Cosmography @ ET

Investigating the plausibility of measuring cosmological parameters with ET

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Overview

- Cosmology
  - Electromagnetic waves
  - Gravitational waves
- Methods
- Results
- Conclusions
- Further Work

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Cosmology

- Exploring the history and dynamics of the universe
  - Hubble constant
  - Matter density Ω_m
  - Spatial curvature Ω_k
  - Dark energy Ω_Λ, w_0, w_a

Encapsulated in luminosity distance

$$d_L(z) = (1+z)\begin{cases} |k|^{-1/2}\sin\left[|k|^{1/2}\int_0^z \frac{dz'}{H(z')}\right] & (k>0) \\ \int_0^z \frac{dz'}{H(z')} & (k=0) \\ |k|^{-1/2}\sinh\left[|k|^{1/2}\int_0^z \frac{dz'}{H(z')}\right] & (k<0) \end{cases}$$

$$H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + (1-\Omega_m-\Omega_k)E(z)\right]^{1/2}$$

$$E(z) \equiv (1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}$$

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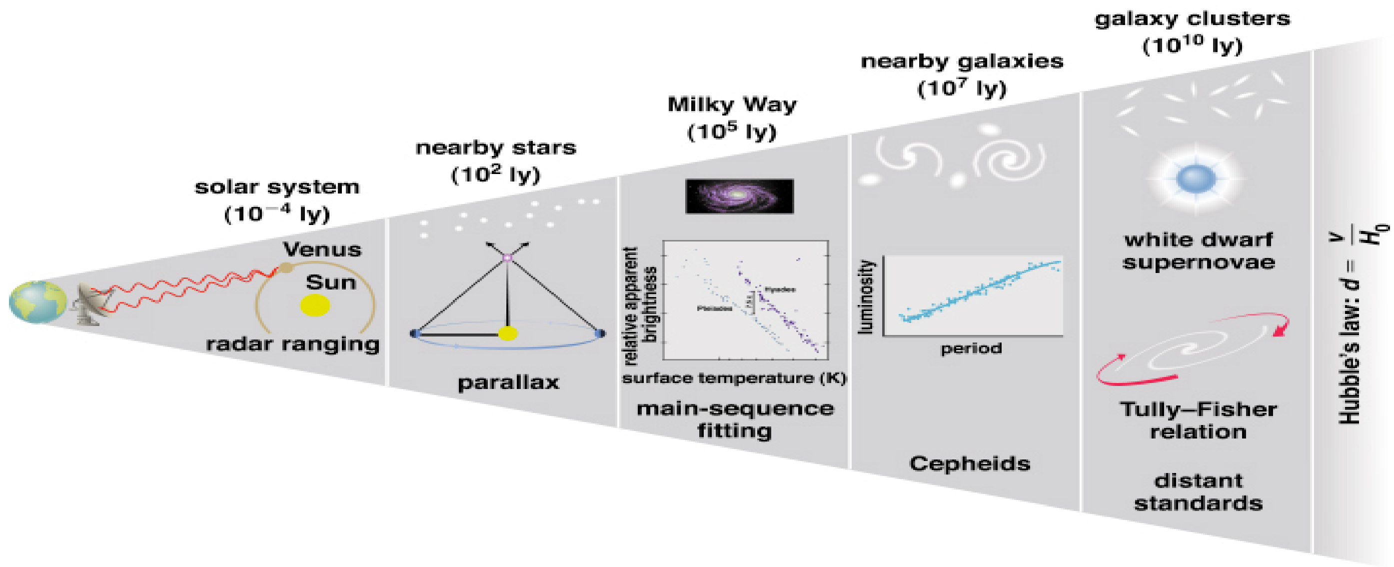
EM measurements
"Standard Candles"



<u>e.g SN1A supernovae</u>

- Intrinsic luminosity (L) known to ~10%
- Measure flux density (F)
- Redshift from spectrum

$$d_L = \sqrt{\frac{L}{4\pi F}}$$

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GW Measurements

“standard sirens”

- Signal of a binary neutron star inspiral in the form of

$$h(t) = A(t)\cos\left(2\phi_0 - 2\phi(t)\right)$$

- Amplitude of GW signal depends on <u>component masses</u> and <u>luminosity distance</u>

$$A(t) = A(t; M, \mu, d_L, \ldots) = \frac{G\mu^{3/5}M^{2/5}}{c^2 d_L}\left(\frac{c^3(t_0 - t)}{5G\mu^{3/5}M^{2/5}}\right)^{-1/4} f(\theta, \phi, \psi, \iota)$$

- However, masses can be determined by the <u>phasing</u> of the signal

$$\phi(t) = \phi(t; M, \mu) \rightarrow \Psi(f; M, \mu) = \alpha + 2\pi f t_0 + \beta\frac{M}{\mu}\left[v^{-5} + \left(\gamma + \delta\frac{\mu}{M}\right)v^{-3} - \epsilon v^{-2} + \ldots\right]$$

GW's determine an <u>absolute</u> luminosity distance

In combination with <u>EM redshift measurements</u>, one can obtain estimates on cosmological constants

