constraints still too loose
  - Does w have *time dependence*, and can it be measured with ET?

How would ET compare with other methods for studying cosmography?

Dark energy and its evolution

- Interested in late-time evolution of universe where anomalous speeding-up of expansion is apparent
- Phenomenological form for EOS of dark energy:

$$w(z) \equiv p_{de}/\rho_{de} = w_0 + w_a(1-a) + \mathcal{O}\left[(1-a)^2\right]$$
$$\simeq w_0 + w_a \frac{z}{1+z}$$

- $d_L(z)$ relation then depends on

$\Omega_m \equiv 8\pi G \rho_{m,0}/3H_0^2$	density of matter normalized to critical density
$\Omega_k \equiv -k/H_0^2$	effect of spatial curvature
H_0	Hubble constant
w_0	dark energy EOS at current epoch
w_a	time dependence of dark energy EOS

Uncertainties on the distance measurement

- Luminosity distance uncertainty receives contributions from:
  - Error due to instrumental noise, σ_{inst}
  - Error due to weak lensing, σ_{lens}

  $\Delta d_L / d_L = (\sigma_{inst}^2 + \sigma_{lens}^2)^{1/2}$

- Weak lensing error $\sigma_{lens} \sim 0.05\,z$
- Instrumental error:
  - "Strong beaming case": GRB beaming so strong that one can assume inclination angle i = 0 for all practical purposes. Compute errors using Fisher matrix, average over sky position:

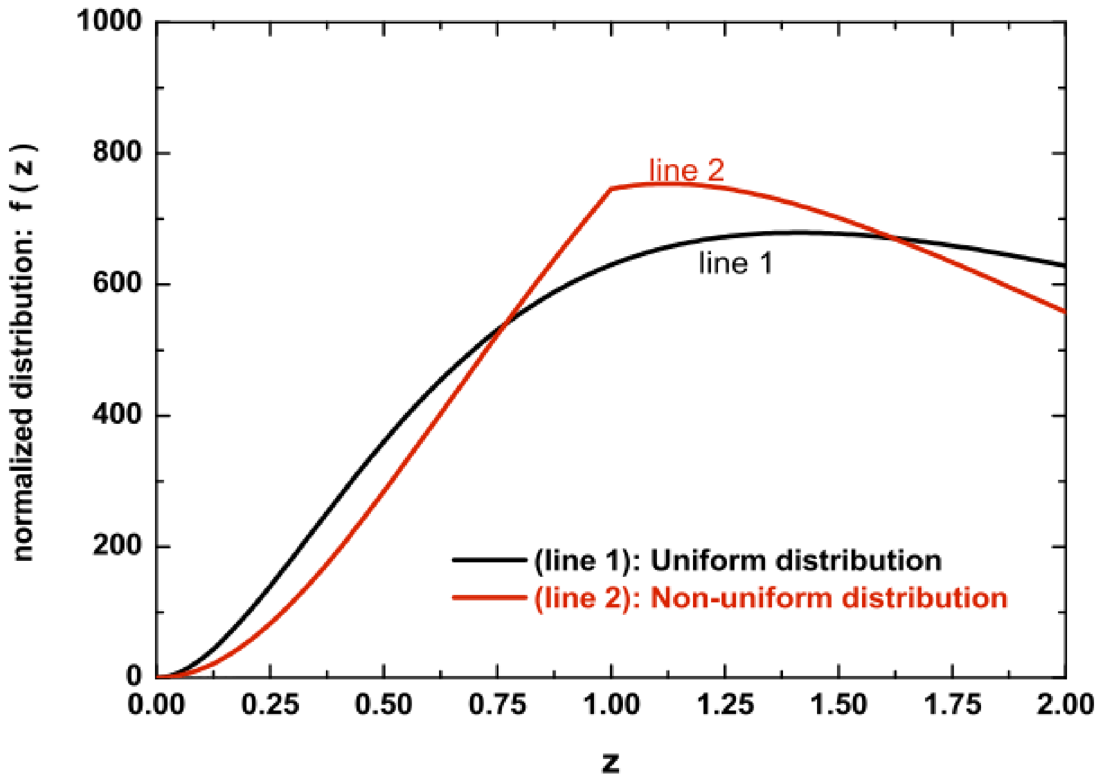
    $$\sigma_{inst} \approx 0.065\,z$$

  - "Realistic case": beam angles up to 40°, so include inclination and polarization angles (i,ψ) in Fisher analysis, then angle-average over sky position *and* orientation but with constraint i < 20°:

    $$\sigma_{inst} \approx 0.12\,z$$

Distribution of sources

- Population of ~1000 "useful" events over several years; up to z ~ 2
- Distribution of sources over redshift:
  - uniform in co-moving volume
  - (crude) fit to Scheider et al. (2001)



