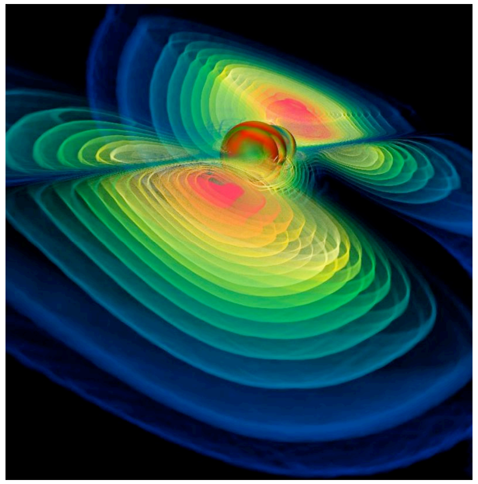
figure courtesy of AEI

Gravitational Wave (GW) Standard Sirens



Samaya Nissanke (CITA)

GW-HEN workshop, APC, 19th May 2009

CITA Canadian Institute For Theoretical Astrophysics

Collaborators:
Neal Dalal (CITA), Daniel Holz (Los Alamos), Scott Hughes (MIT), Jonathan Sievers (CITA)

[Nissanke et al. (2009): arXiv 0904.1017; Nissanke et al. : in prep]

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- (Very brief) Introduction to Standard Sirens:

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    - Results: (I). distance measures and (II). Hubble's parameter.

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- Standard Sirens for an advanced ground-based GW detector network.
  - Methodology.
  - Results: (I). distance measures and (II). Hubble's parameter.
- Present and Future Work.

Introduction to Standard Sirens

Cosmology: expansion history of the universe

- Luminosity distance -- redshift relationship:

$$D_L(z_s) = \frac{c(1+z)}{H_0\sqrt{\Omega_K}} \sinh\left[\sqrt{\Omega_K}\int_0^{z_s} \frac{H_0}{H(z)} dz\right]$$

where

$$\frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_{\rm de}(1+z)^{3(1+w)} + \Omega_K(1+z)^2}.$$

- Standard candles give a measure of the luminosity distance: cepheids, SN1a ...

- ...GW standard sirens: Inspiralling Compact Binaries (ICBs) -- an **absolutely** calibrated measure.

Space and worldwide network of gravitational wave (GW) interferometers

LIGO Livingston (4km)

LIGO Hanford (4km + 2km)

VIRGO (3km)

- Principal sources are inspiralling and merging compact binaries (ICBs/MCBs)
- Detection and measurement of GWs requires accurate source modelling in the form of GW templates.
- Matched filtering maximises SNR.

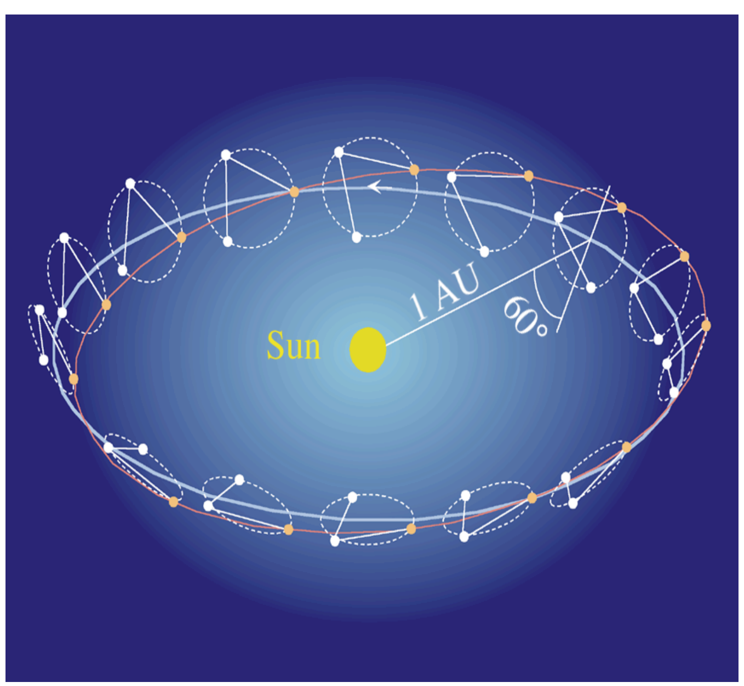
LISA

Space and worldwide network of gravitational wave (GW) interferometers

LIGO Livingston (4km)

LIGO Hanford (4km + 2km)

VIRGO (3km)



LISA

- Principal sources are inspiralling and merging compact binaries (ICBs/MCBs)
- Detection and measurement of GWs requires accurate source modelling in the form of GW templates.
- Matched filtering maximises SNR.

Gravitational Waveforms for Standard Sirens

- Inspiral (analytic):
  - Post-Newtonian (PN) approximation

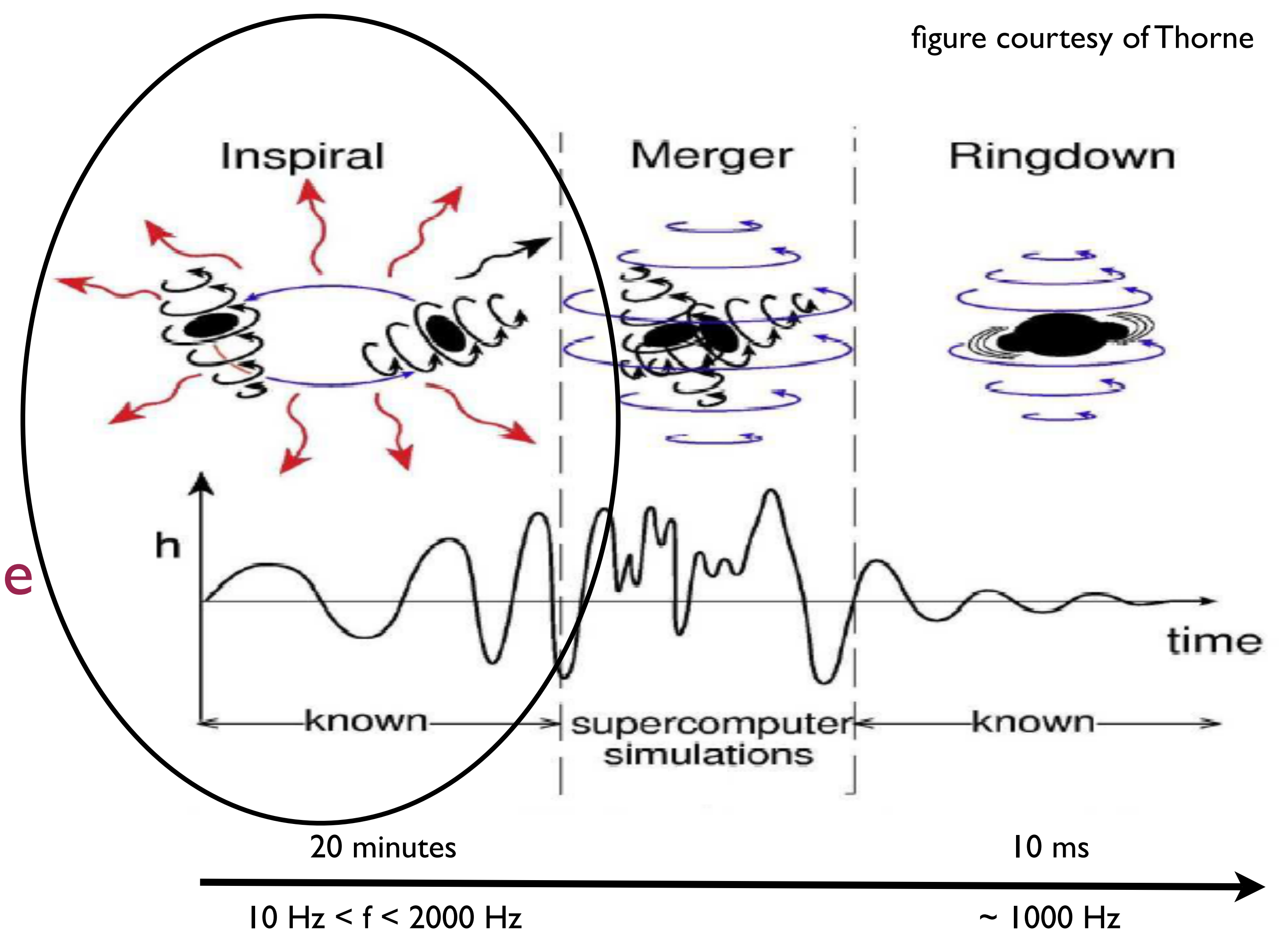
  - Extraction of Source Parameters:

h (masses, spins, inclination angle, sky position.......**luminosity distance**)

- Standard sirens: mapping out the expansion history of the universe

LUMINOSITY DISTANCE -- REDSHIFT RELATIONSHIP

figure courtesy of Thorne



Gravitational Waveforms for Standard Sirens

- Inspiral (analytic): Post-Newtonian (PN) approximation: expansion in

  $v/c \to 0$ as $c \to \infty$

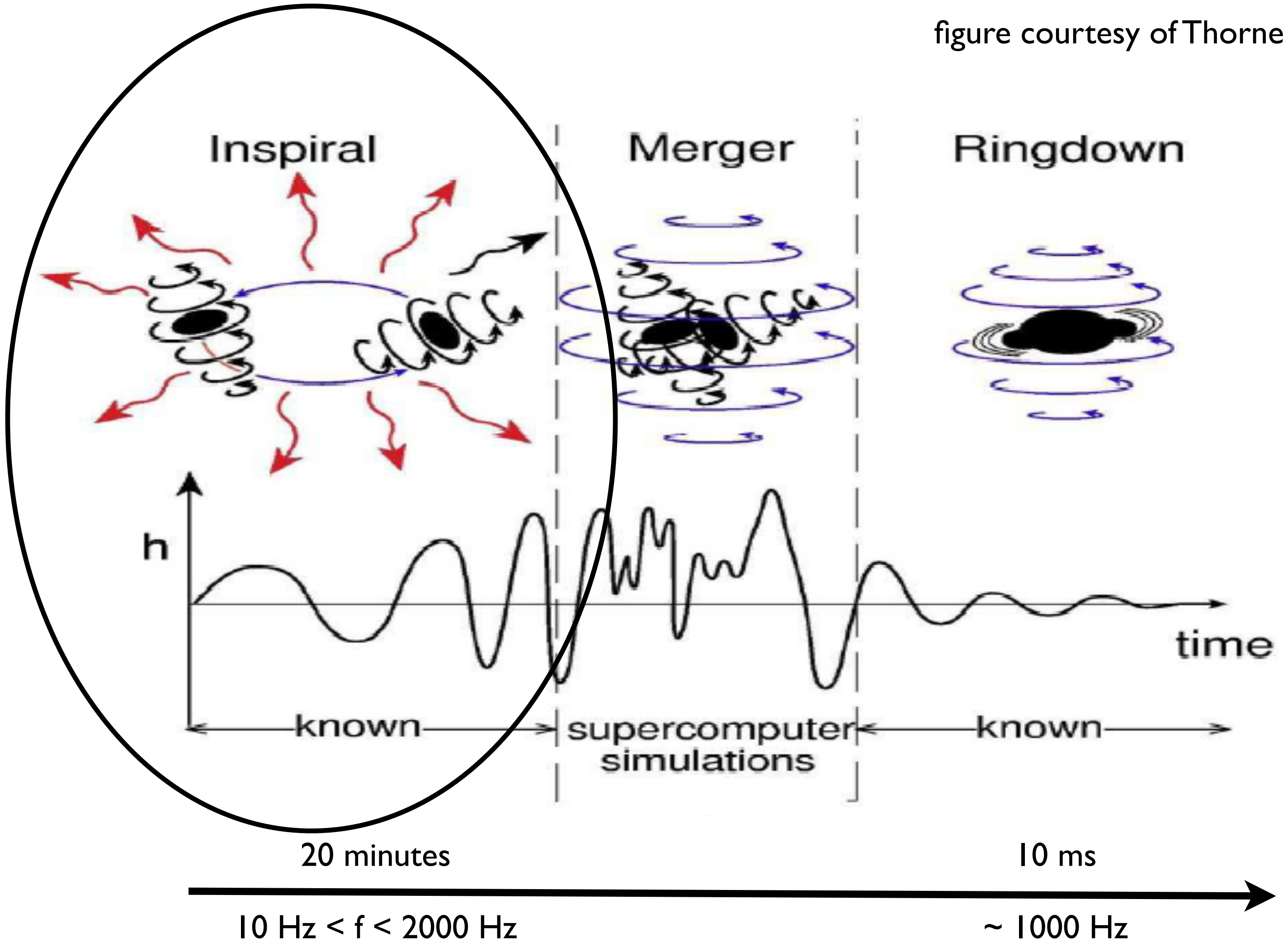
  Adiabatic: $T_{radn.reac.} \gg T_{orbital}$

- Extremely accurate and well modelled (tidal effects at 5PN).

- SNR dominated by inspiral for NS/NS and NS/BH binaries.

Hughes and Flanagan (1997).

figure courtesy of Thorne



Standard sirens: measuring luminosity distance

- Absolute measure of luminosity distance at detector (ground/space):

$$h_M(t) = F_+(\theta,\phi,\psi)h_+(t) + F_\times(\theta,\phi,\psi)h_\times(t)$$

where

$$\begin{aligned} h_+(t) &= 2\frac{\mathcal{M}^{5/3}(\pi f(t))^{2/3}}{D_L}(1+\cos^2(\hat{\mathbf{L}}\cdot\hat{\mathbf{n}}))\cos\Phi(t) \\ h_\times(t) &= -4\frac{\mathcal{M}^{5/3}(\pi f(t))^{2/3}}{D_L}\cos(\hat{\mathbf{L}}\cdot\hat{\mathbf{n}})\sin\Phi(t)\,. \end{aligned}$$

- Degeneracy of parameters in the amplitude.
- GW polarisation gives inclination angle.
- Network (timing of signals) or modulation of LISA gives source localisation and polarisation.

Standard sirens: measuring luminosity distance

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$$h_\times(t) = -4\frac{\mathcal{M}^{5/3}(\pi f(t))^{2/3}}{D_L}\cos(\hat{\mathbf{L}}\cdot\hat{\mathbf{n}})\sin\Phi(t)\,.$$

$$\cos(inc) \equiv \hat{\mathbf{L}}\cdot\hat{\mathbf{n}}$$

- Degeneracy of parameters in the amplitude.
- GW polarisation gives inclination angle.
- Network (timing of signals) or modulation of LISA gives source localisation and polarisation.

EM counterpart for ICBs: Standard Sirens

- The ICB waveform (PN Inspiral):

  Absolute measure of luminosity distance at detector (ground/space).

- Electromagnetic counterpart:

  Schutz (1986); Chernoff and Finn (1993); Finn (1996).

  Redshift: z!

  Source Localisation: reduces parameter space and improves errors in luminosity distance.

  Time of merger: reduces detection threshold SNR.

- LISA: electromagnetic counterpart? lensing?

  e.g. Holz and Hughes (2005); Arun et al. (2006,2008).

- Advanced ground based detectors.

Nissanke et al. (2009): arXiv:0904.1017
Dalal, Holz, Hughes, Jain (2006).