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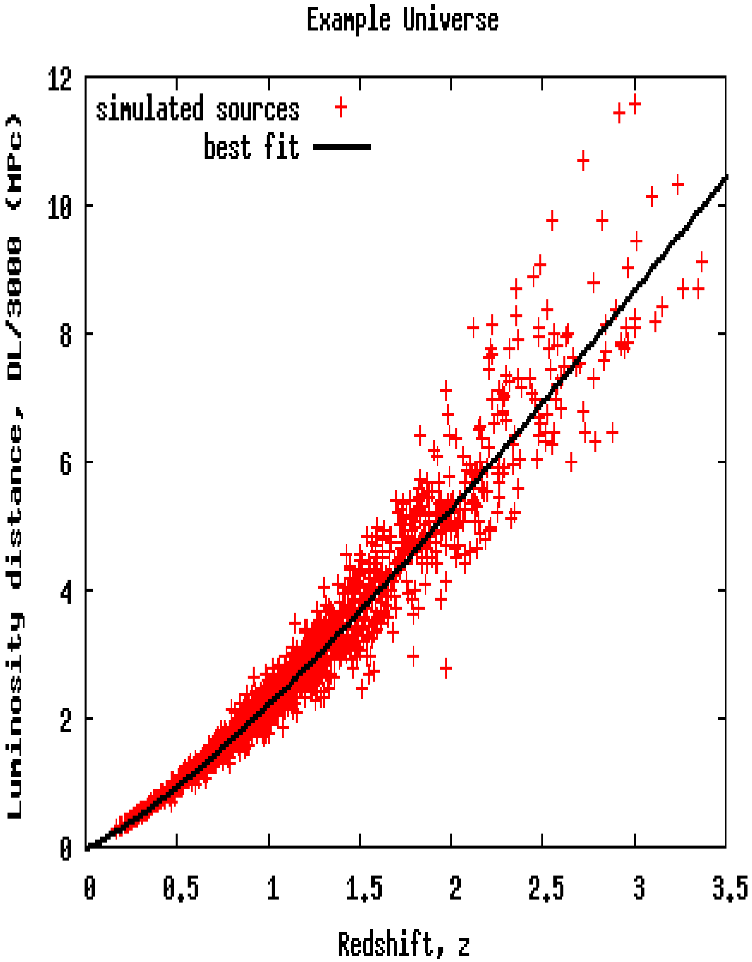
Method



- Source distribution rate

$$\frac{dR}{dz} =\propto \frac{1}{1+z} \begin{cases} 1+2z & z<1 \\ \frac{3}{4}(5-z) & z>1 \end{cases}$$

- Error in dl calculated by adding errors in quadrature
  - Weak lensing (~0.05z)
  - Detector error (~1/SNR)
- Levenberg-Marquardt algorithm fits luminosity distance wrt set of parameters
  - Minimise chi2
  - Gradient descent
- Simulate 10.000 universes to get the spread in parameters

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Results

	Model	$\Omega_m, \Omega_\Lambda, w_0$	Ω_Λ, w_0	$w_0, w1$	Ω_m, Ω_k
Ω_m	0.27	$0.27 \pm 0.03\,(12.56\%)$	-	-	$0.27 \pm 0.02(5.83\%)$
Ω_Λ	0.73	$0.73 \pm 0.02\,(2.96\%)$	$0.73 \pm 0.03\,(4.11\%)$		
Ω_k	0.00	-	-		$0.00 \pm 0.05(-\%)$
w_0	-1.00	$-1.01 \pm 0.14\,(13.89\%)$	$-1.01 \pm 0.08\,(7.91\%)$	$-1.00 \pm 0.05\,(5.41\%)$	
w_1	0.00	-	-	$0.00 \pm 0.32\,(-\%)$	

	Model	$\Omega_k, w0$	$\Omega_\Lambda, \Omega_k, w_0$	Ω_k, w_1	Ω_k, w_0, w_1
Ω_m	0.27		-	-	-
Ω_Λ	0.73		$0.74 \pm 0.03\,(4.61\%)$	-	-
Ω_k	0.00	$0.03 \pm 0.09(-\%)$	$0.07 \pm 0.12\,(-\%)$	$0.00 \pm 0.03(-\%)$	$0.11 \pm 0.14(-\%)$
w_0	-1.00	$-1.05 \pm 0.12(11.67\%)$	$-1.10 \pm 0.25\,(22.51\%)$	-	$-1.18 \pm 0.28(23.54\%)$
w_1	0.00			$-0.04 \pm 0.2(-\%)$	$-0.00 \pm 0.62(-\%)$

Compared to EM measurements (WMAP, SNIa, BAO)

$$\Omega_m = 0.274 \pm 0.015,\ \Omega_\Lambda = 0.726 \pm 0.015,\ -0.018 < \Omega_k < 0.008,\ -1.14 < w_0 < -0.88$$

