LIGO

VIRGO

# Gravitational Astronomy with Advanced and 3G Detectors: Prospects and Challenges

First Dutch Meeting on Gravitational Waves, 19 January 2012, Amsterdam

B.S. Sathyaprakash

School of Physics and Astronomy, Cardiff University, UK

ET EINSTEIN TELESCOPE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

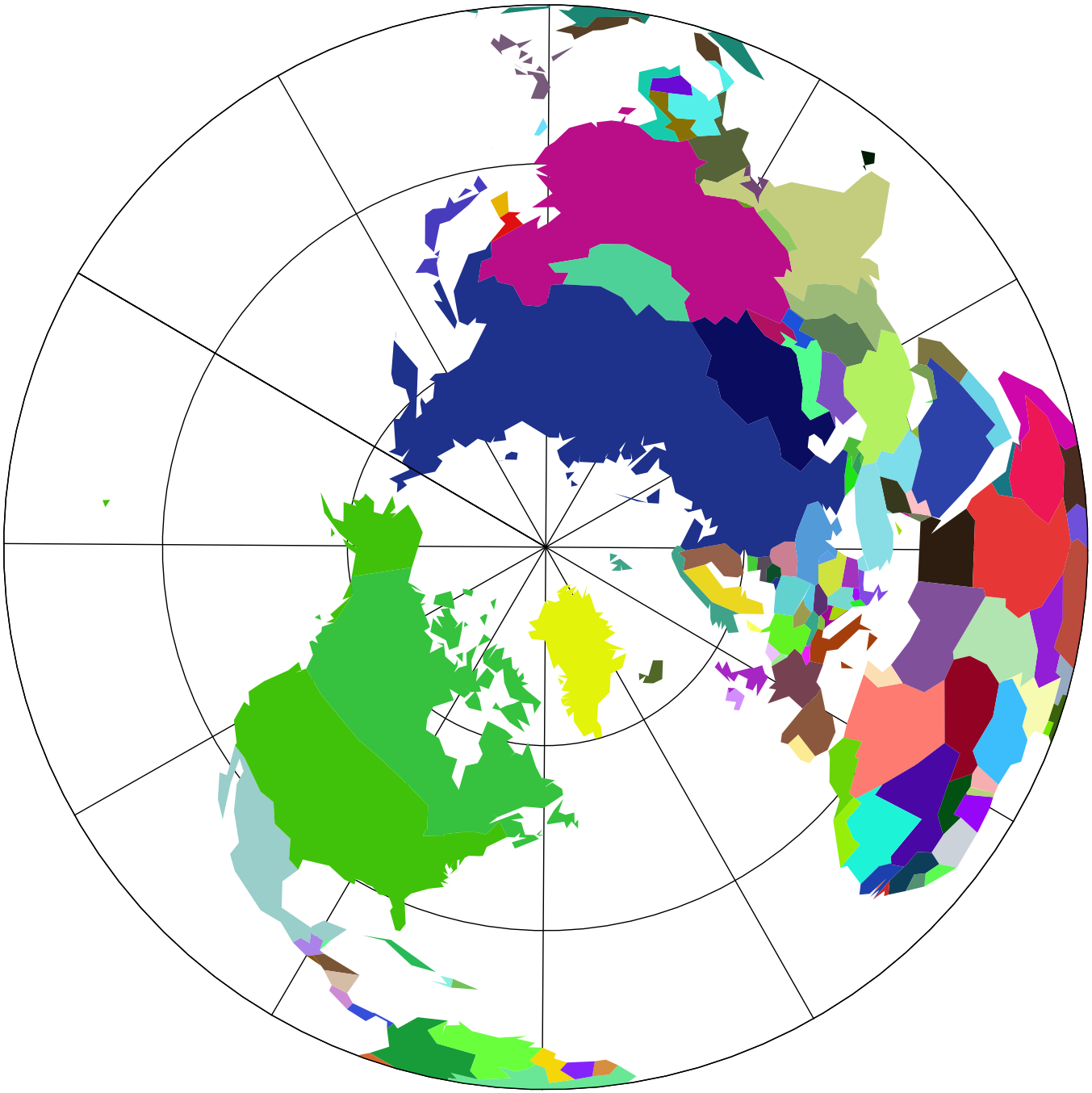
LSC

# Advanced LV Primary Science Objectives

- Make a direct detection of gravitational waves
  - Binary neutron stars are the most likely sources
- Constrain the rate of compact binary coalescences
  - Current rates are uncertain by 3 orders of magnitude. Advanced detectors will measure the rate to within a factor of a few in the local (<500 Mpc) Universe
- Detect binary black holes and neutron star-black hole binaries
  - First ever detection of such systems - a new population of astronomical sources
- Verify GRB-GW Association
  - Check if compact binaries in which at least one of the companions is a neutron star are progenitors of short gamma-ray bursts
- Measure the Hubble parameter to within 5%
  - Compact binary inspirals are self-calibrating standard sirens
  - To be useful as standard candles it is necessary to identify the host and measure its redshift and so sky localization is a key science objective
  - If we binary black holes occur in sufficient numbers then EM identification may not be necessary but it would still be necessary to have a good resolution
- Carry out strong field tests of general relativity

# What will ET observe and what can it tell?

- Observe radiation from
  - BH collisions when the Universe was still in its infancy assembling the first galaxies
  - NS collisions when star formation in the Universe was at its peak
  - Formation of black holes and neutron stars in supernovae and collapsars in the local neighbourhood
  - Might observe stochastic backgrounds of cosmological and astrophysical origin
- LV and ET could provide new insights into
  - The secret births and lives of black holes and neutron stars, their demographics, populations and their masses and spins
  - Hubble parameter, dark energy and its variation with redshift
  - Equation-of-state of matter at supra-nuclear densities
  - Early history of the Universe's evolution



# Detector Networks

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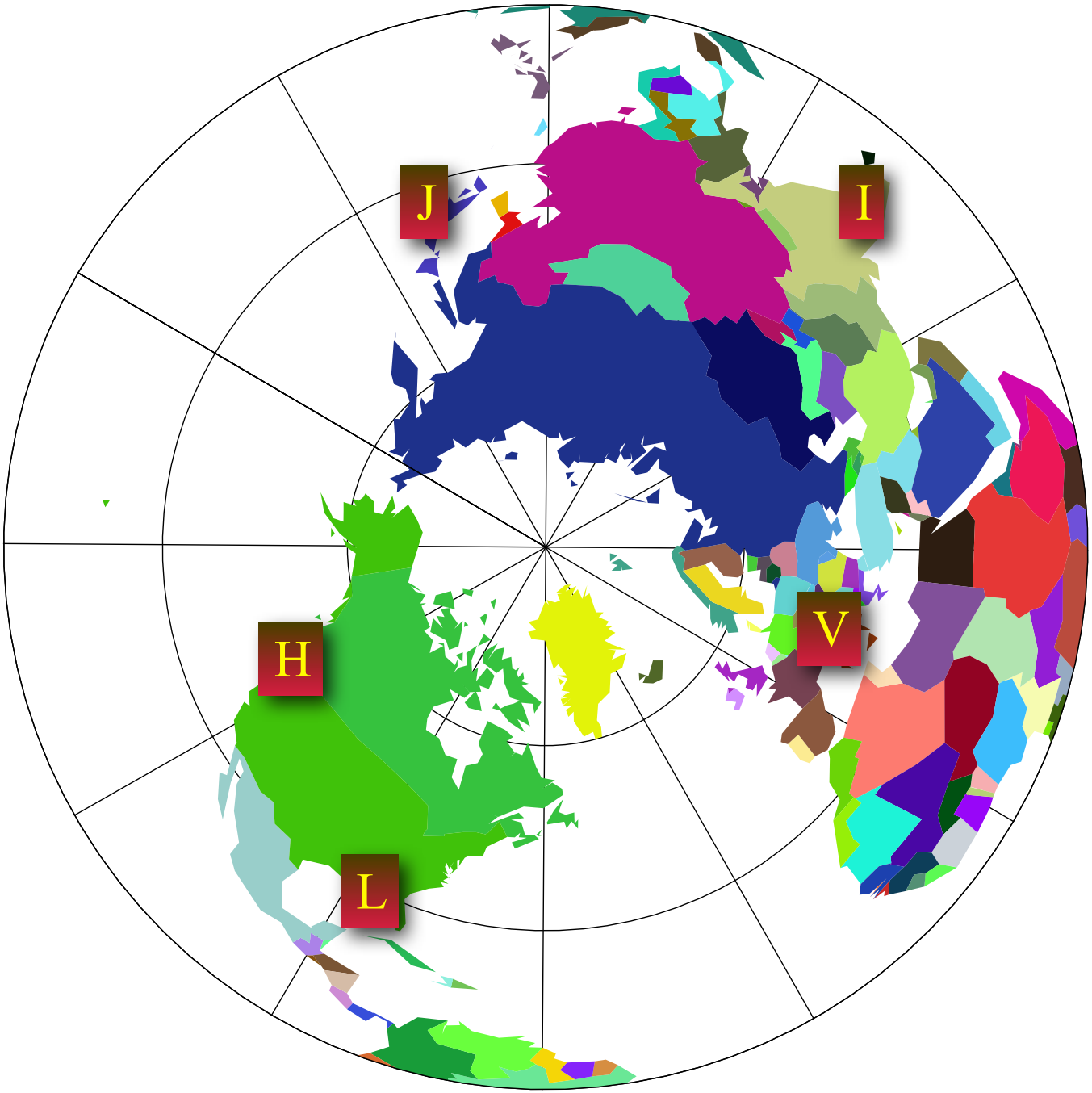
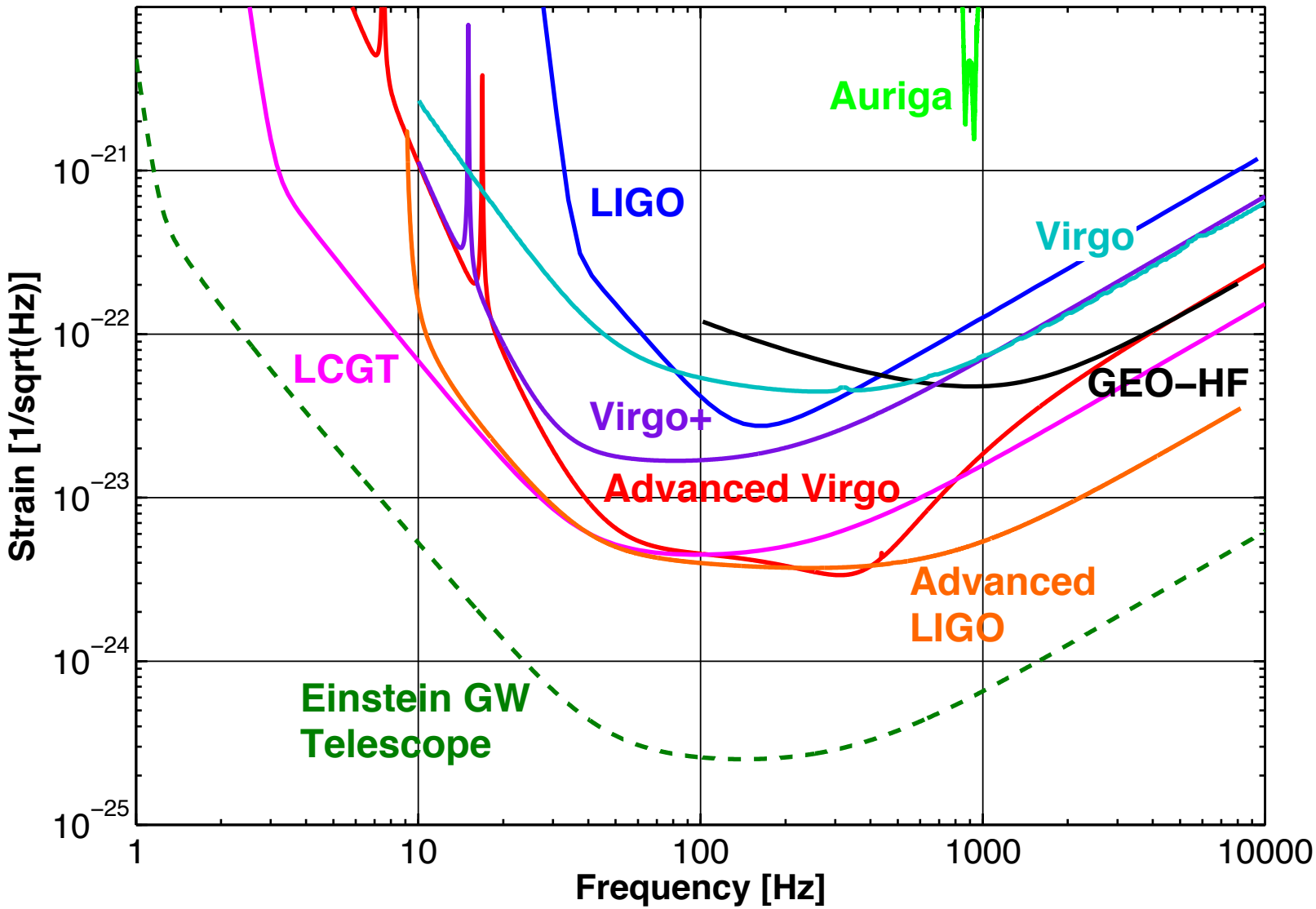
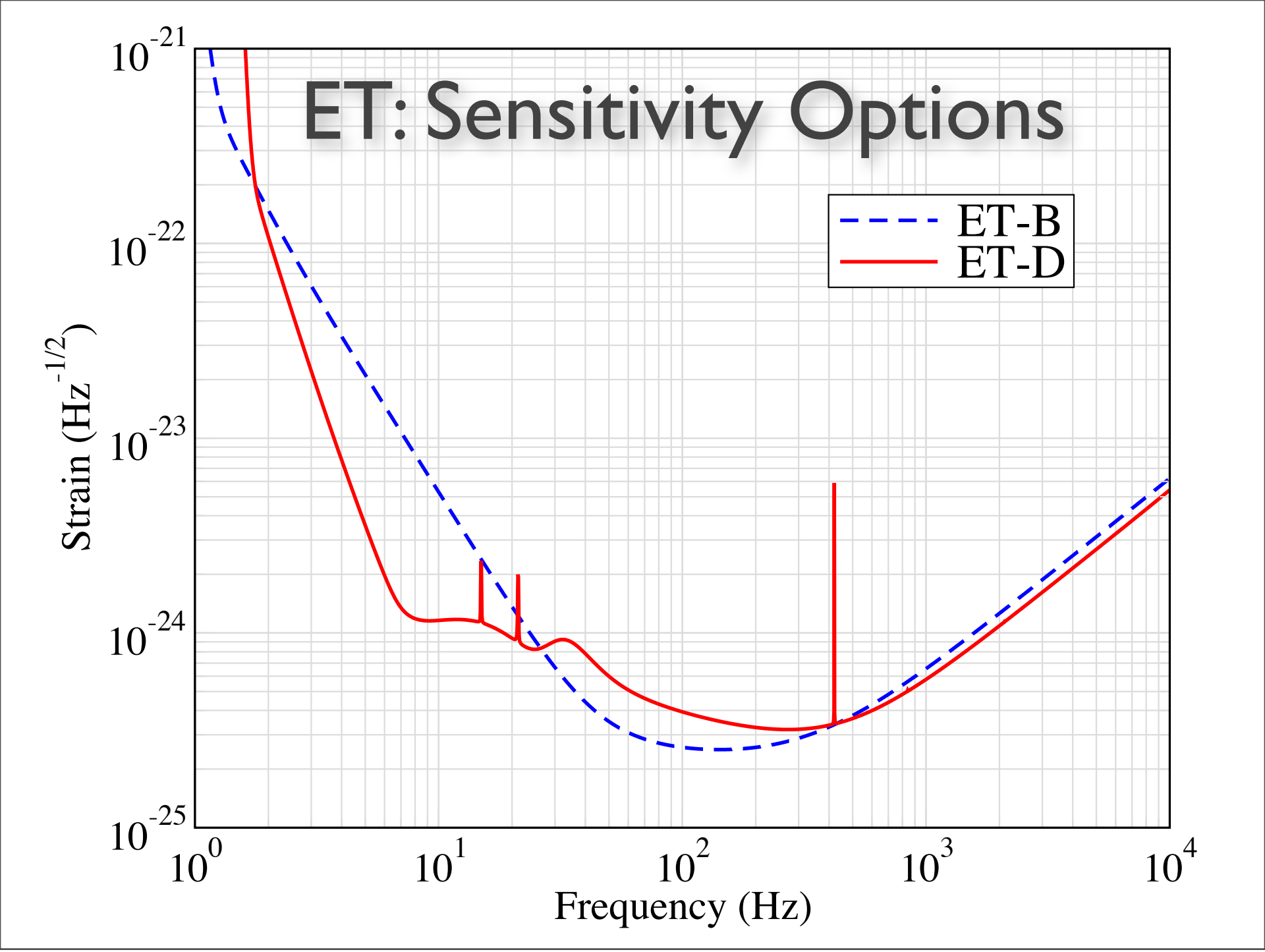
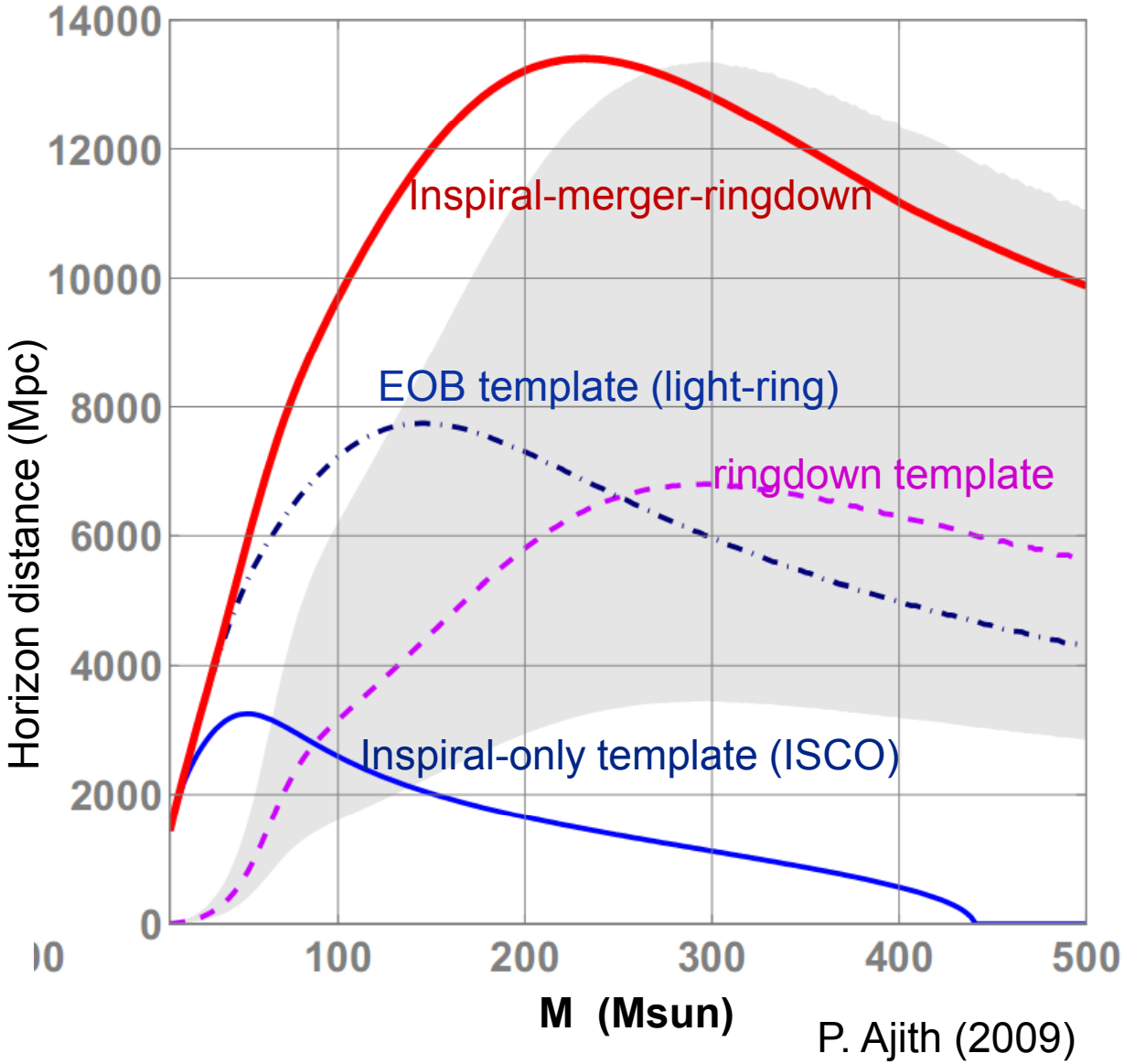


# Expected Sensitivities: Advanced and 3G Detectors



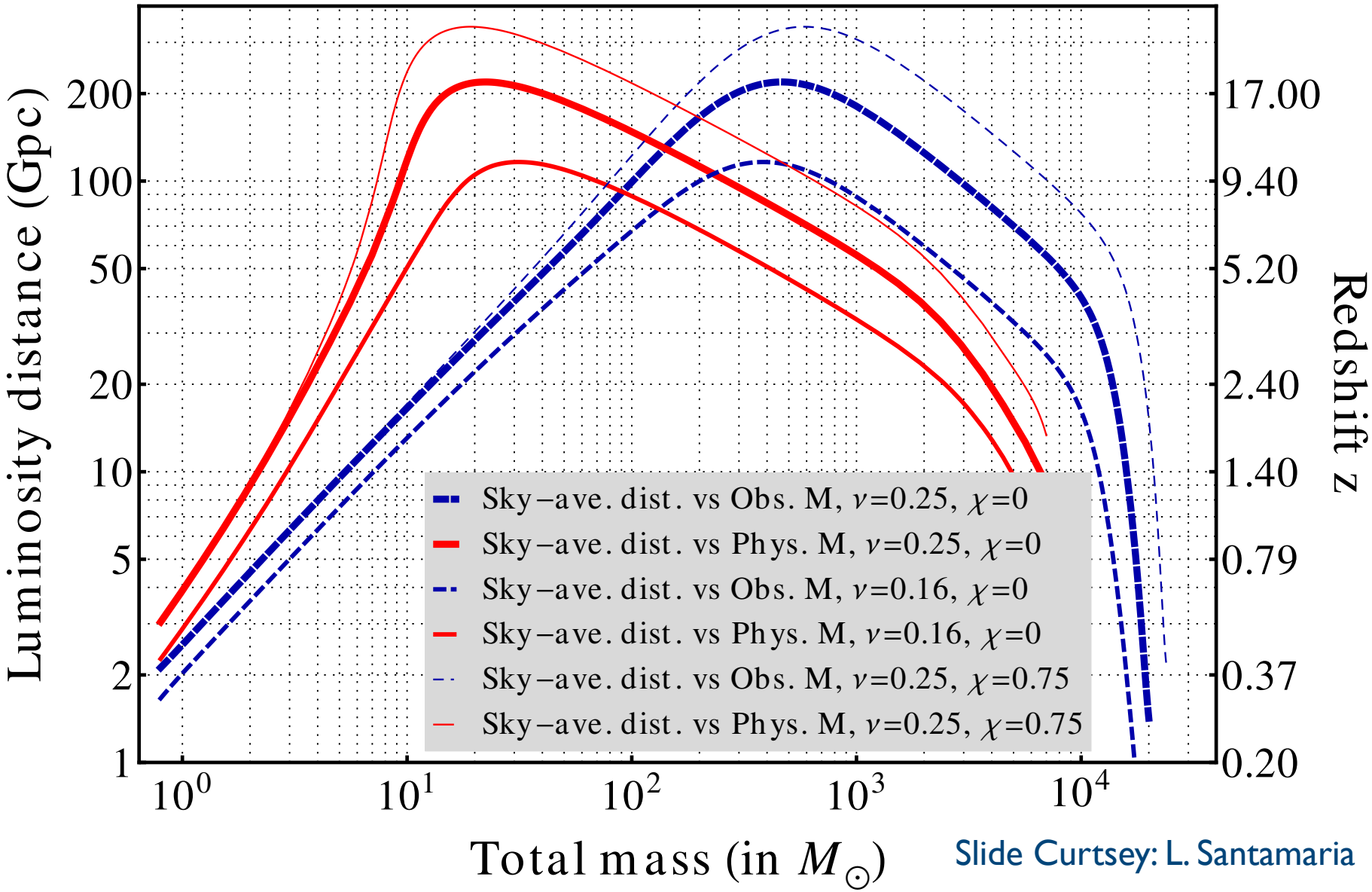

ET: Sensitivity Options
ET-B
ET-D
Strain (Hz^-1/2)
Frequency (Hz)
10^-21
10^-22
10^-23
10^-24
10^-25
10^0
10^1
10^2
10^3
10^4

# LV Distance Reach for Compact Binaries




P. Ajith (2009)

# ET Distance Reach for Compact Binary Mergers




Slide Curtsey: L. Santamaria

Class. Quantum Grav. **27** (2010) 173001 (25pp) doi:10.1088/0264-9381/27/17/173001