Standard sirens for adv. LIGO/VIRGO type detectors

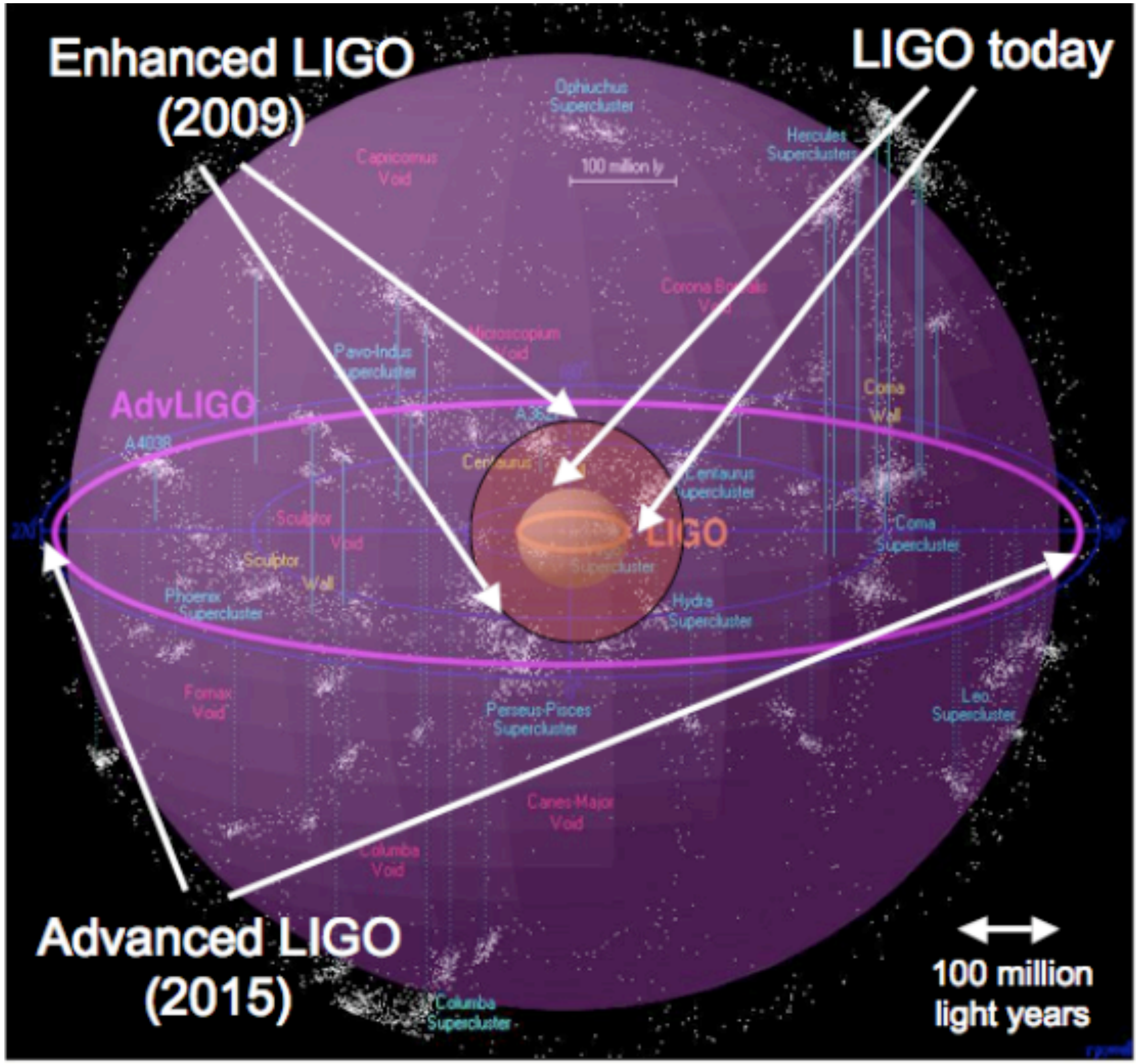
Enhanced and Advanced LIGO

Initial LIGO:
NS/NS - 15 Mpc;
NS/10 $M_\odot$ BH - 30 Mpc

Enhanced LIGO (2009--11):
(x2 in sensitivity = x10 in volume)

Advanced LIGO (2015):
(x10 in sensitivity = x1000 in volume)
NS/NS - 300 Mpc;
NS/BH - 650 Mpc

www.ligo.caltech.edu

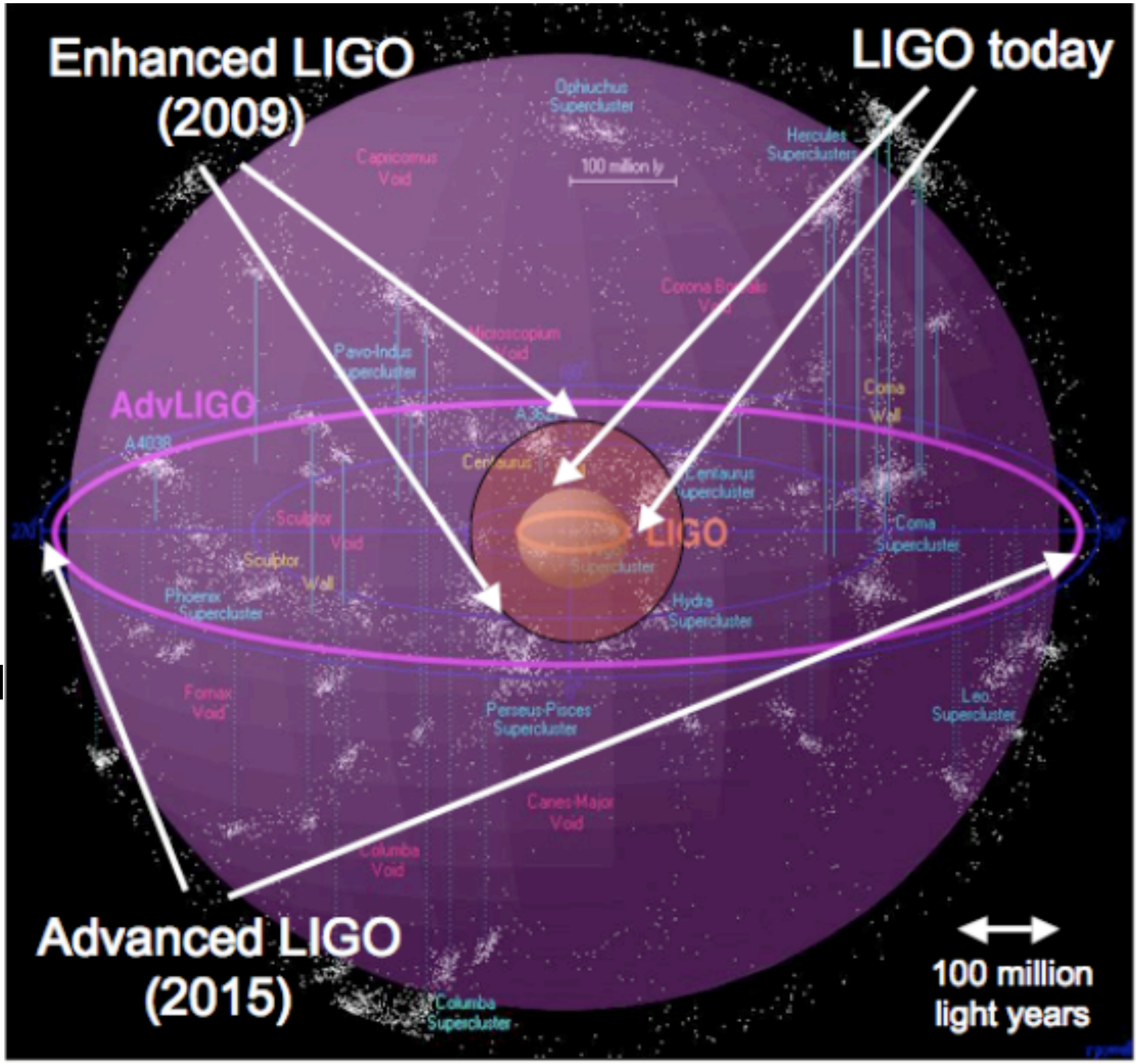


[see Marion and Van der Brand's talk y'day]

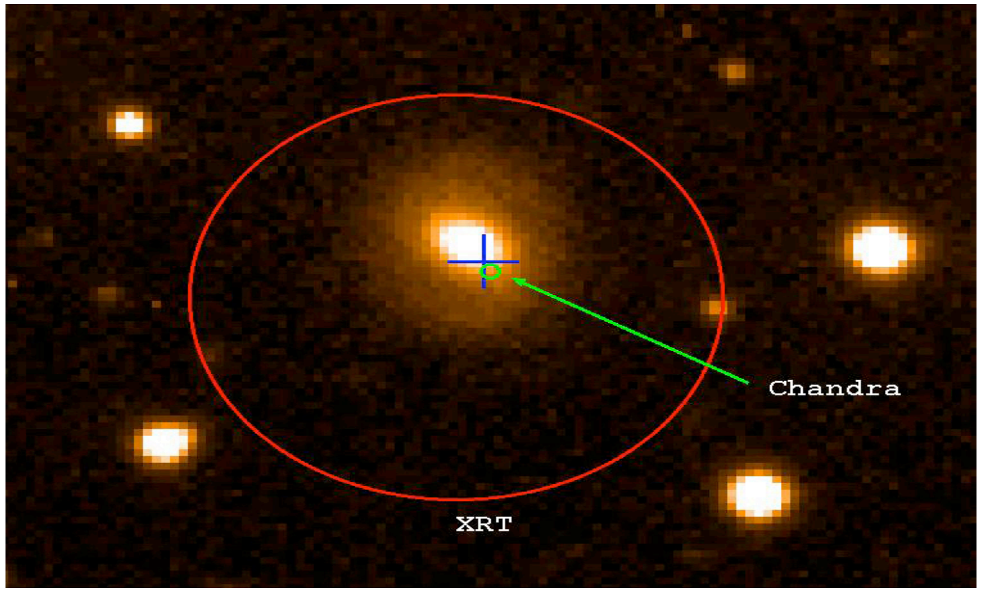
Electromagnetic counterpart?

www.ligo.caltech.edu

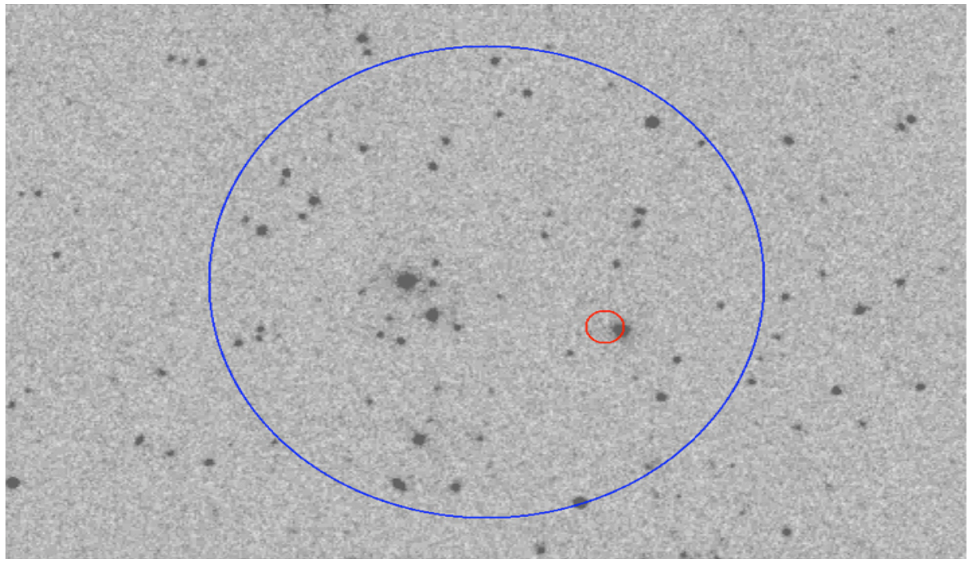
- Recent short hard gamma ray (SHB) observations.
  [Dalal, Holz, Hughes, Jain (2006)]
- Advanced LIGO (2015): coincident SHB observations: NS/NS ~ 600 Mpc; NS/BH ~ 1300 Mpc.
  [Kochanek and Piran (1993); Nakar (2007)]
- Leading progenitor model: NS/NS and NS/BH binaries.
- Lensing effects negligible.



Short Hard GRBs (SHBs)



GRB 050724 observed by Swift's X-ray telescope (red) and X-ray (Chandra) observations



GRB 050509b observed by Swift's γ-ray (blue) & X-ray (red) instruments

- Long (>2 s) and short GRBs ?
- Over past four years, γ-ray observatories have seen optical and X-ray afterglows for SHBs for the first time ...

  z and (subarcsecond) **n** together.
- ~/> 30 SGRBs; small sample size.
- Diverse properties (host galaxies); large range of z (0.1--1.8).
- Two systems with tentative opening angles (~20°).

[see Fox and Guetta's talk]

Single GW channel

Science output	No EM counterpart
NS/NS or NS/BH progenitor model	redshifted masses
	redshifted spins
collimation of jet: SHB engine	orientation
host galaxy	source localisation
	no redshift
	luminosity distance

Multi EM, GW (and HEν?) channels

e.g. HERMES (see Fox's talk)

Science output	No EM counterpart	γ-ray and afterglow
SNR threshold ↓		time of merger
NS/NS or NS/BH progenitor model	redshifted masses	masses
	redshifted spins	spins
collimation of jet: SHB engine	orientation	orientation?
host galaxy	source localisation	
Standard Sirens	no redshift	redshift
	luminosity distance	luminosity distance

Methodology

Parameter estimation?

- Central quantity: posterior PDF

$$p(\boldsymbol{\theta}|s) \propto p(\boldsymbol{\theta})\mathcal{L}_{\rm total}(s|\boldsymbol{\theta})$$

- Likelihood:

$$\mathcal{L}_{\rm det}(s_{\rm det}|\boldsymbol{\theta}) \propto e^{-2\,\mathrm{Re}\int_0^\infty df\,\frac{(\tilde{h}(f;\boldsymbol{\theta})-\tilde{s}(f))^*(\tilde{h}(f;\boldsymbol{\theta})-\tilde{s}(f))}{S_n(f)}}$$

$$s_{\rm det}(t) = h_{\rm det}(t;\tilde{\boldsymbol{\theta}}) + n_{\rm det}(t)\,.$$

[Finn (1992); Cutler and Flanagan (1994)]

- Priors: more later - critical to selection criteria

MCMC exploration

- Metropolis-Hastings MCMC exploration of posterior PDF (using cosmoMC).

[Bridle and Lewis (2002); http://cosmologist.info/cosmomc/]

- Restricted 2 PN waveform in the frequency domain: 7 parameter system.

$$(\text{masses},\ D_L,\ \cos(inc), \psi, t_c,\ \phi_c)$$

- Gaussian and interferometric specific noise.
- Independent noise between interferometers: total likelihood of the network is product of individual likelihoods at each detector.

MCMC exploration for standard sirens

- Different network configurations: LIGO Hanford, LIGO Livingston, VIRGO, AIGO, LCGT.

Network I

MCMC exploration for standard sirens

- Different network configurations: LIGO Hanford, LIGO Livingston, VIRGO, AIGO, LCGT.

Network IIA

MCMC exploration for standard sirens

- Different network configurations: LIGO Hanford, LIGO Livingston, VIRGO, AIGO, LCGT.

Network IIB

MCMC exploration for standard sirens

- Different network configurations: LIGO Hanford, LIGO Livingston, VIRGO, AIGO, LCGT.

Network III

MCMC exploration for standard sirens

- Different network configurations: LIGO Hanford, LIGO Livingston, VIRGO, AIGO, LCGT.

- Two fiducial binaries: non-spinning NS-NS and NS-10 $M_\odot$ BH systems.