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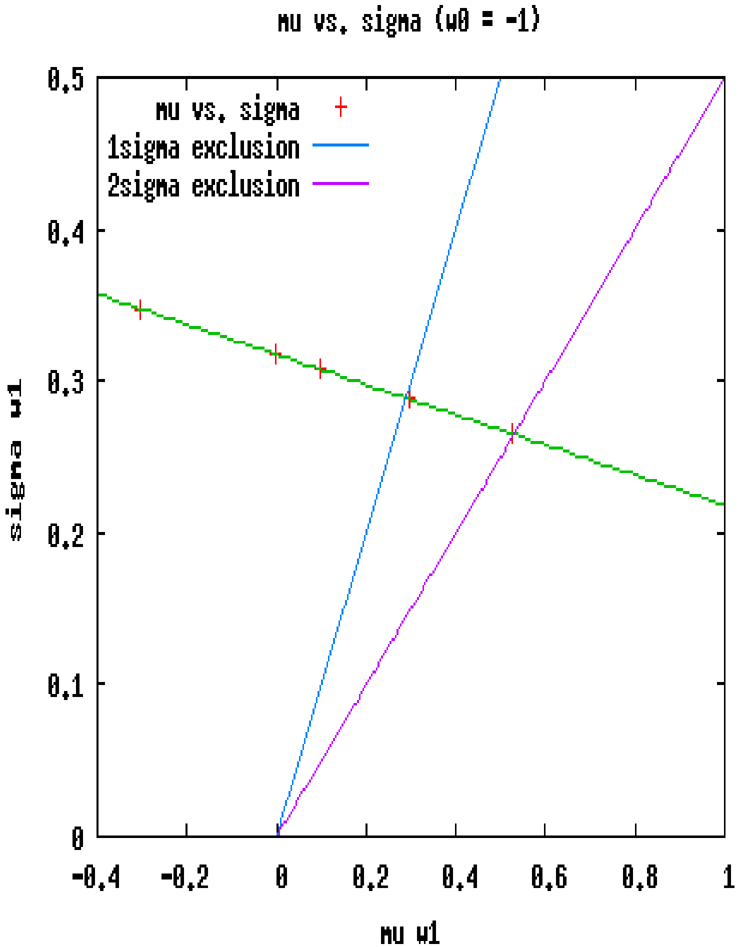
$W_a = 0$ exclusion



When can we exclude $w_a=0$?

- Assume all parameters except for w_0 and w_a to be constrained
- Model universes with $w_a = c$
- Vary c over a range of values

- $w_a=0.29$ σ exclusion
- $w_a=0.53$ 2σ exclusion
- Linear dependence of σ on μ
- Dark Energy Task force
  - σ ~ 0,3

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Conclusion

- Einstein Telescope can provide an accurate, absolute distant measurement

- Measured accuracy of Einstein Telescope are comparable with current electromagnetic measurements.

- However, limited resolving power once spacial curvature is considered

Excellent supplement to current understanding of the universe

Further Work

- Trade-of study between ET-B and ET-C
  - Investigating the <u>low frequency</u> dependence of cosmology by the means of the “xylophone” construction

- Further study to dark energy parameters and curvature

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Backup slides

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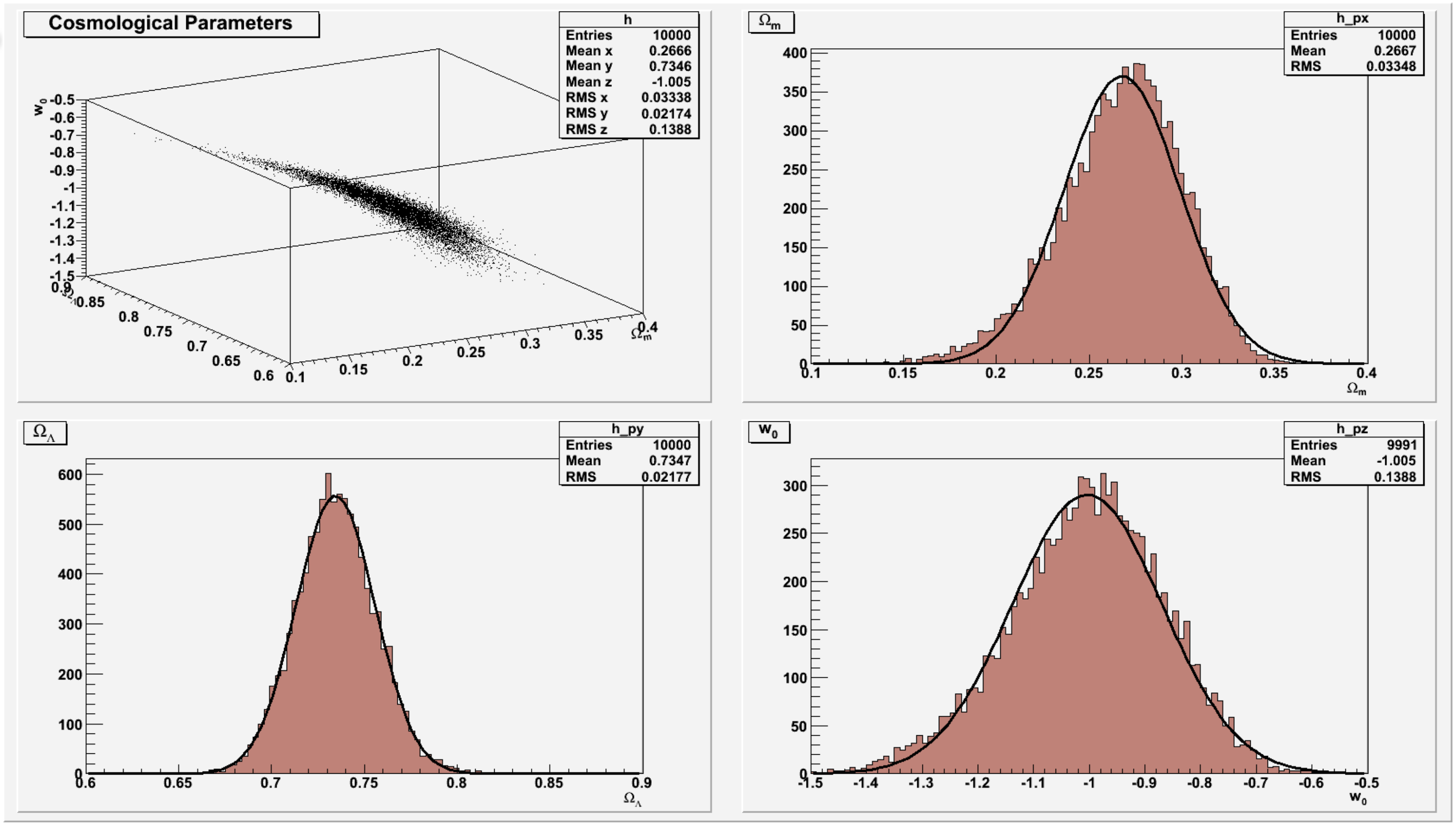
Raw Data (Ωm, ΩL, w0)