Basic method

- Parameters to be measured:

$$(w_0, w_a, \Omega_m, \Omega_k, h_0)$$

- Assuming distance errors are Gaussian distributed for individual sources in the population, construct Fisher matrix for cosmological parameters:

Derivatives w.r.t. the parameters (i, j = 1, ..., 5)

$$F_{ij}^{\mathrm{GW}} = \sum_k \frac{\partial_i(\ln d_L(z_k))\partial_j(\ln d_L(z_k))}{(\Delta \ln d_L(z_k))^2}$$

Sum over the sources (k = 1, ..., 1000)

- Measurement uncertainties on the parameters:

$$\Delta p_i = \sqrt{(F^{\mathrm{GW}})^{-1}_{ii}}$$

Measurement accuracies from GW alone

- If all parameters estimated together, large errors for most:

$$\Delta w_0 = 1.69,\ \Delta w_a = 5.95,\ \Delta\Omega_m = 0.514,\ \Delta\Omega_k = 1.30,\ \Delta h_0 = 7.00 \times 10^{-3}$$

- Assume that, e.g., $(\Omega_m,\ \Omega_k,\ h_0)$ already measured by other means, and leave only $(w_0,\ w_a)$ free:

$$\Delta w_0 = 0.039,\ \Delta w_a = 0.244$$

- Or, make assumption on values of $(w_0,\ w_a)$ and leave $(\Omega_m,\ \Omega_k,\ h_0)$ free:

$$\Delta\Omega_m = 0.014,\ \Delta\Omega_k = 0.056,\ \Delta h_0 = 3.22 \times 10^{-3}$$

Want to be more concrete concerning prior information

Using the Planck CMB prior

- Can use temperature and polarization anisotropies in the Cosmic Microwave Background (CMB) for prior information on $(\Omega_m,\ \Omega_k,\ h_0)$
- Assume predicted accuracies for Planck
- Fisher matrix:

$$F_{ij}^{\rm CMB} = \sum_{\ell=2}^{\ell_{\rm max}} \sum_{XX',YY'} \frac{\partial C_\ell^{XX'}}{\partial p_i} {\rm Cov}^{-1}(D_\ell^{XX'}, D_\ell^{YY'}) \frac{\partial C_\ell^{YY'}}{\partial p_j}$$

- Marginalize so that it refers only to $(w_0, w_a, \Omega_m, \Omega_k, h_0)$
- Measurement uncertainties $\Delta p_i = \sqrt{(F^{\rm CMB})^{-1}_{ii}}$
- Results:

$$\Delta w_0 = 0.411,\ \Delta w_a = 0.517,\ \Delta\Omega_m = 8.88\times 10^{-2},\ \Delta\Omega_k = 2.27\times 10^{-3},\ \Delta h_0 = 0.115$$

CMB will not significantly constrain $(w_0,\ w_a)$ *but can provide a prior on* $(\Omega_m,\ \Omega_k,\ h_0)$