MCMC exploration for standard sirens

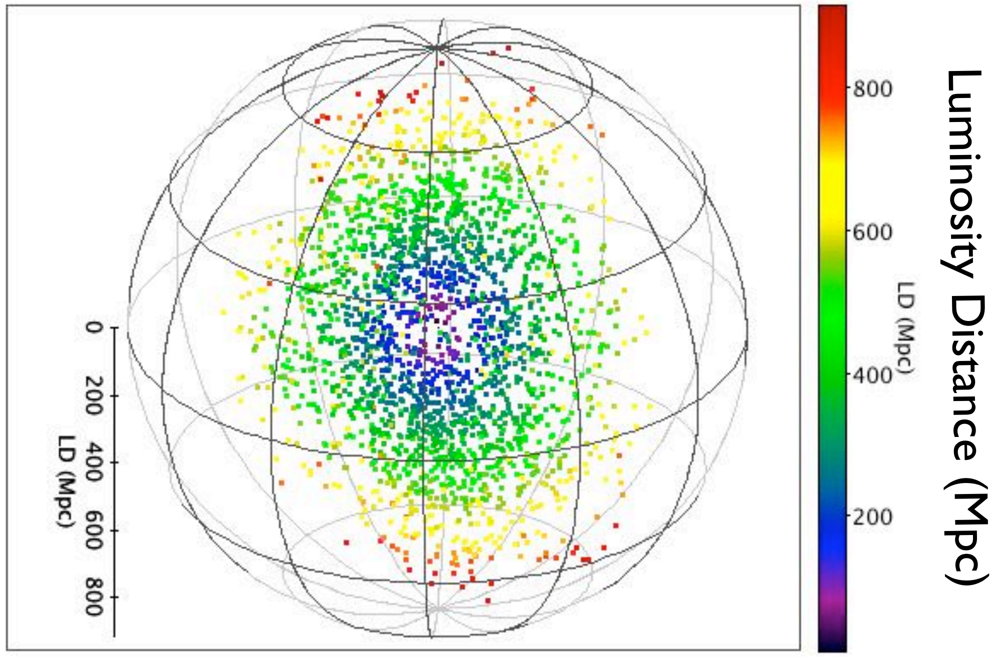
- Different network configurations: LIGO Hanford, LIGO Livingston, VIRGO, AIGO, LCGT.

- Two fiducial binaries: non-spinning NS-NS and NS-10 $M_{\odot}$ BH systems.
- Assume beaming of SHBs with a ~ 25° opening angle: how do errors in the luminosity distance decrease?

Selection criteria (NS/NS): detection rates

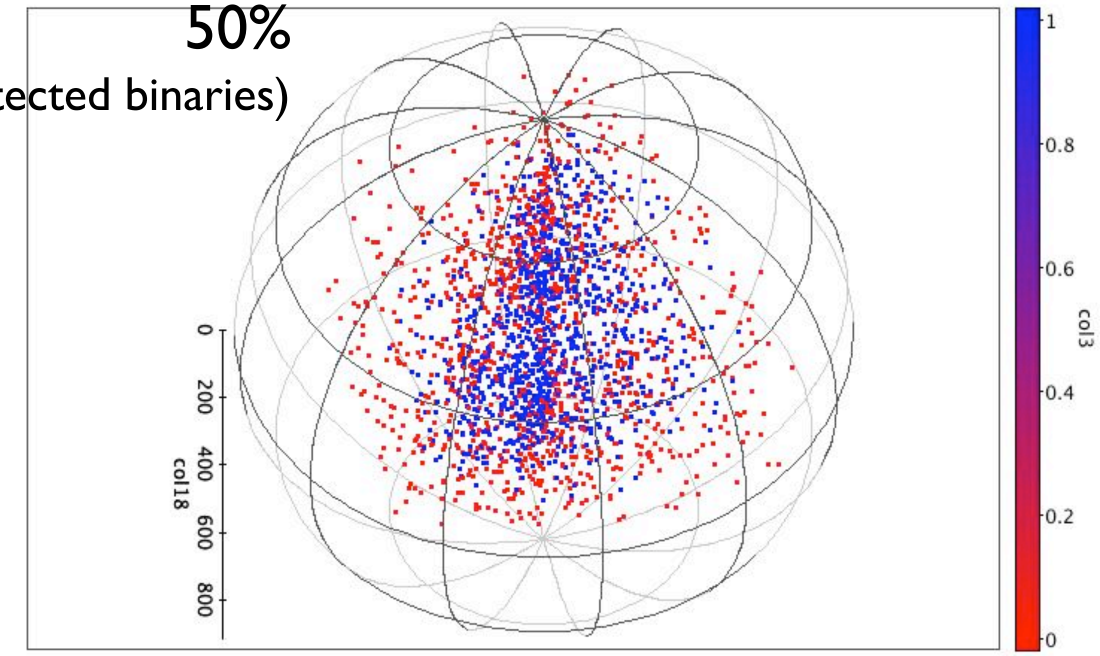
- Selection of a million binaries out to z = 1 with a constant comoving density.
- Detection threshold: for each binary and detector network, we ask whether its SNR > 7.5 ?
- Obtain detection rates for each network configuration.

Blue: detected
Red: not detected



Total detected binaries by Network III

50%
(% of detected binaries)



Detected binaries by Network I

Selection criteria (NS/NS): detection rates

- Selection of a million binaries out to z = 1 with a constant comoving density.
- Detection threshold: for each binary and detector network, we ask whether its SNR > 7.5 ?
- Obtain detection rates for each network configuration.

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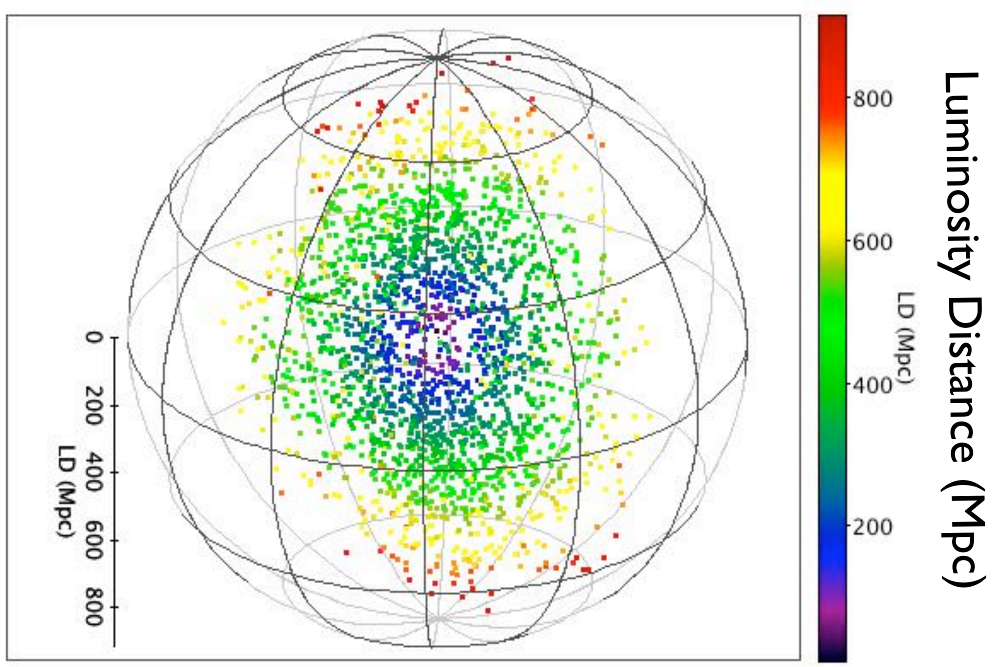
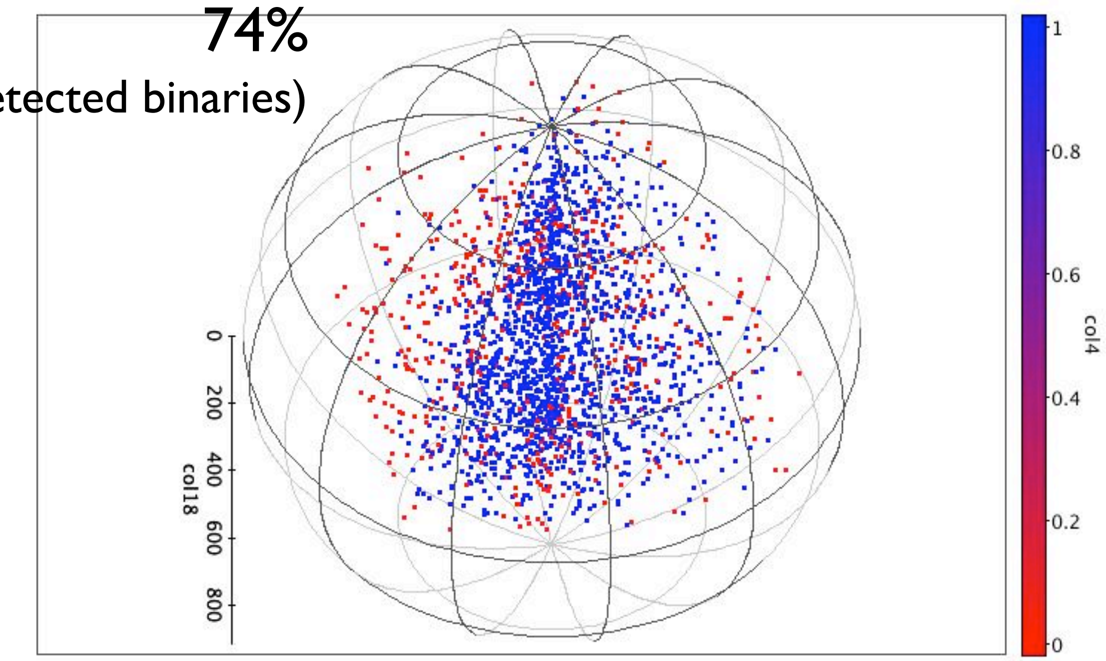


Total detected binaries by Network III

74%
(% of detected binaries)



Detected binaries by Network IIA

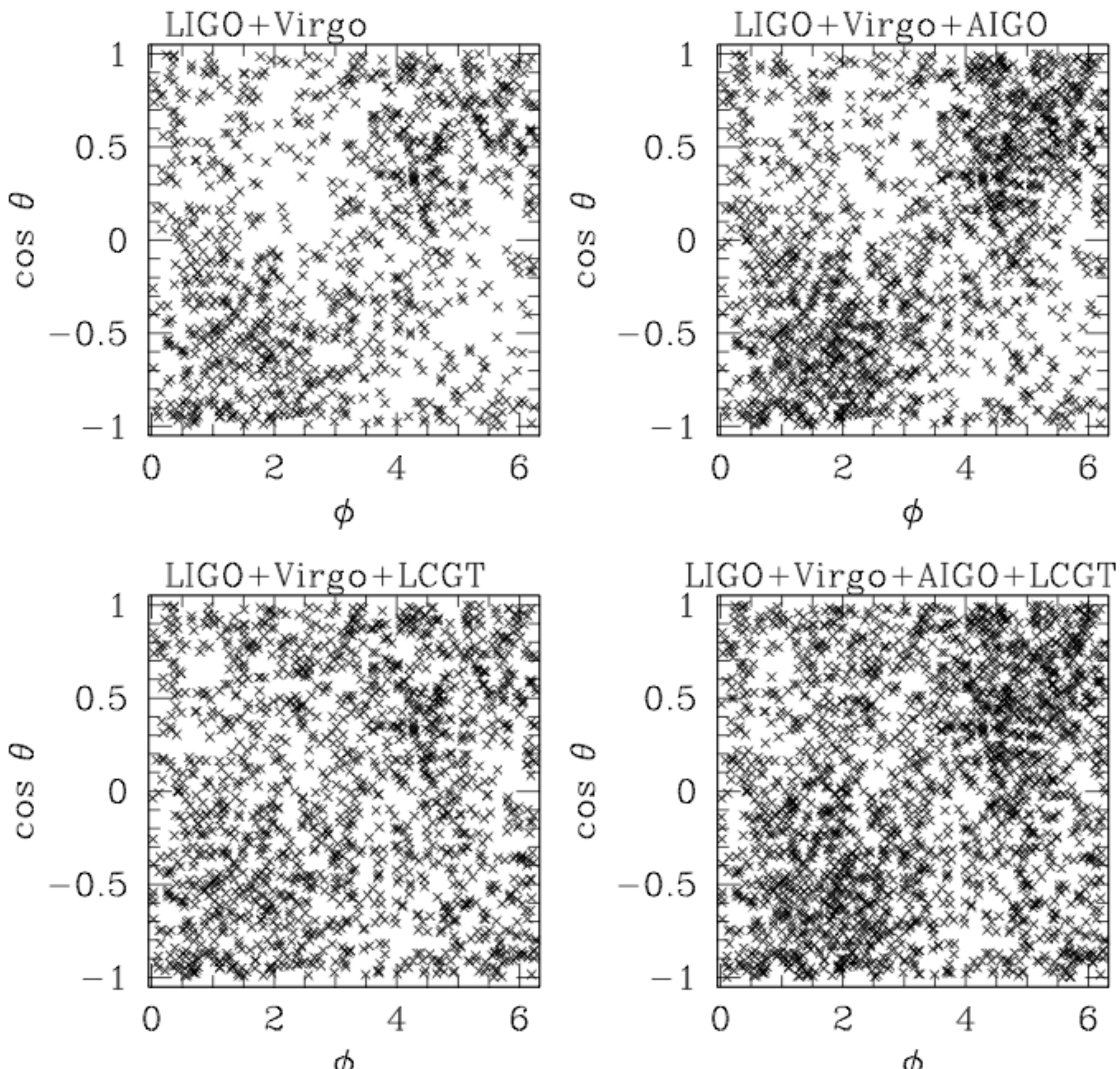
Selection criteria (NS/NS): detection rates

50%
(% of total detected binaries)