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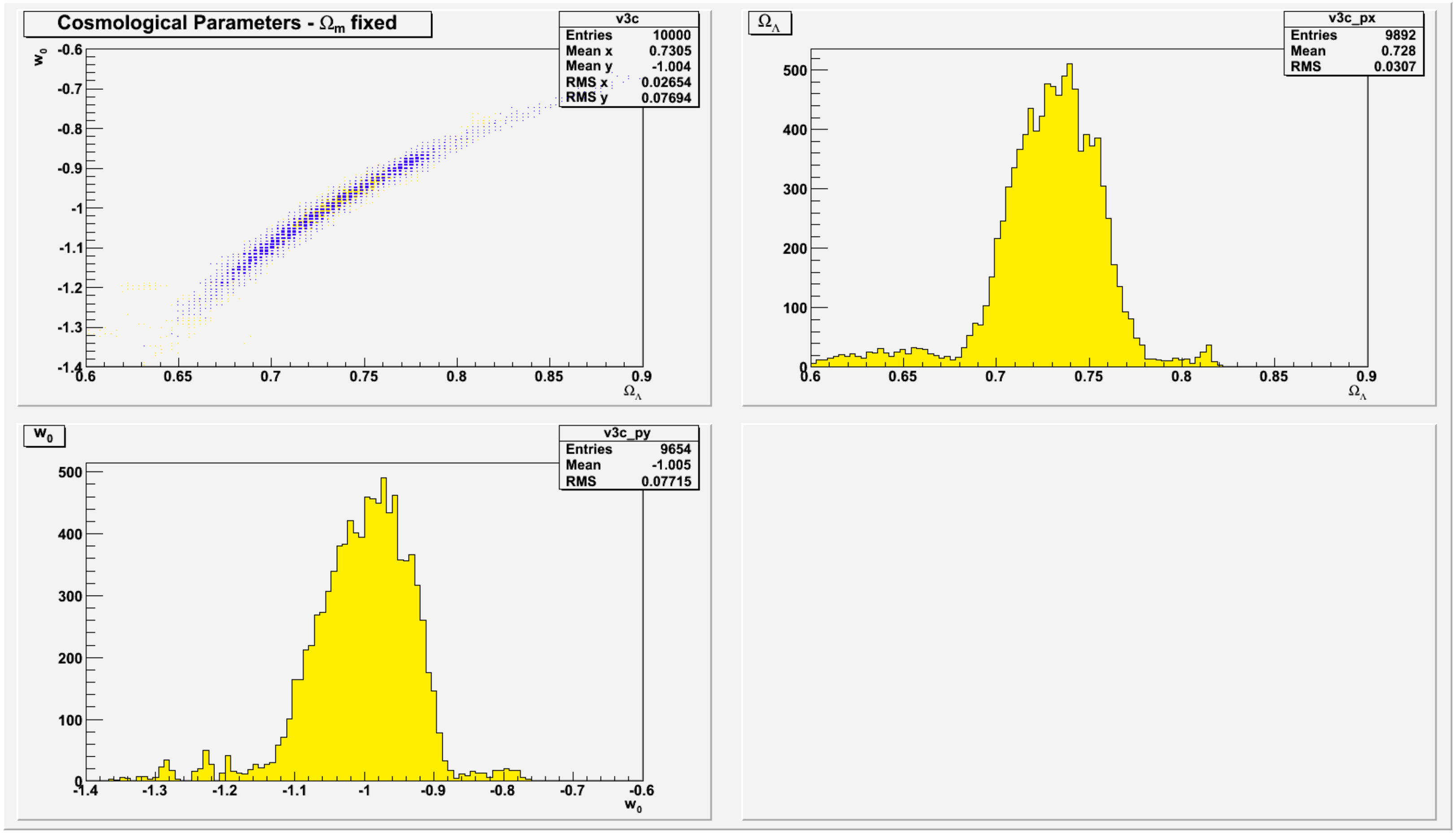
Raw Data (ΩL, w0)