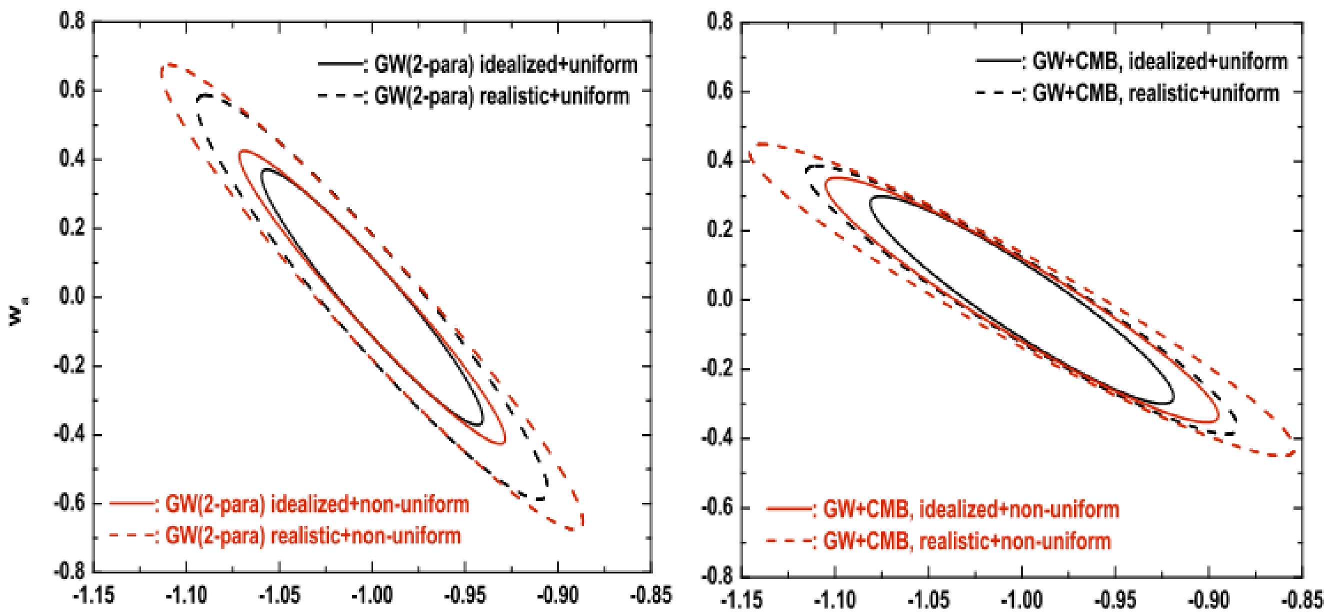
Using the Planck CMB prior

- Add Fisher matrices from GW and CMB measurements to find a combined Fisher matrix
- Inverse gives uncertainties from combined GW and CMB observations:

$$\Delta w_0 = 0.053,\ \Delta w_a = 0.197,\ \Delta\Omega_m = 3.69\times10^{-3},\ \Delta\Omega_k = 6.47\times10^{-4},\ \Delta h_0 = 3.67\times10^{-3}$$

Compare with *assumption* that $(\Omega_m,\ \Omega_k,\ h_0)$ known with essentially no error:

$$\Delta w_0 = 0.039,\ \Delta w_a = 0.244$$



Comparison with supernovae observations

- Observations of SNIa *also* need to be supplemented with other information (e.g., CMB) in order to give information about $(w_0,\, w_a)$
- Consider future SNAP (SuperNova/Acceleration Probe)
  - 300 low redshift sources (0.03 < z < 0.08)
  - 2000 high redshift sources (0.1 < z < 1.7)
- Also combine with predicted Planck CMB accuracies, then