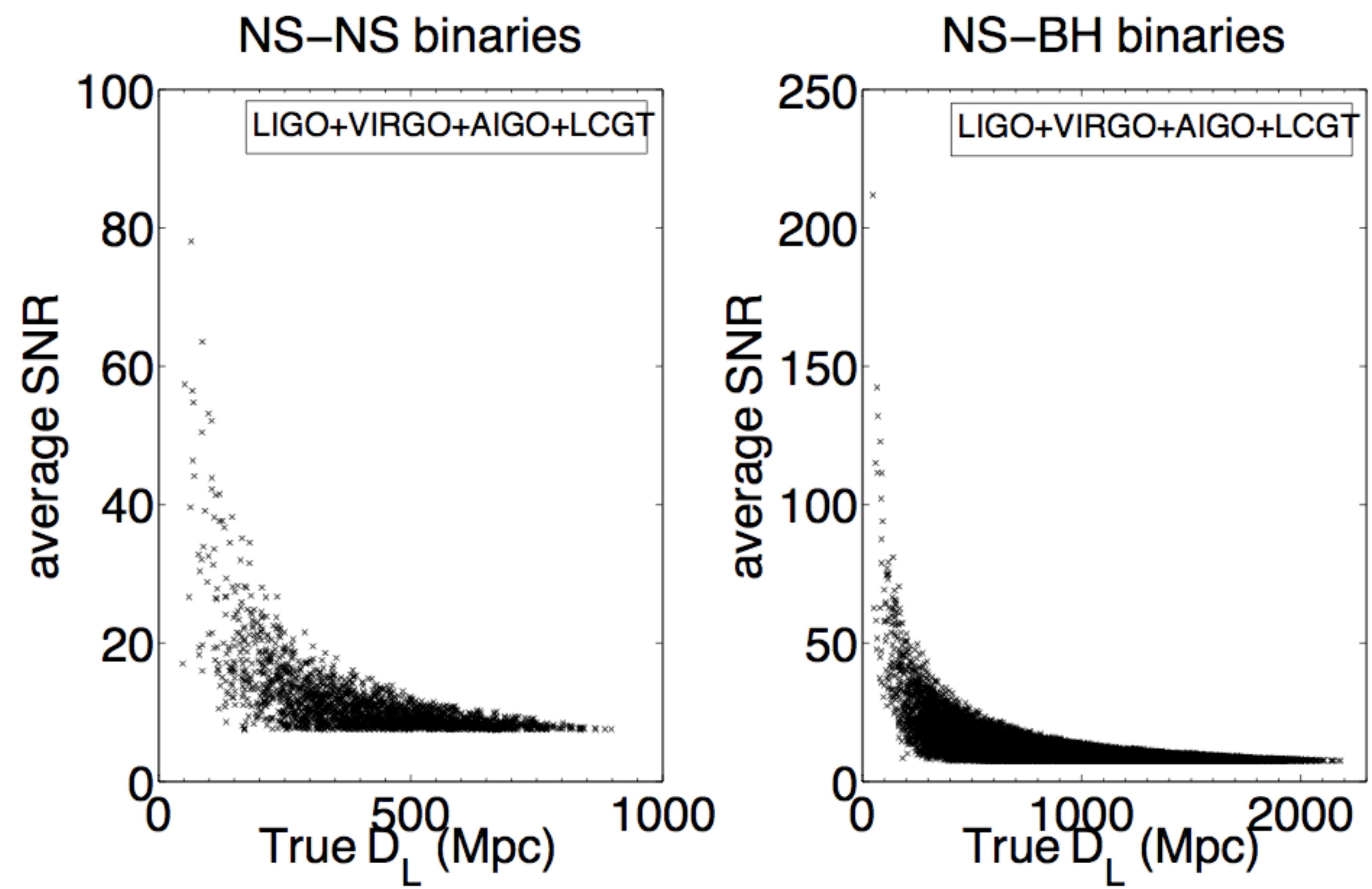
74%

72%

100%

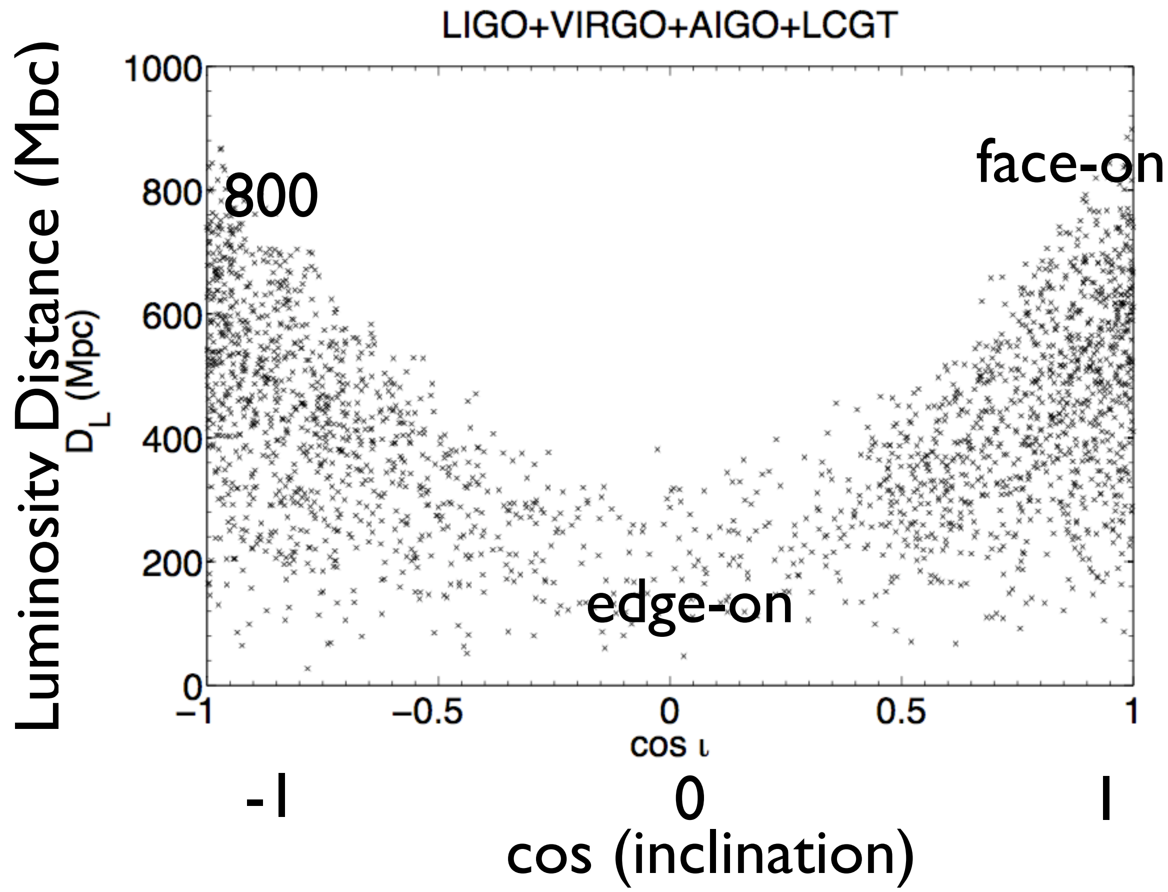


Selection criteria : SNR vs. Luminosity distance



Selection criteria (NS/NS): prior densities

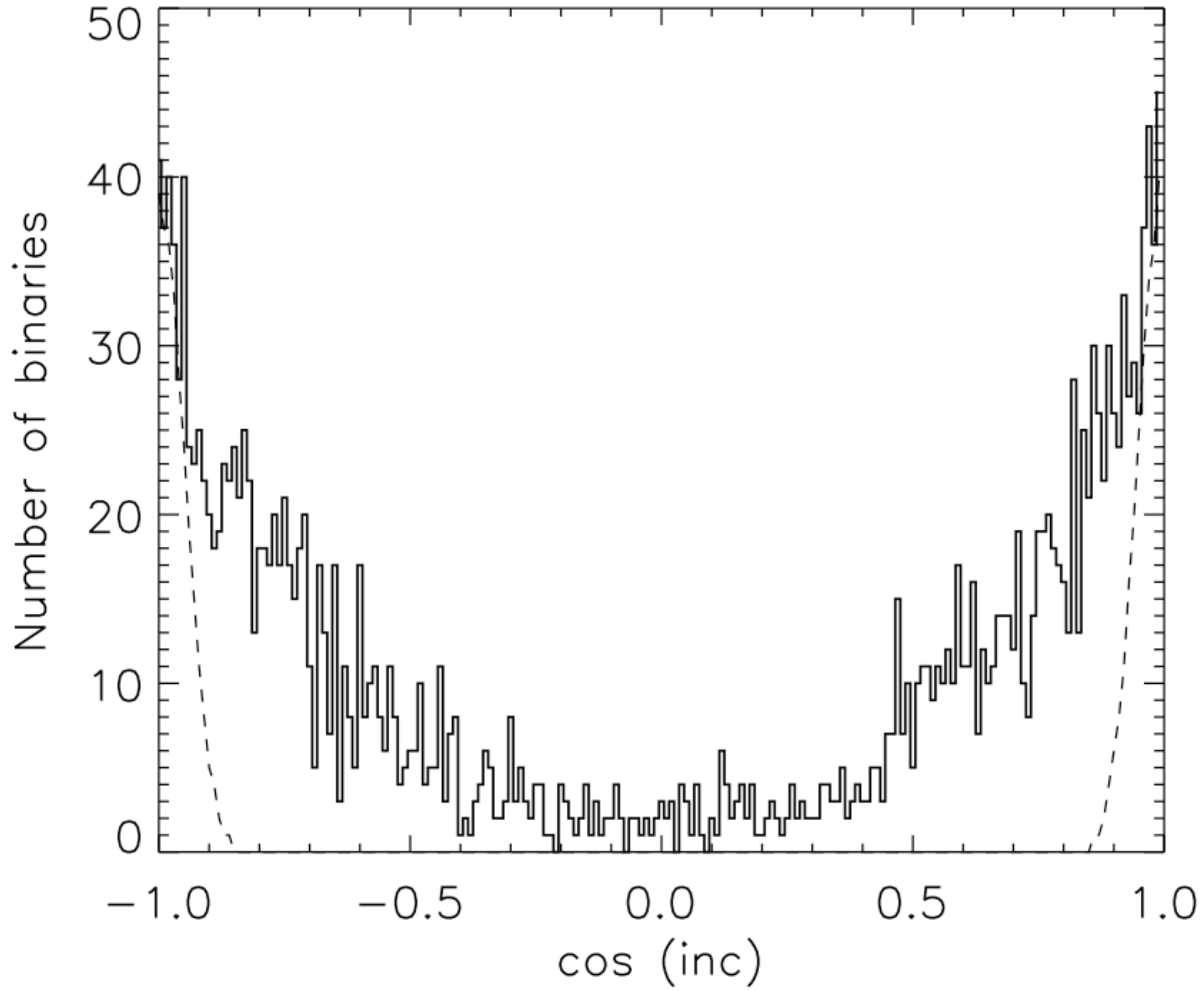
- Detection prior on selected sample with const. comoving volume.
- Uniform priors in all other parameters (including inclination angle).



Joint 2D prior density

Selection criteria: NS-NS beamed (prior densities)

- Beamed subsample selected from total sample assuming a gaussian inclination probability distribution with a ~ 25° opening angle.



Results I: Distance measures

Nissanke et al. (2009): arXiv:0904.1017

Review of distance measurement accuracies

- Fisher matrix method breaks down at relatively high SNR: the probability density function (D_L) can be significantly non-Gaussian:

  10-30 % errors in D_L out to 600 Mpc in NS/NS and to 1400 Mpc in NS/BH.

- Non-negligible and important degeneracies between luminosity distance and inclination angle of binary.

  e.g. Cutler and Flanagan (1994)

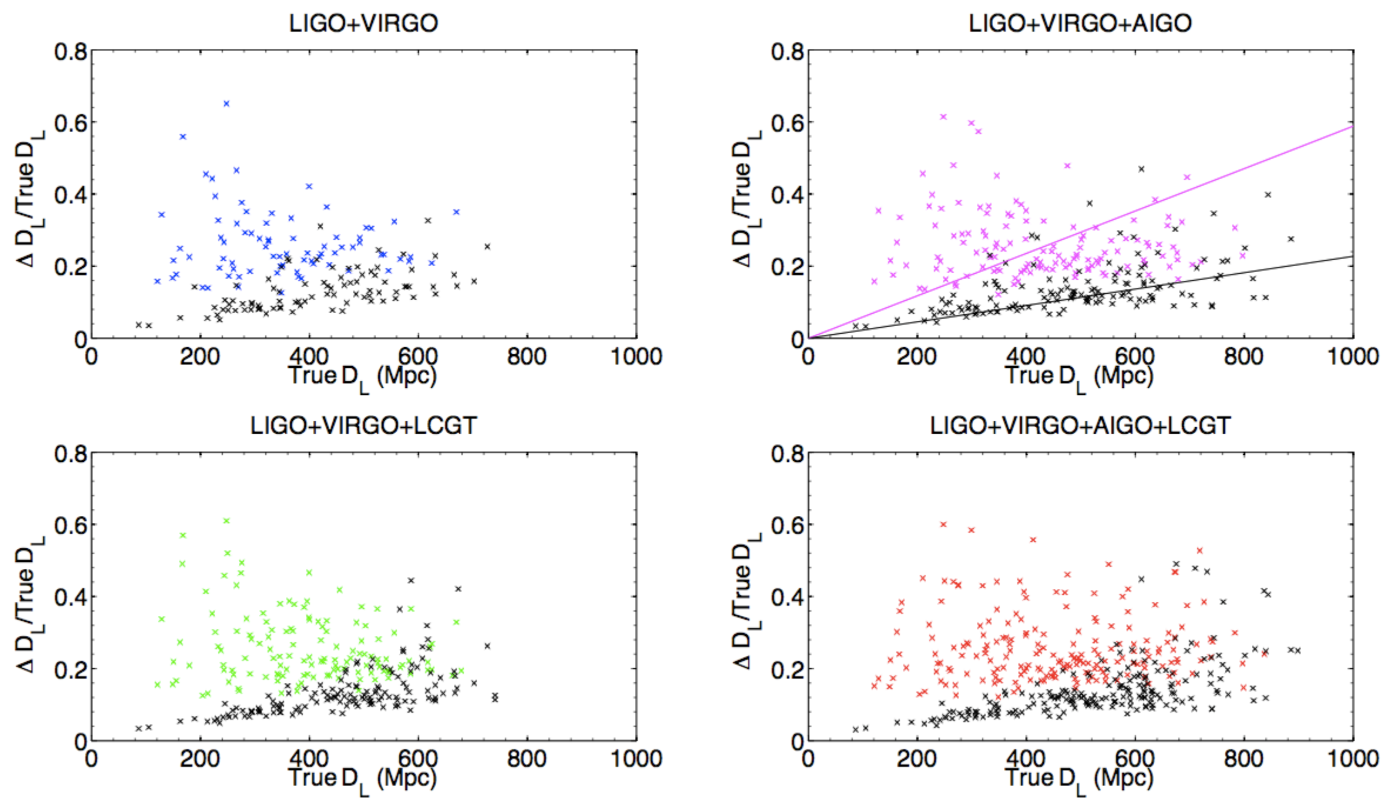
- Face-on or edge-on nature of binary introduces systematic bias...

- ... but taking sky averages for many differently orientated standard sirens removes this bias cf. GW astronomy!

- Strong dependence on different instances of noise realisations when signal is simulated.