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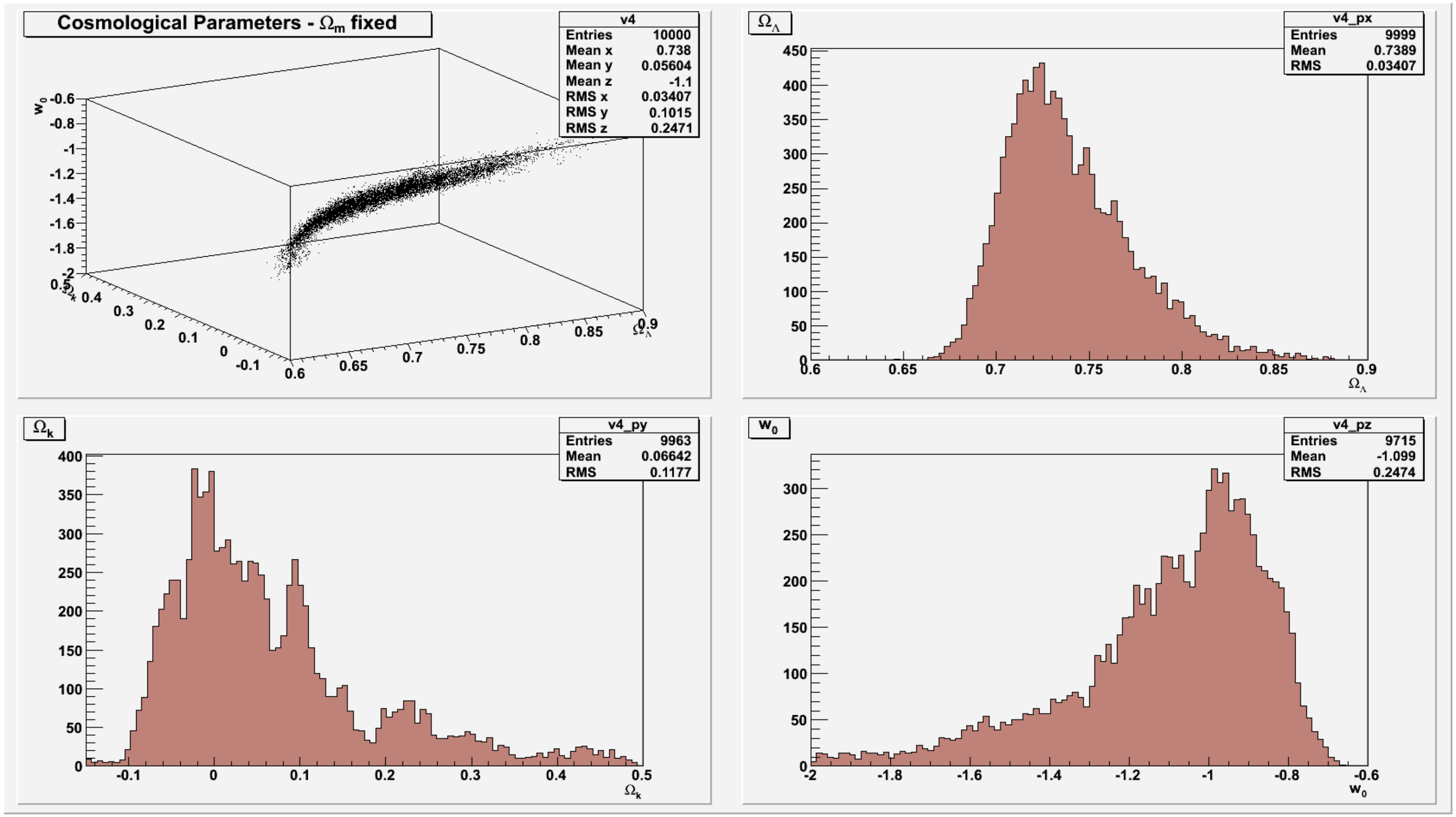
Raw Data (ΩL, Ωk, w0)