**TOPICAL REVIEW**

# Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors

**Table 5.** Detection rates for compact binary coalescence sources.

| IFO | Source[a] | $\dot{N}_{\rm low}$ yr$^{-1}$ | $\dot{N}_{\rm re}$ yr$^{-1}$ | $\dot{N}_{\rm high}$ yr$^{-1}$ | $\dot{N}_{\rm max}$ yr$^{-1}$ |
|---|---|---|---|---|---|
| Initial | NS–NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS–BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| | BH–BH | $2 \times 10^{-4}$ | 0.007 | 0.5 | |
| | IMRI into IMBH | | | <0.001[b] | 0.01[c] |
| | IMBH-IMBH | | | $10^{-4}$ [d] | $10^{-3}$ [e] |
| Advanced | NS–NS | 0.4 | 40 | 400 | 1000 |
| | NS–BH | 0.2 | 10 | 300 | |
| | BH–BH | 0.4 | 20 | 1000 | |
| | IMRI into IMBH | | | 10[b] | 300[c] |
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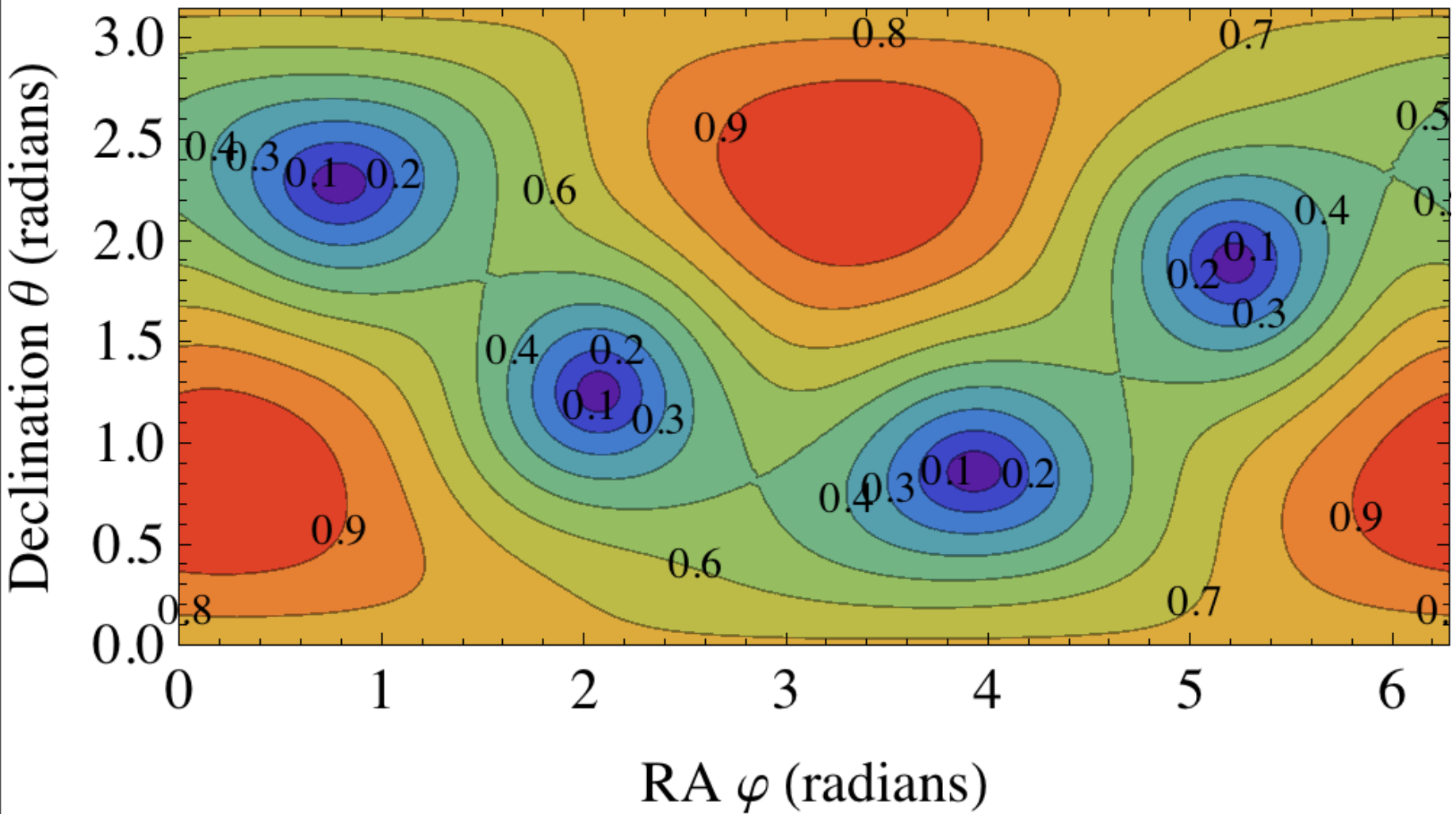
# Virgo's Antenna Pattern



ET
EINSTEIN
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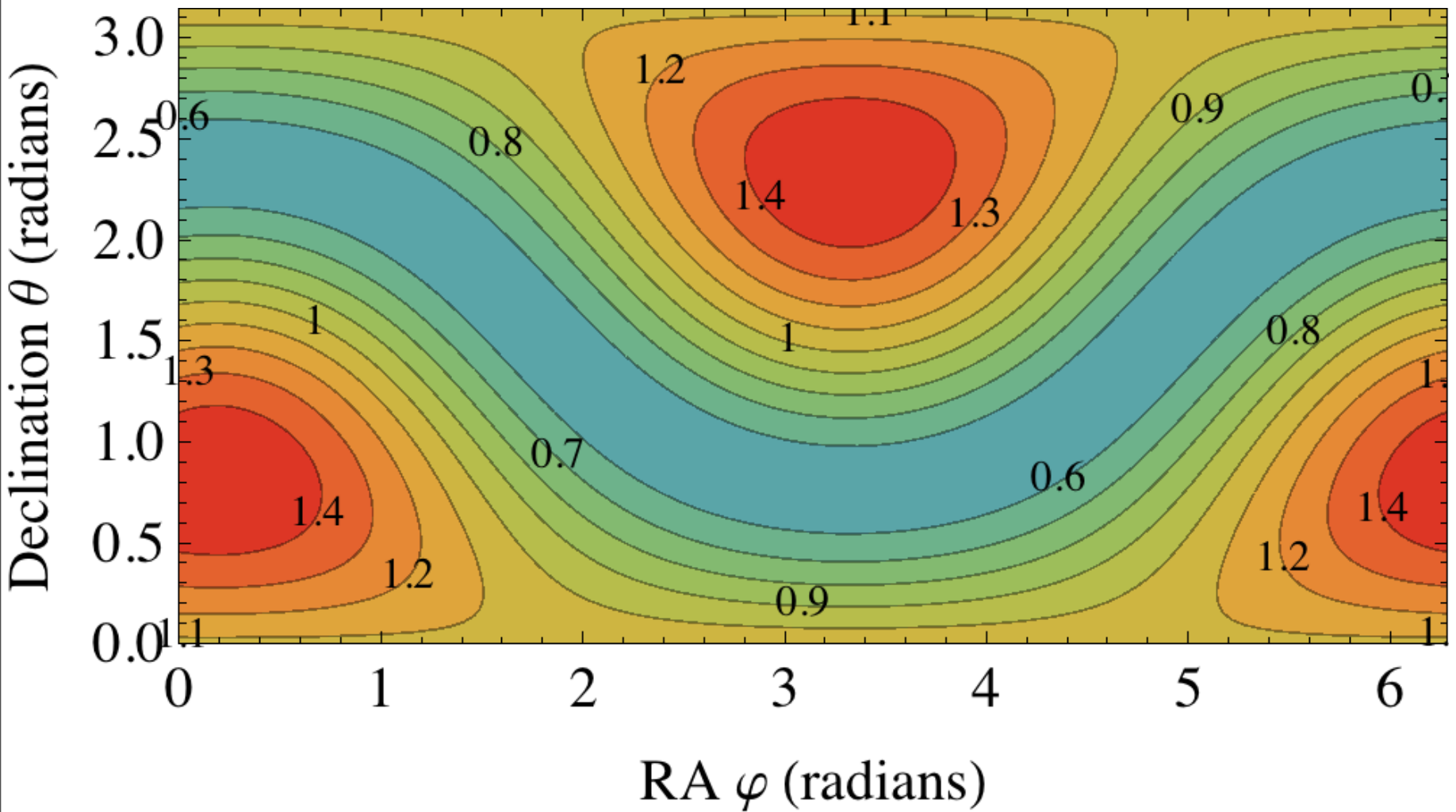
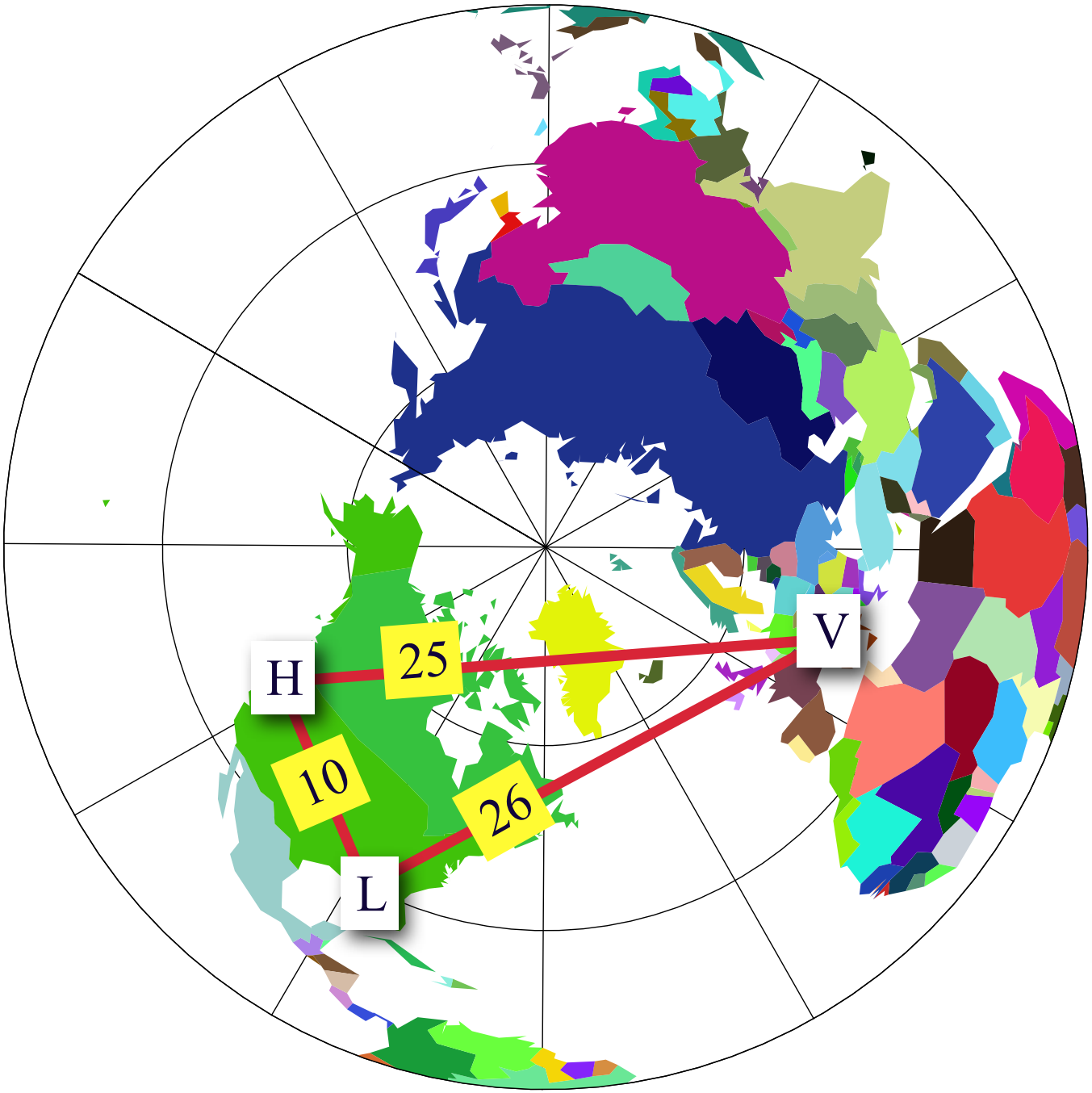
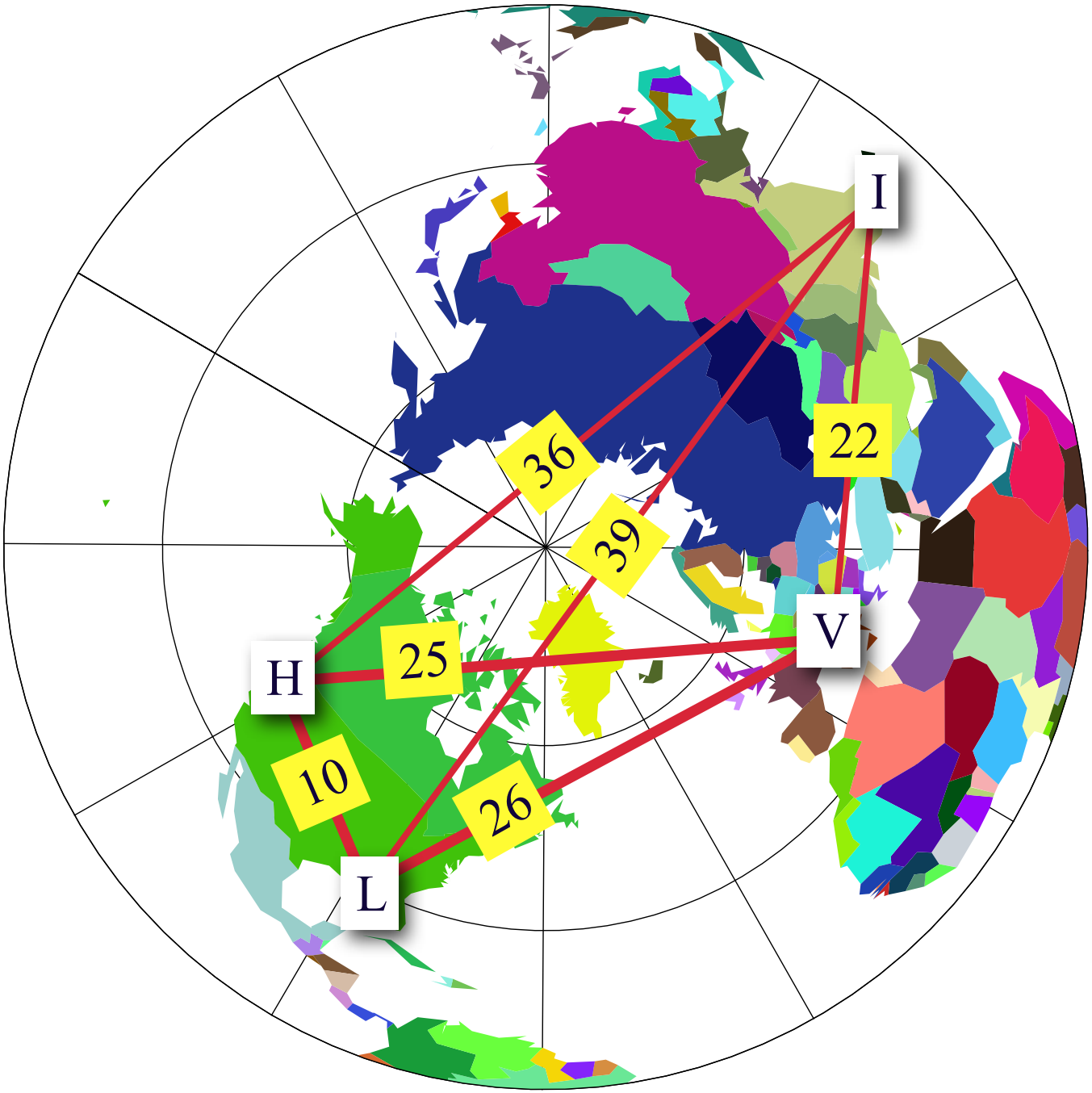
# ET's Antenna Pattern






# Baselines

in light travel time (ms)

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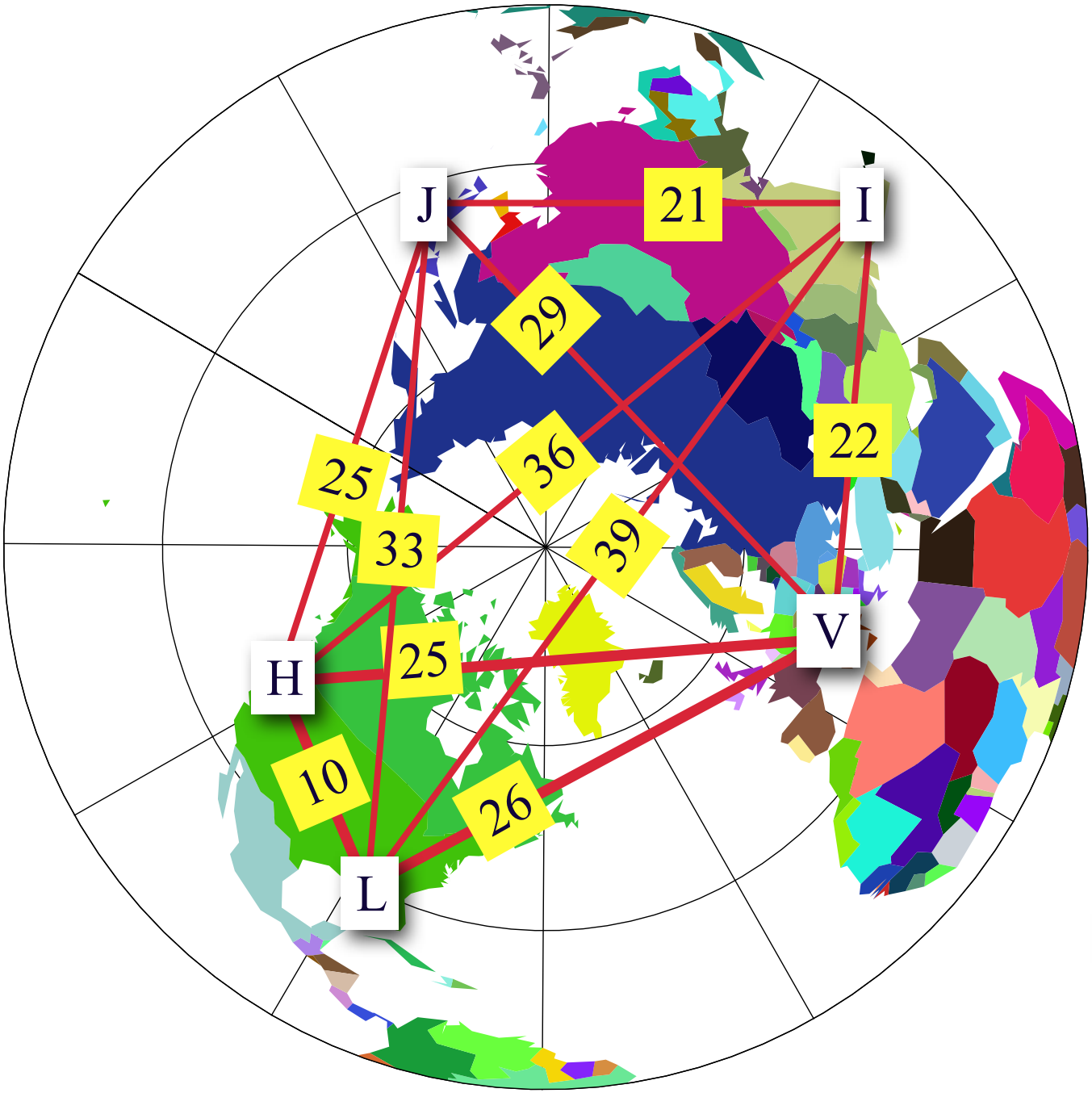
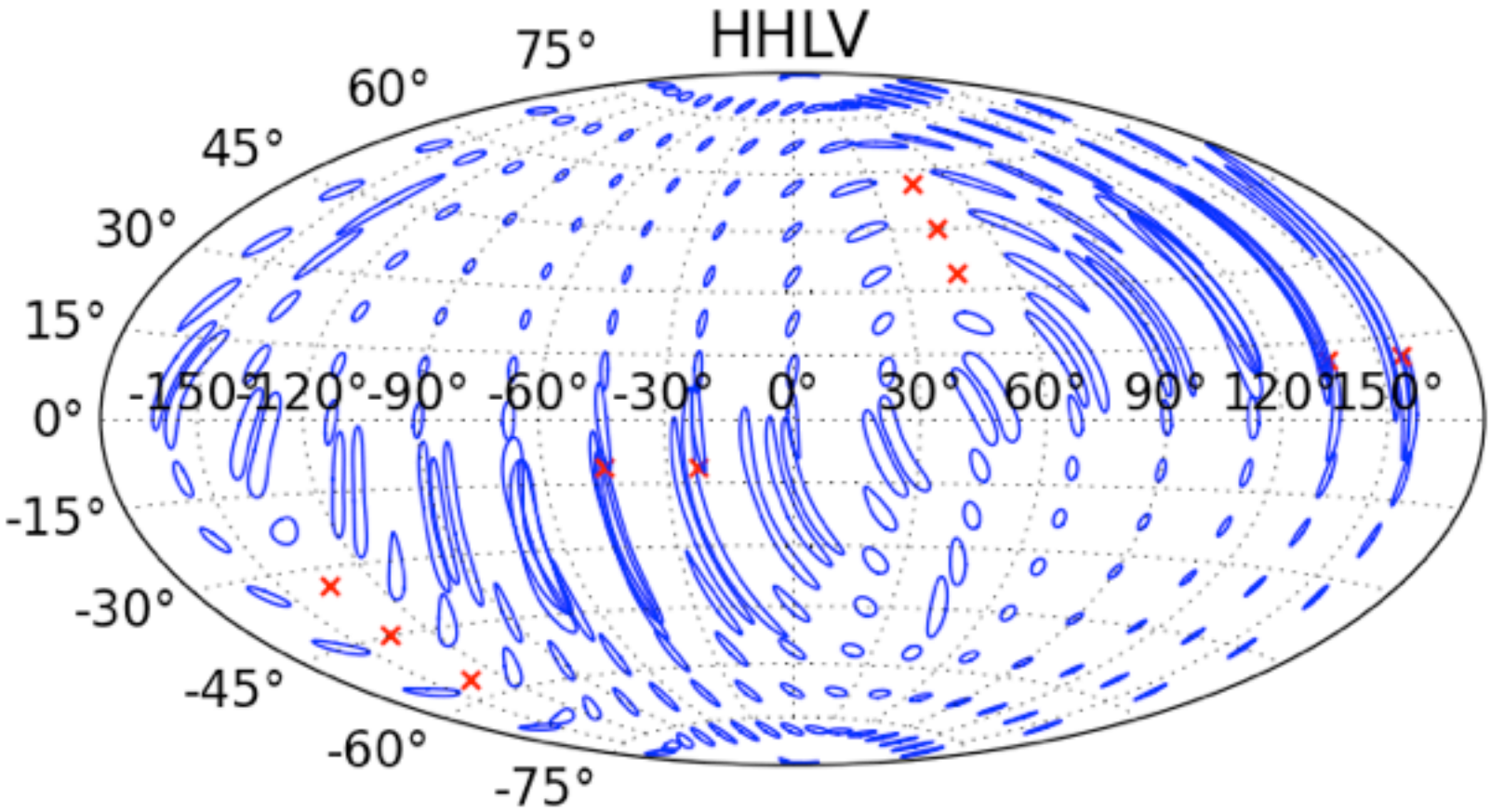



# Baselines

in light travel time (ms)

# Sky Localization Error Ellipses




Red crosses denote regions where the network has blind spots

Fairhurst 2011

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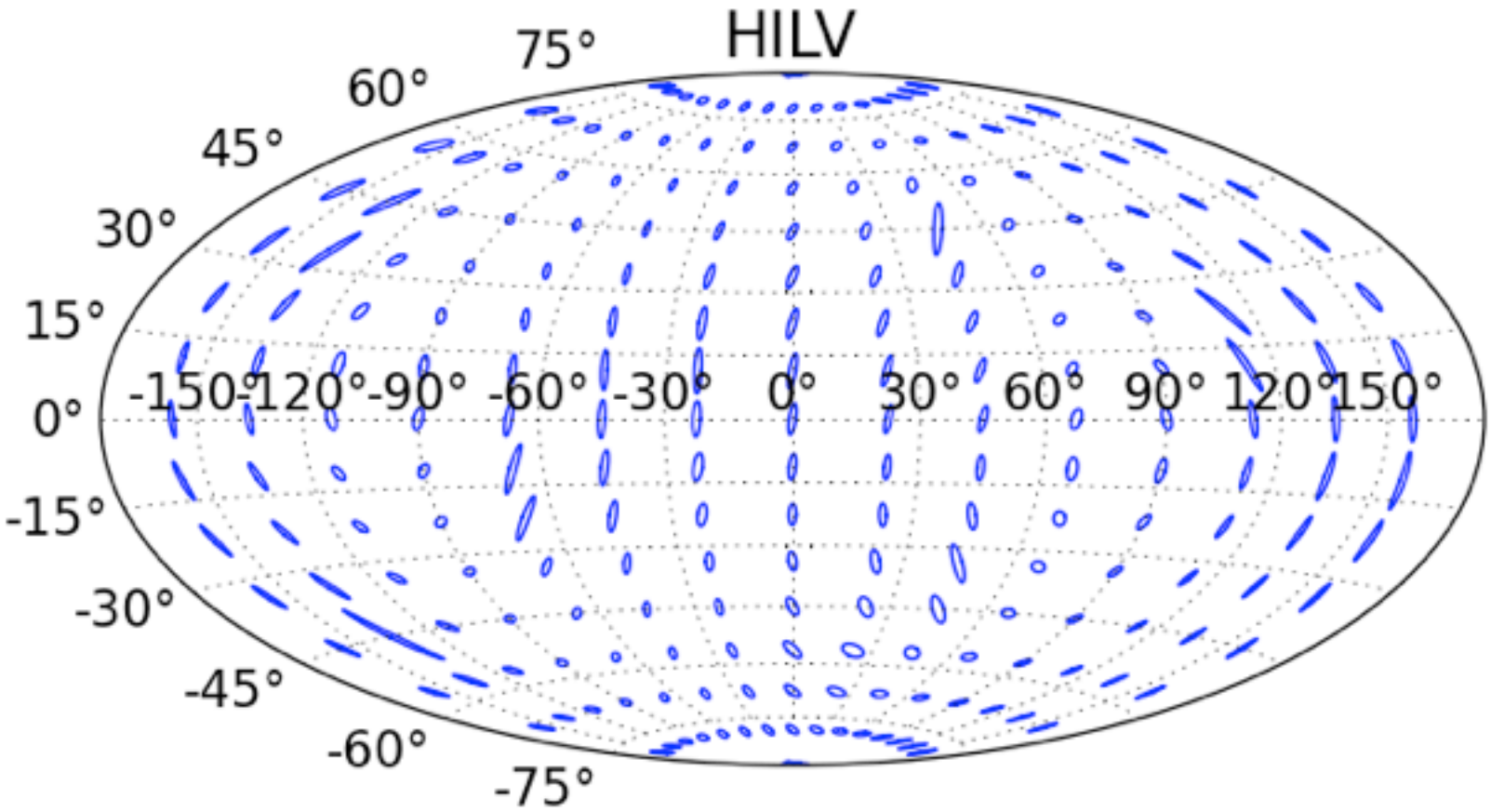