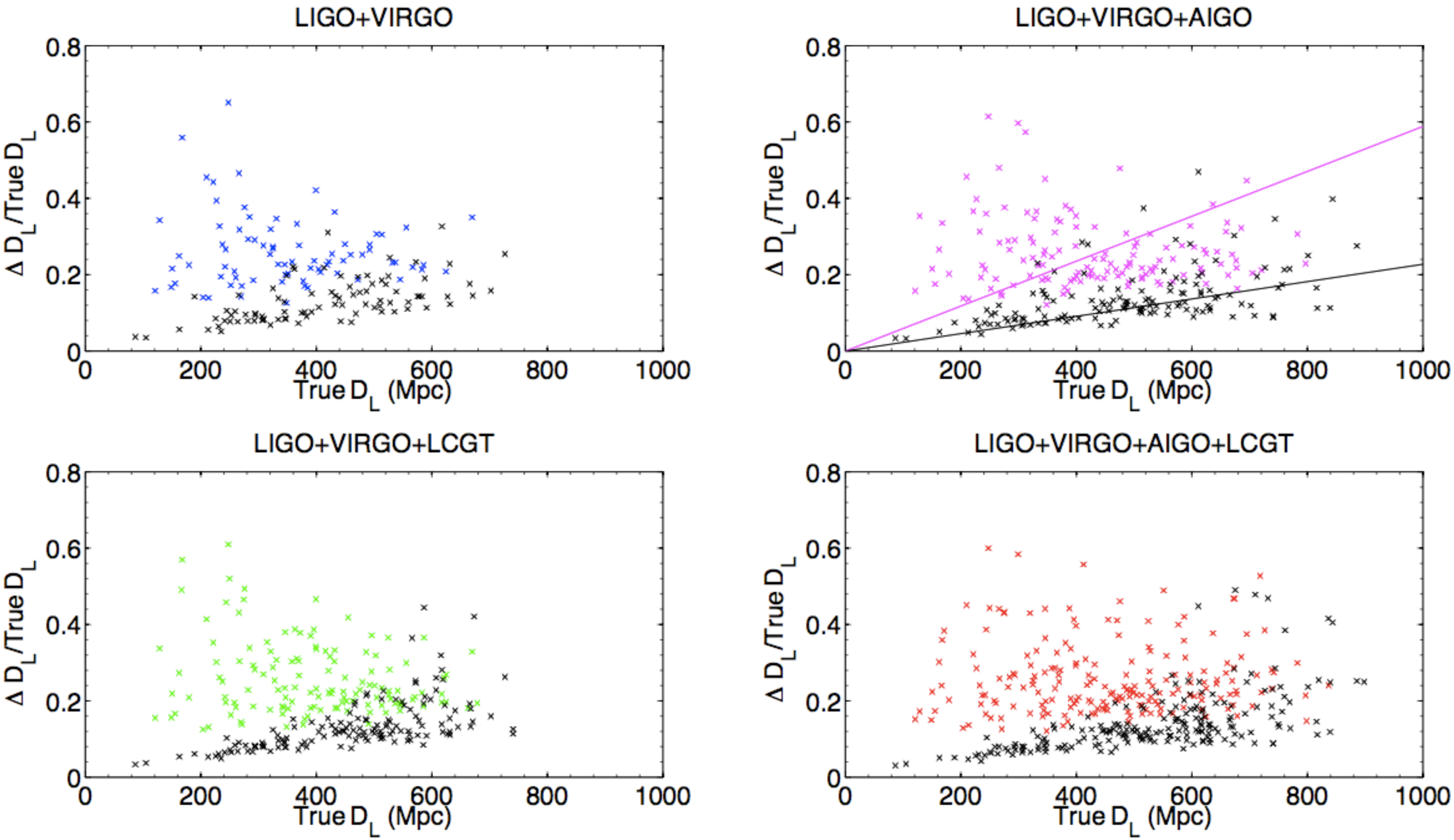
Distance Measurement Accuracies: NS-NS binaries

- Keep a unique instance of noise realisation constant at each detector.
- 200 unbeamed and 200 beamed NS/NS binaries randomly selected from our total detected sample.



$$\frac{\Delta D_L}{\tilde{D}_L}$$

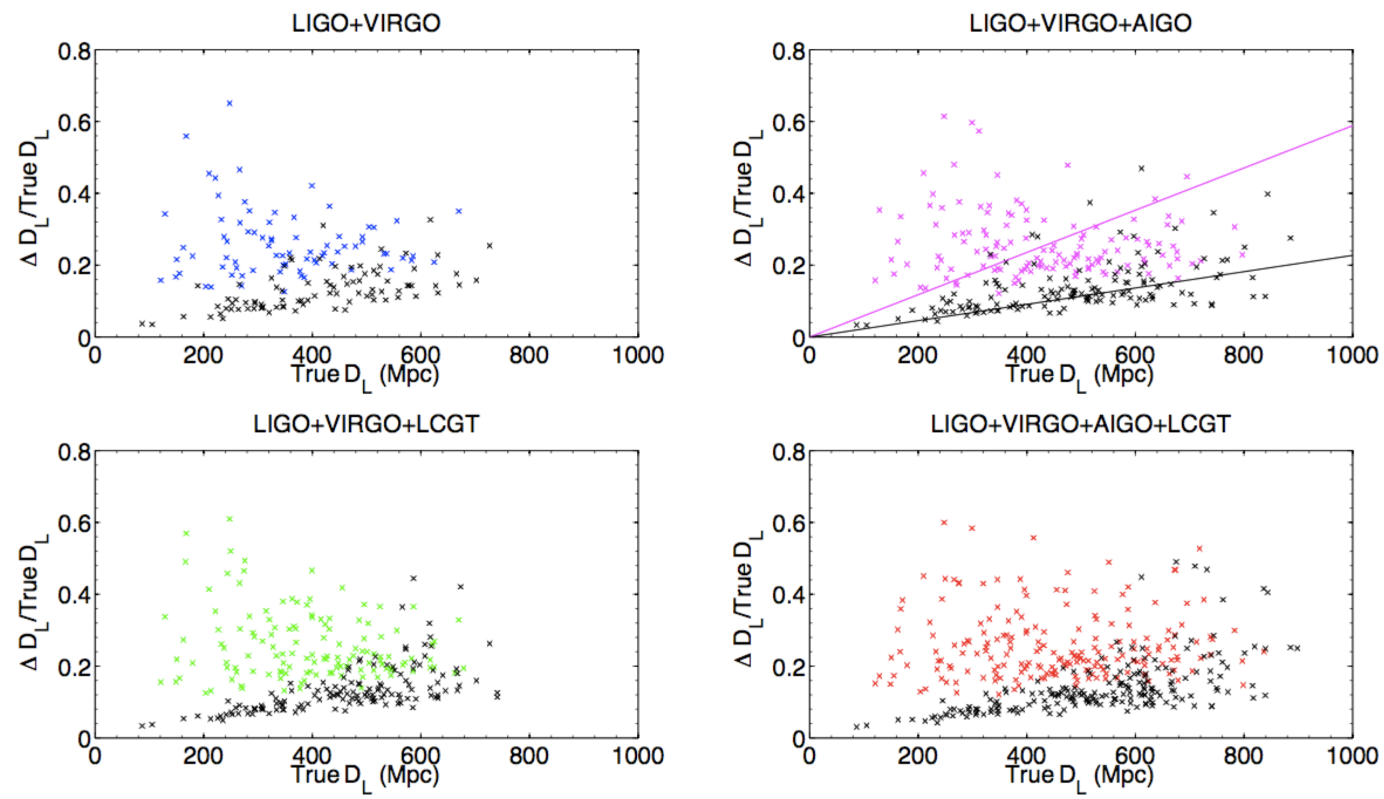
Distance Measurement Accuracies: NS-NS binaries



Distance Measurement Accuracies: NS-NS binaries

- Two distinct distributions: beamed and unbeamed.
- Beaming prior improves distance measurements by a factor of ~2 by breaking cos (inc) - D_L degeneracy.
- Large scatter, in particular, for isotropic case.

Fisher matrix breaks down even at relatively low D_L: Fundamental cos(inc) - D_L degeneracy.



- Addition of detectors increases number of detected binaries (detectable volume and increase in sky coverage)

Future work for distance measures

- Understanding impact of priors and systematic errors arising from limitation in the theoretical source modelling.

- Will the addition of spin precession and higher harmonics in PN waveform break important degeneracies in parameters such as the luminosity distance -- inclination angle to the binary?

Results II: constraining Hubble's parameter

Nissanke et al. (2009): in prep.

Ensemble vs. individual standard siren measurements?

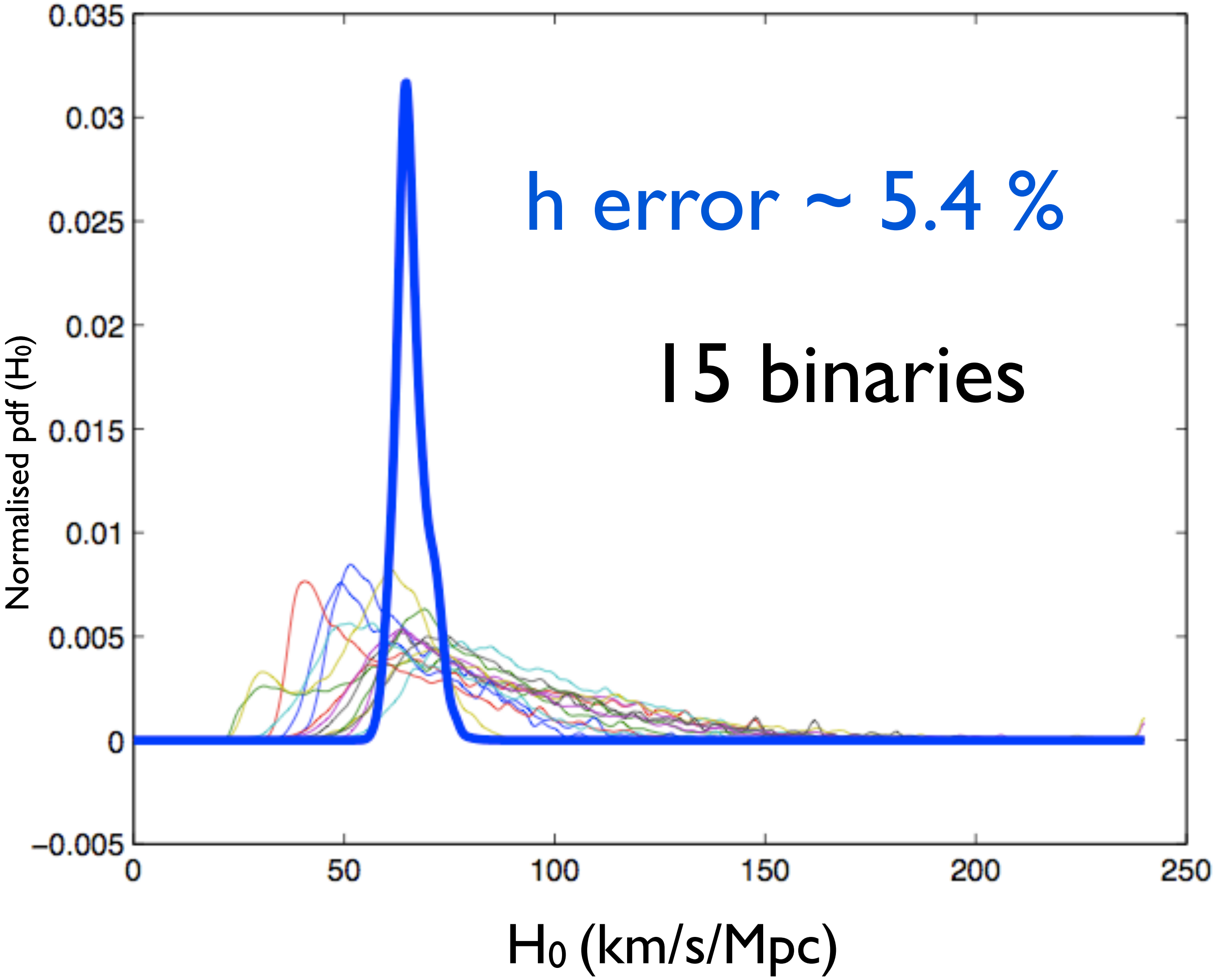
- At first blush, results do not seem encouraging....
- ...however, we are interested in ensemble and not individual standard siren measurements.
- The joint post. PDF in H_0 (or any cosmological parameter) for *n* events becomes increasingly well constrained as *n* increases.
- The detected number of binaries is critical (number of detectors and SHB progenitor model).

Results: NS/NS binary (5 yrs.)

- Five year observation period assuming 10 GW-SHB events per year per Gpc^{-3}.

[see Guetta's talk]

Only three detectors: NS-NS isotropic

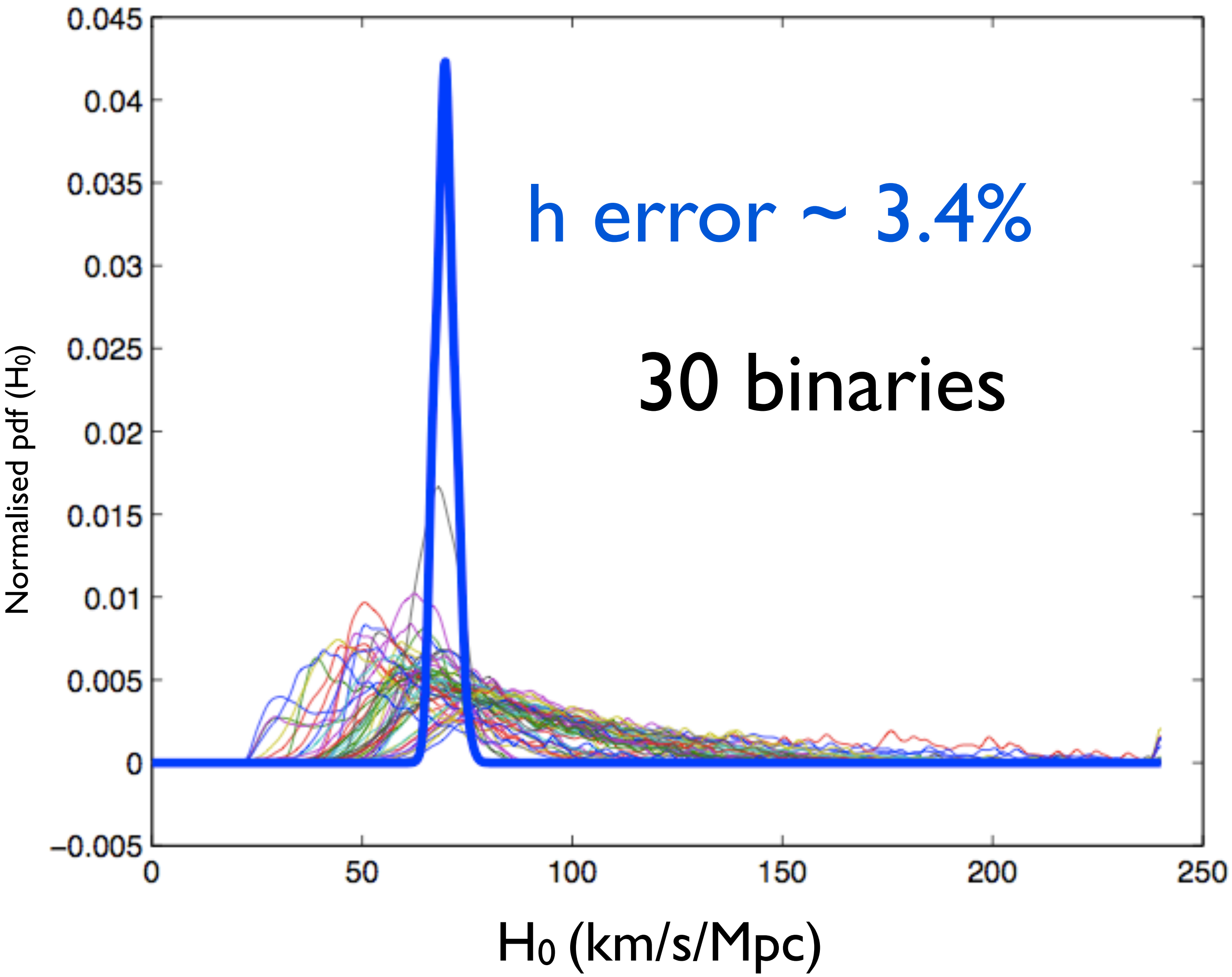


Results: NS/NS binary (5 yrs.)