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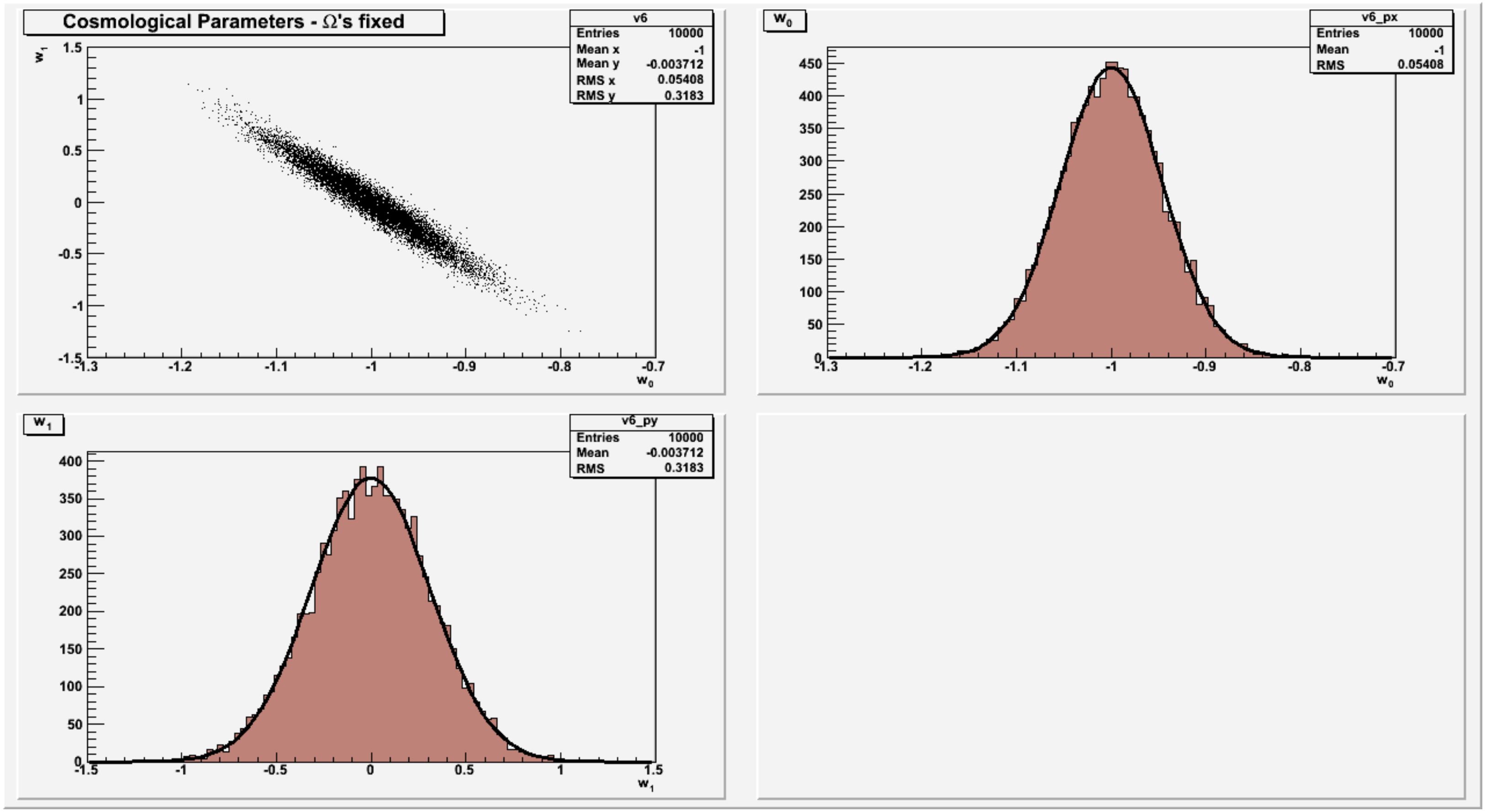
Raw Data (w0, w1)



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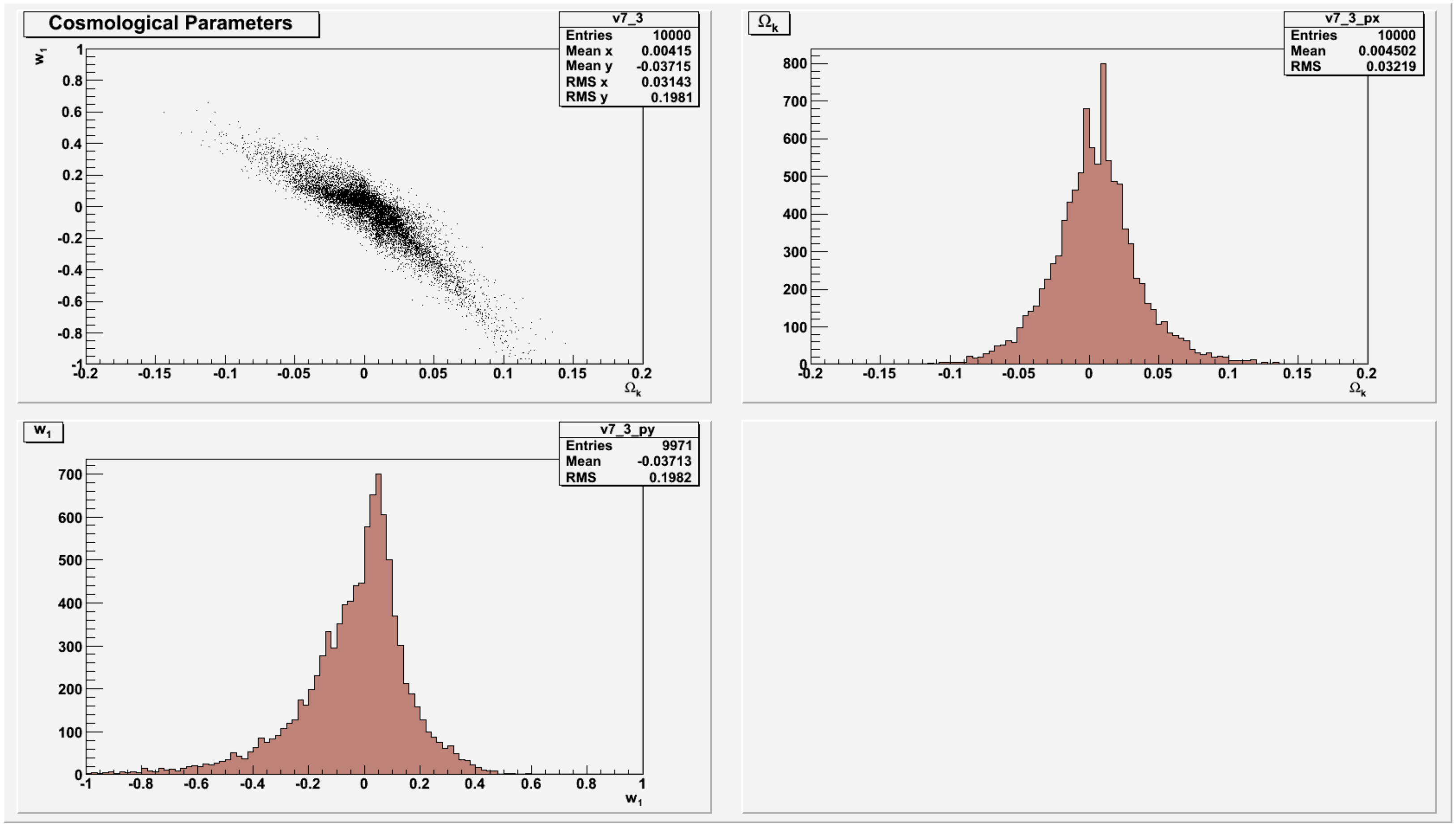
Raw Data (Ωk, w1)