Fairhurst 2011

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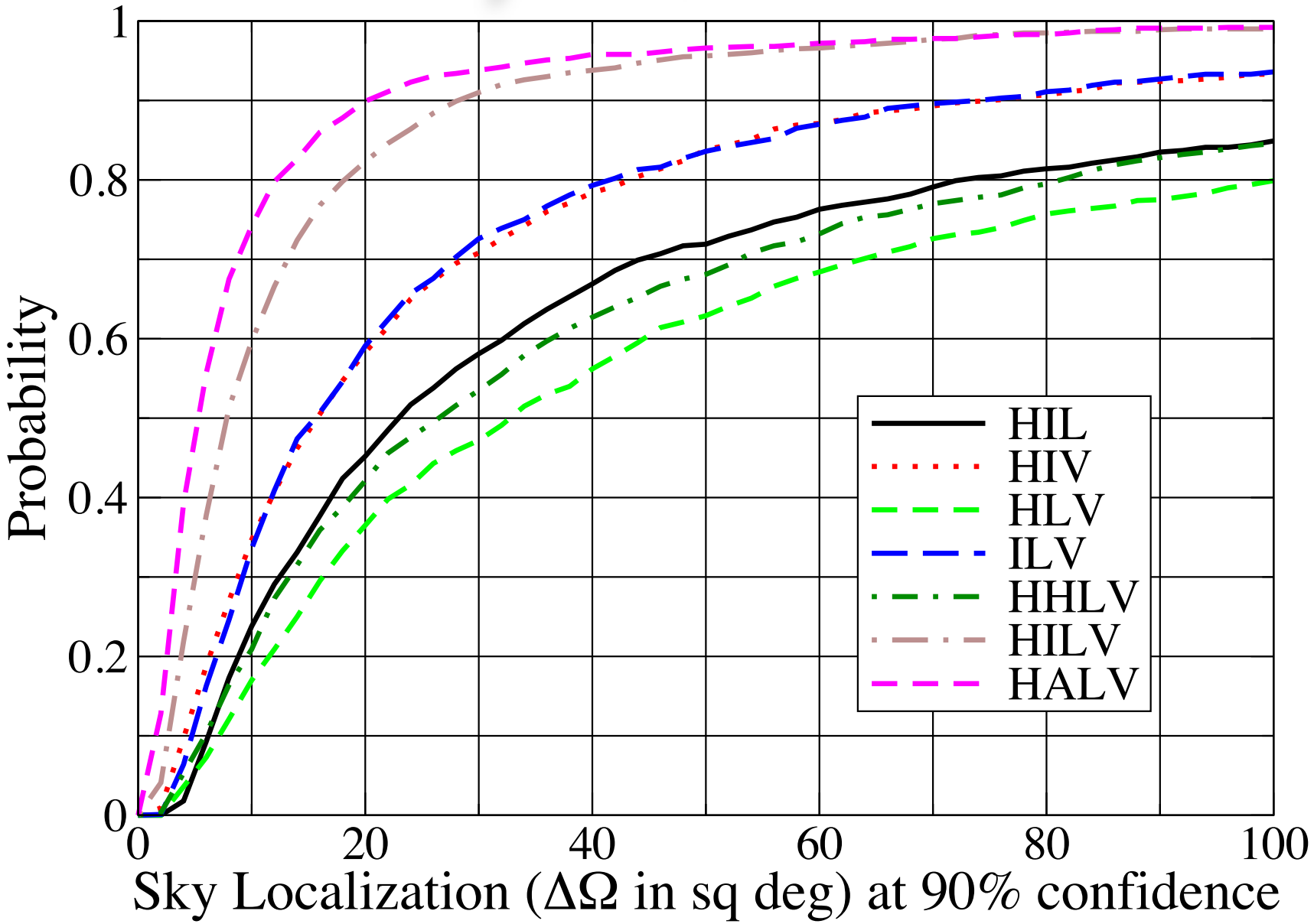

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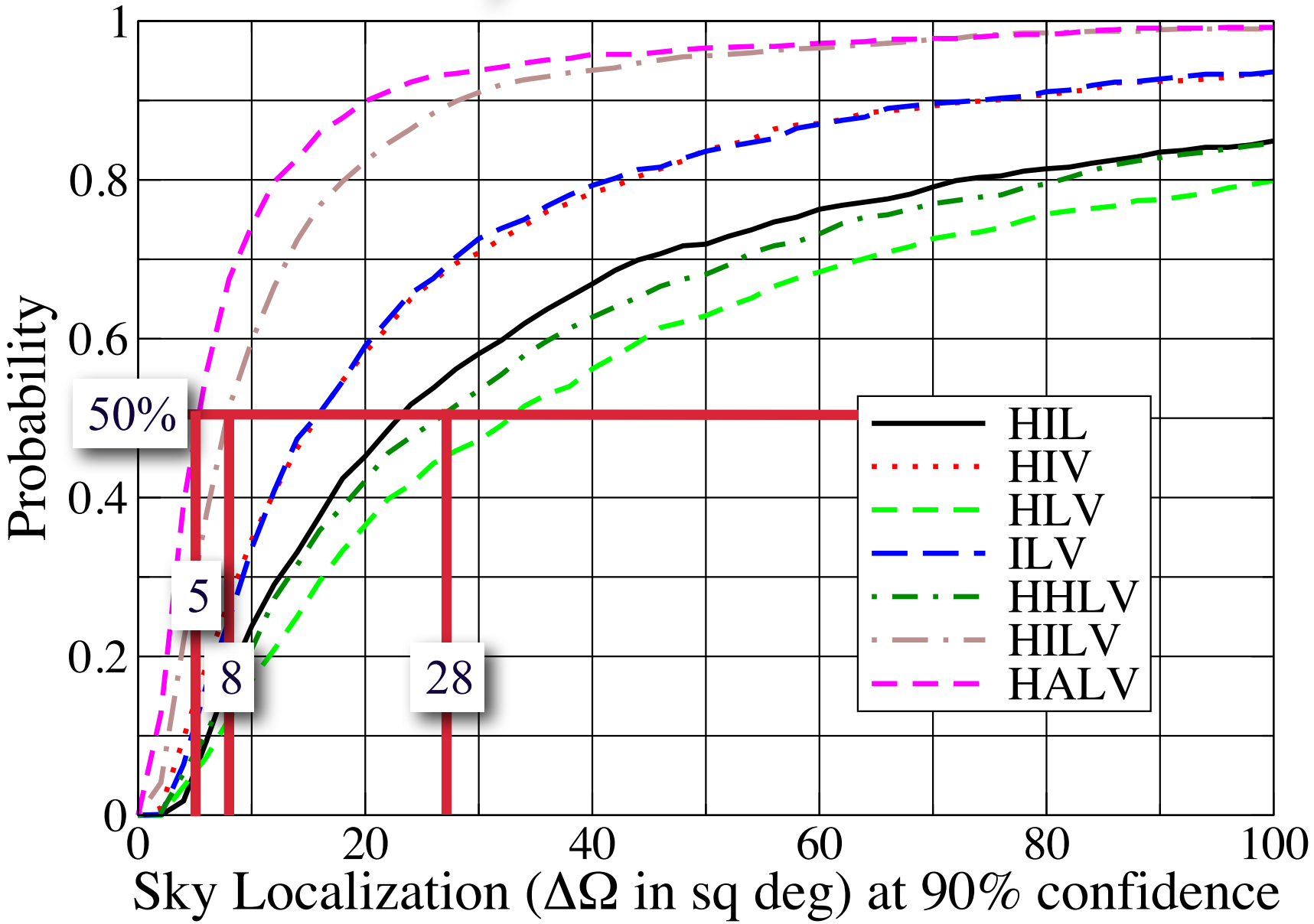

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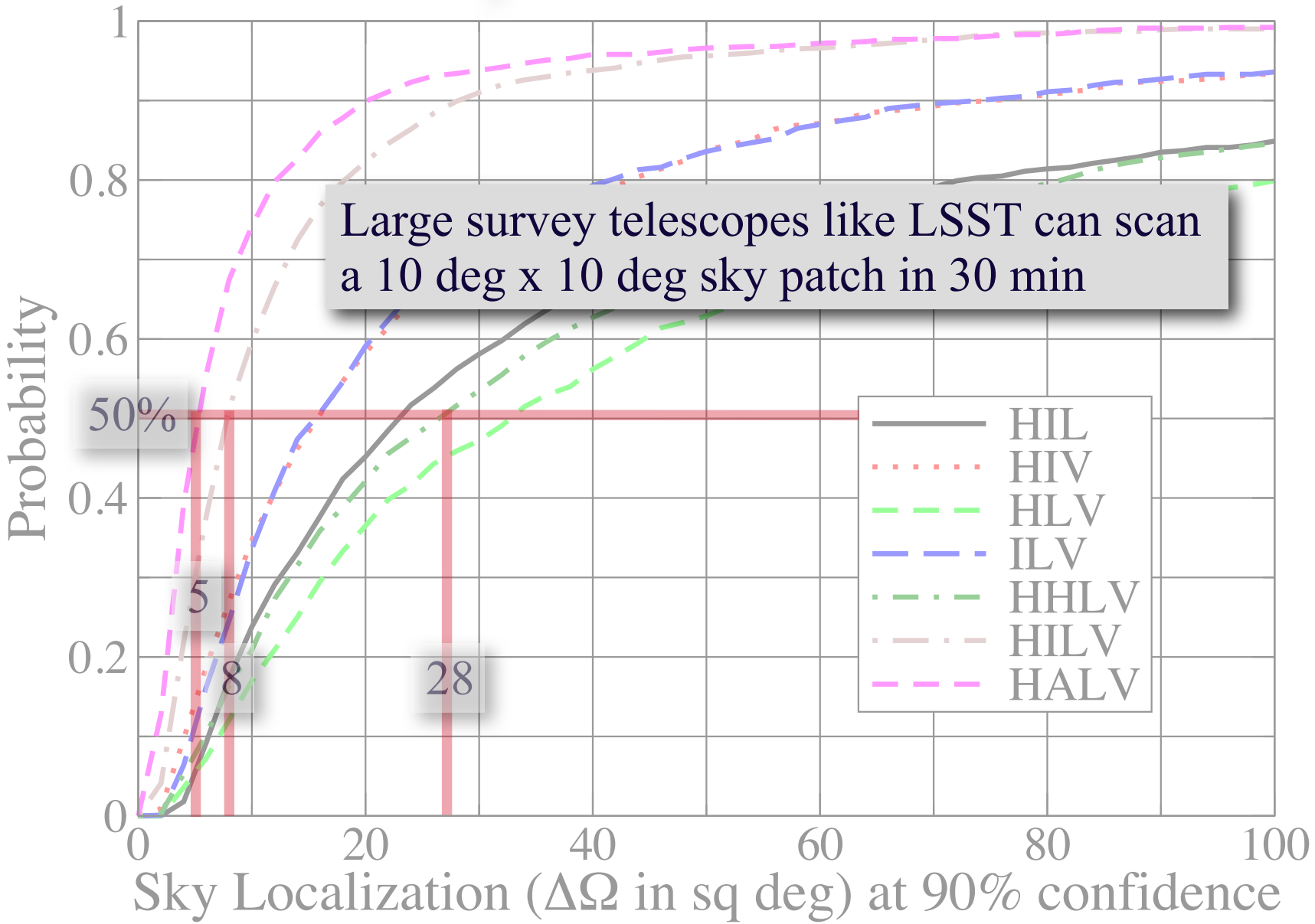
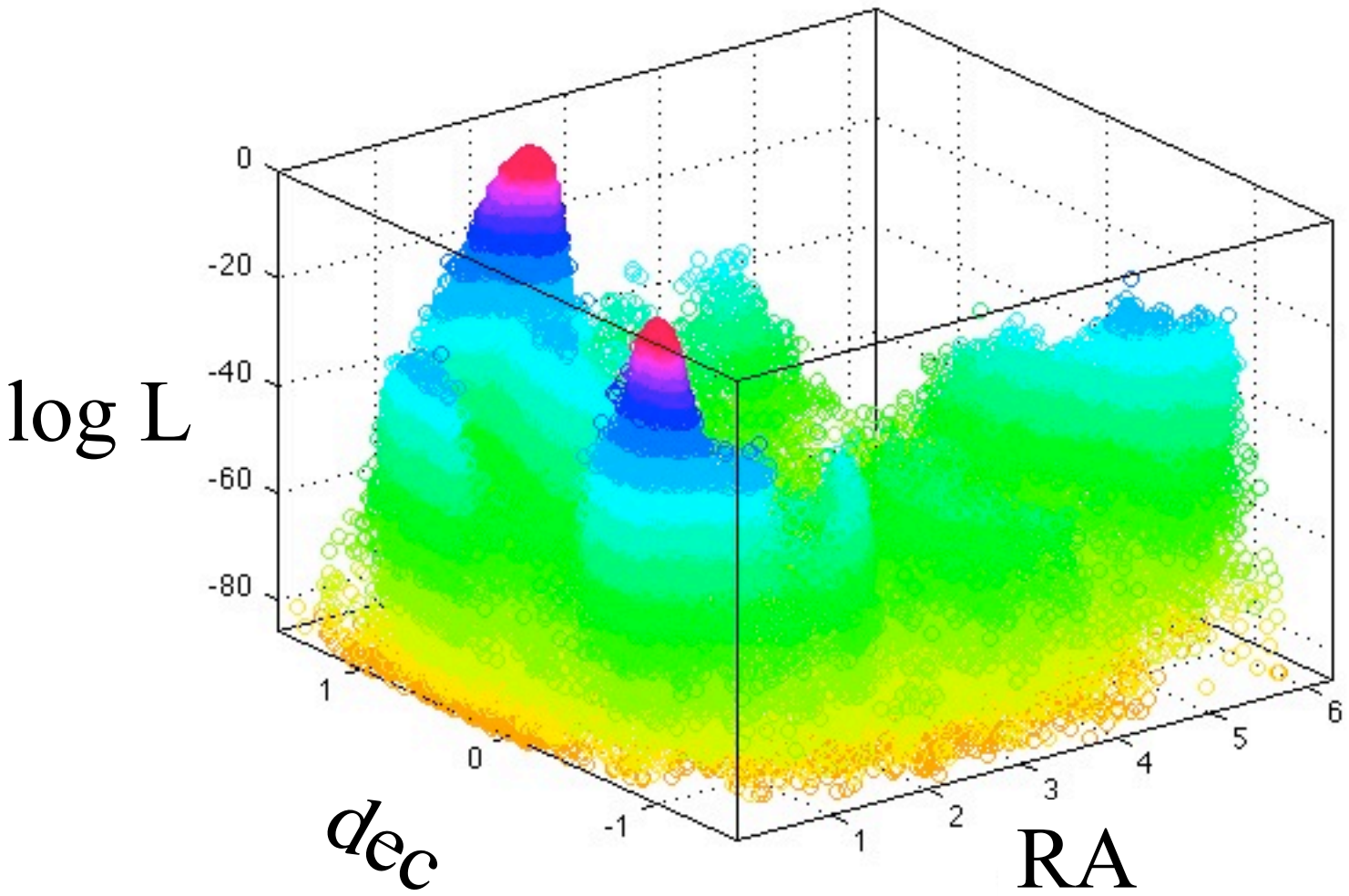
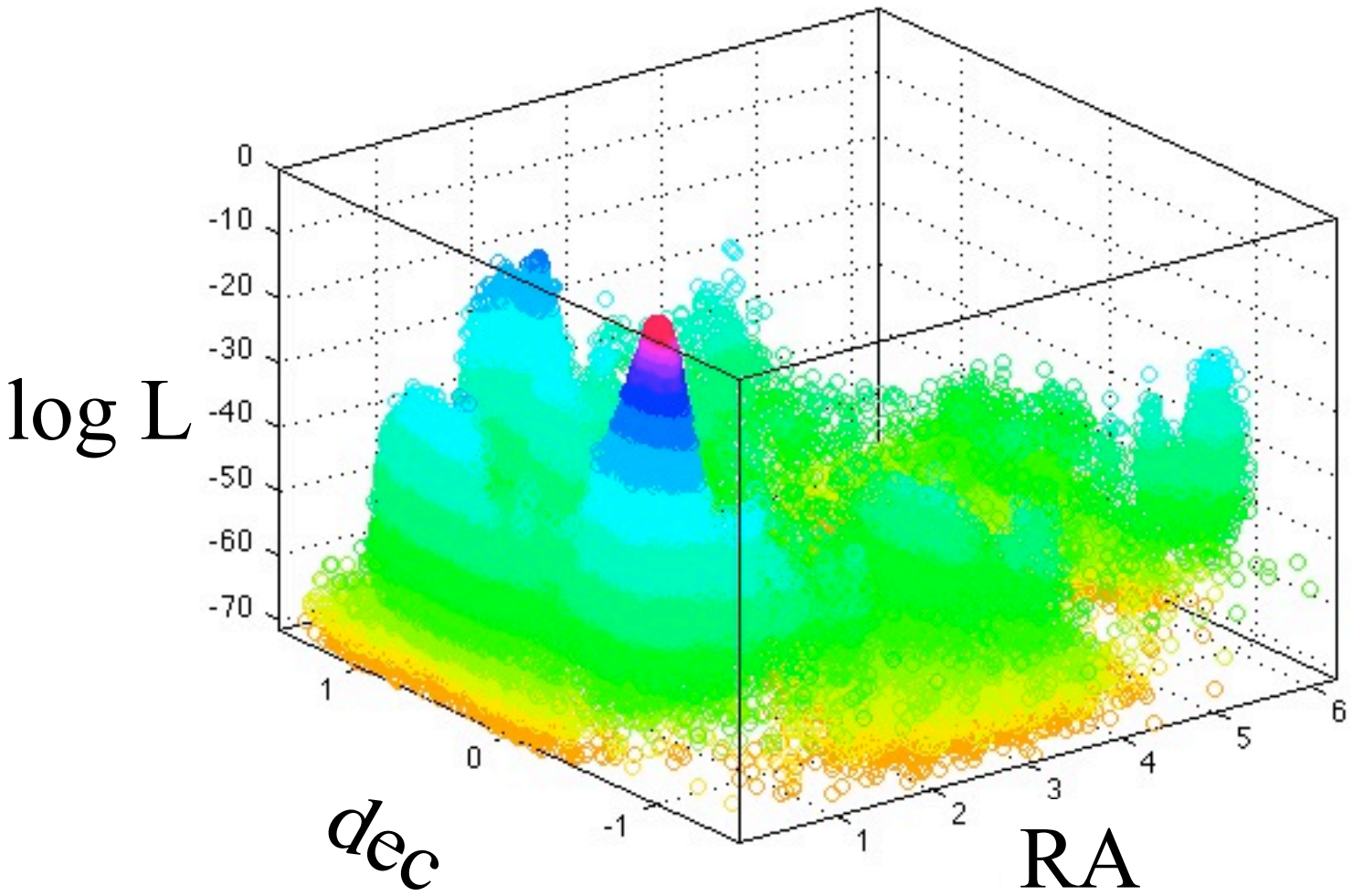


# Likelihood Surfaces for HHLV




Veitch 2011

# Likelihood Surfaces for HILV

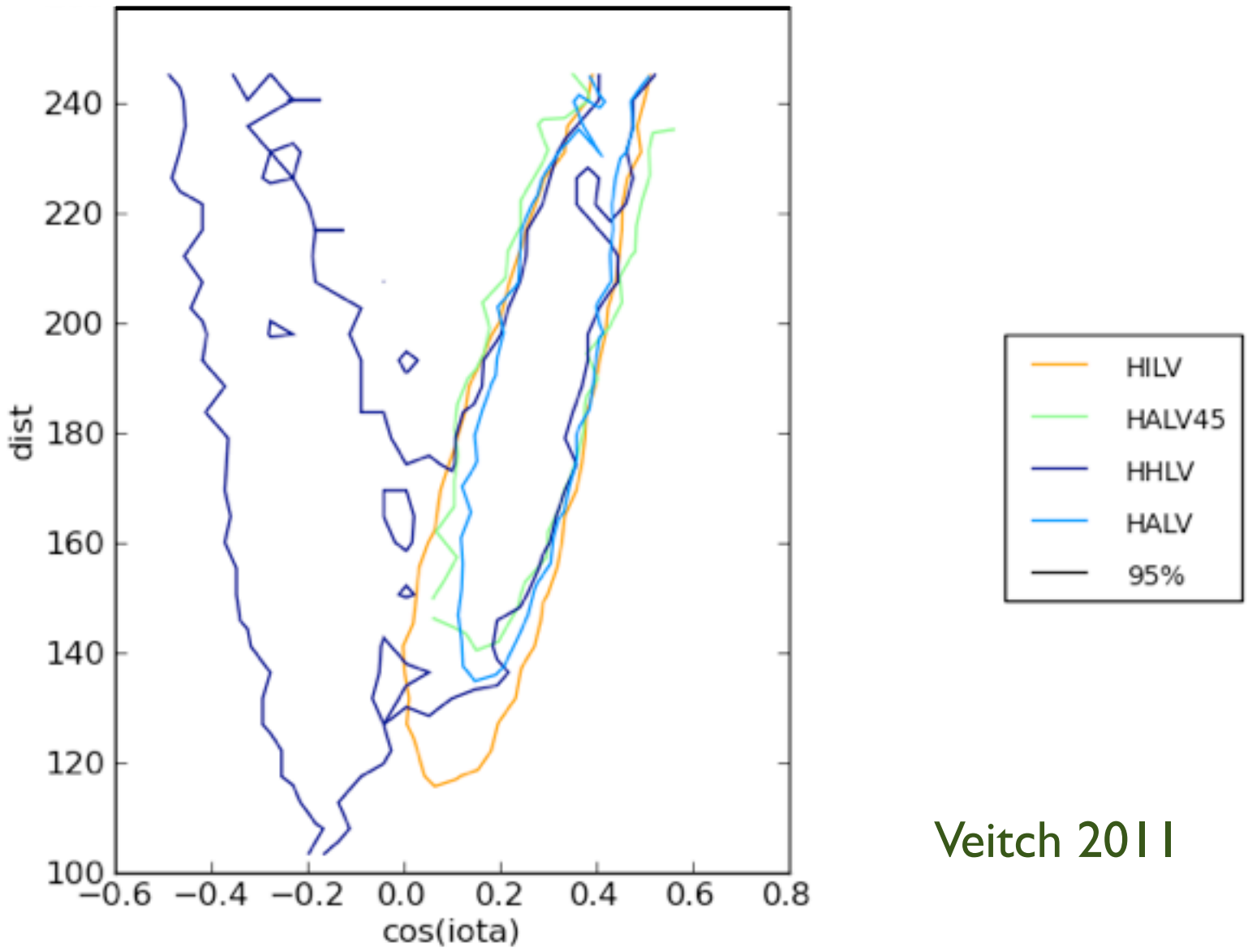



Veitch 2011

# Resolving $D_L$- $\iota$ degeneracy

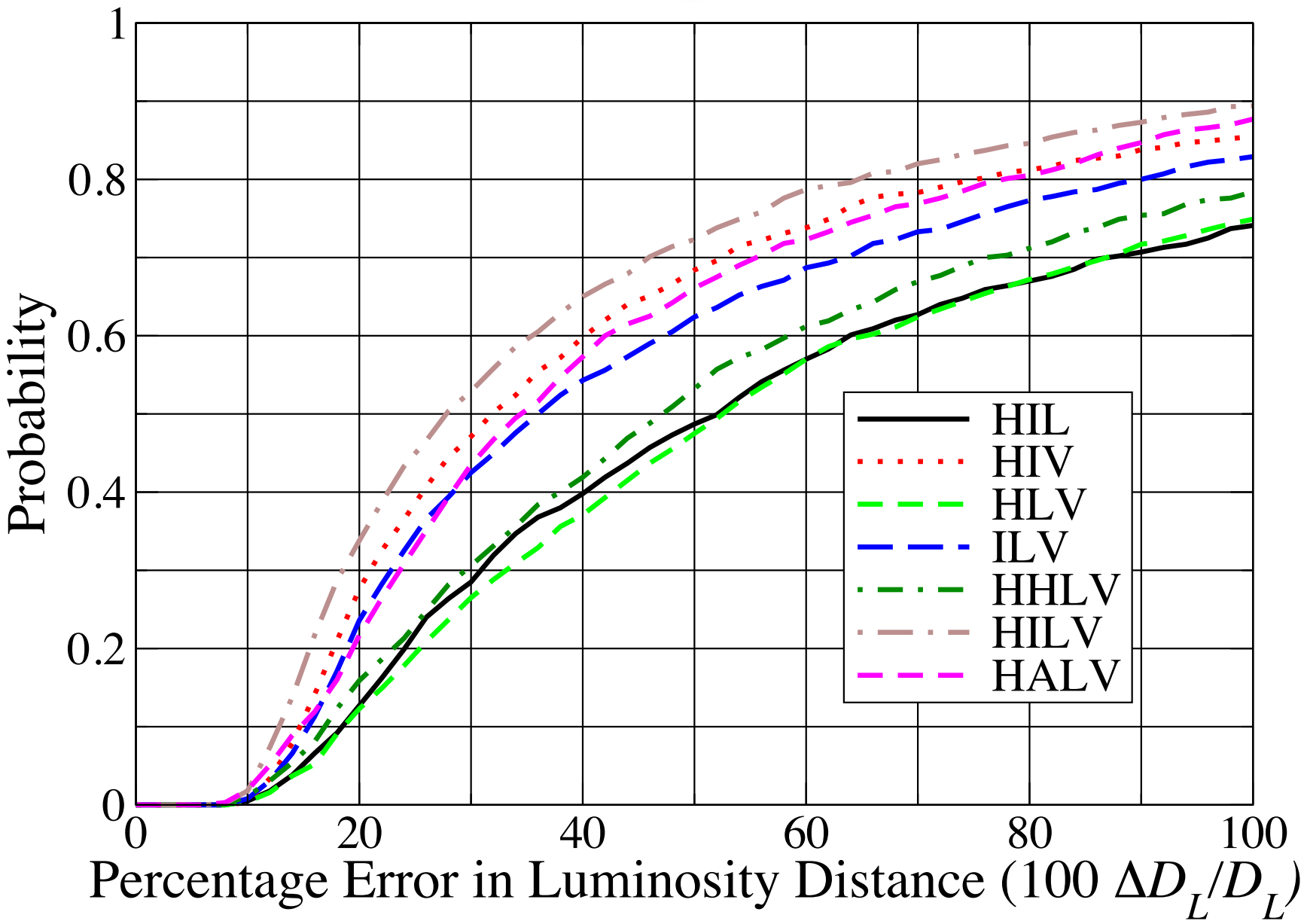
- With a 3-site network luminosity distance and inclination angle are highly degenerate, especially for face-on systems
  - These are precisely the kind of systems that will have GRB counterparts
  - Measuring the inclination angle is critical for confirming that GRB emission is beamed and to constrain the opening angle to say within about 40 degrees
- With a 4-site network the degeneracy is broken
  - Additionally, luminosity distance gets measured to a factor of 2 better
  - Even 3-site networks of HIV and, to a lesser extent but still significant, ILV have better distance measurement capability than HHLV