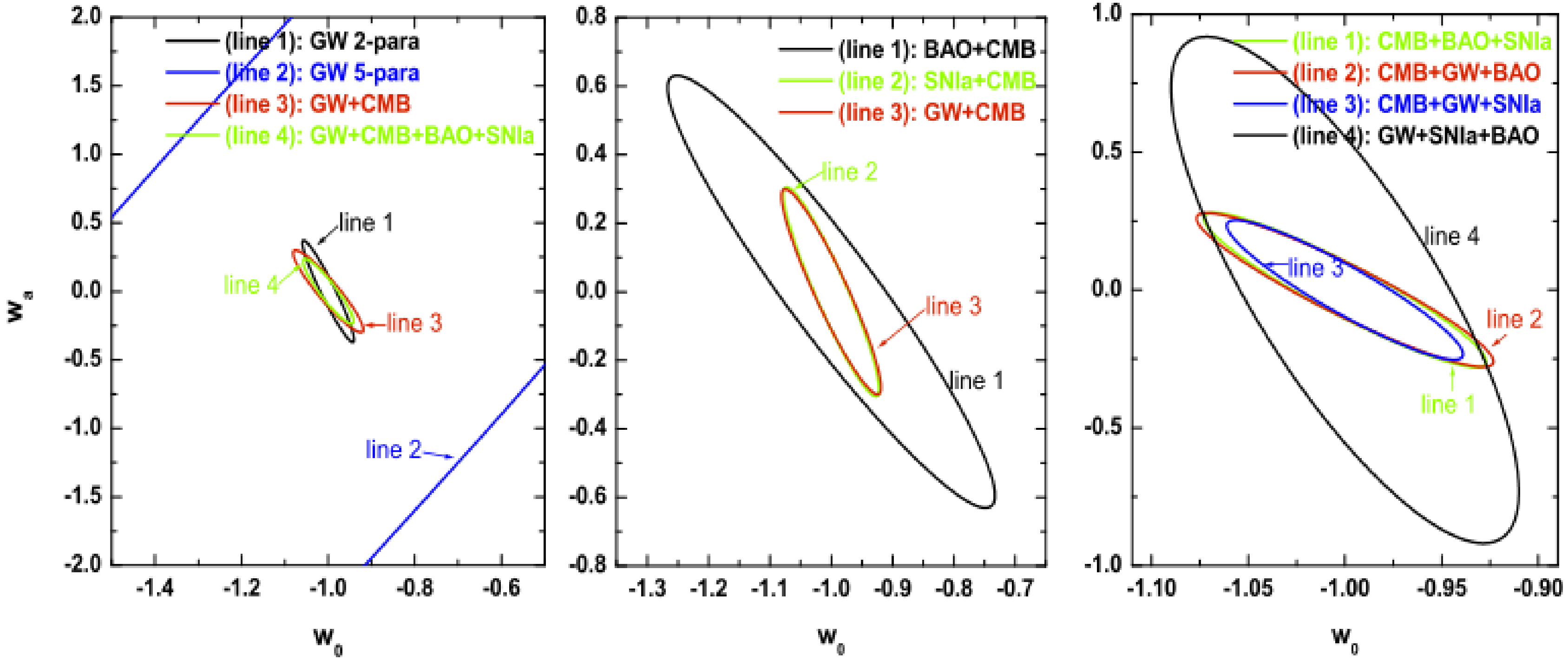
$$\Delta w_0 = 0.051,\ \Delta w_a = 0.201,\ \Delta\Omega_m = 3.49 \times 10^{-3},\ \Delta\Omega_k = 6.52 \times 10^{-4},\ \Delta h_0 = 3.39 \times 10^{-3}$$

- Compare with GW + CMB:

$$\Delta w_0 = 0.053,\ \Delta w_a = 0.197,\ \Delta\Omega_m = 3.69 \times 10^{-3},\ \Delta\Omega_k = 6.47 \times 10^{-4},\ \Delta h_0 = 3.67 \times 10^{-3}$$

Note once again: GW standard sirens are self-calibrating

Comparison with other observations



GW+CMB+SNIa+BAO: $\Delta w_0 = 0.045, \ \Delta w_a = 0.173$

Zhao, Baskaran, Li, CVDB, *in preparation*

Summary

- Measuring dark energy equation-of-state and its time-variability $(w_0,\, w_a)$

(Zhao, Baskaran, Li, CVDB)