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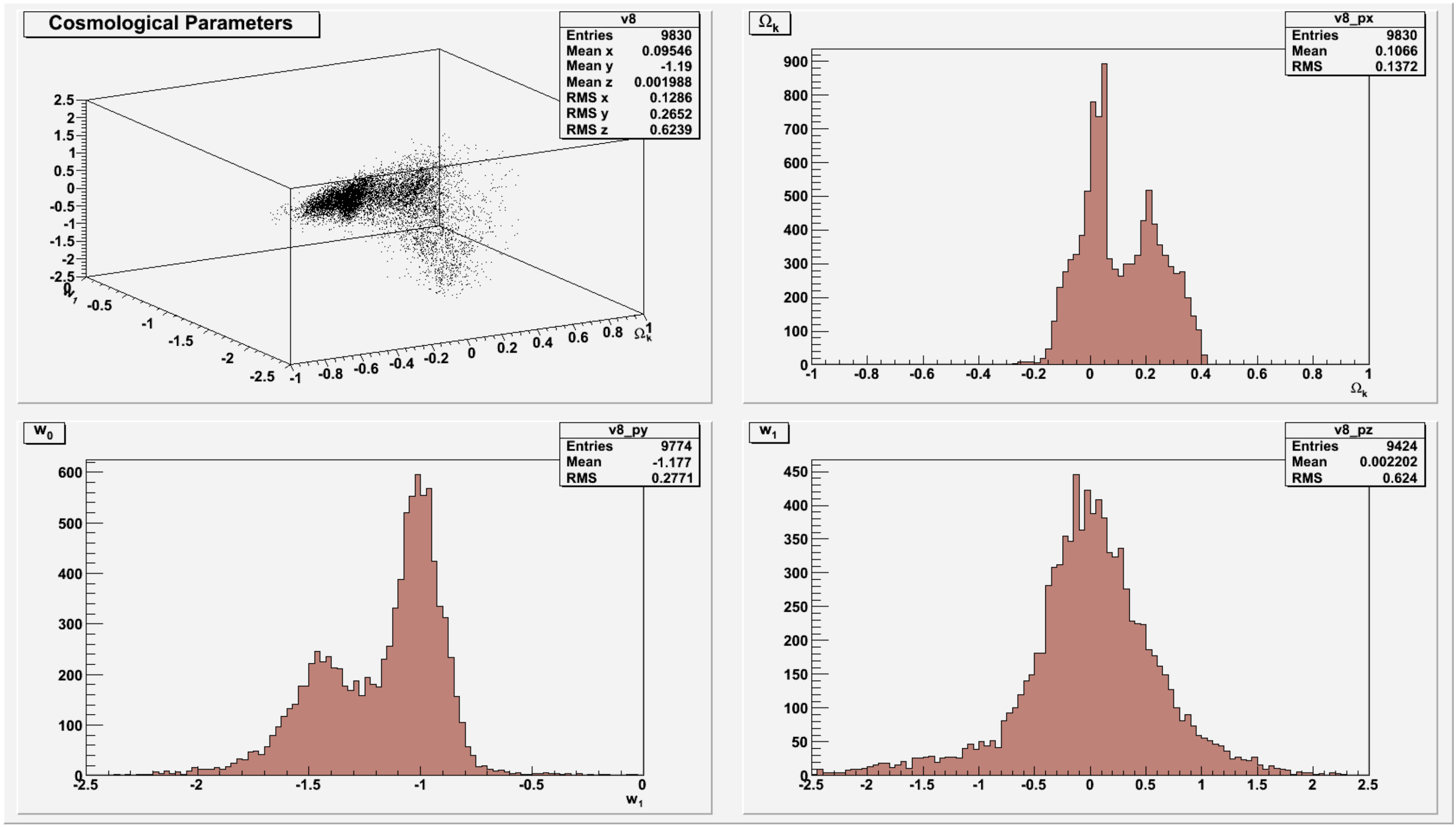
Raw data (Ωk, w0,w1)



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References

- “Cosmography with the Einstein Telescope”, B.S. Sathyaprakash et al.