- Five year observation period assuming 10 GW-SHB events per year per Gpc^{-3}.
- Increase in number of detectors substantially helps in pinning down H_0 up to a factor ~1.5:

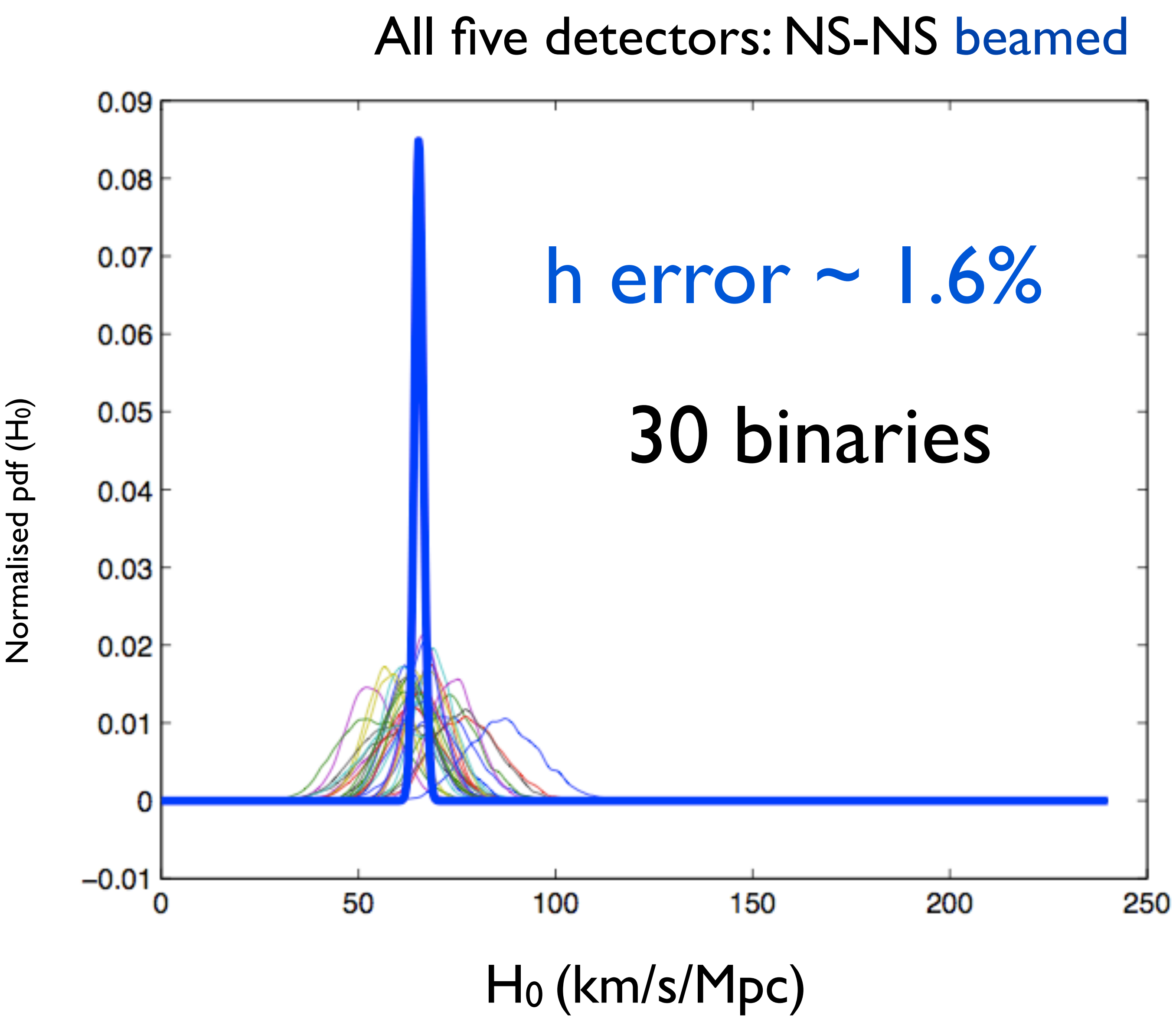
  measurement errors in luminosity distance decrease and detected number of binaries increase.

All five detectors: NS-NS isotropic



Results: NS/NS binary (5 yrs.)

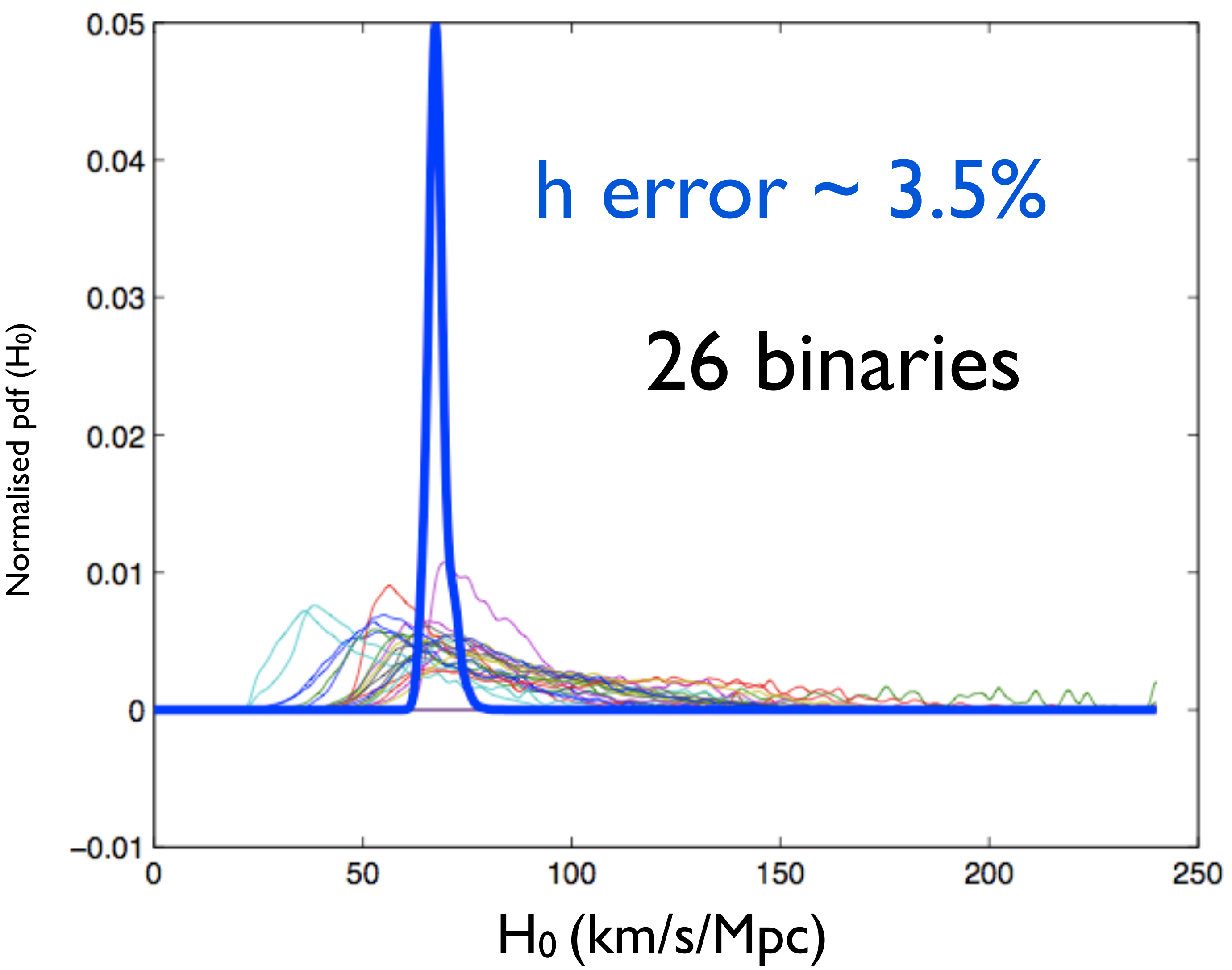
- Five year observation time assuming 10 GW-SHB events per year per Gpc^{-3}.
- Errors in H_0 improve by at least a factor of > two when we assume collimation of sources.



Results: NS/BH binary (1 yr.)

- One year observation time assuming 10 GW-SHB events per year per Gpc^{-3}.
- Total number of detected binaries significantly increases ~ 55 NS-BH GW-SHBs per year cf. ~ 6 in the NS-NS case.
- Increase in number of detectors substantially helps in pinning down H_0.

Only three detectors: NS-BH isotropic



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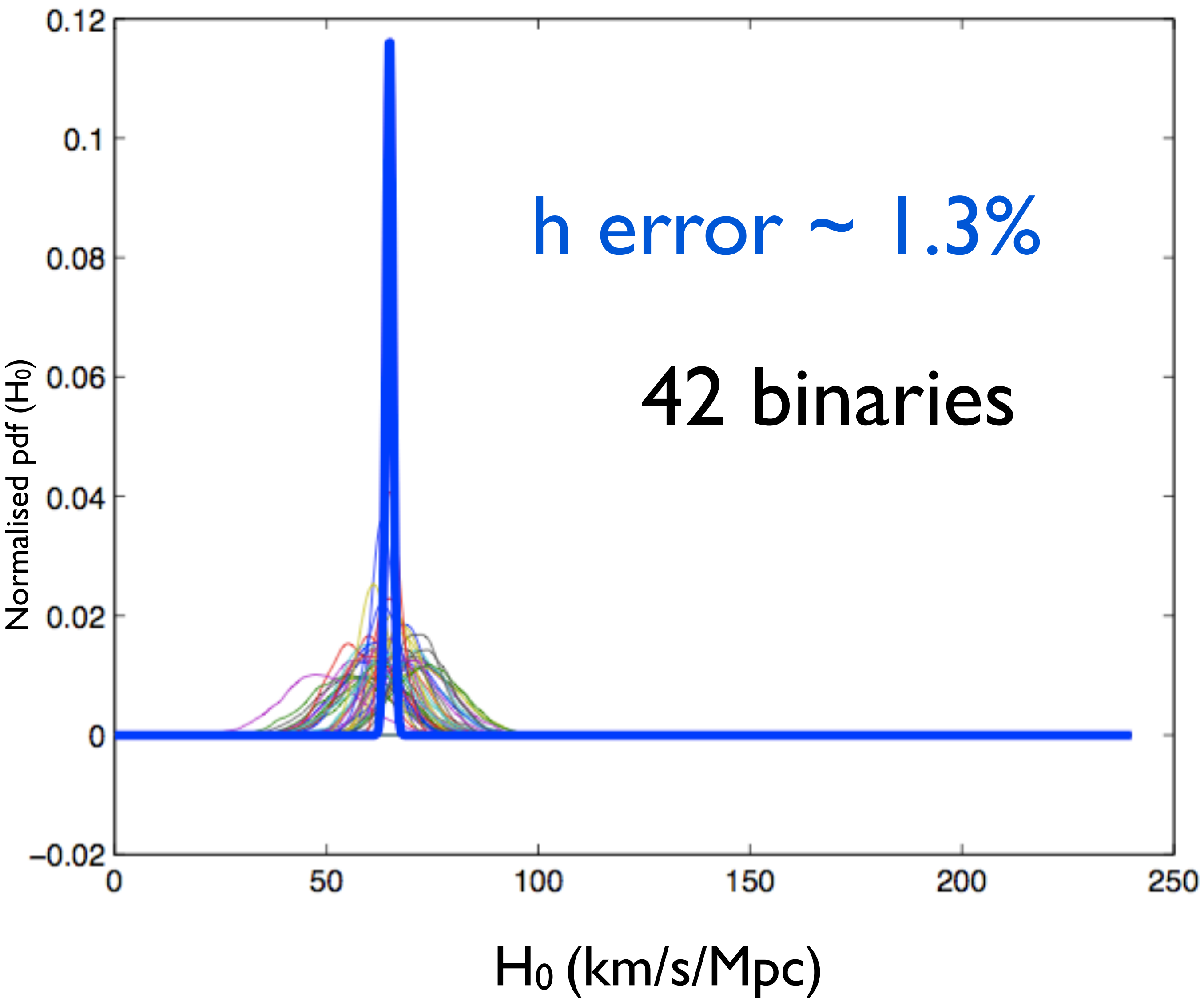
Four detectors (LCGT): NS-BH beamed



Summary of H_0 results

	NS-NS $\xrightarrow{\sim\times 4}$	NS-BH
H_0: Observation time (nos. of binaries)	5.5% ~ 5 years (15)	3.5% ~1 year (26)
beamed SHB	improves by > ×2	
3 →5 detector network	improves by ~ ×1.5	

- Expect errors to decrease with √(Observation Time).

Summary for standard sirens

- GW standard sirens offer a complementary technique to constrain cosmological parameters. Independent of the cosmological distance ladder.

- Clean, well modelled systems: no need to treat systematic problems as with SN1a (evolutionary aspects, dust extinction etc...).

Beyond Standard Sirens

- SHB observations (redshift, source localisation, beaming) will help GW astronomy and cosmology...
- ... but converse case is true too!

  Information about the extent of collimation of SHBs and source localisation (host environment) will constrain progenitor models.

Single GW channel: constraints on SHB progenitor model

- Assume no electromagnetic counterpart -- how well can one localise the ICBs.?

  ~ few to 10s of square degrees with advanced 3 det. network.

  [Blair et al. (2006); Cavalier et al.(2008); Nissanke et al. (2009): in prep.]

- What can be said about the extent of gamma-ray collimation?

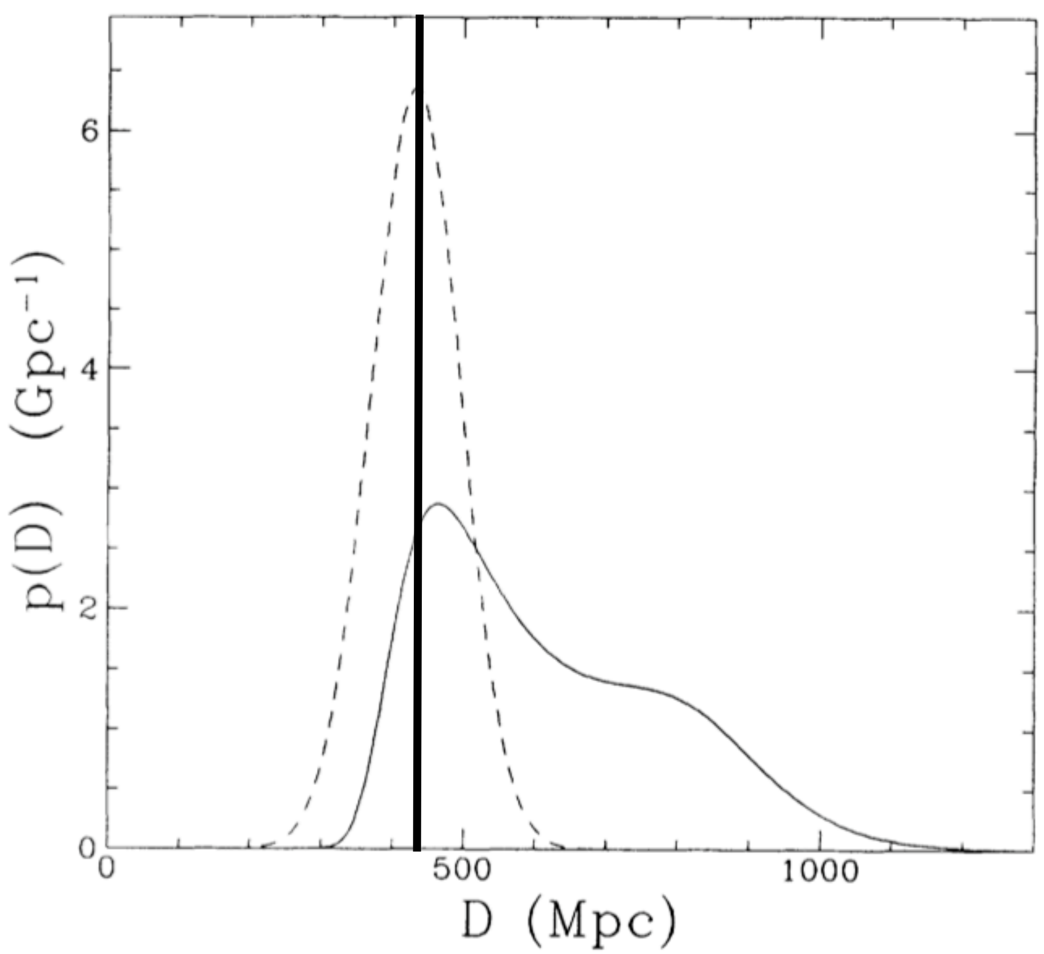
  ~ $|\cos(\mathrm{inc})| < 0.3$ (predominantly face-on binaries).

[Nissanke et al. (2009): arXiv:0904.1017]

Thank you.

Test case: Introducing the CF binary

SNR: 12.4 (5.8)
Best fit Distance: 432 Mpc
cos(inc) = 0.31
NS/NS system
ADV. LIGO H, LIGO L, VIRGO



Cutler and Flanagan (1994)

Fisher information matrix?