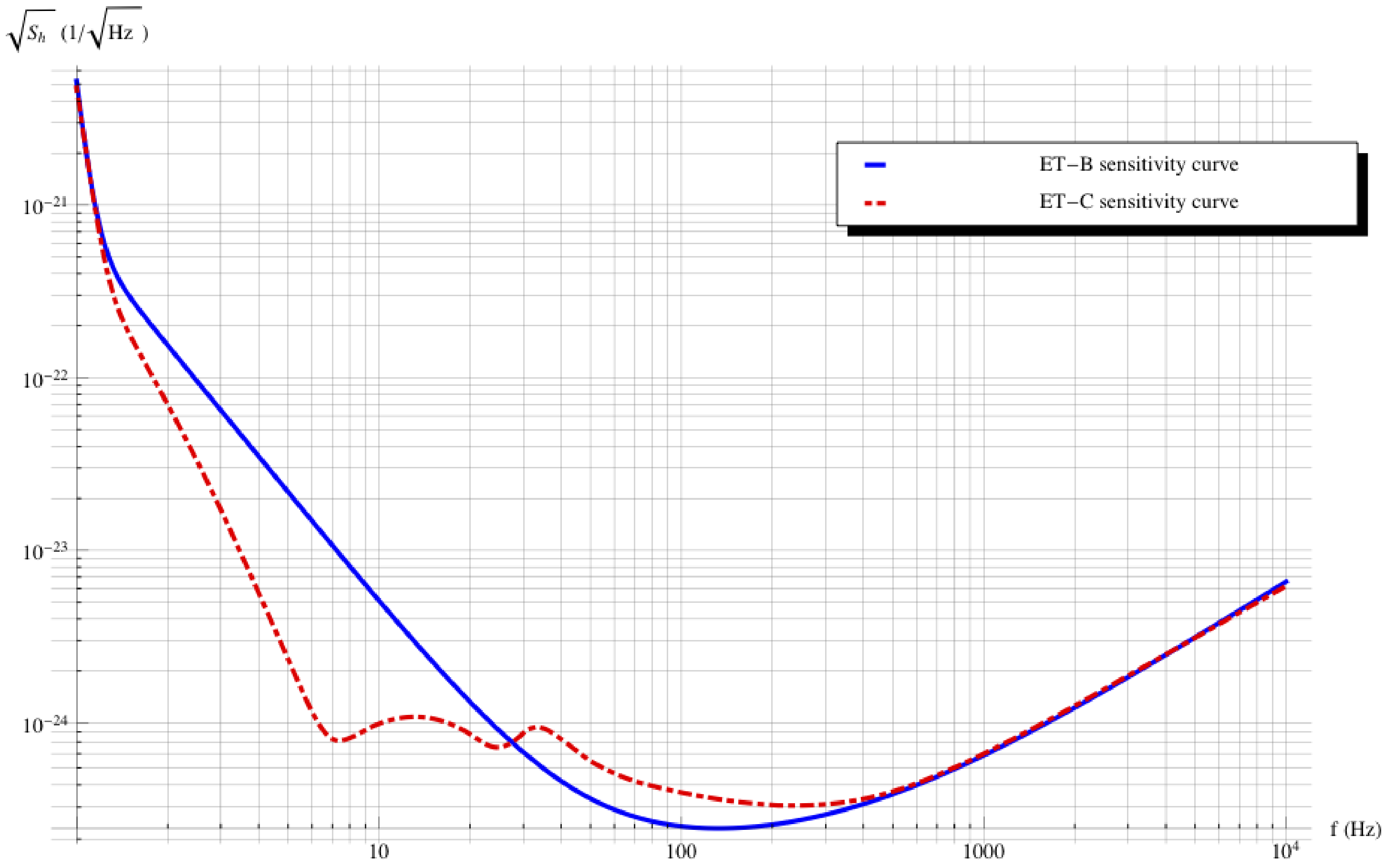
  - Use of the predicted Planck CMB sensitivity as a "prior" for $(\Omega_m,\, \Omega_k,\, h_0)$ is almost the same as assuming these are exactly known
  - Allowing GRB beaming angles up to 40° degrades parameter estimation by factor ~2
  - GW+CMB gives essentially the same accuracies as future SNIa+CMB from SNAP and Planck, but *no dependence on a cosmic distance ladder*
  - Combining multiple probes (GW+CMB+SNIa+BAO):