# Breaking Distance-Inclination Degeneracy




Veitch 2011

# Luminosity Distance



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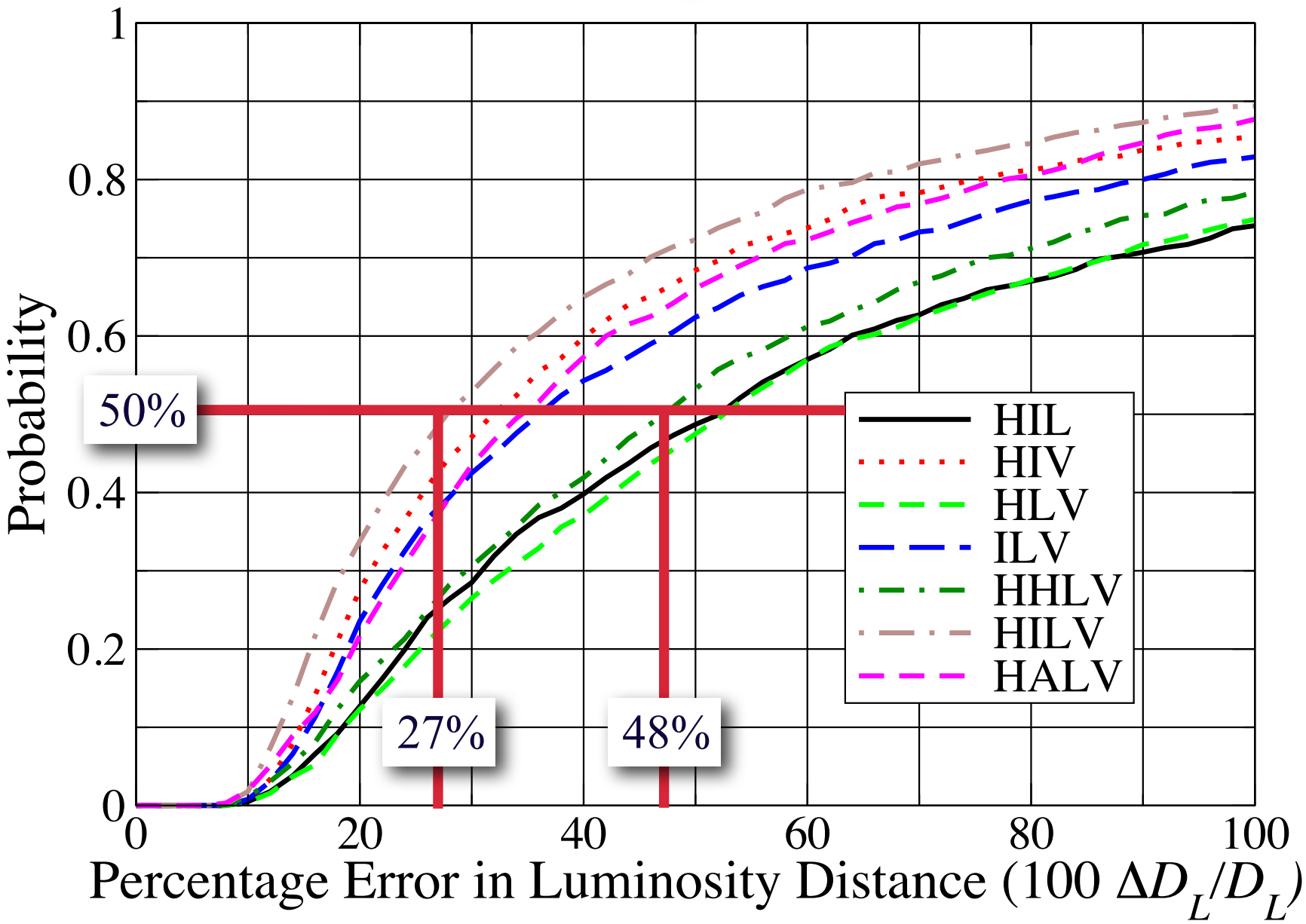
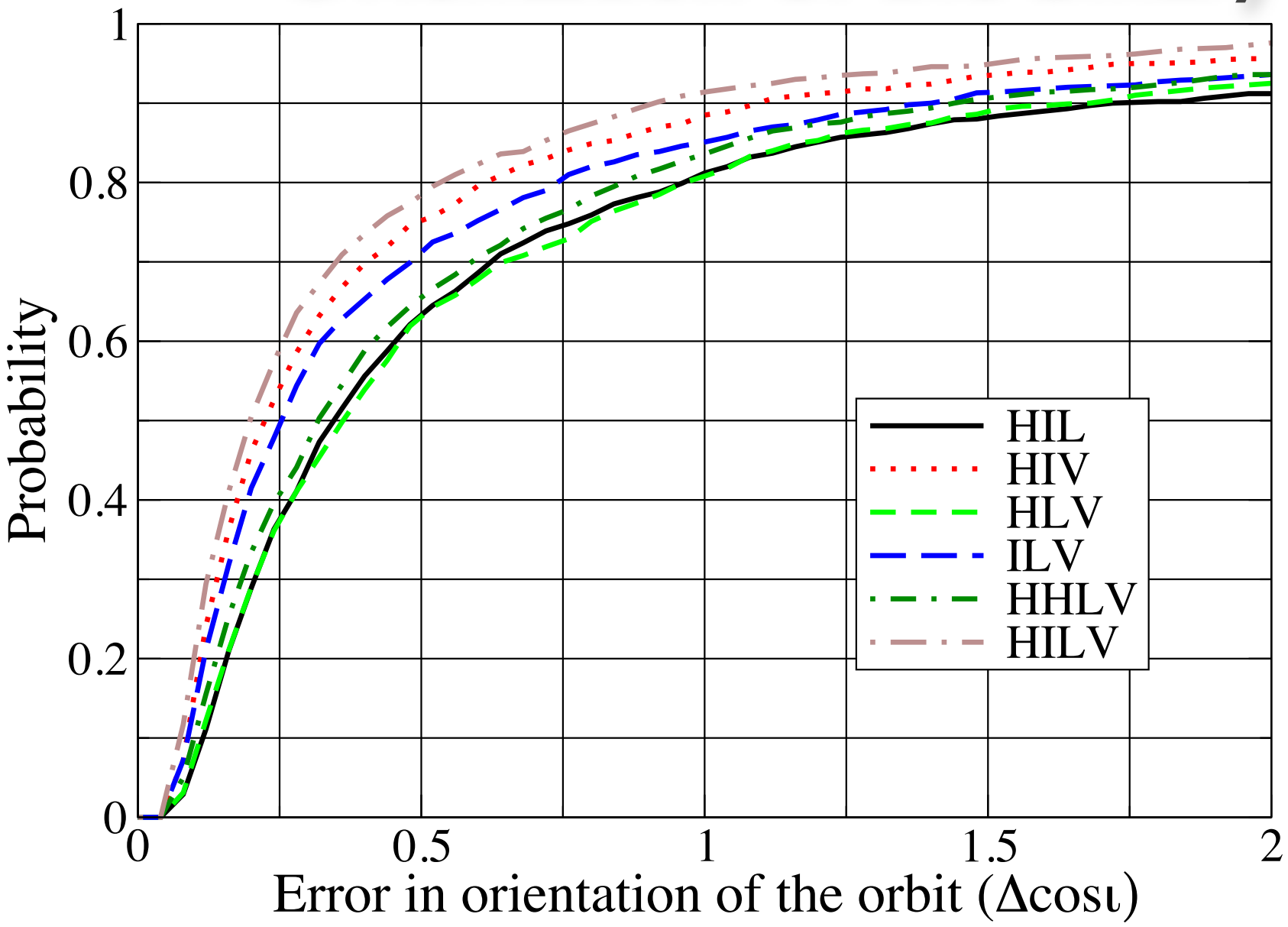


# Orientation of the Binary



# 3G

- A single 3G will not be adequate for gravitational astronomy
- How good is a net work of just 2 3-G sites?
- A combination of 3G and 2G might help but this needs to be explored further

# Fundamental Physics

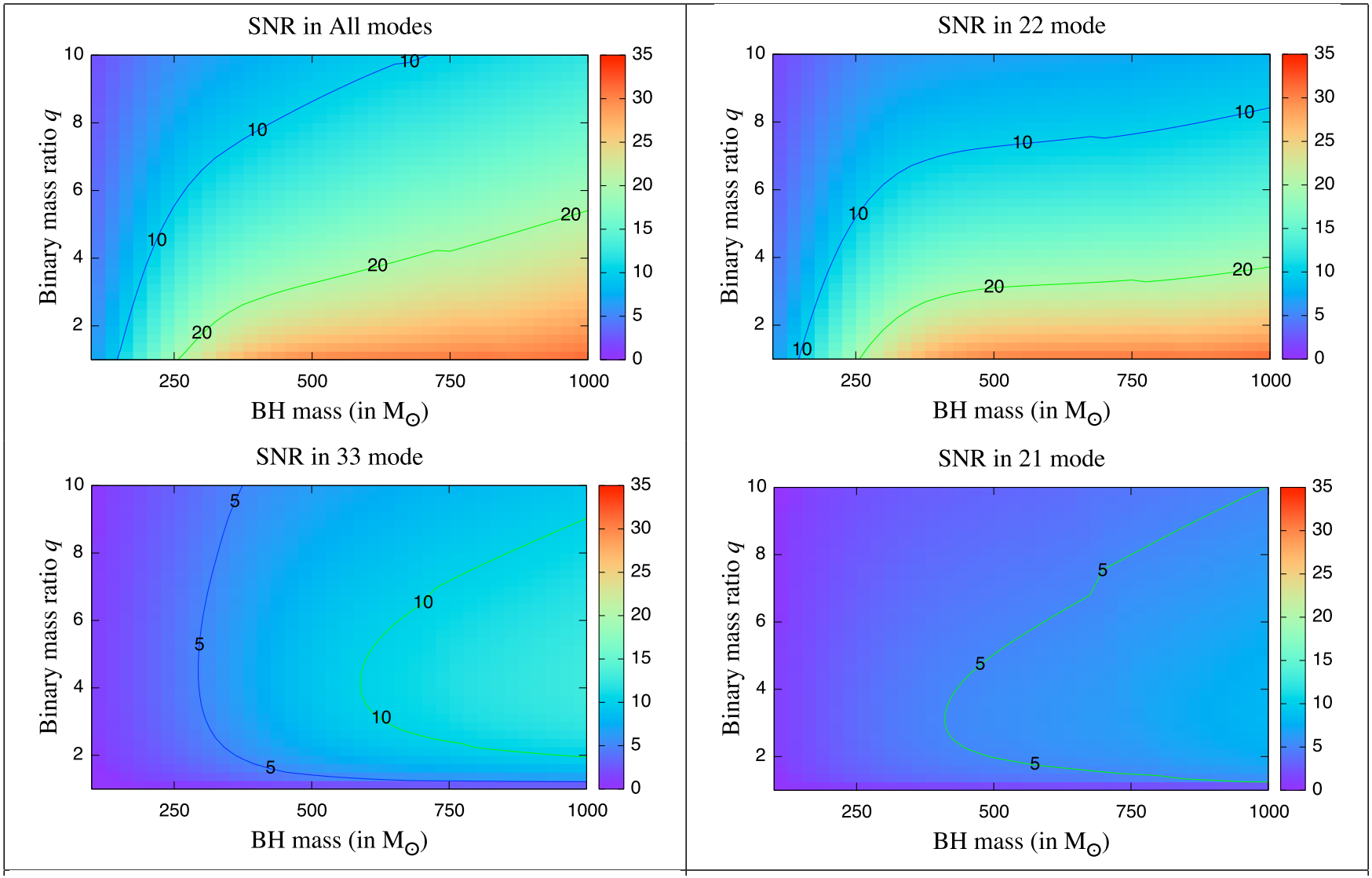
- Properties of gravitational waves
  - Testing GR beyond the quadrupole formula
    - Binary pulsars consistent with quadrupole formula; they don't measure properties of GW
  - How many polarizations are there?
    - In Einstein's theory only two polarizations; a scalar-tensor theory could have six
  - Do gravitational waves travel at the speed of light?
    - There are strong motivations from string theory to consider massive gravitons
    - Binary pulsars constrain the speed to few parts in a thousand
    - GW observations can constrain to 1 part in $10^{18}$
- EoS of dark energy
  - Black hole binaries are standard candles/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?
- An independent constraint/measurement of neutrino mass
  - Delay in the arrival times of neutrinos and gravitational waves

# Testing Black Hole No-Hair Theorem

- Deformed black holes are unstable; they emit energy in their deformation as gravitational waves
  - Superposition of damped waves with many different frequencies and decay times
  - In Einstein's theory, frequencies and decay times all depend only on the mass $M$ and spin $j$ of the black hole
- Measuring two or modes would constrain Einstein's theory or provide a smoking gun evidence of black holes
  - 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
- The amplitude of the modes cary additional information about what caused the deformity

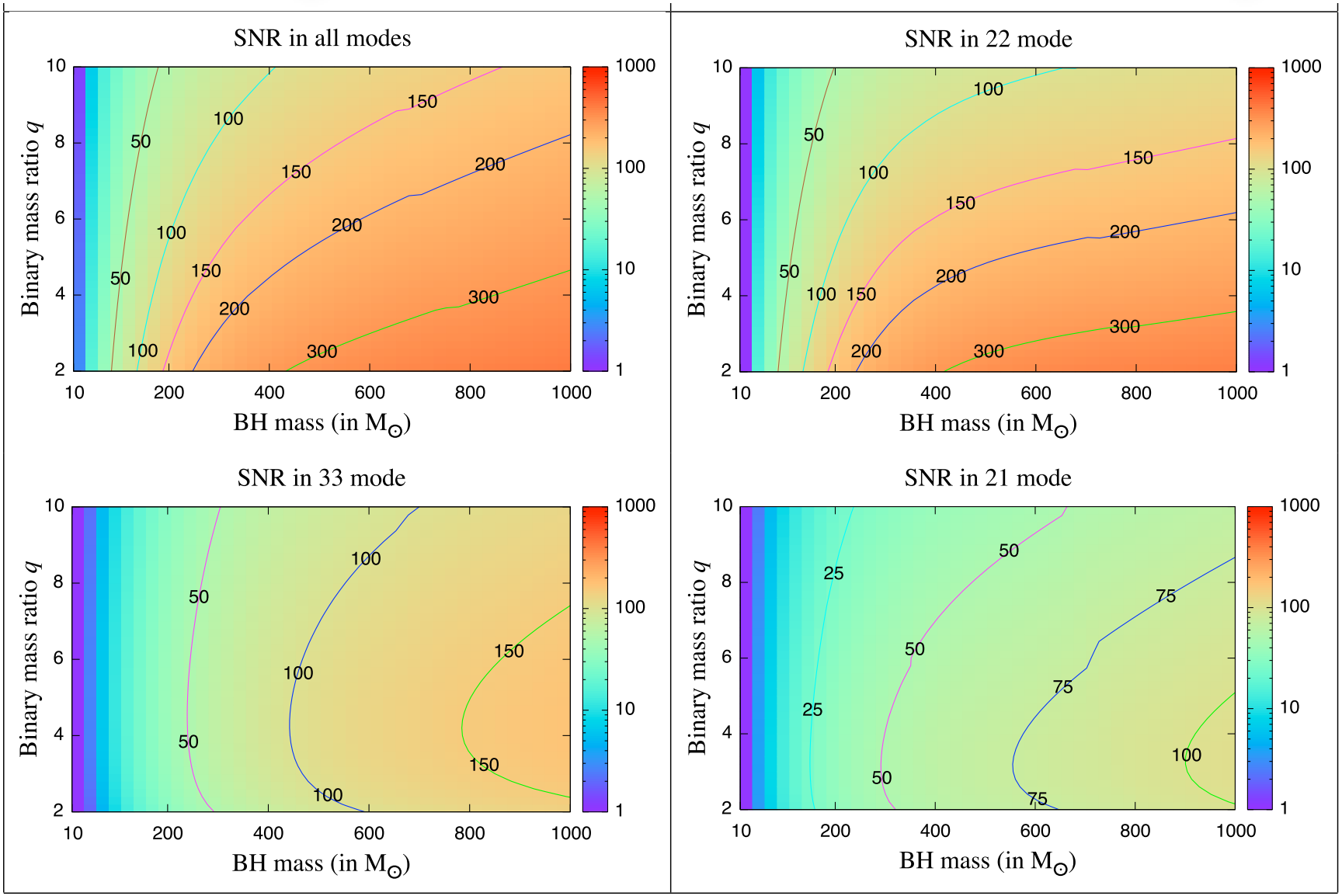
Dreyer et al (2004), Berti, Cardoso, Will (2006), Berti Cardoso, Cardoso, Cavaglia (2007)

# Visibility of QNMs in aLIGO at 3 Gpc



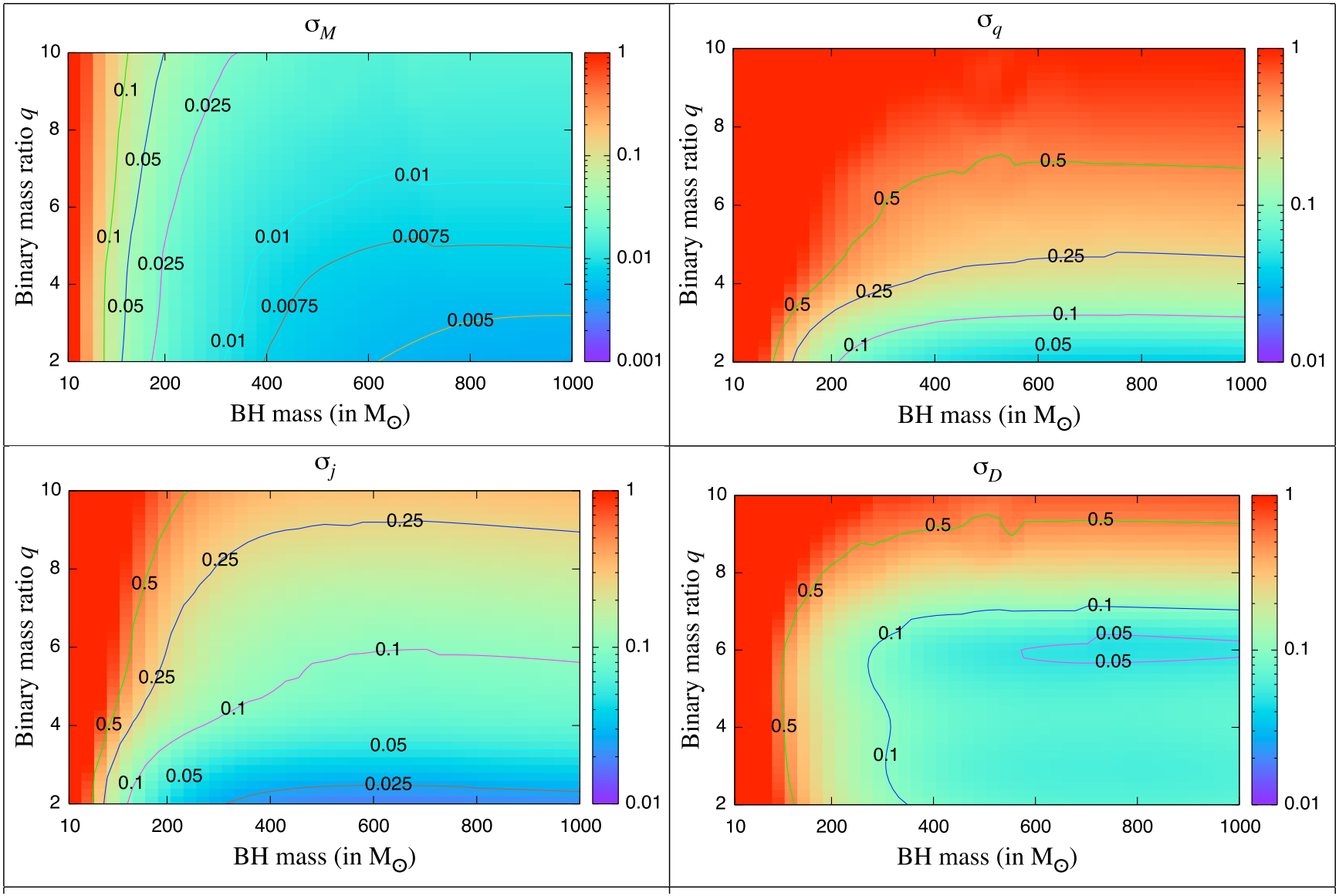

Kamaretsos, Hannam, Husa, BSS (2011)

# Visibility of QNMs in ET at 3 Gpc




Kamaretsos, Hannam, Husa, BSS (2011)

# Measuring Quasi-Normal Modes




Kamaretsos, Hannam, Husa, BSS (2011)

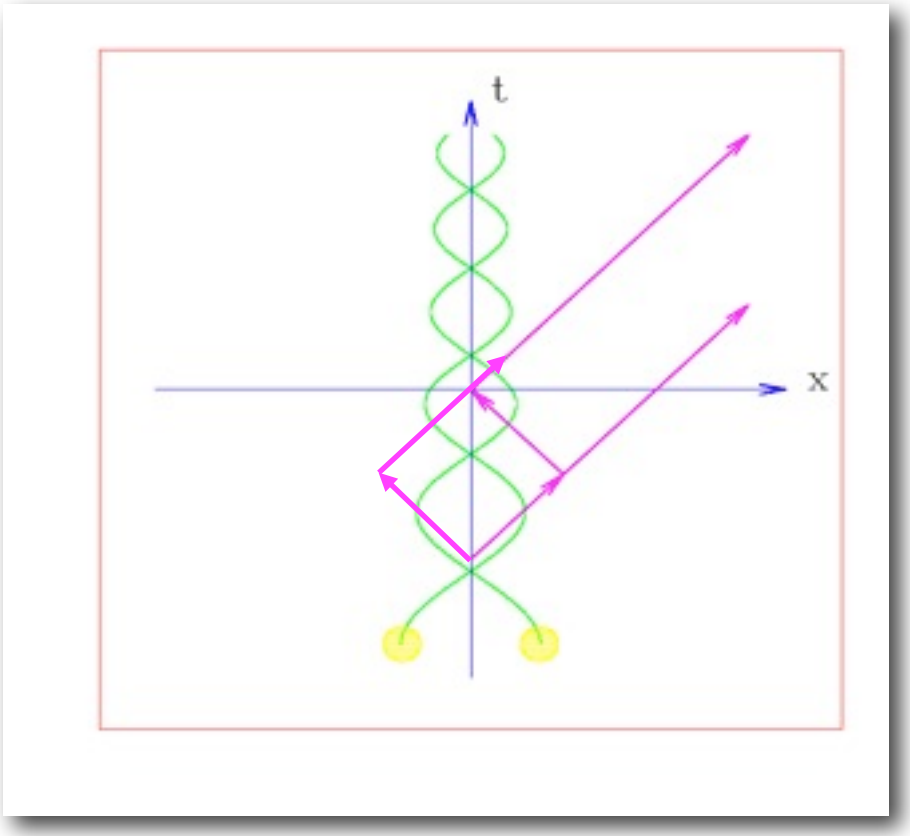
# BBH Signals as Testbeds for GR

- Gravity gets ultra-strong during a BBH merger compared to any observations in the solar system or in binary pulsars
  - In the solar system: $\phi/c^2 \sim 10^{-6}$
  - In a radio binary pulsar it is still very small: $\phi/c^2 \sim 10^{-4}$
  - Near a black hole $\phi/c^2 \sim 1$
  - Merging binary black holes are the best systems for strong-field tests of GR
- Dissipative predictions of gravity are not even tested at the 1PN level
  - In binary black holes even $(v/c)^7$ PN terms will not be adequate for high-SNR (~100) events