[Dalal et al. (2006)]

- 'Gaussian approximation'(Fisher matrix method) in high SNR limit:

$$\exp\left[-\left(h(\boldsymbol{\theta})-s|h(\boldsymbol{\theta})-s\right)/2\right] \simeq \exp\left[-\frac{1}{2}\left(\frac{\partial h}{\partial\theta^a}\middle|\frac{\partial h}{\partial\theta^b}\right)\delta\theta^a\delta\theta^b\right]$$

where $\delta\theta^a = \theta^a - \tilde{\theta}^a$

- Fisher and covariance matrix:

$$\Gamma_{ab} \equiv \left(\frac{\partial h}{\partial\theta^a}\middle|\frac{\partial h}{\partial\theta^b}\right) \quad ; \quad \Sigma^{ab} = (\Gamma^{ab})^{-1}$$

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- Exploring short gamma-ray bursts as gravitational wave standard sirens.

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Dalal et al. (2006): PRD 74, 063006

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  Neal Dalal (CITA), Daniel Holz (Los Alamos), Scott Hughes (MIT), Jonathan Sievers (CITA).

- Exploring short gamma-ray bursts as gravitational wave standard sirens.

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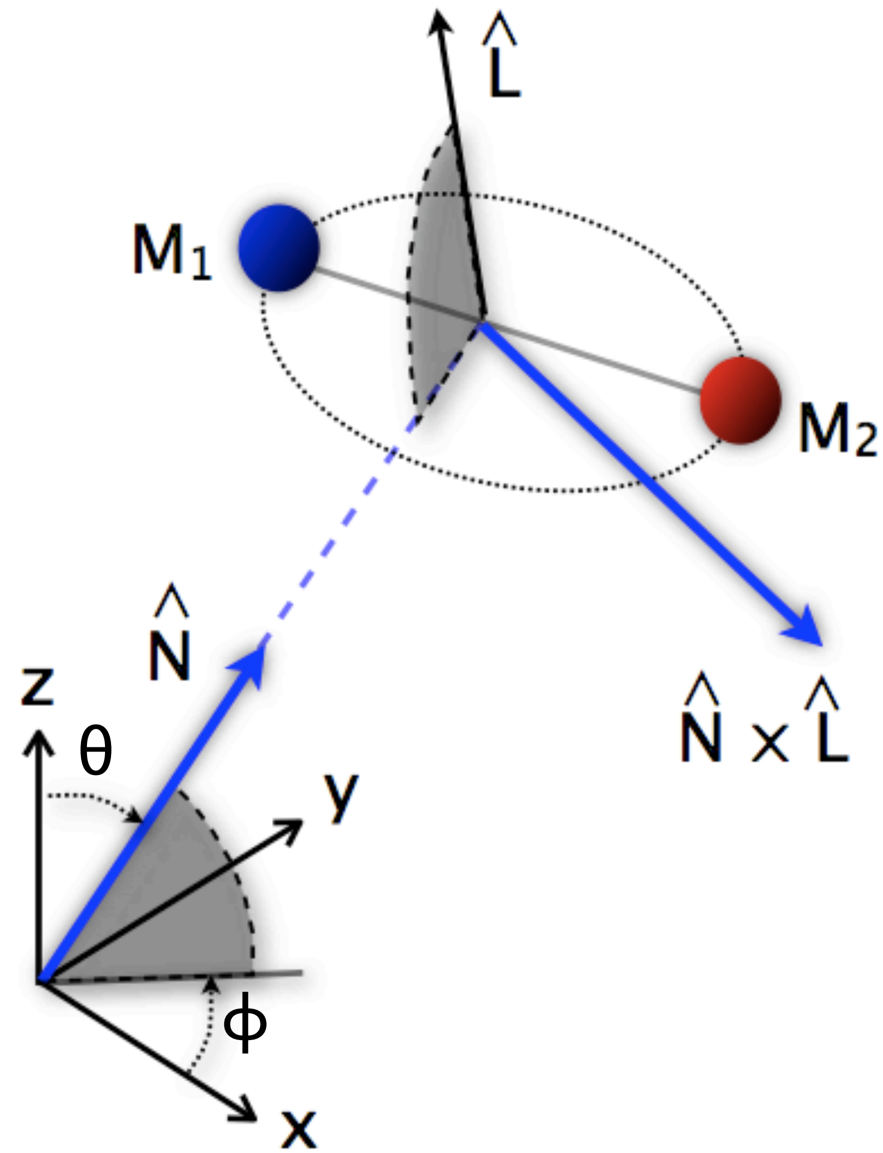
Single GW channel

- Parameters of interest:

$$\boldsymbol{\theta} = \{\mathcal{M}, \mu, \mathbf{D_L}, \cos(inc) \equiv \hat{\mathbf{L}} \cdot \hat{\mathbf{n}}, \theta, \phi, \psi, t_c, \phi_c\}$$

NS/NS or NS/BH:
Progenitor model



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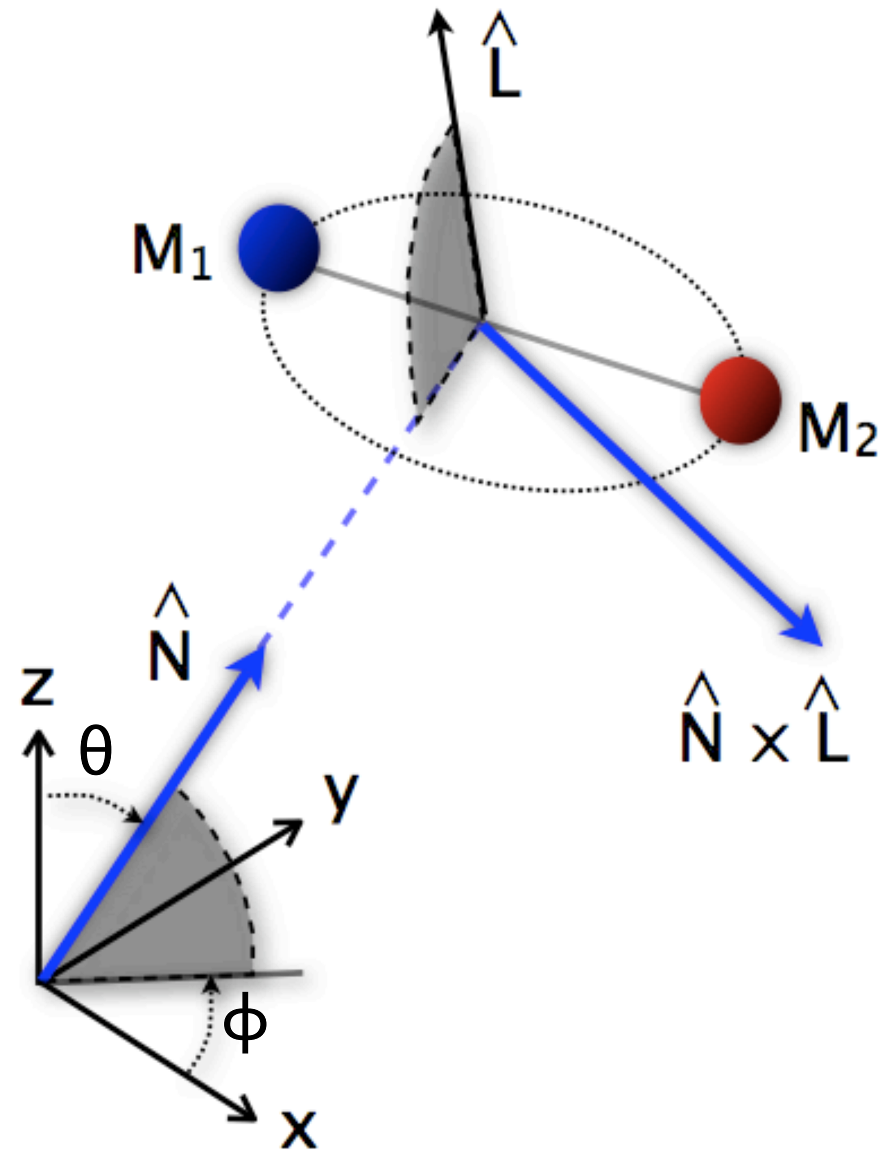
extent of collimation: SHB engine



where

$$\mu = \frac{m_1 m_2}{m_1 + m_2}(1+z)$$

$$\mathcal{M} = \mu^{3/5}(m_1 + m_2)^{2/5}(1+z)$$

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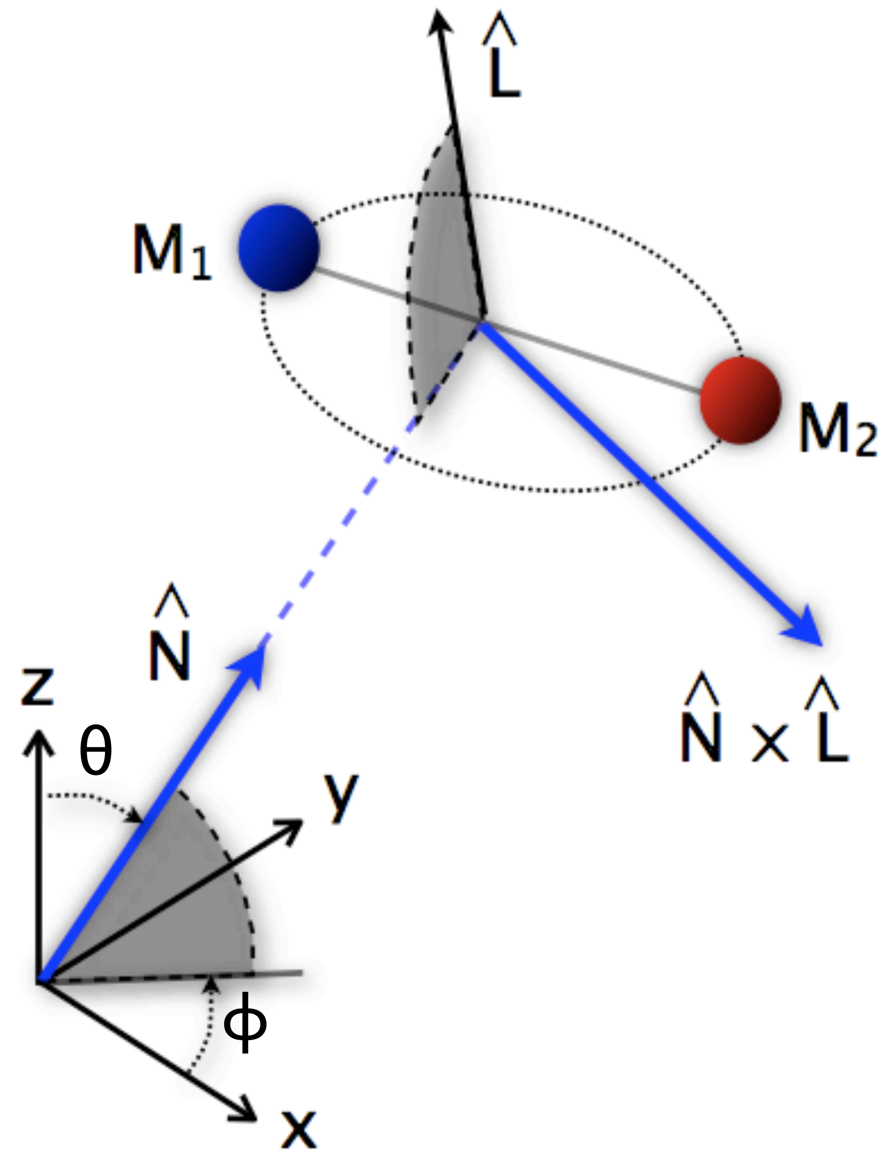
source position:
host galaxy



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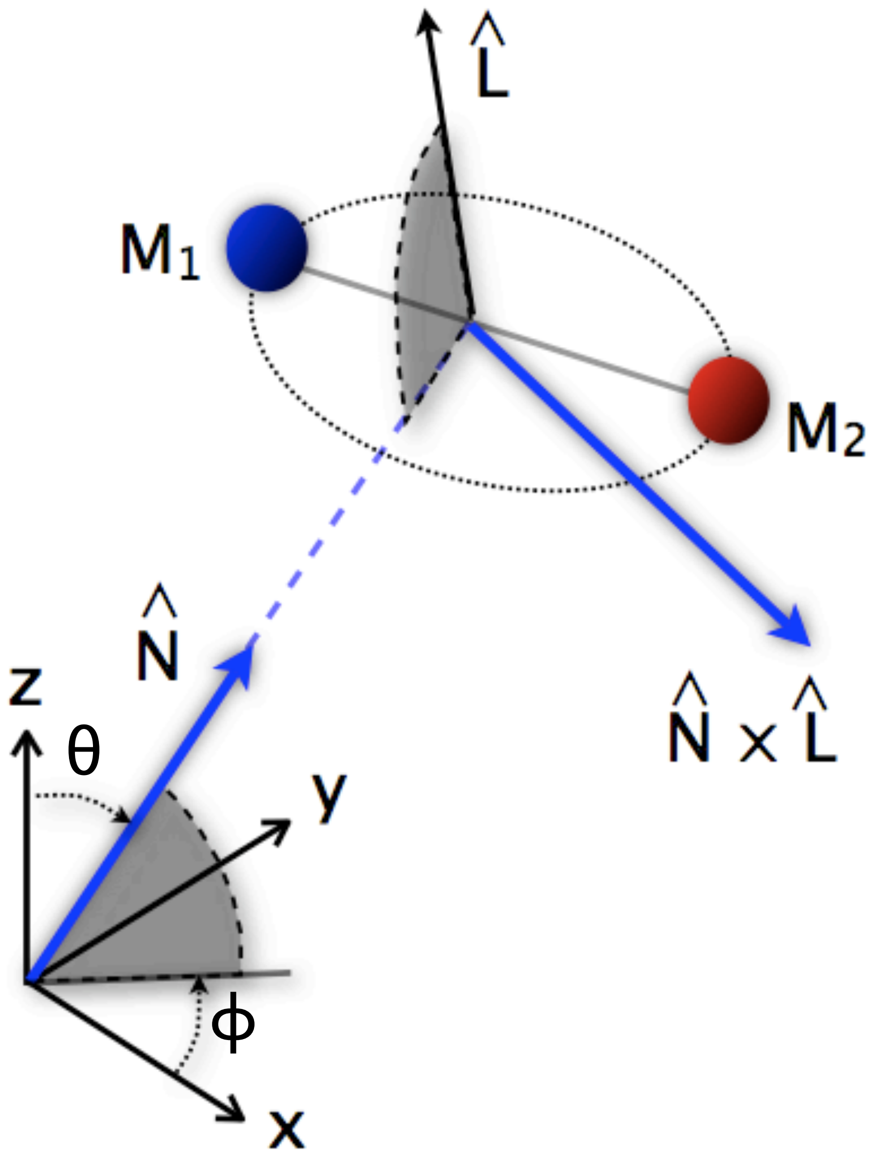
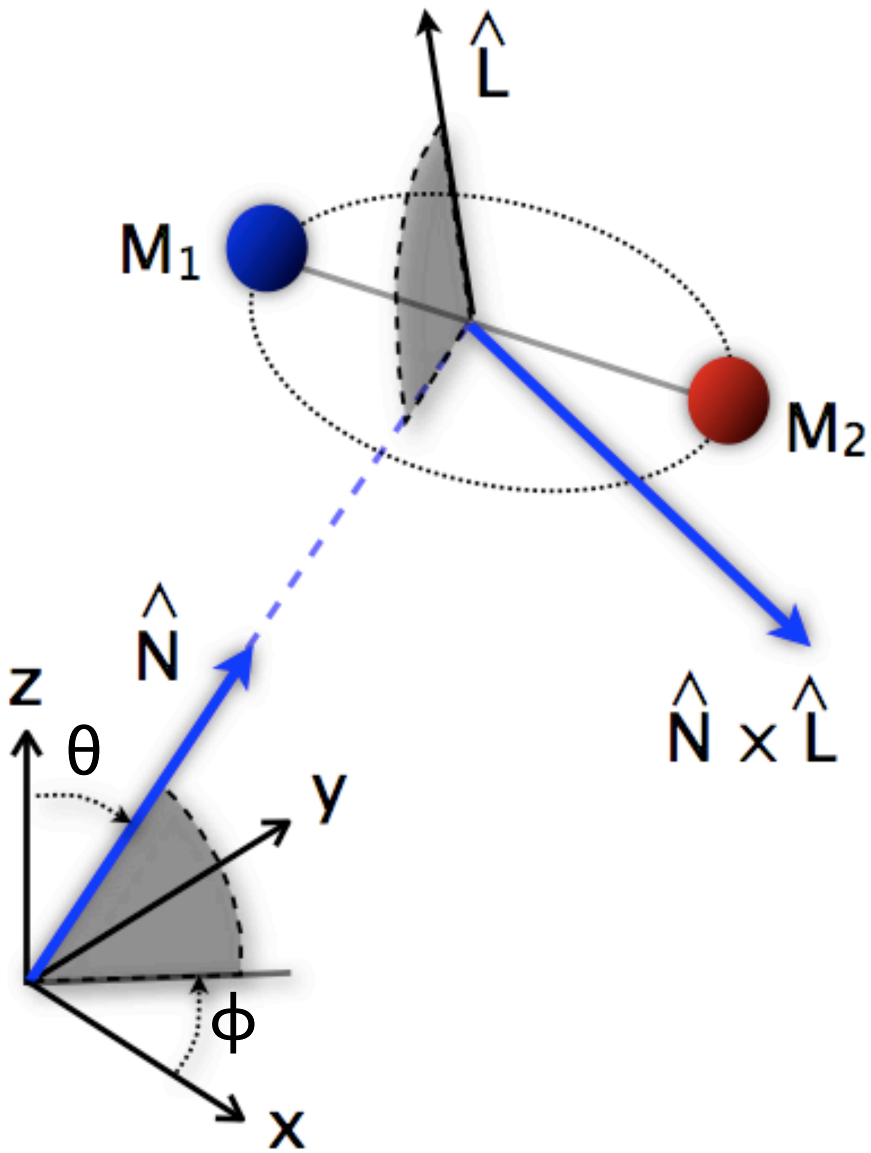
frequency chirp:
dynamical flow -
time dependence
of source



