Understanding Neutron Stars from Gravitational Wave Observations

Binary Neutron Star Coalescence as a Fundamental Physics
Laboratory: INT, Seattle, 30 June 2014

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- Focus here on **binary** neutron star mergers

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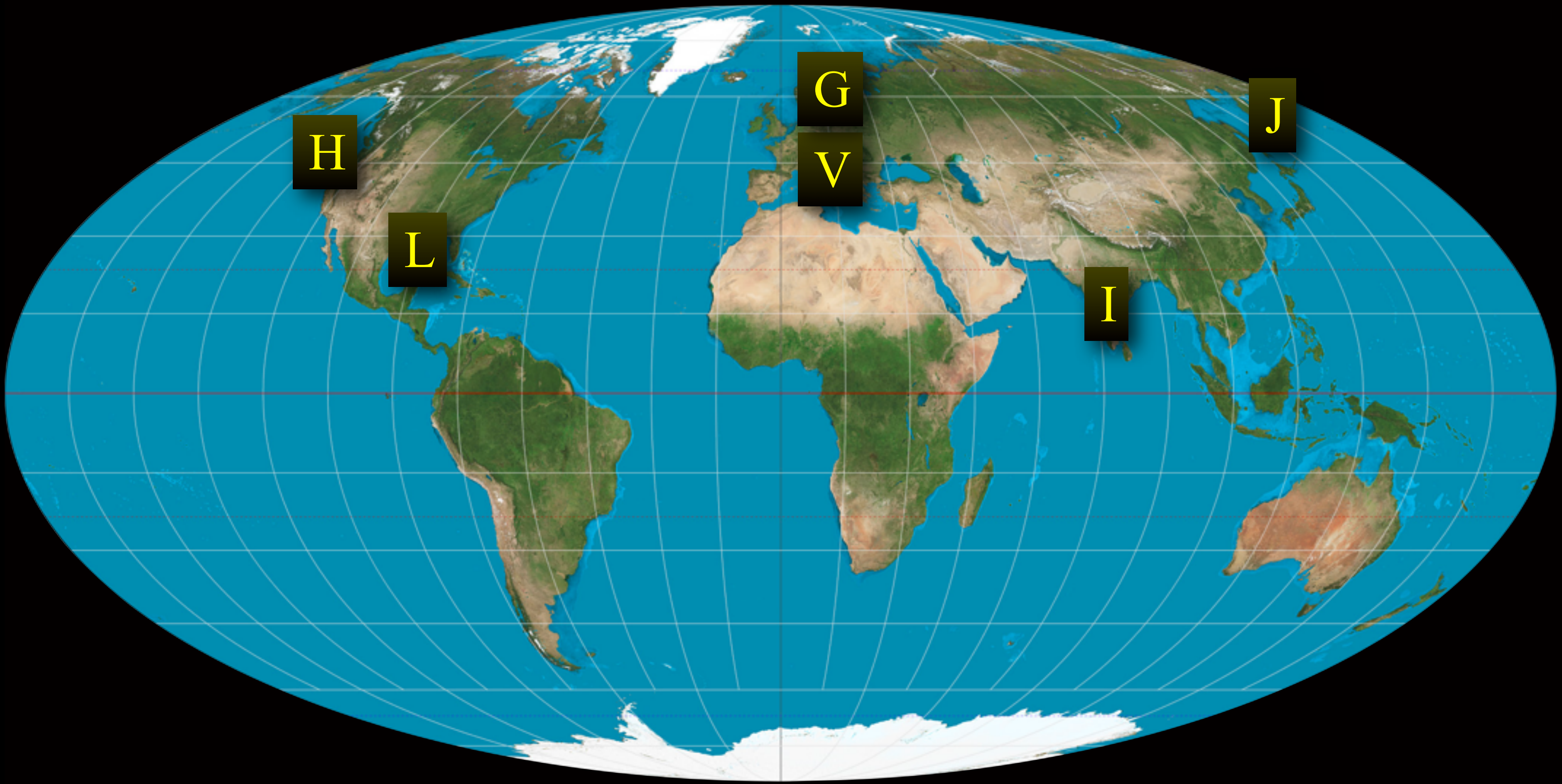
World Network of Gravitational Wave Detectors