# Testing GR by observing non-linear effects

- Binary inspiral waveform depends on many post-Newtonian coefficients
  - $\Psi_0, \Psi_2, \Psi_{3,\ldots}$
  - They correspond to different physical effects, e.g. GW tails
- In the case of non-spinning binaries $\Psi_0, \Psi_2, \Psi_{3,\ldots}$ depend on just the two masses $m_1$ and $m_2$
- By assuming they are all independent one can check to see if GR is the correct theory

Gravitational wave tails




Blanchet and Schaefer (1994)

# How can we test non-linear effects?

- If Einstein's theory is a correct description of gravity, then the phasing of the waveform is given by

$$\psi_i(\mathcal{M},\eta) = \mathcal{M}^{-5/3} f_i(\eta)\,(\pi \mathcal{M}\,\eta^{-3/5})^{(i-5)/3}$$

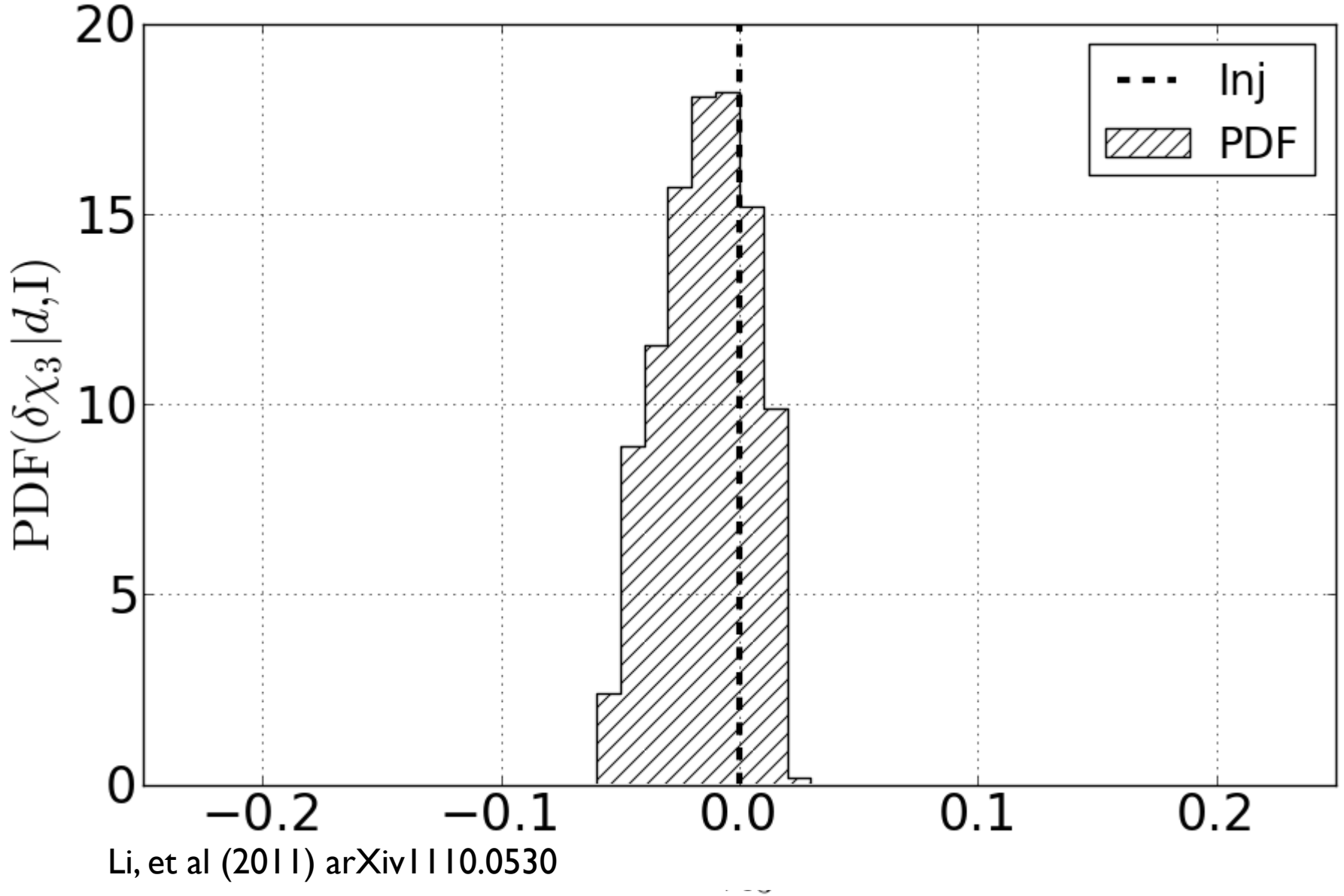
- Deviations from GR can be phenomenologically modelled as

$$\begin{aligned}
\psi_1^{\rm GR}(\mathcal{M},\eta) = 0 \;&\rightarrow\; \mathcal{M}^{-5/3}(\pi \mathcal{M}\,\eta^{-3/5})^{-4/3}\delta\chi_1,\\
\psi_2^{\rm GR}(\mathcal{M},\eta) \;&\rightarrow\; \mathcal{M}^{-5/3} f_2(\eta)\,(\pi \mathcal{M}\,\eta^{-3/5})^{-1}\,[1+\delta\chi_2]\,,\\
\psi_3^{\rm GR}(\mathcal{M},\eta) \;&\rightarrow\; \mathcal{M}^{-5/3} f_3(\eta)\,(\pi \mathcal{M}\,\eta^{-3/5})^{-2/3}\,[1+\delta\chi_3]\,.
\end{aligned}$$

Li, et al (2011) arXiv1110.0530, arXiv1111.5274

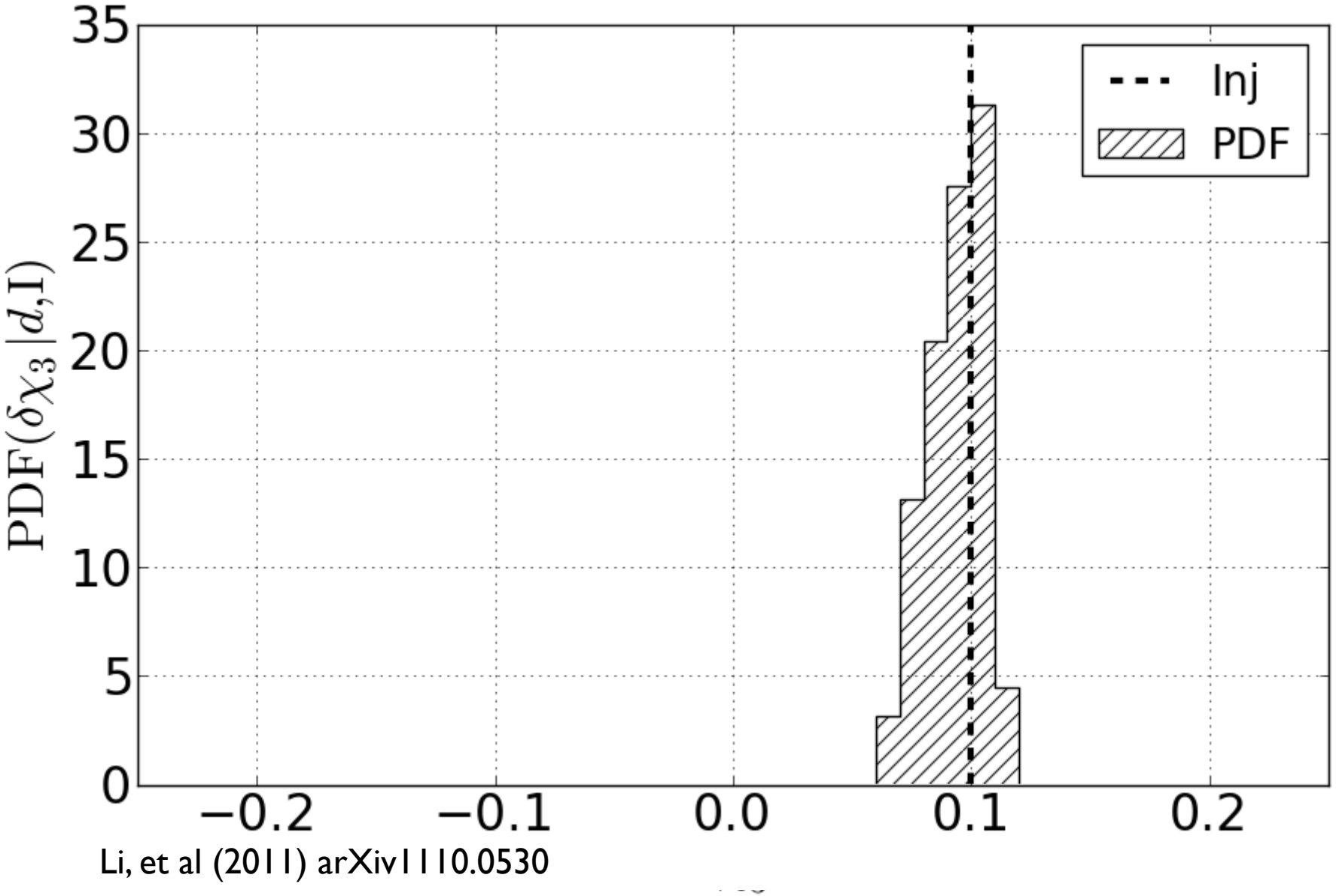
# Use Bayesian Inference to Test GR

## *1. Example: A GR injection*



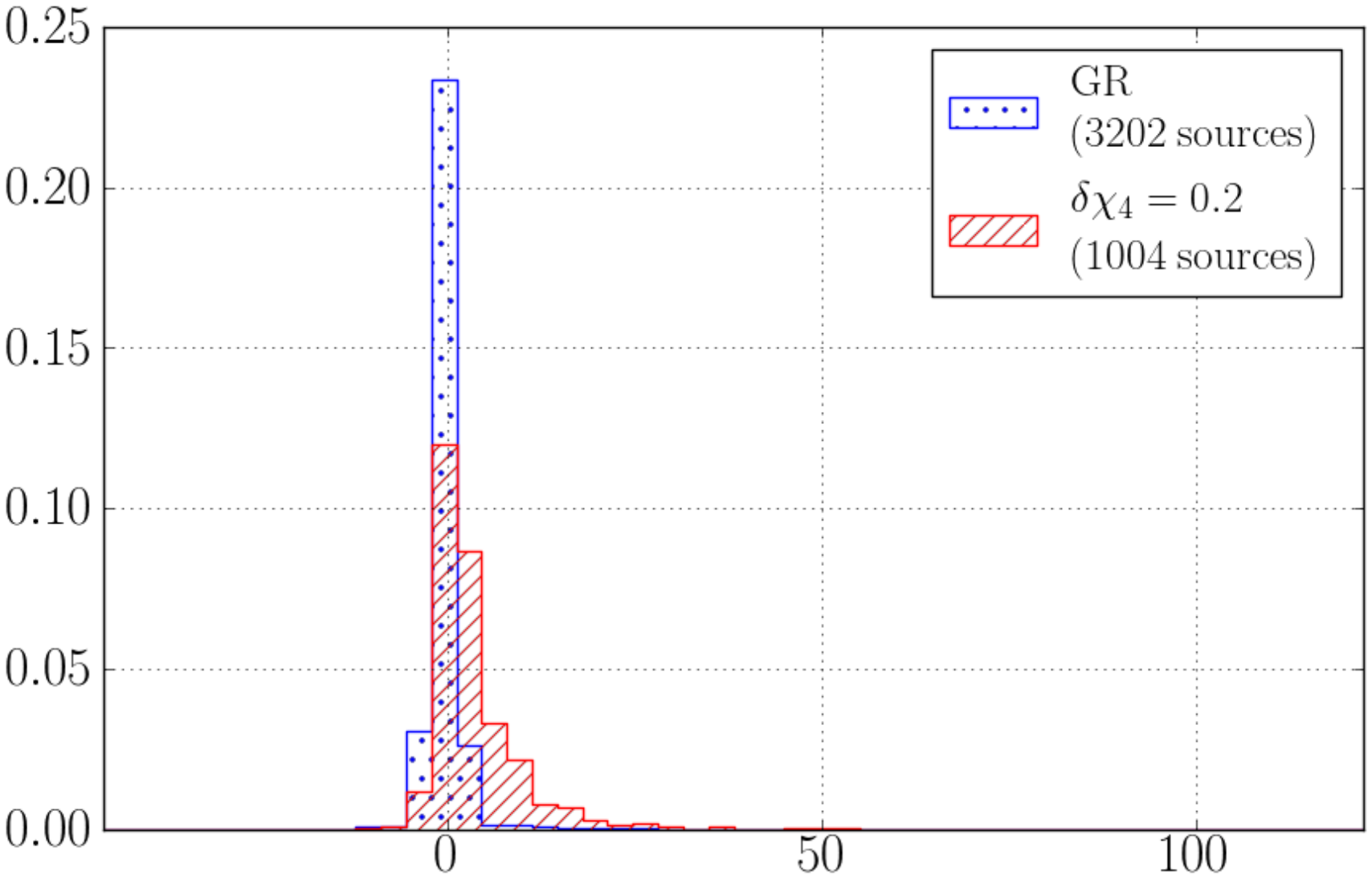

Li, et al (2011) arXiv1110.0530

## 2. *Example: A signal with* $\delta\chi_3 = 0.1$.



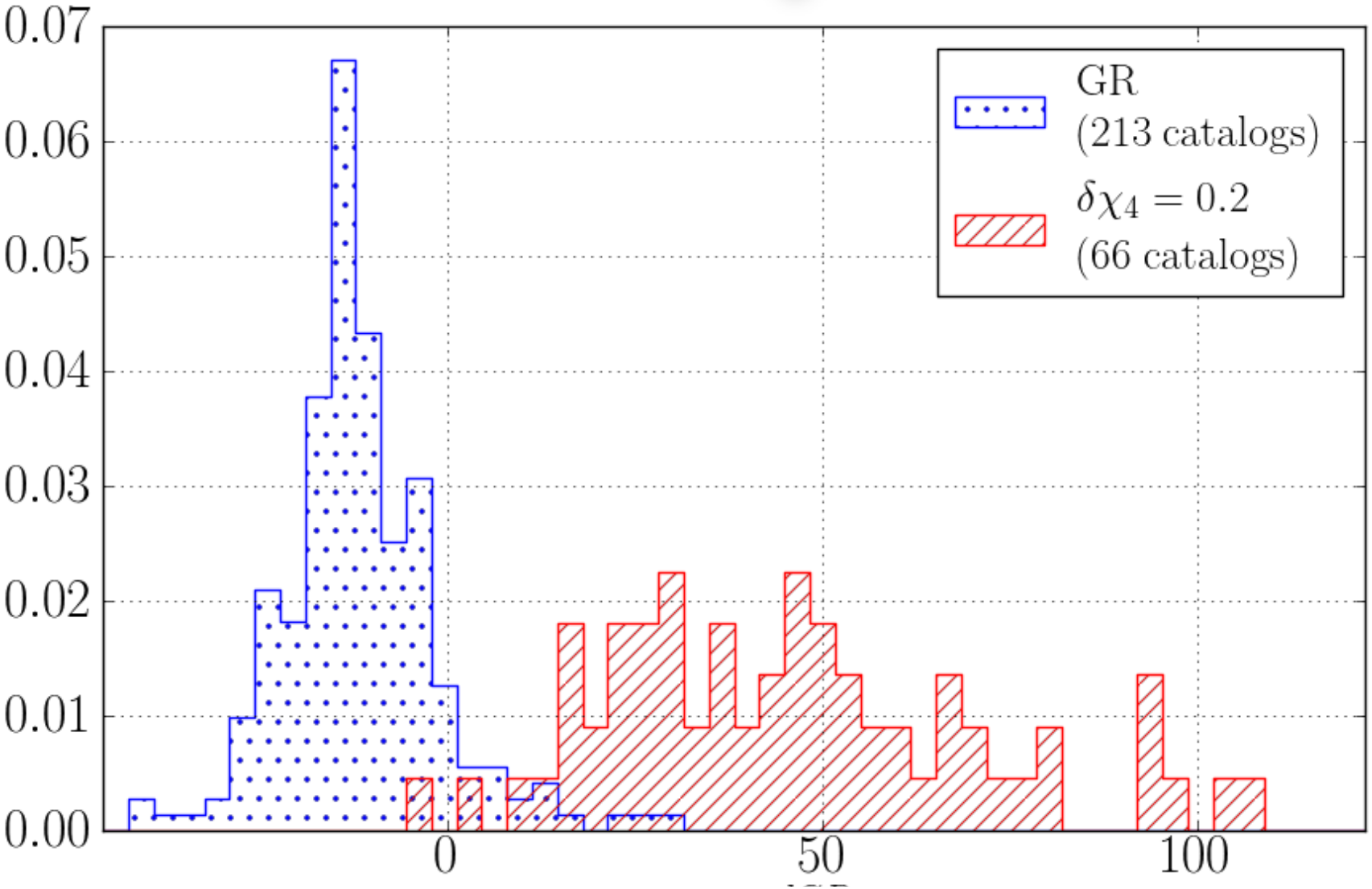

Li, et al (2011) arXiv1110.0530

# Combining Multiple Observations: A Single Catalogue




Li, et al (2011) arXiv1111.5274

# Combining Multiple Observations: 15 Catalogues




Li, et al (2011) arXiv1111.5274

# Cosmology

- Cosmography
  - Build the cosmic distance ladder, strengthen existing calibrations at high $z$
  - Measure the 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 black holes
  - Might explore hierarchical growth of central engines of black holes
- Dipole anisotropy in the Hubble parameter
  - The Hubble parameter will be "slightly" different in different directions due to the local flow of our galaxy
- 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

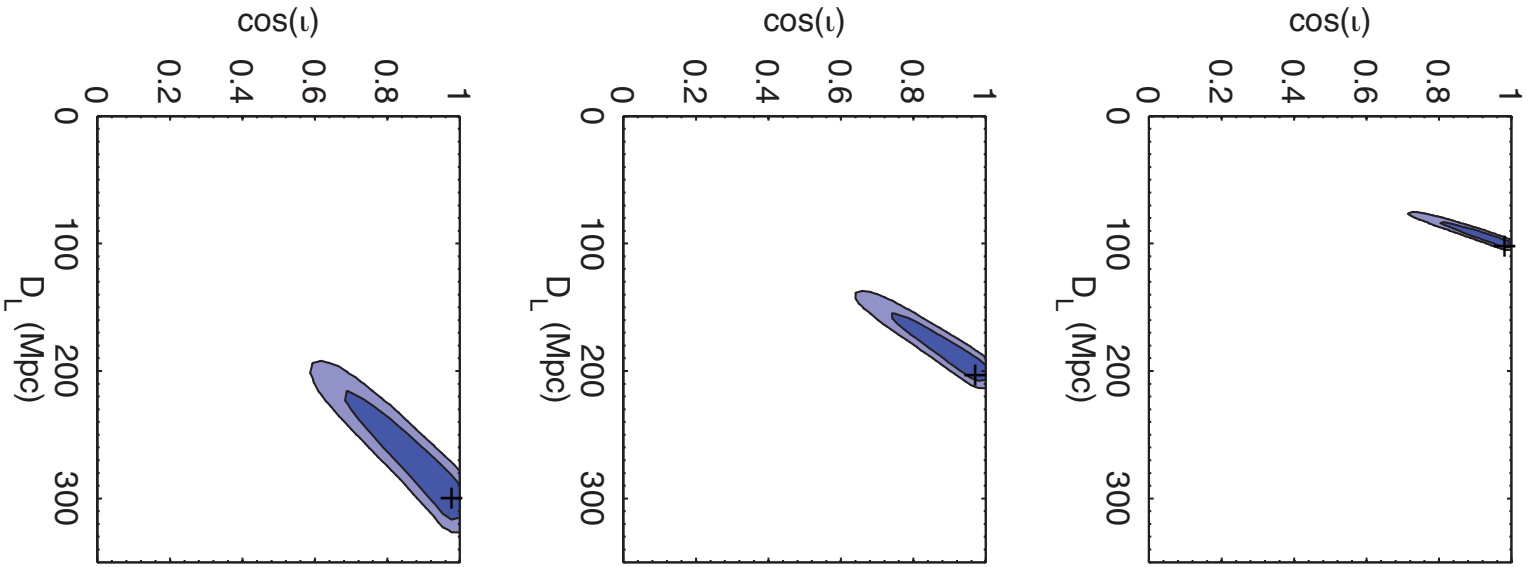
# Hubble Constant from Advanced Detectors

EXPLORING SHORT GAMMA-RAY BURSTS AS GRAVITATIONAL-WAVE STANDARD SIRENS

Samaya Nissanke[1,2], Scott A. Hughes[2], Daniel E. Holz[3], Neal Dalal[1], Jonathan L. Sievers[1]

*Draft version April 7, 2009*

is further augmented by a factor of 1.12. At this rate, we find that *one* year of observation should be enough to measure $H_0$ to an accuracy of $\sim 1\%$ if SHBs are dominated by beamed NS-BH binaries using the "full" network of LIGO, Virgo, AIGO, and LCGT—admittedly,



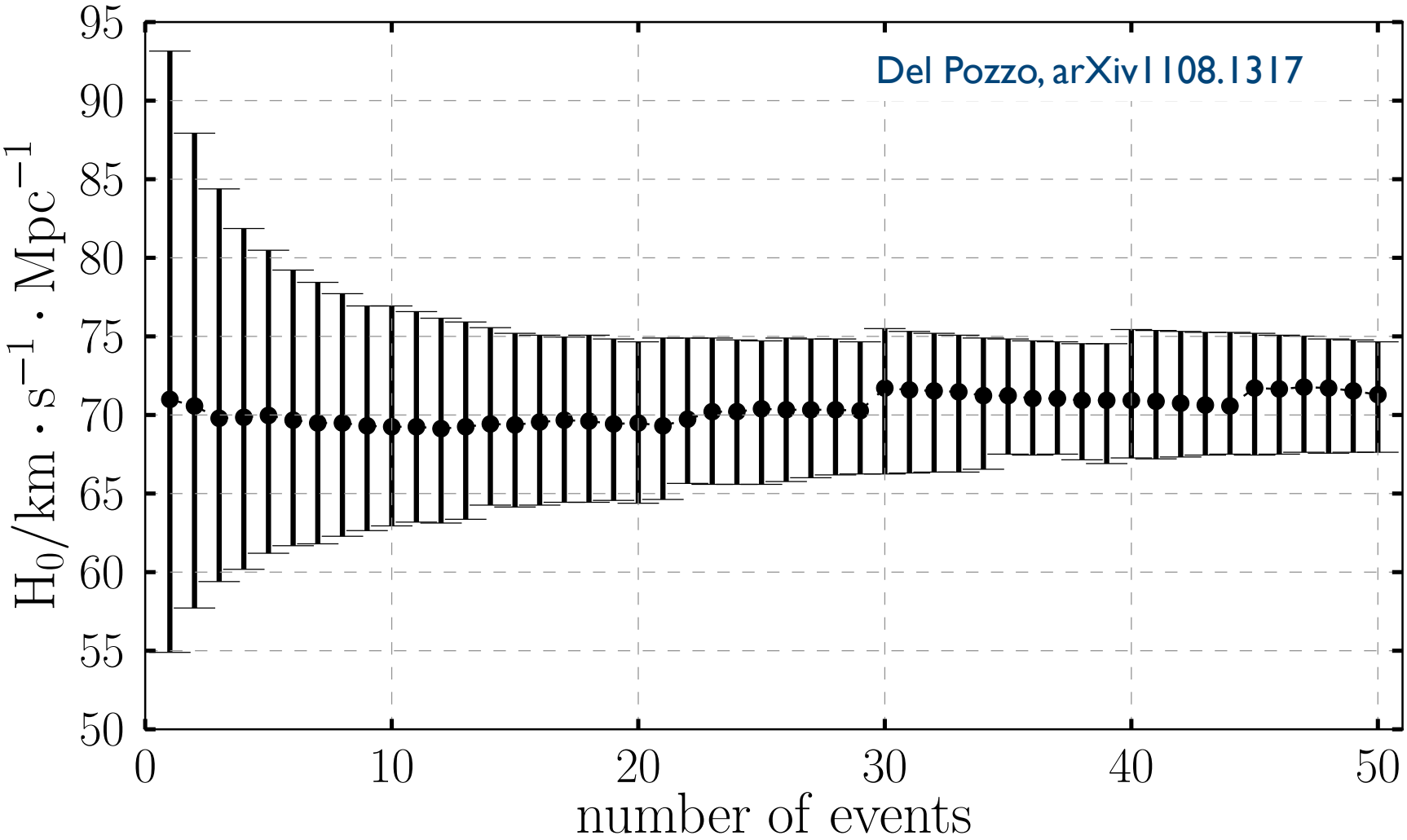
# Hubble Constant from Advanced Detectors without EM counterparts