Multi- EM and GW channels

- Parameters of interest:

$$\boldsymbol{\theta} = \{\mathcal{M}, \mu, \mathbf{D_L}, \cos(inc) \equiv \hat{\mathbf{L}} \cdot \hat{\mathbf{n}}, \theta, \phi, \psi, t_c, \phi_c\}$$



Standard sirens for LISA

- Without counterpart,

  sky positions < 1 deg;
  luminosity distance < 10%

- With optical counterpart,

  luminosity distance < 0.1%

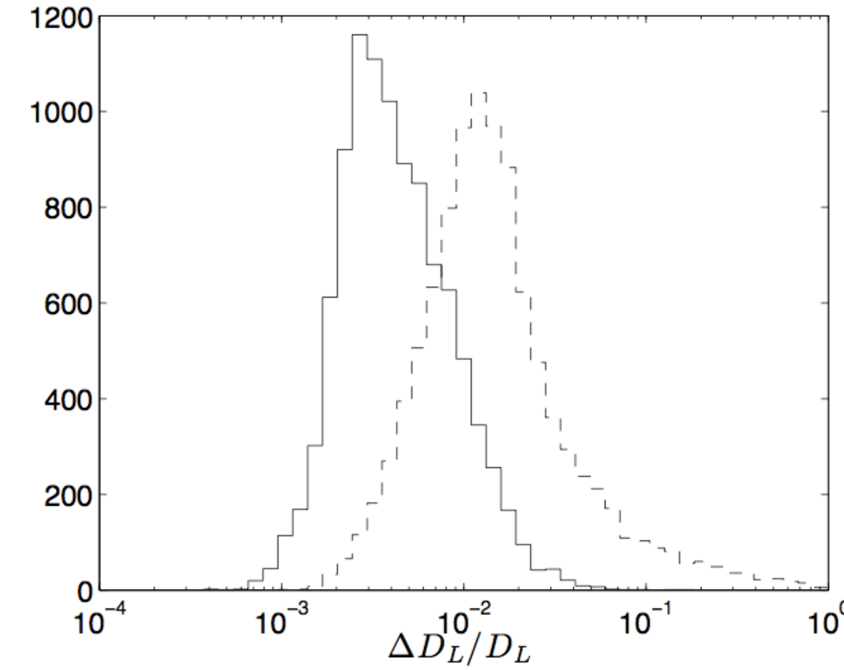
- Possible electromagnetic counterparts?

  gas within binary is driven onto larger BH: super-Eddington accretion, outflows/jets.

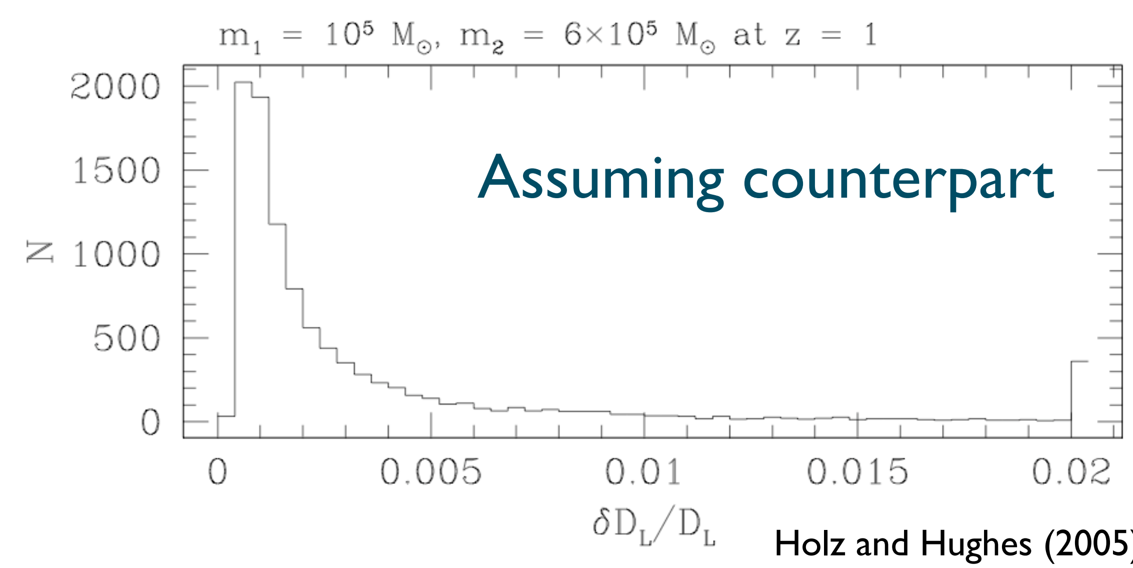
  delayed afterglows: inspiral hollows out circumbinary gas, which subsequently infalls after merger.

[e.g. Milosavljevic, Phinney, etc.]

No em counterpart

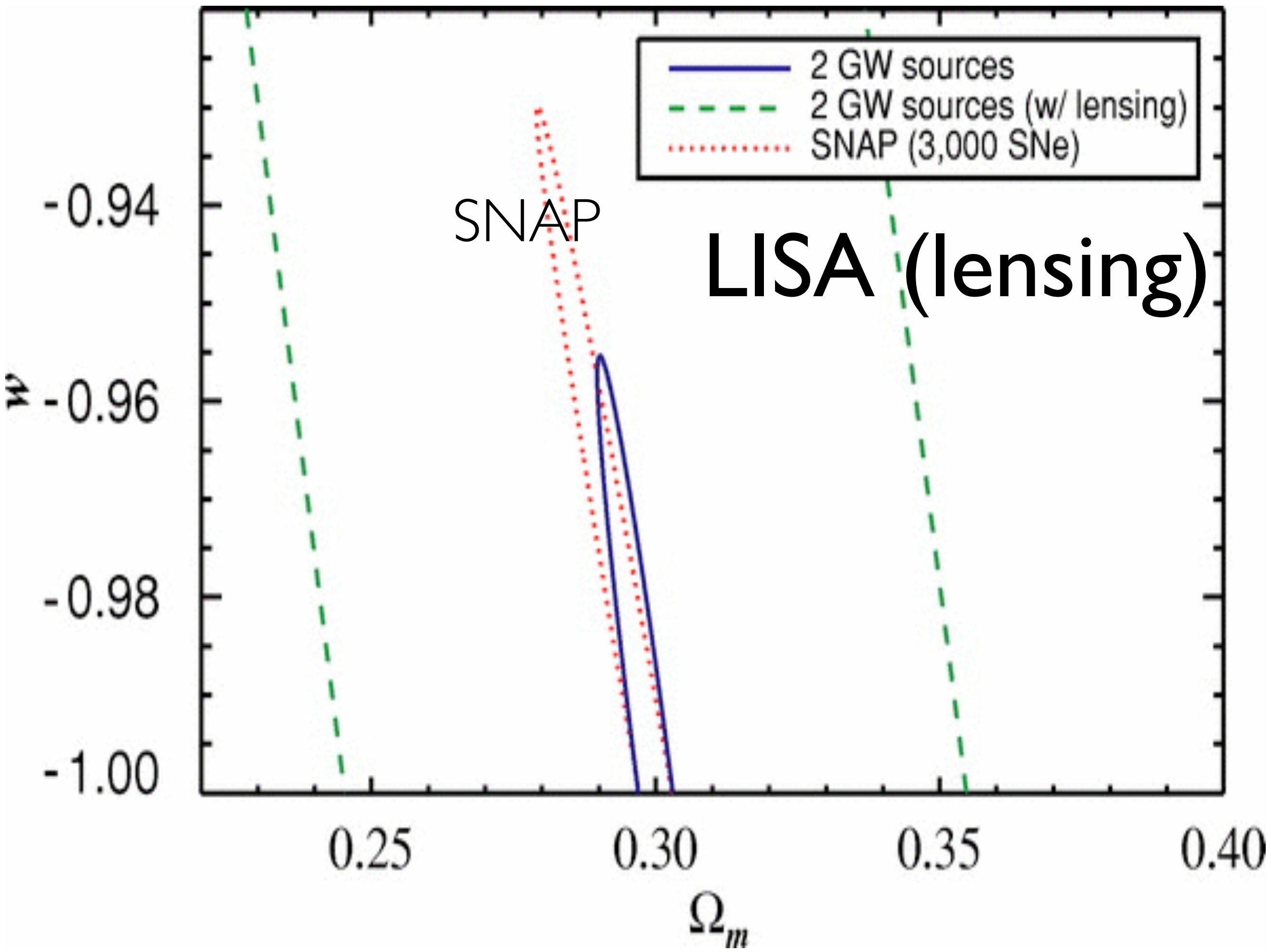


Lang and Hughes (2006,2007)



Holz and Hughes (2005)

Standard sirens for LISA



Holz and Hughes (2005)

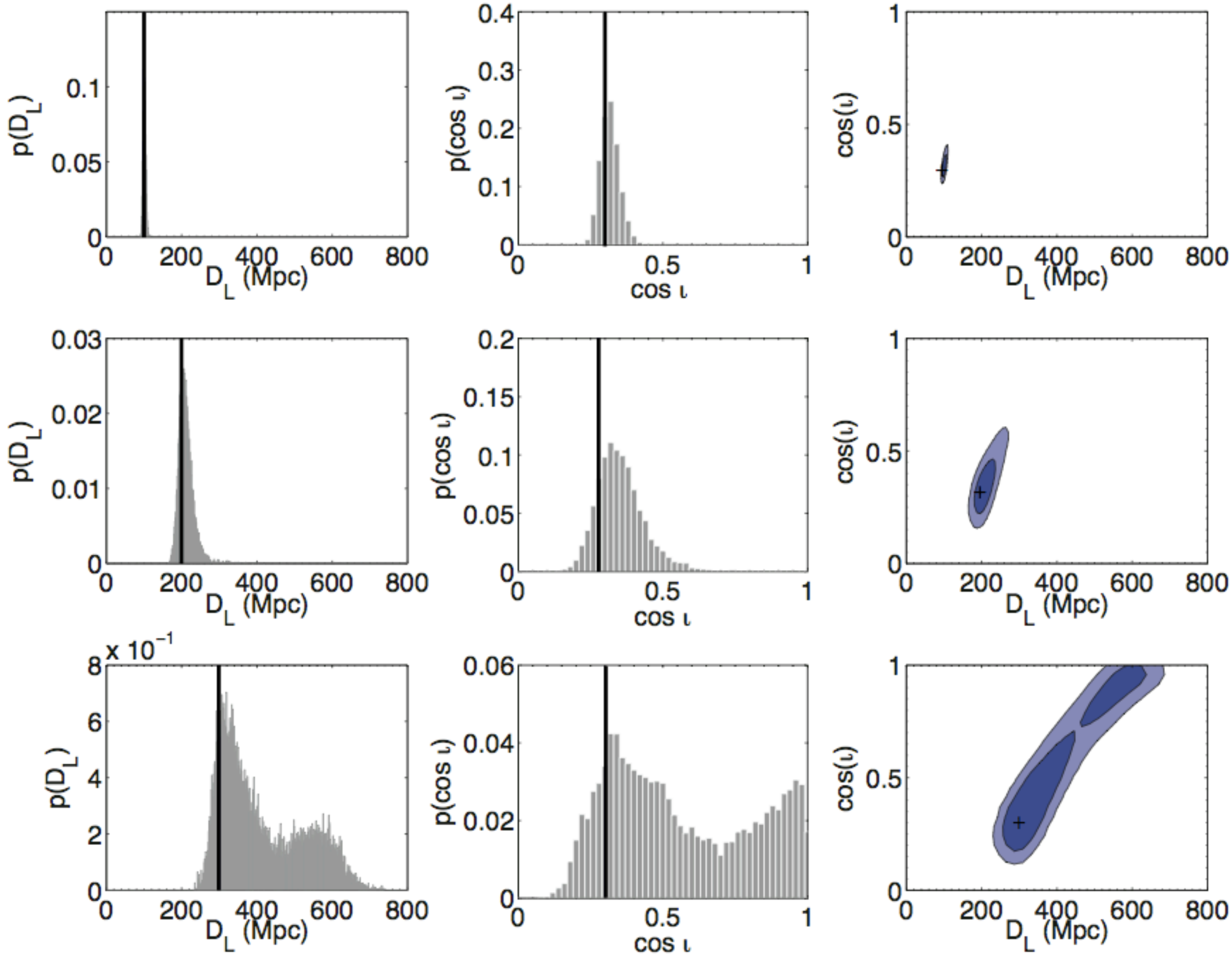
- Main drawback ... universe in non homogeneous...gravitational lensing...
- For LISA standard sirens to be useful, must have ~100 (sufficient statistics) to average out lensing.
- Merger rates, EM counterparts still uncertain.

Breakdown of Gaussian approx.: variation of D_L

True D_L = 100 Mpc
SNR = 53.6

True D_L = 200 Mpc
SNR = 26.8

True D_L = 300 Mpc
SNR = 17.9



Breakdown of Gaussian approx.: variation of D_L

True D_L = 400 Mpc
SNR = 13.4

True D_L = 500 Mpc
SNR = 10.7

True D_L = 600 Mpc
SNR = 8.9