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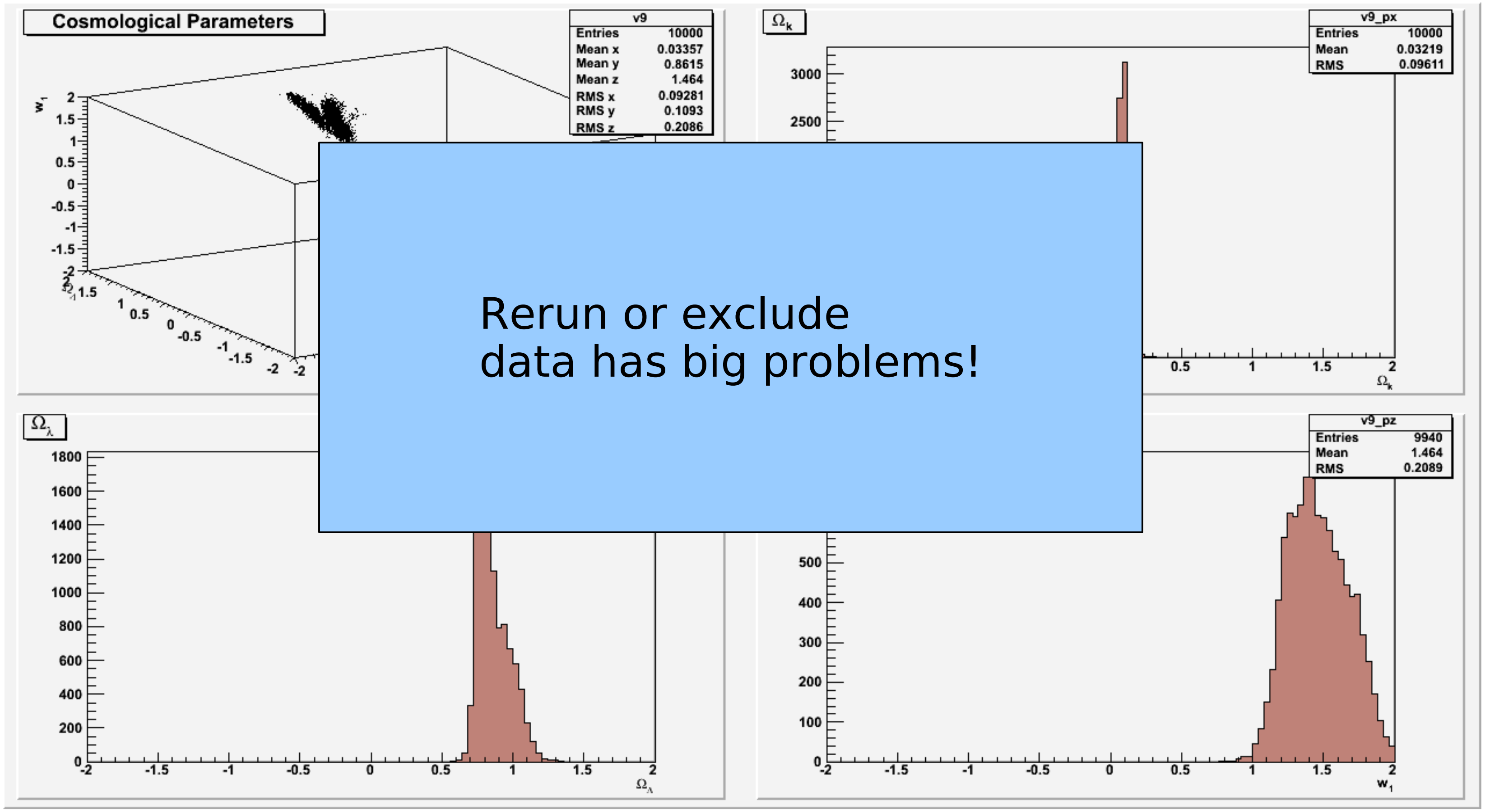
Trash

Motivation

- ET has the potential of acting like GW equivalent of standard candles -> “standard sirens”
  - Provides a new way of doing cosmography
  - Need optical measurements to determine redshift
  - Cosmic distance ladder independent
- However, contribution to cosmography is relatively unknown
  - Paper has been/will be published with an initial exploration on this topic [?]
- Presented work is an extension to this paper, giving you a more extensive set of parameters
  - Dark energy
  - Spacial curvature

Raw Data (Ωk, ΩL, w1)



Rerun or exclude
data has big problems!

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GW measurements

"standard sirens"

- Amplitude of inspiral signal depends on chirpmass and luminosity distance

$$
\begin{aligned}
h(t) &= \frac{\nu\, M^{5/3}}{D_{\rm eff}}\, \omega^{2/3} \cos[2\Phi(t - t_0;\, M,\, \nu) + \Phi_0] \\
D_{\rm eff} &\equiv \frac{D_{\rm L}}{\left[F_+^2 (1+\cos^2(\iota))^2 + 4F_\times^2 \cos^2(\iota)\right]^{1/2}},
\end{aligned}
$$

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