- 25 events:
  - $H_0 = 69 \pm 3$ km s$^{-1}$ Mpc$^{-1}$ (~4% at 95% confidence)

Del Pozzo, arXiv1108.1317

- 50 events:
  - $H_0 = 69 \pm 2$ km s$^{-1}$ Mpc$^{-1}$ (~3% at 95% confidence)
- WMAP7+BAO+SnIa (Komatsu et al.,2011):
  - $H_0 = 70.2 \pm 1.4$ km s$^{-1}$ Mpc$^{-1}$ (~2% at 68% confidence)

# Error in $H_0$ with Catalogue Size



# ET: Measuring Dark Energy and Dark Matter

- ET will observe 100's of binary neutron stars and GRB associations each year
- GRBs could give the host location and red-shift, GW observation provides $D_L$

Class. Quantum Grav. **27** (2010) 215006 B S Sathyaprakash *et al*

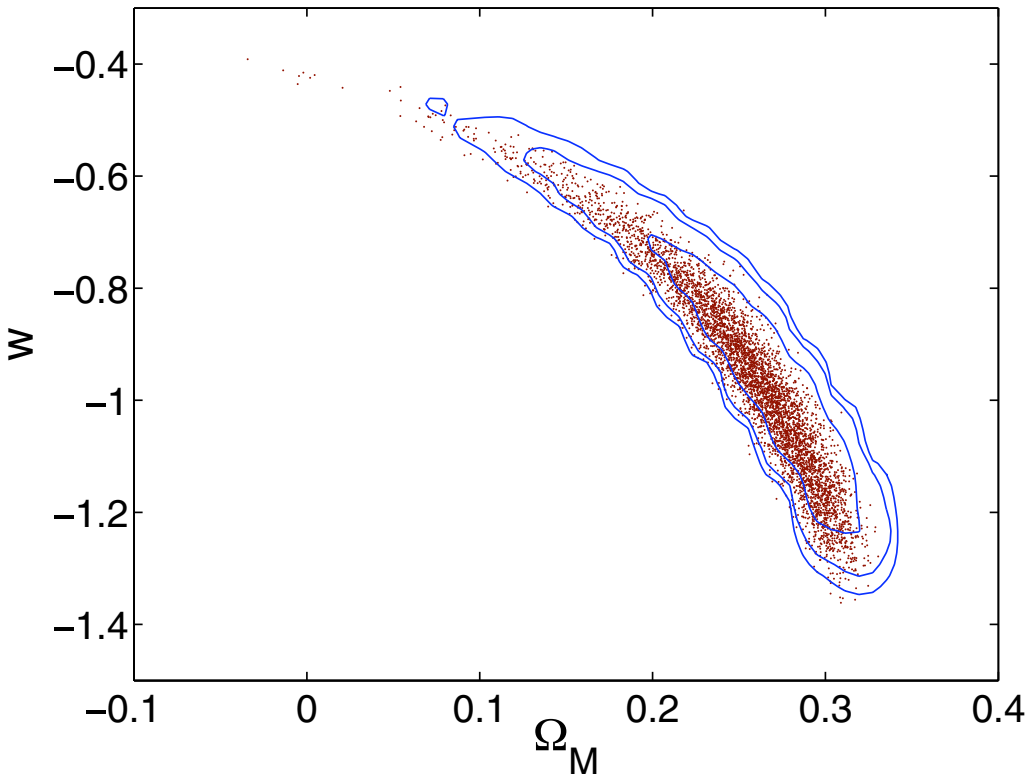
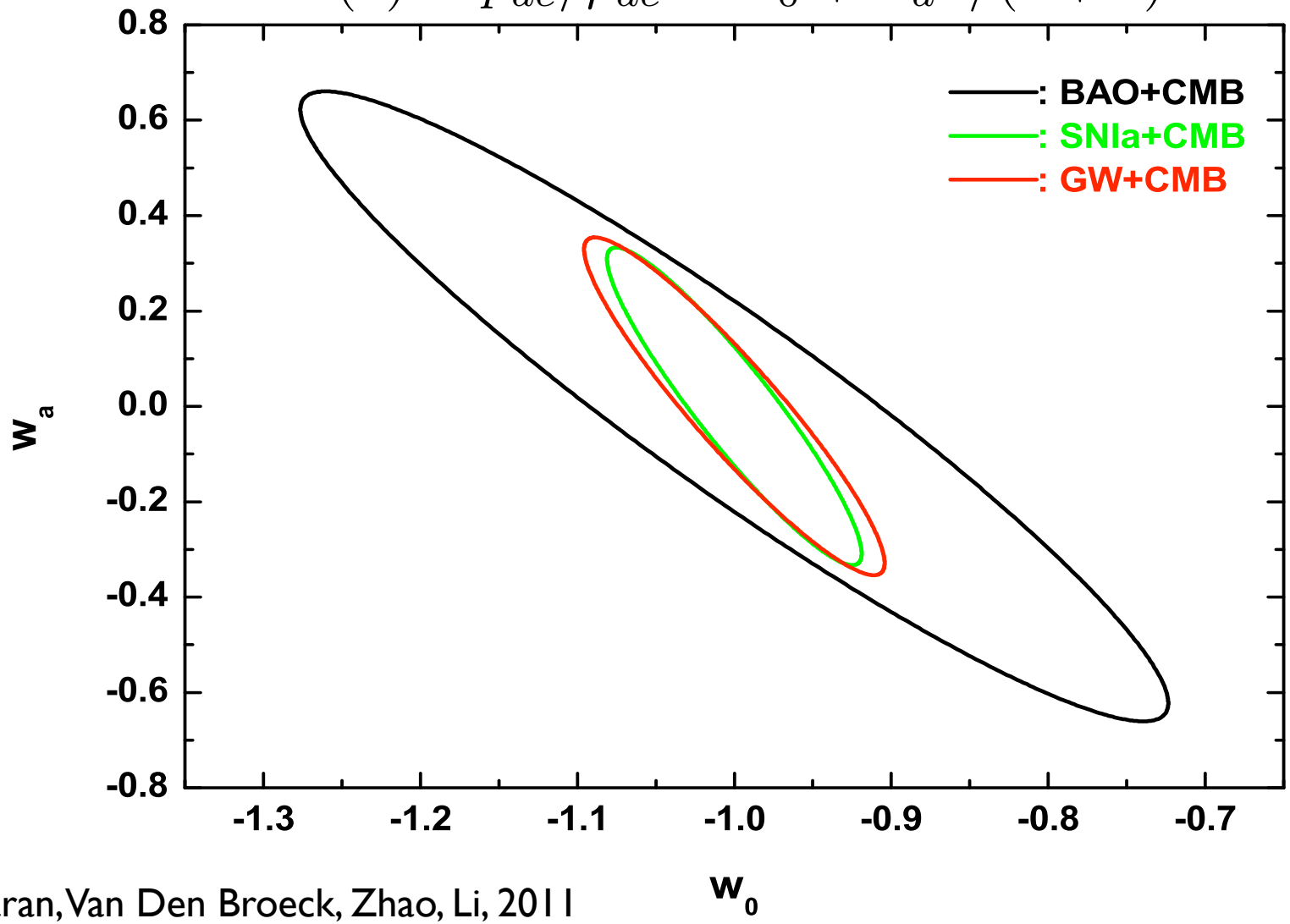



**Figure 3.** Scatter plot of the retrieved values for $(\Omega_\Lambda, w)$, with 1-$\sigma$, 2-$\sigma$ and 3-$\sigma$ contours, in the case where weak lensing is not corrected.

# Measuring $w$ and its variation with $z$

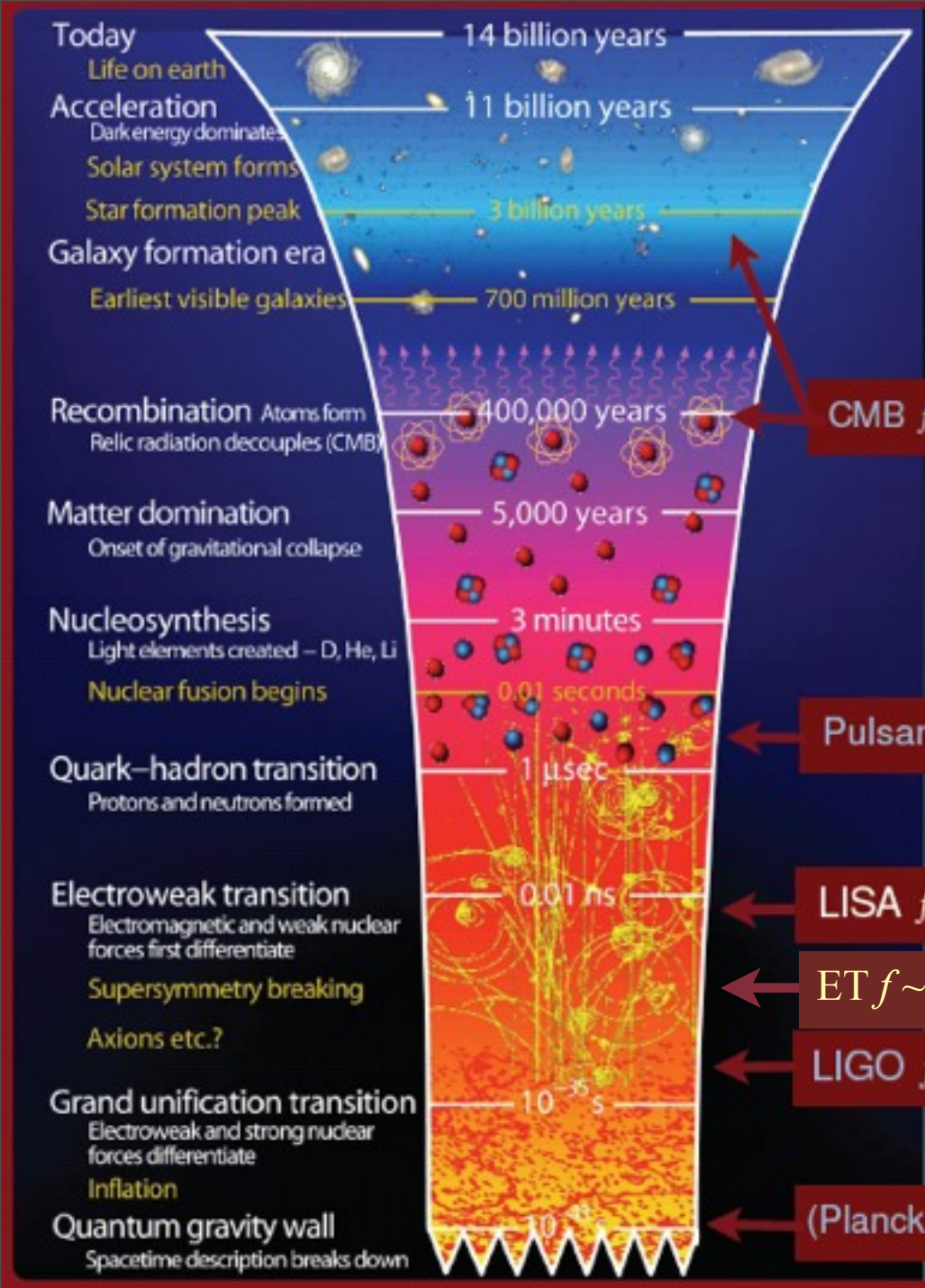
$$w(z) \equiv p_{de}/\rho_{de} = w_0 + w_a z/(1+z)$$




Baskaran, Van Den Broeck, Zhao, Li, 2011

Slide from Shellard

# A brief history of the Universe




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)

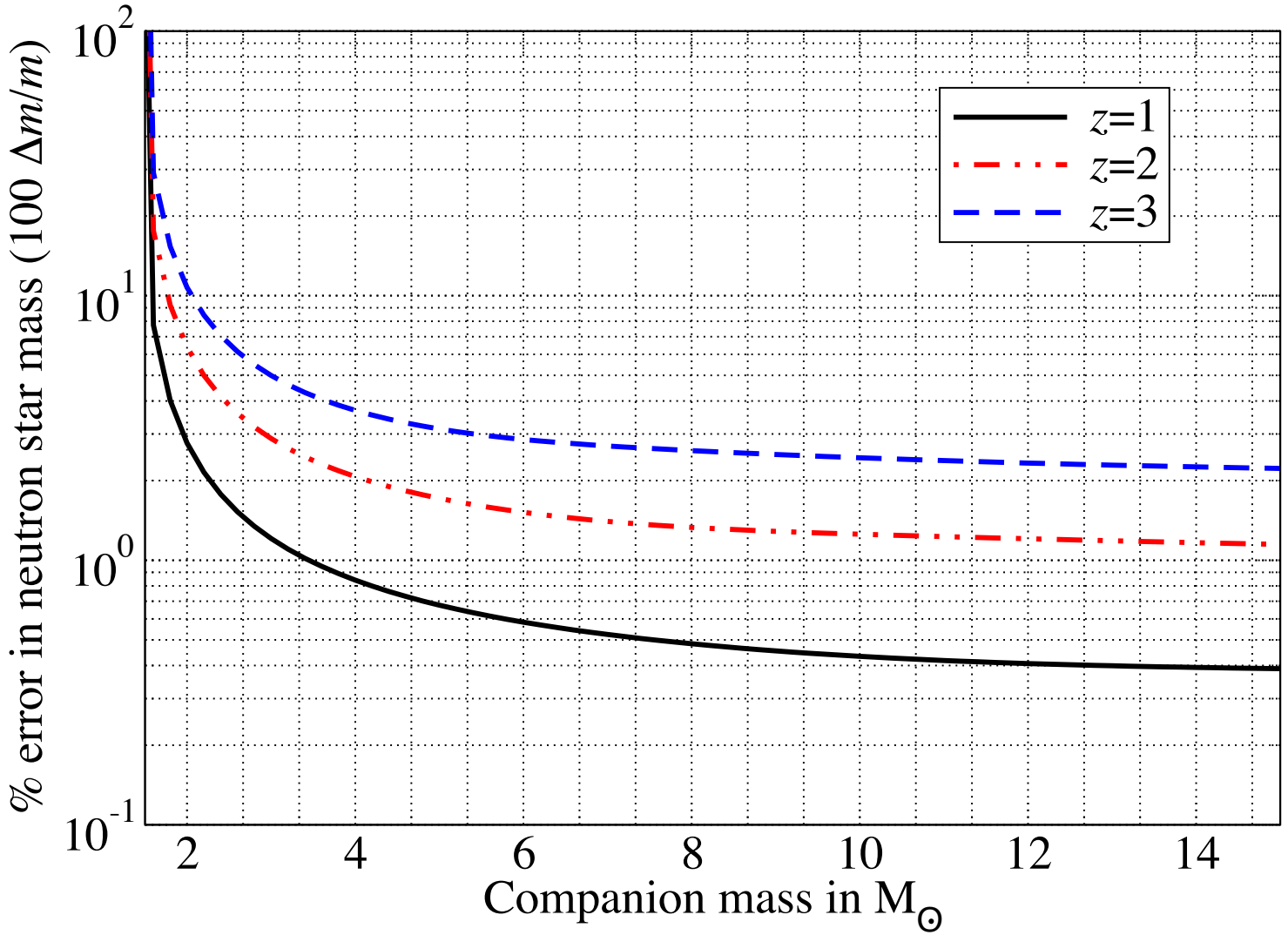
LIGO $f \sim 100$ Hz probes $t_e \sim 10^{-24}$s ($T \sim 10^8$GeV)

(Planck scale $f \sim 10^{11}$Hz has $t_e \sim 10^{-43}$s ($T \sim 10^{19}$GeV)

# Astrophysics

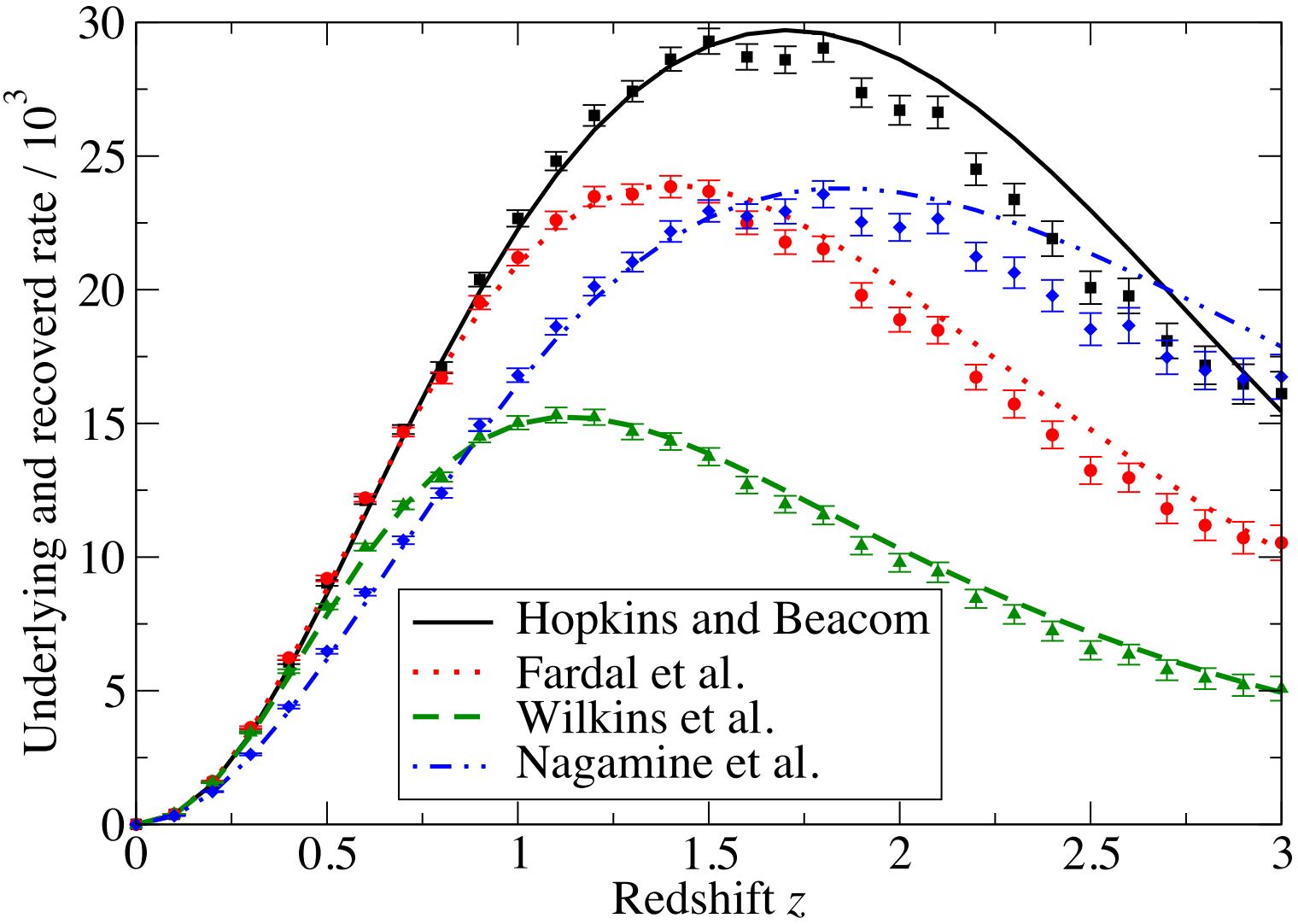
- Unveiling progenitors of short-hard GRBs
  - Understand the demographics and different classes of short-hard GRBs
- Understanding Supernovae
  - Astrophysics of gravitational collapse and accompanying supernova?
- Evolutionary paths of compact binaries
  - Evolution of compact binaries involves complex 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 as small as 1 part in a billion (10μm)
  - 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

# Measuring the Mass Function of Neutron Stars




Slide from Van Den Broeck

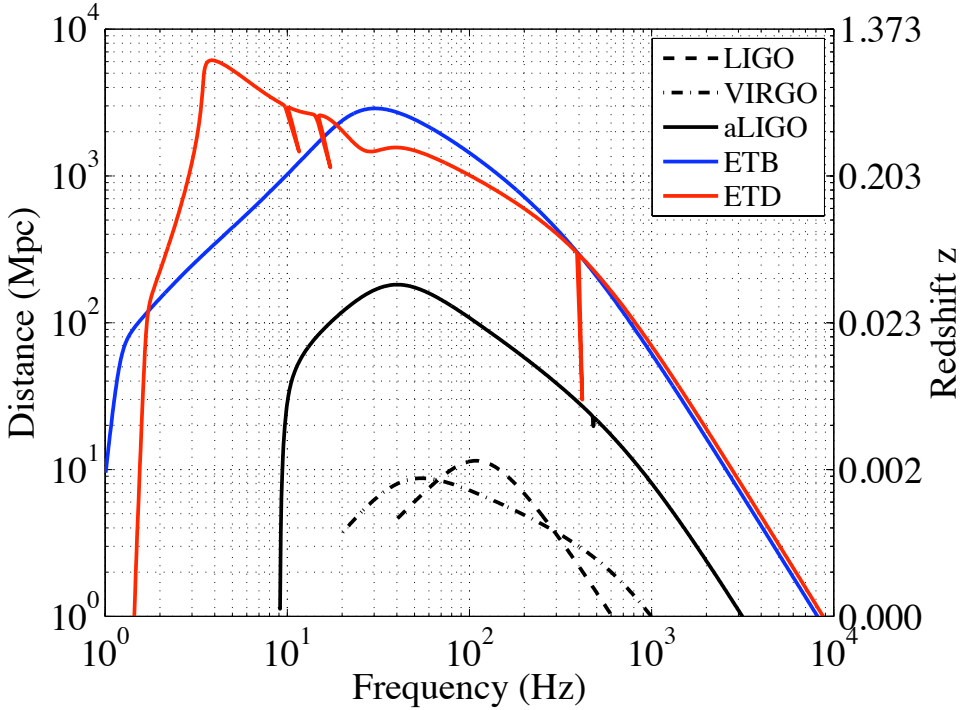
# Inferring the History of Star Formation Rate

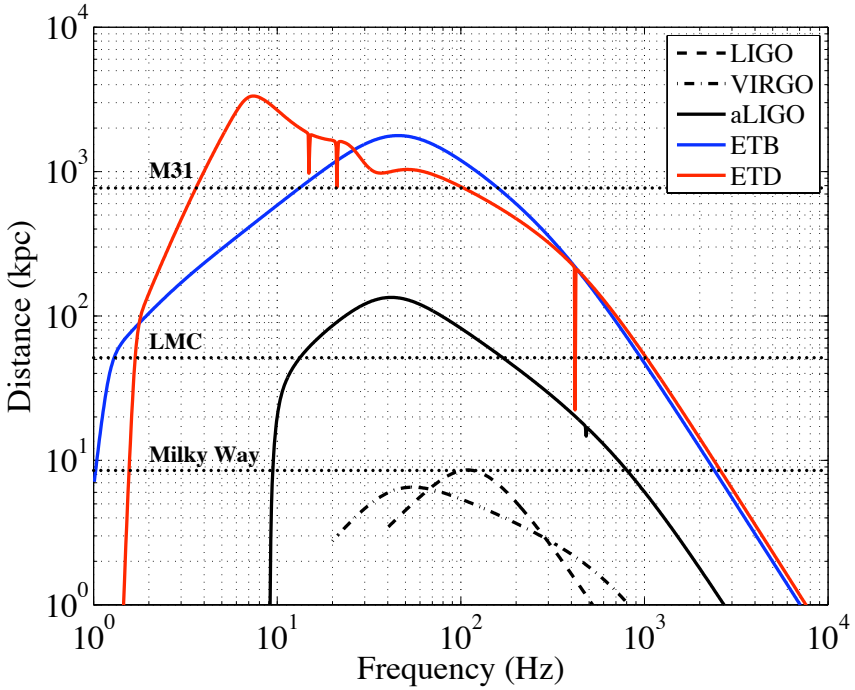



Slide from Van Den Broeck

# Unveiling the Origin of GRBs

- ET can detect model-independent radiation from collapsars if $E_{GW} > 5\% \, M_{\odot}$
- Soft Gamma Repeaters could be seen both in the Milky Way and the local neighbourhood provided if $E_{GW} > 10^{-8} \, M_{\odot}$