$$\Delta w_0 = 0.045,\ \ \Delta w_a = 0.173$$

... which is a 6% improvement on CMB+SNIa+BAO

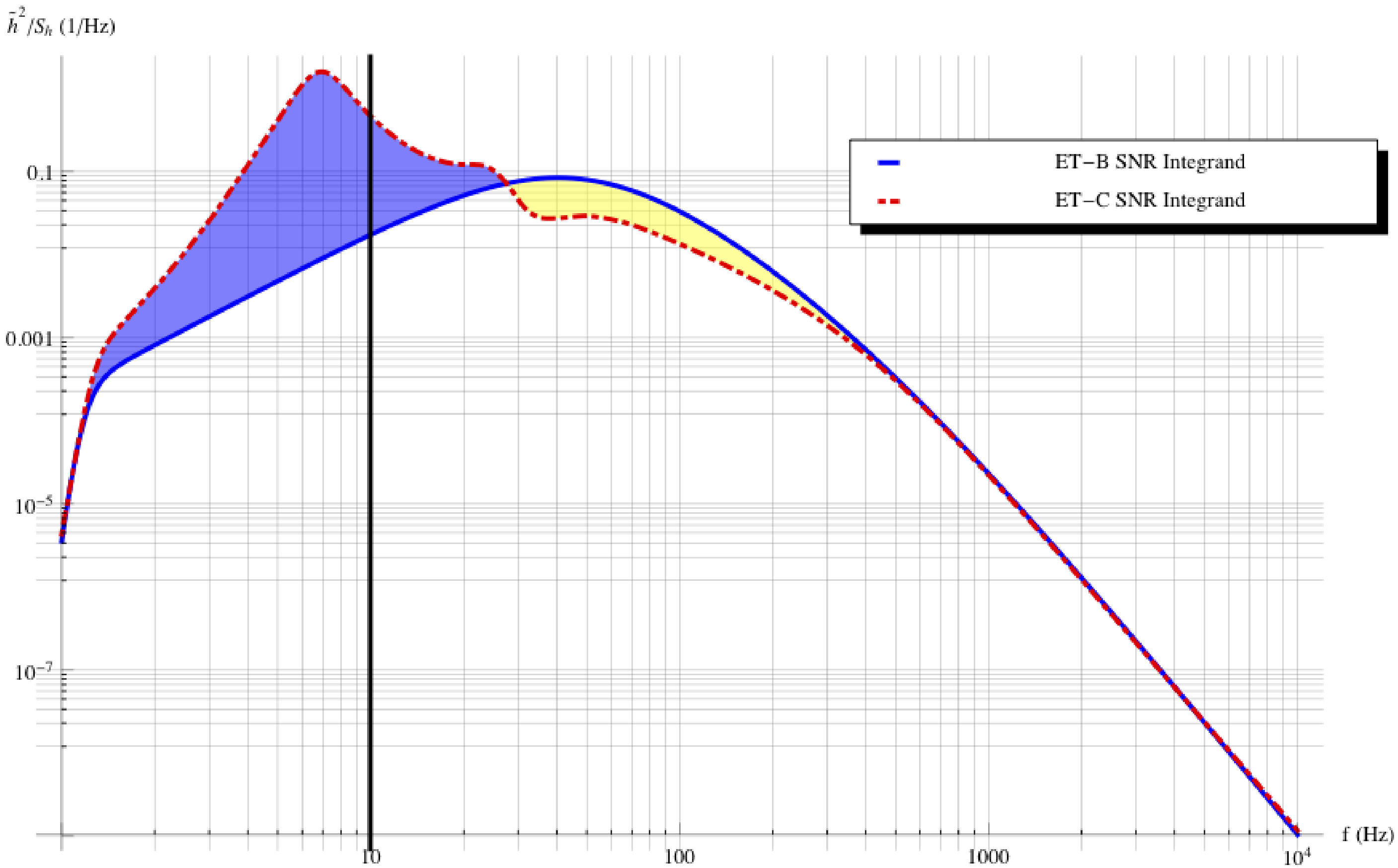
Part 2: ET-B versus ET-C

"Original" proposal (ET-B) versus xylophone (ET-C):



Part 2: ET-B versus ET-C

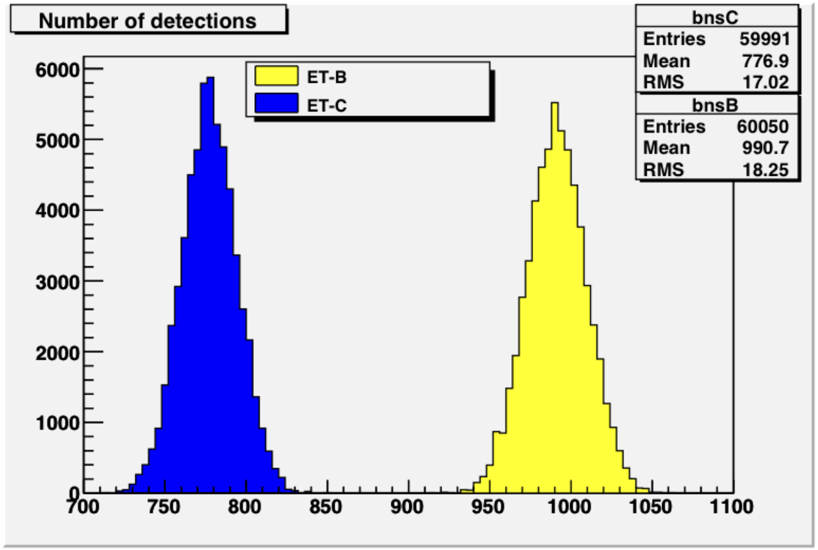
Difference in SNR integrand:



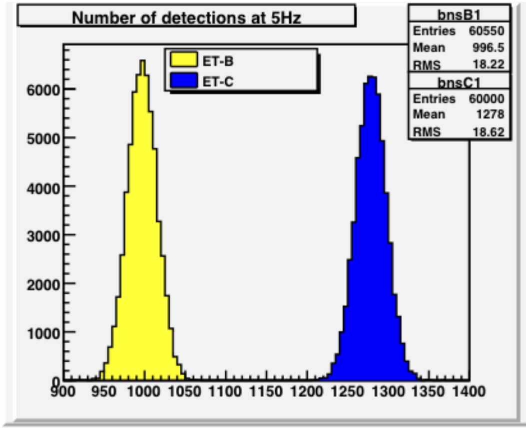
Effect of lower cut-off frequency

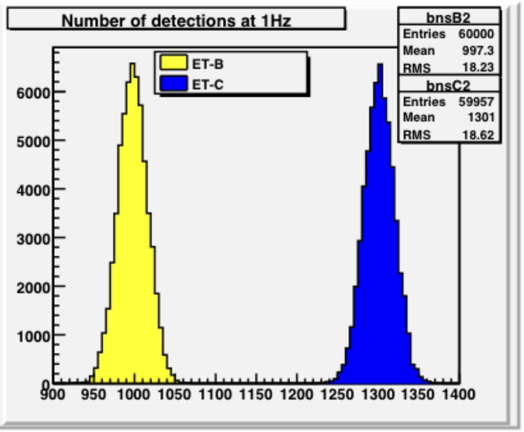
Detection rates:

f_{lower} = 10 Hz



f_{lower} = 5 Hz, 1 Hz





Improvement in parameter estimation in going to ET-C

(ET-C uncertainties) / (ET-B uncertainties):

f_{lower} = 10 Hz

Model	Ω_M	Ω_{DE}	Ω_k	w_0	w_1
Ω_M, Ω_{DE}, Ω_k, w_0, w_1	1.215	1.005	1.049	1.050	1.057
Ω_M, Ω_{DE}, Ω_k	1.298	1.207	1.228	–	–
Ω_M, Ω_{DE}, w_0, w_1	1.104	1.096	–	1.186	1.207
Ω_M, Ω_{DE}, w_0	1.162	1.162	–	1.164	–
Ω_M, Ω_{DE}	1.178	1.178	–	–	–
w_0, w_1	–	–	–	1.158	1.183
w_0	–	–	–	1.151	-
Average relative improvement:	−15.11%				

f_{lower} = 5 Hz

Model	Ω_M	Ω_{DE}	Ω_k	w_0	w_1
Ω_M, Ω_{DE}, Ω_k, w_0, w_1	0.813	0.992	0.967	0.923	0.989
Ω_M, Ω_{DE},Ω_k	0.777	0.826	0.810	–	–
Ω_M, Ω_{DE}, w_0, w_1	0.877	0.884	–	0.828	0.833
Ω_M, Ω_{DE}, w_0	0.815	0.815	–	0.830	–
Ω_M, Ω_{DE}	0.849	0.849	–	–	–
w_0, w_1	–	–	–	0.858	0.842
w_0	–	–	–	0.863	–
Average relative improvement:	13.75%				

f_{lower} = 1 Hz

Model	Ω_M	Ω_{DE}	Ω_k	w_0	w_1
Ω_M, Ω_{DE}, Ω_k, w_0, w_1	0.805	0.993	0.967	0.914	0.969
Ω_M, Ω_{DE},Ω_k	0.765	0.816	0.799	–	–
Ω_M, Ω_{DE}, w_0, w_1	0.872	0.879	–	0.821	0.820
Ω_M, Ω_{DE}, w_0	0.804	0.804	–	0.819	–
Ω_M, Ω_{DE}	0.838	0.838	–	–	–
w_0, w_1	–	–	–	0.850	0.834
w_0	–	–	–	0.854	–
Average relative improvement:	14.66%				