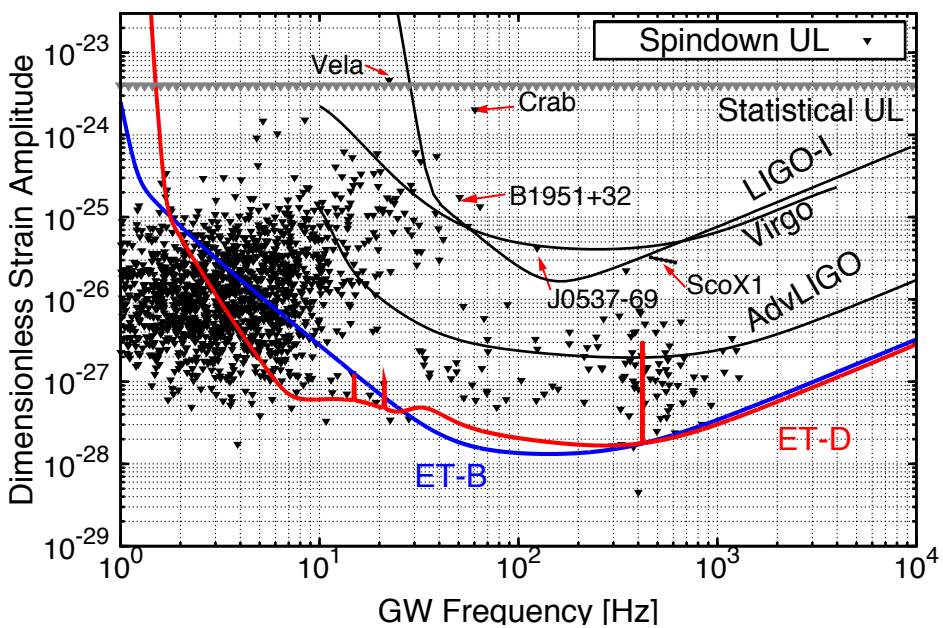


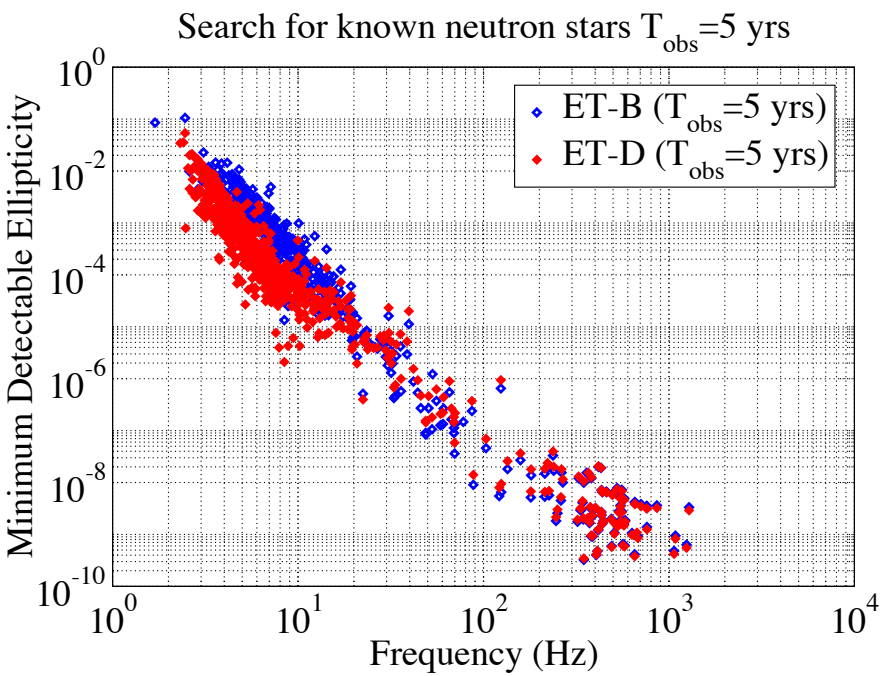




Slides from Clark and Sutton

# Mountains on Neutron Stars

- ET will check if neutron stars (10 km in radius) have mountains that are smaller than 10 micro meters
- This could constrain models about their crustal strengths

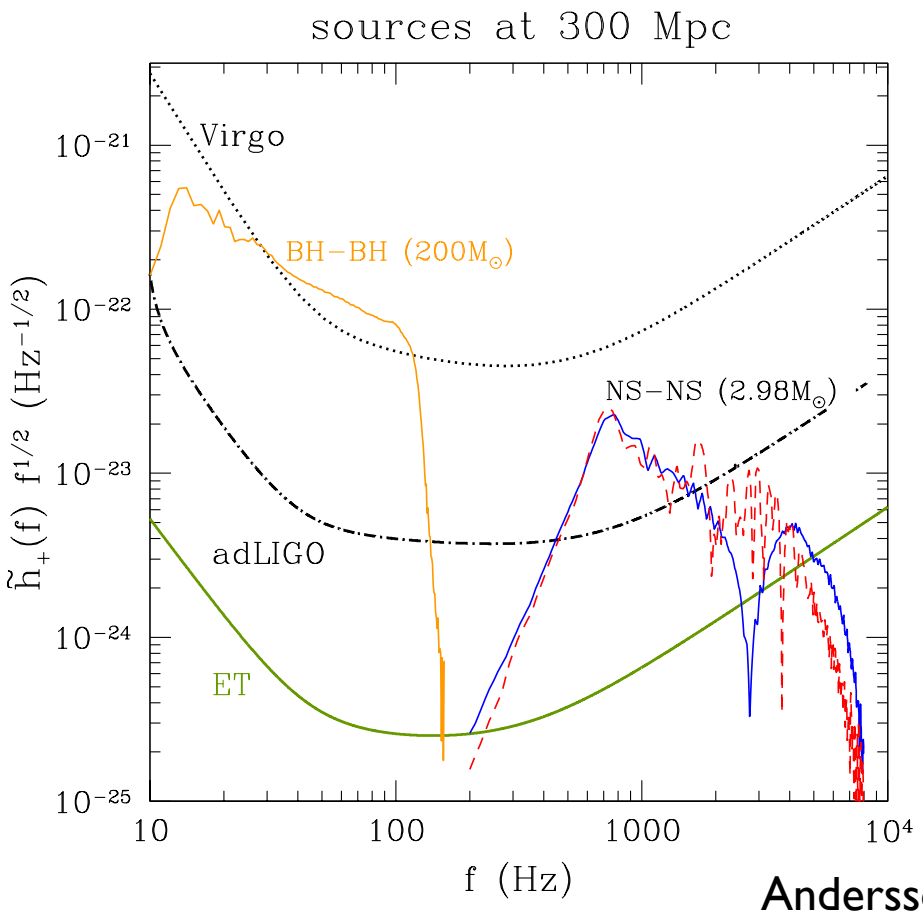


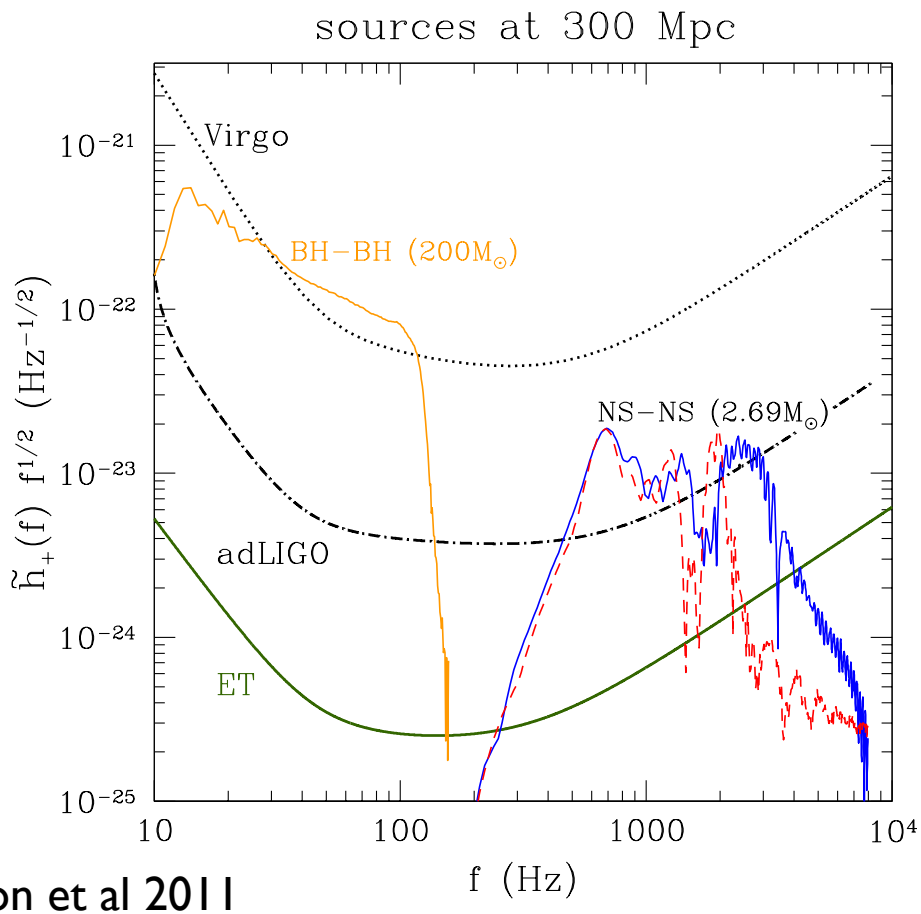




Slides from Krishnan, Palomba and Prix

# Neutron star mergers and equation of state of neutron stars

- Spectrum of gravitational radiation from black hole binaries is featureless (that's why they are standard candles)
- Radiation from binary neutron star mergers carries an imprint of the star's mass and equation of state



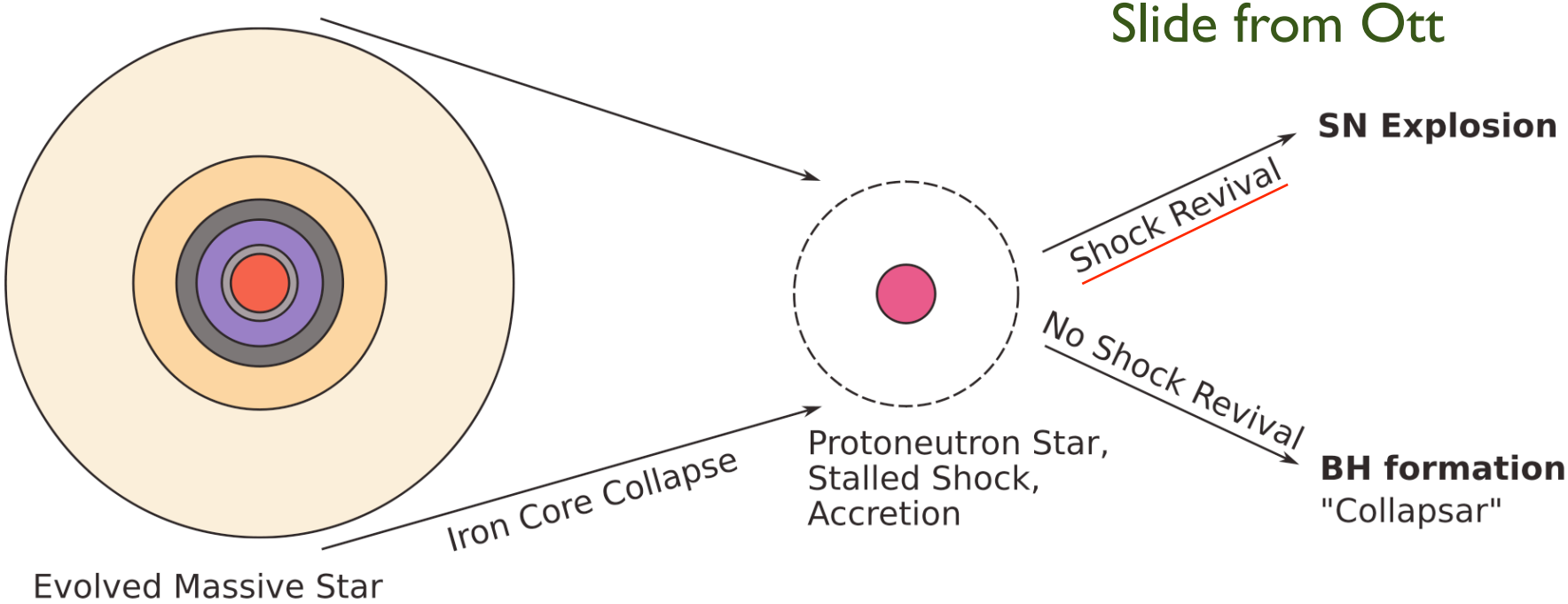

Andersson et al 2011

# 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?

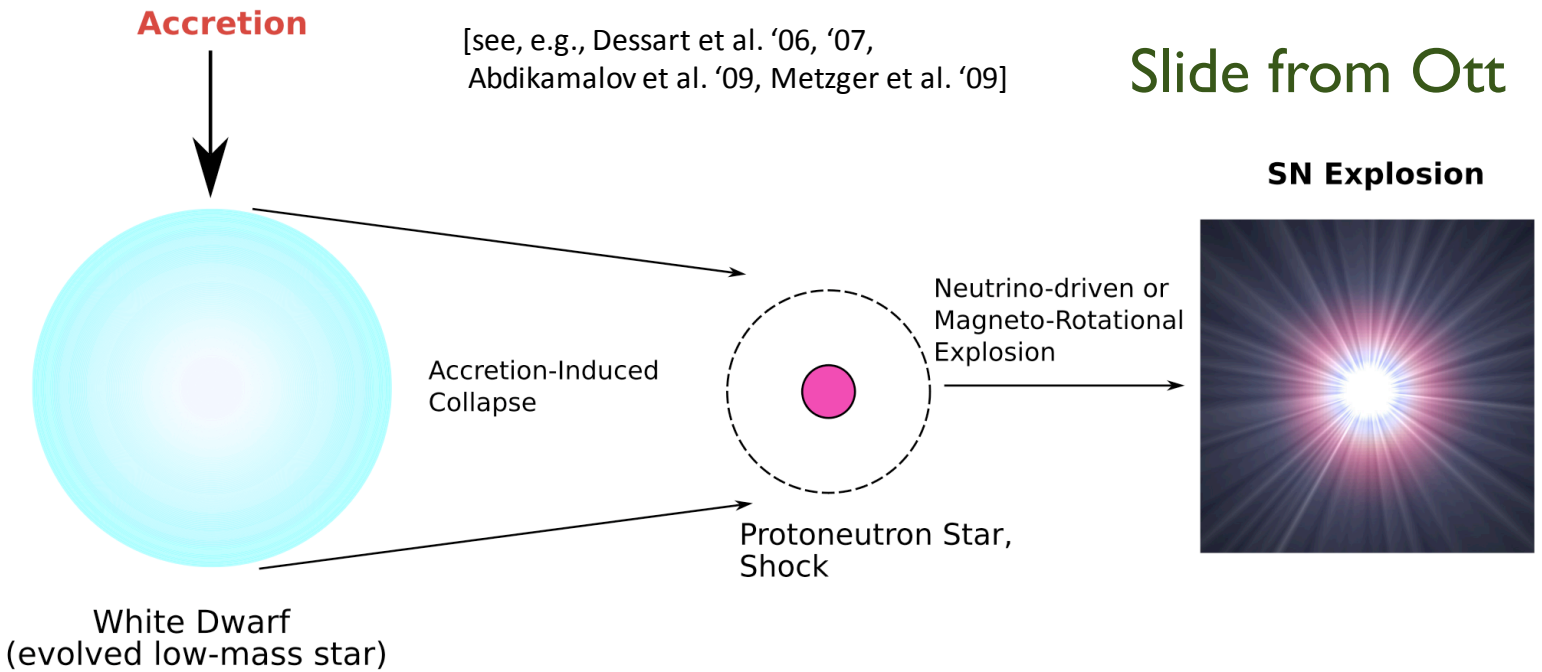
# Core Collapse SNe

Slide from Ott




- 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

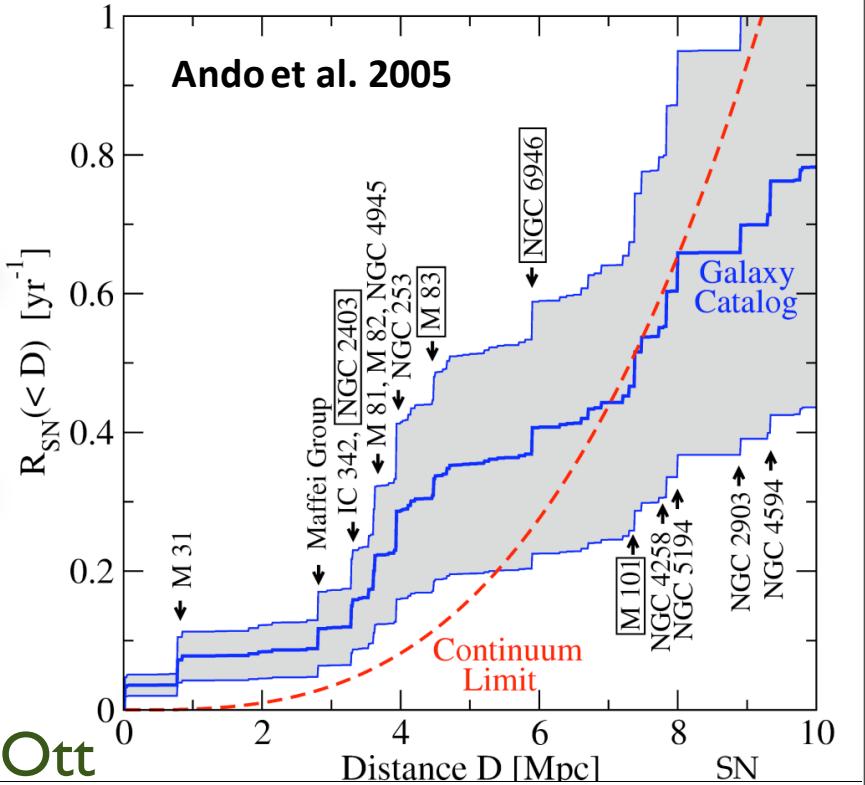
# Accretion Induced Collapse



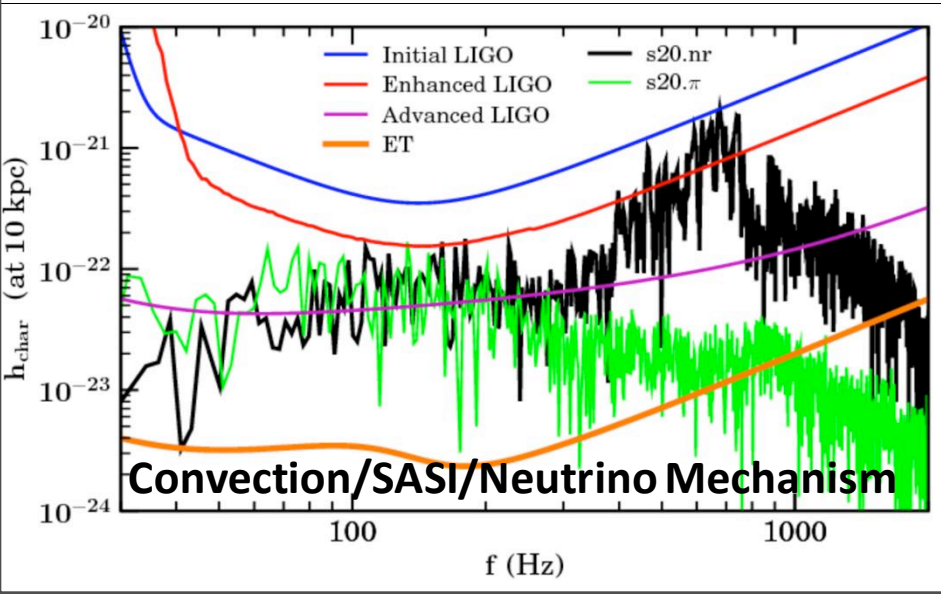

- Collapse of accreting, probably rotating White Dwarfs
  - Neutrino-driven or magneto-rotational explosion
- Explosion probably weak, sub-luminous
  - Might not be seen in optical
- Potential birth site of magnetars - highly ($10^{15}$- $10^{16}$ G) magnetized neutron stars

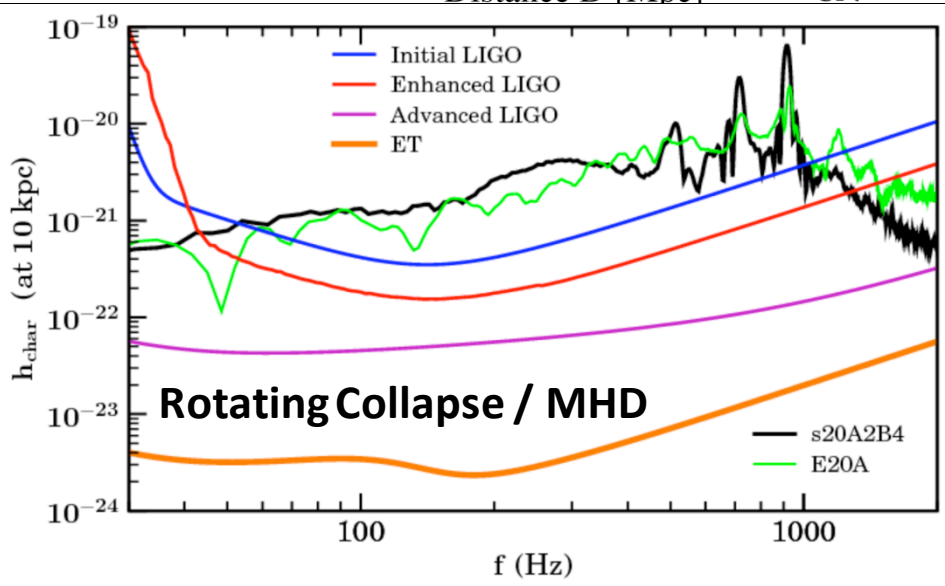
# SNe Rate in ET

- 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 of neutrino mass
- Plots show the spectra of SNe at 10 Kpc for two different models




Slide from Ott



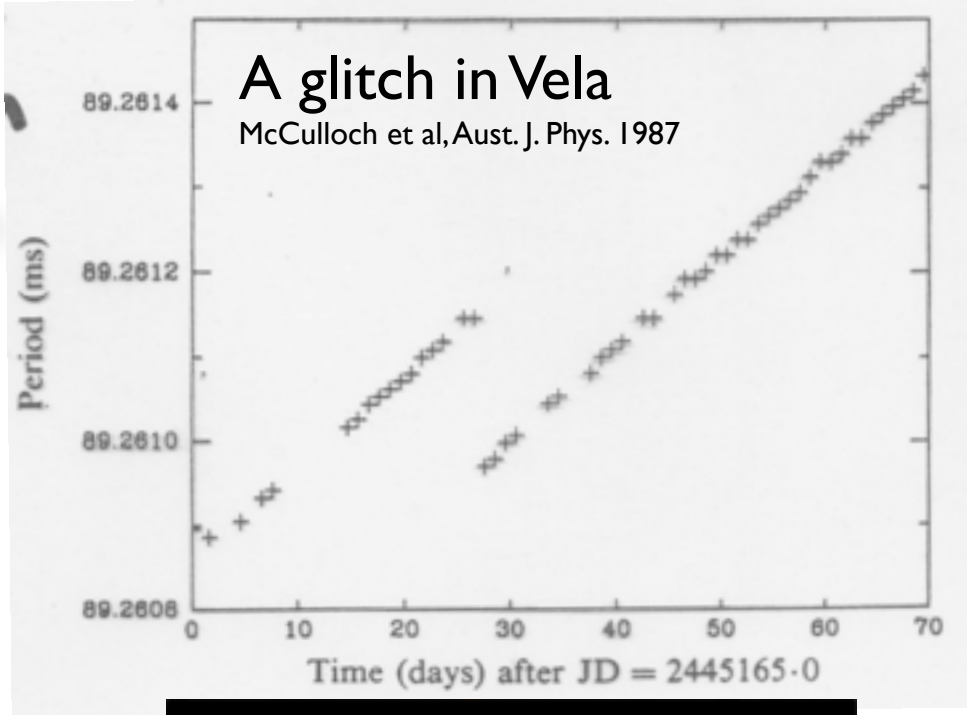
# Pulsar Glitches

- 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 of superfluid core couples to the curst, imparting energy to the crust

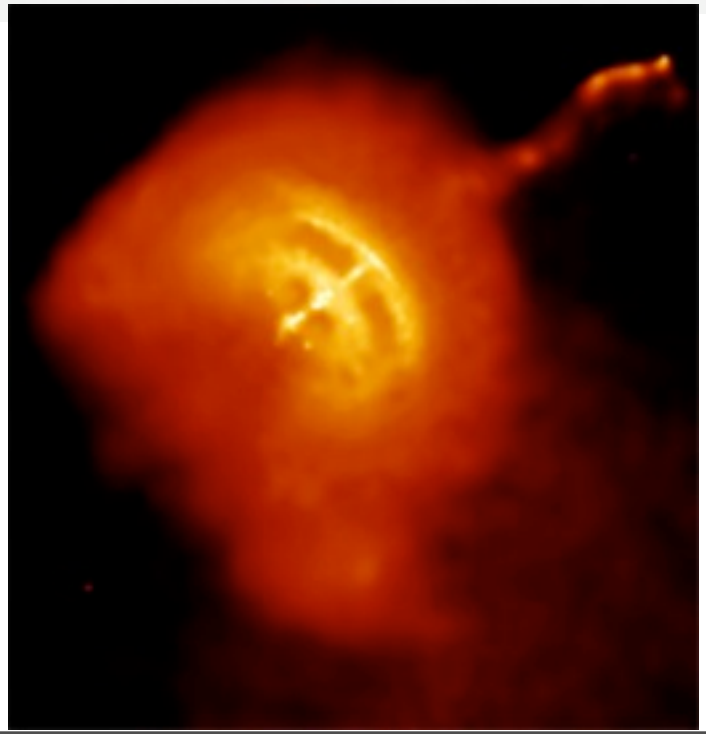
$$\Delta J \sim I_* \Delta\Omega \qquad \Delta E = \Delta J \Omega_{\rm lag}$$

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

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

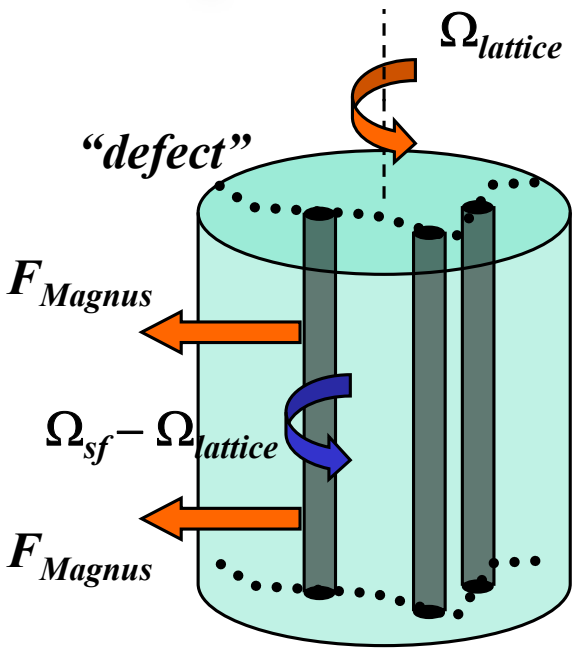


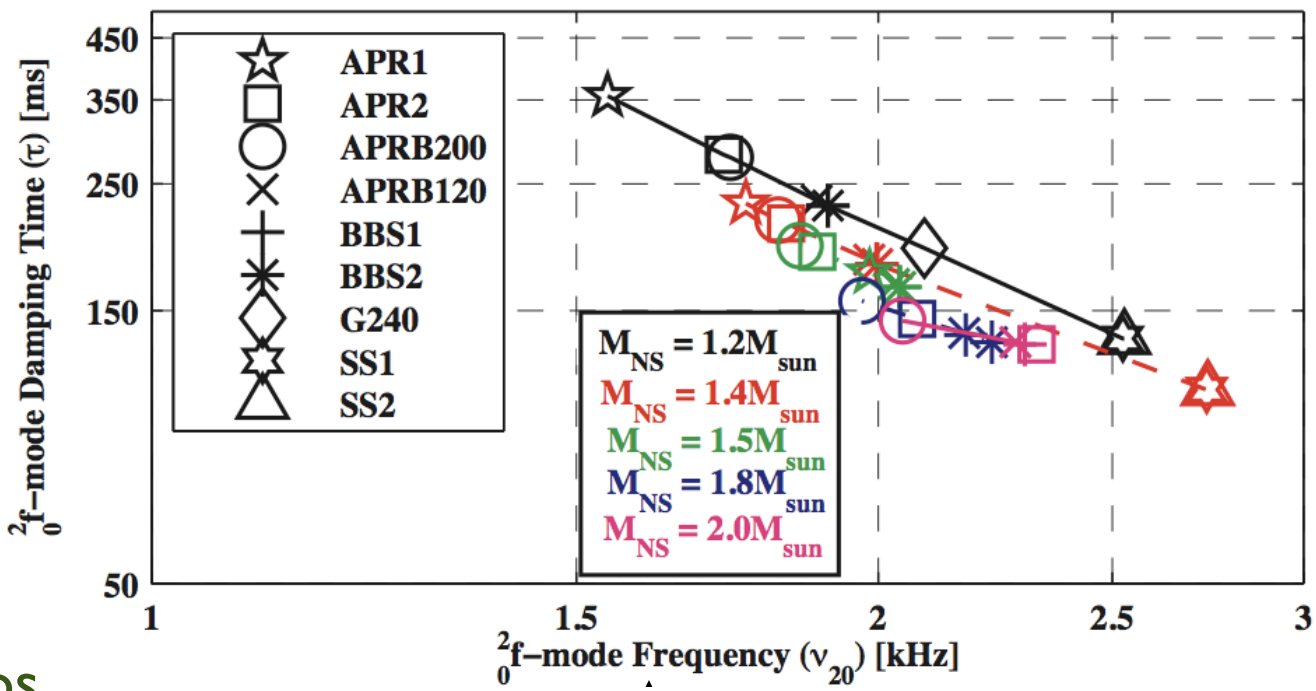

A composite Vela image



# 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



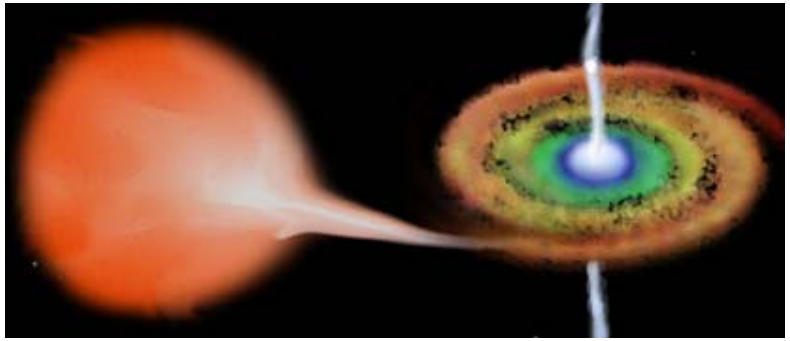




Slide from Melatos

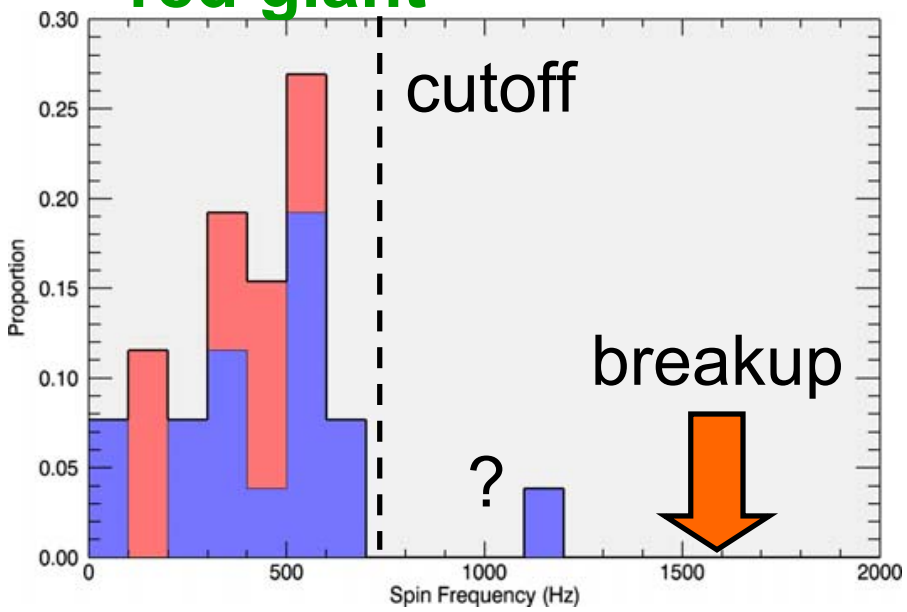
# Accreting Neutron Stars

- 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

Slide from Melatos



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




**pulses** & **burst oscillations**

# Challenges

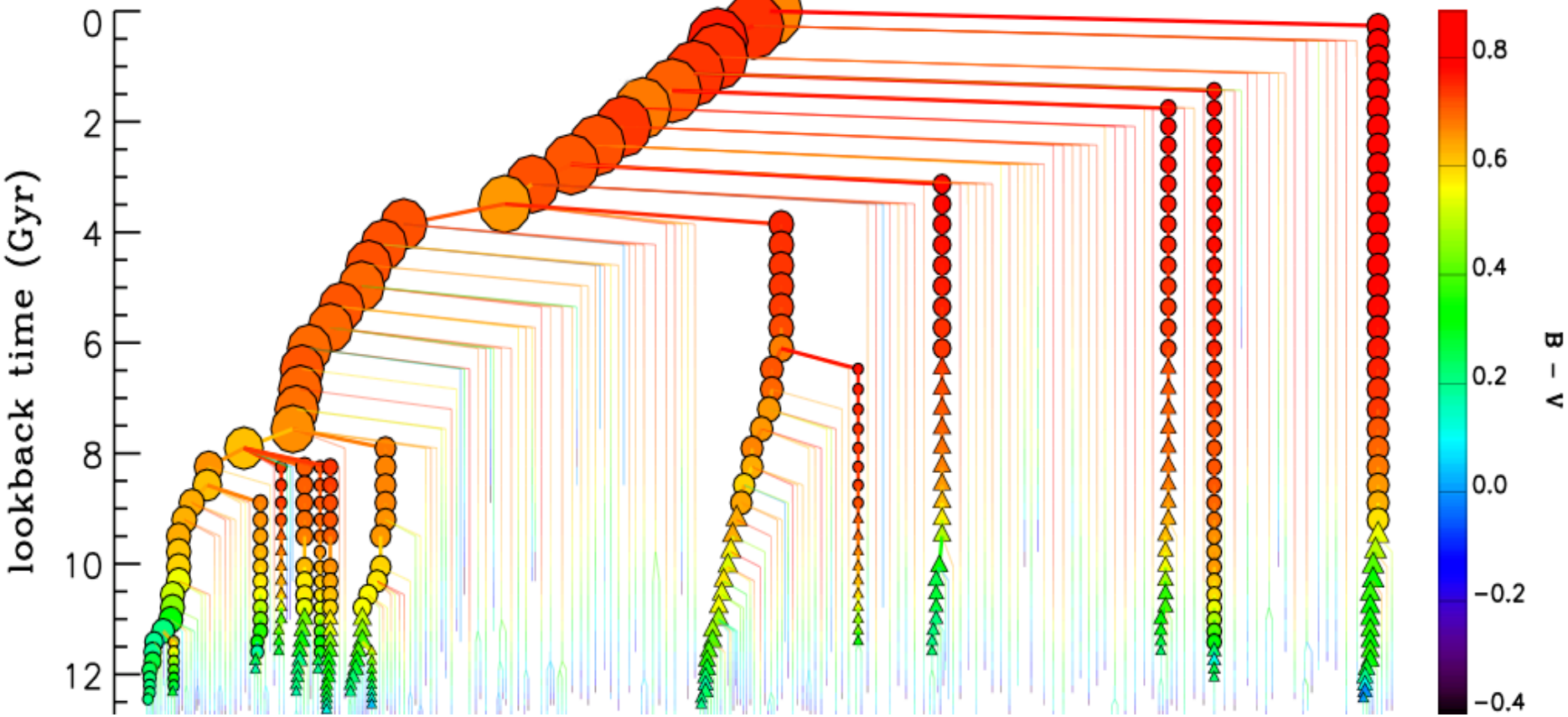
- Reliable estimation of the background rate
  - Current demands on detection confidence are far too high
    - A false alarm rate (FAR) of 1 per several thousand years
  - New algorithms are needed so that we can make a detection with a FAR of 1 per 100 years
- Developing waveforms that are as close to GR prediction as possible
  - Precession due to spins, higher order modes, inspiral-merger-ringdown
    - Numerical relativity is still far away from producing on-the-fly template waveforms
- Handling longer waveforms
  - In LV "Transient" signals could last for 30 minutes are longer
- Faster algorithms for parameter estimation
  - Nested sampling and multi-nest algorithms are already effective but they are still not fast enough
    - The event rate could be as high as several per day

# Summary

- Gravitational wave detectors can potential impact
  - Fundamental Physics
    - Is the nature of gravitational radiation as predicted by Einstein?
    - Is Einstein theory the correct theory of gravity?
    - Are black holes in nature black holes of GR?
    - Are there naked singularities?
  - Astrophysics
    - What is the nature of gravitational collapse?
    - 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?
    - What is dark energy?
    - What phase transitions took place in the early Universe?
    - What were the physical conditions at the big bang?

# Hierarchical Growth of Black Holes in Galactic Nuclei

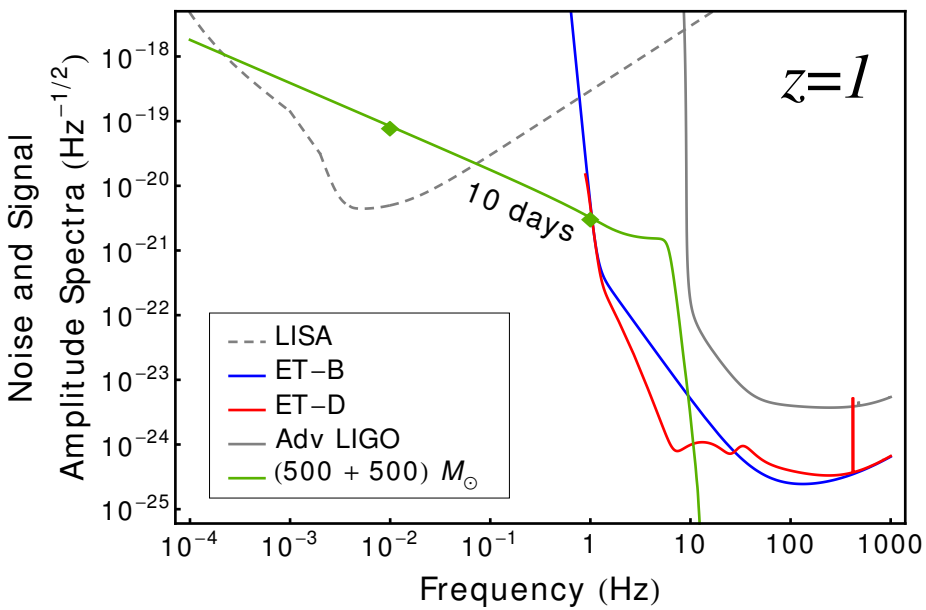
Slide from Sesana

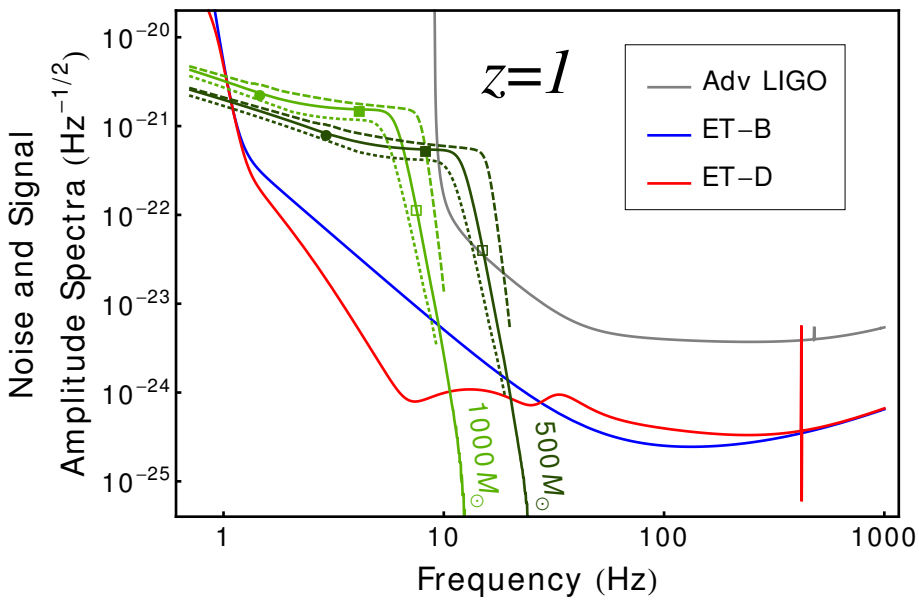



- Initially small black holes may grow by hierarchical merger
  - ET could observe seed black holes if they are of order 1000 solar mass

# Observing Intermediate-mass Black Hole Binaries

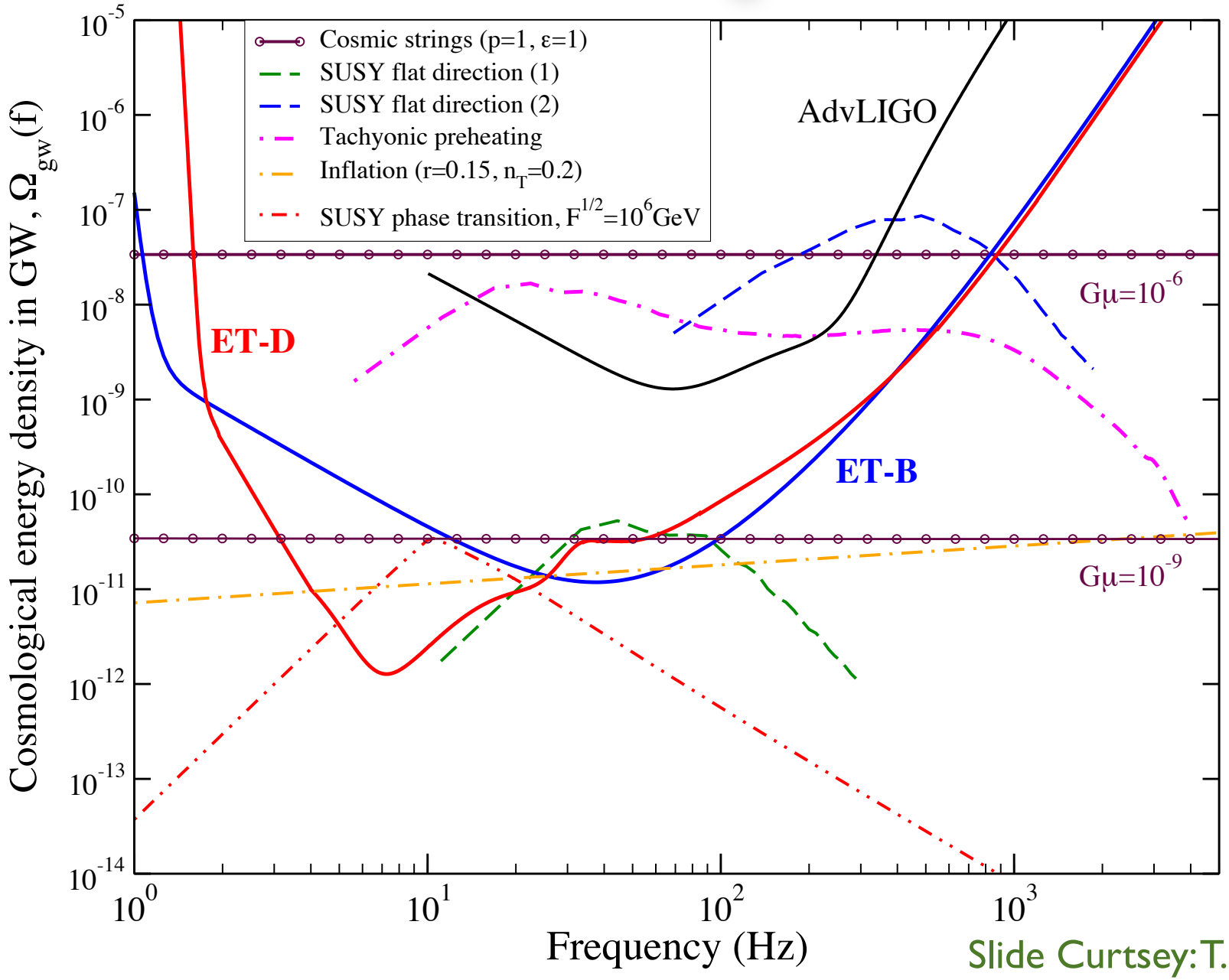
- Ultra-luminous X-ray sources might be hosting black holes of mass one thousand solar masses
- 100 solar mass black holes could be seeds of galaxy formation
- ET could observe black hole populations at different red-shifts and resolve questions about black hole demographics



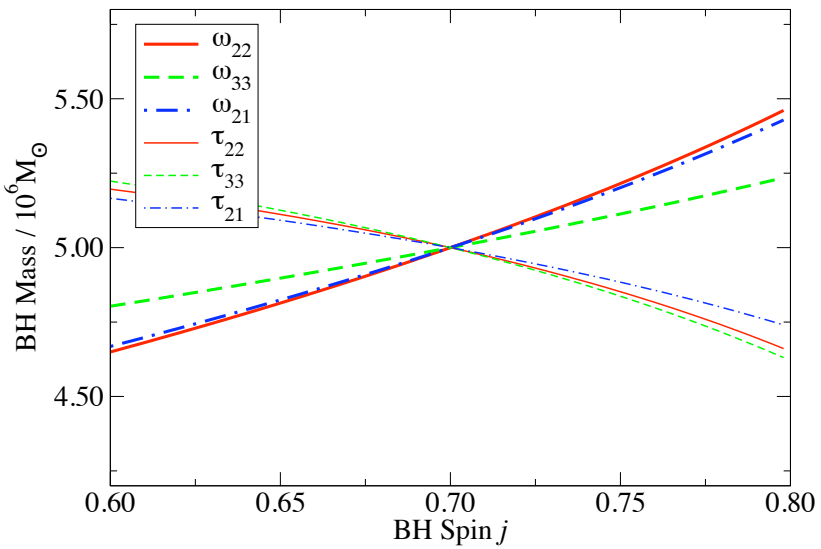

Slide Curtsey: L. Santamaria

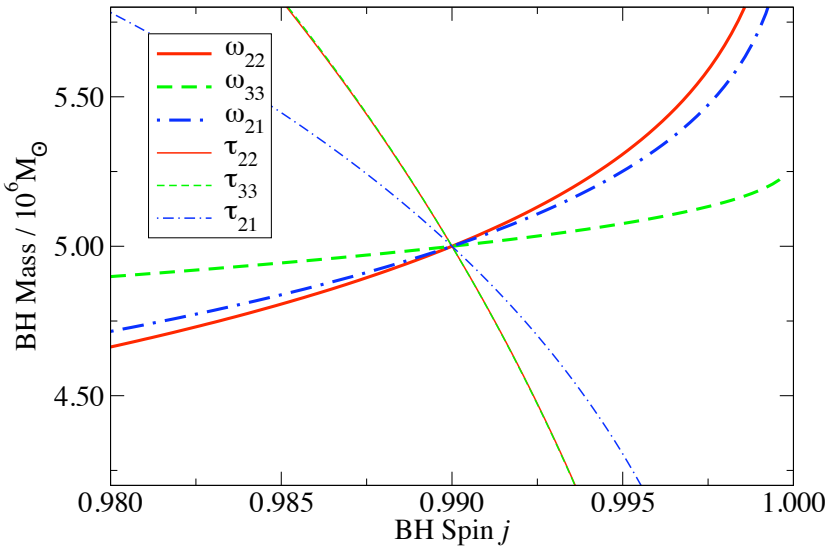
# Primordial Backgrounds

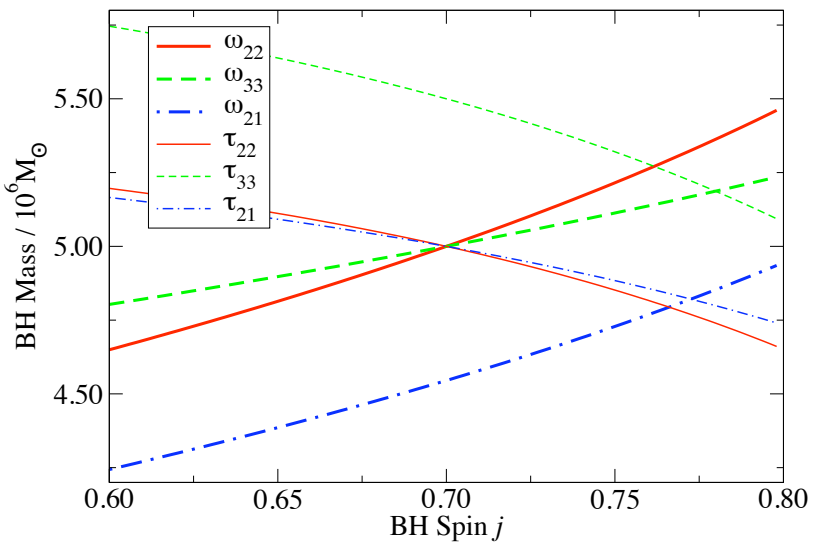


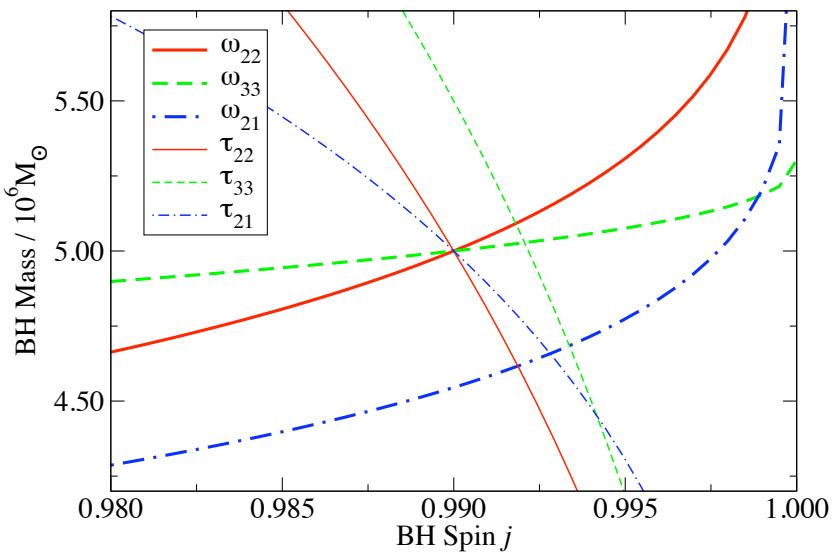

Slide Curtsey: T. Dent

# Testing GR with QNMs




Kamaretsos, Hannam, Husa, BSS (2011)

Poster 25: Gossan