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- No detections so far but beginning to impact astrophysics

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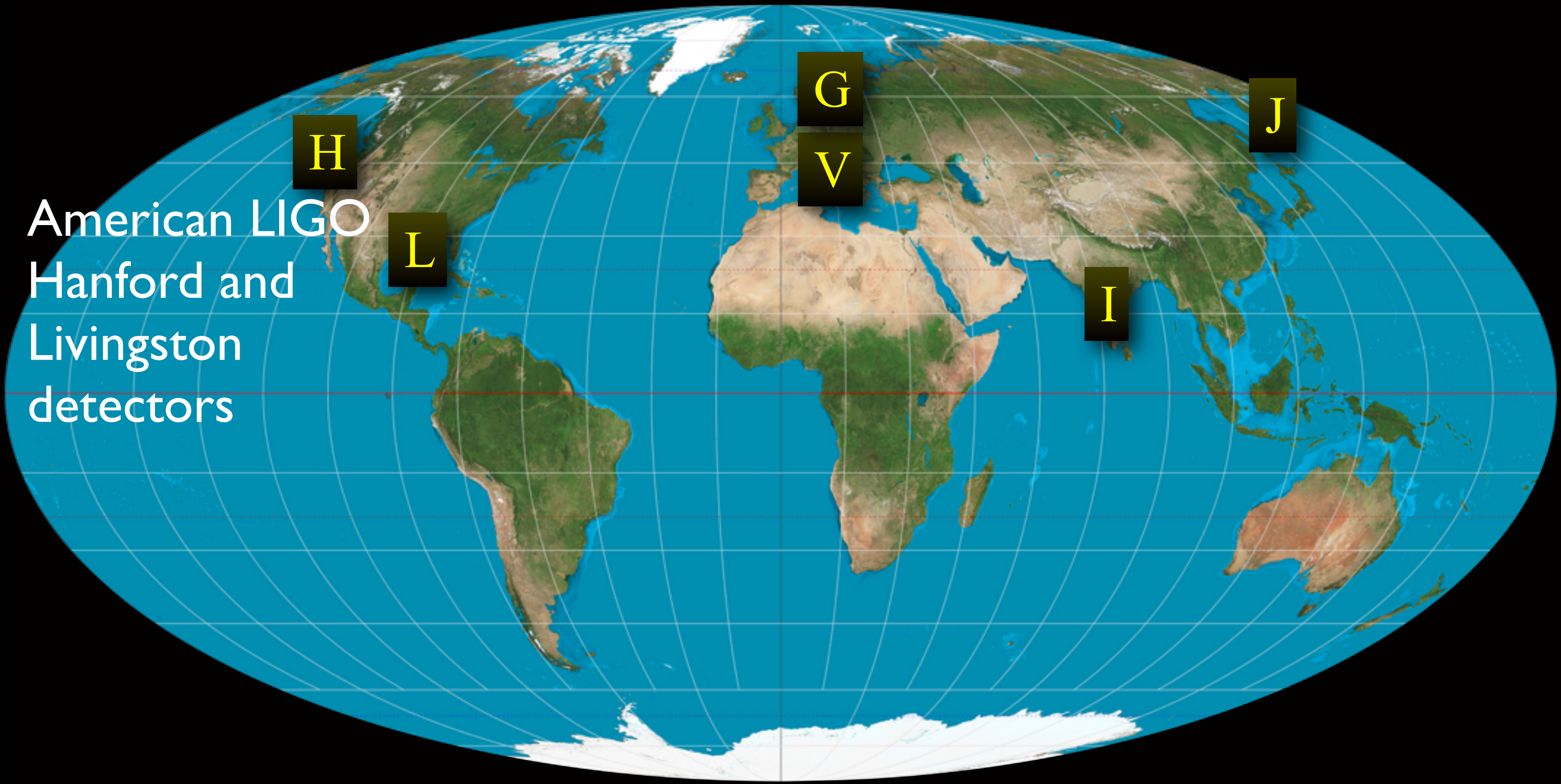

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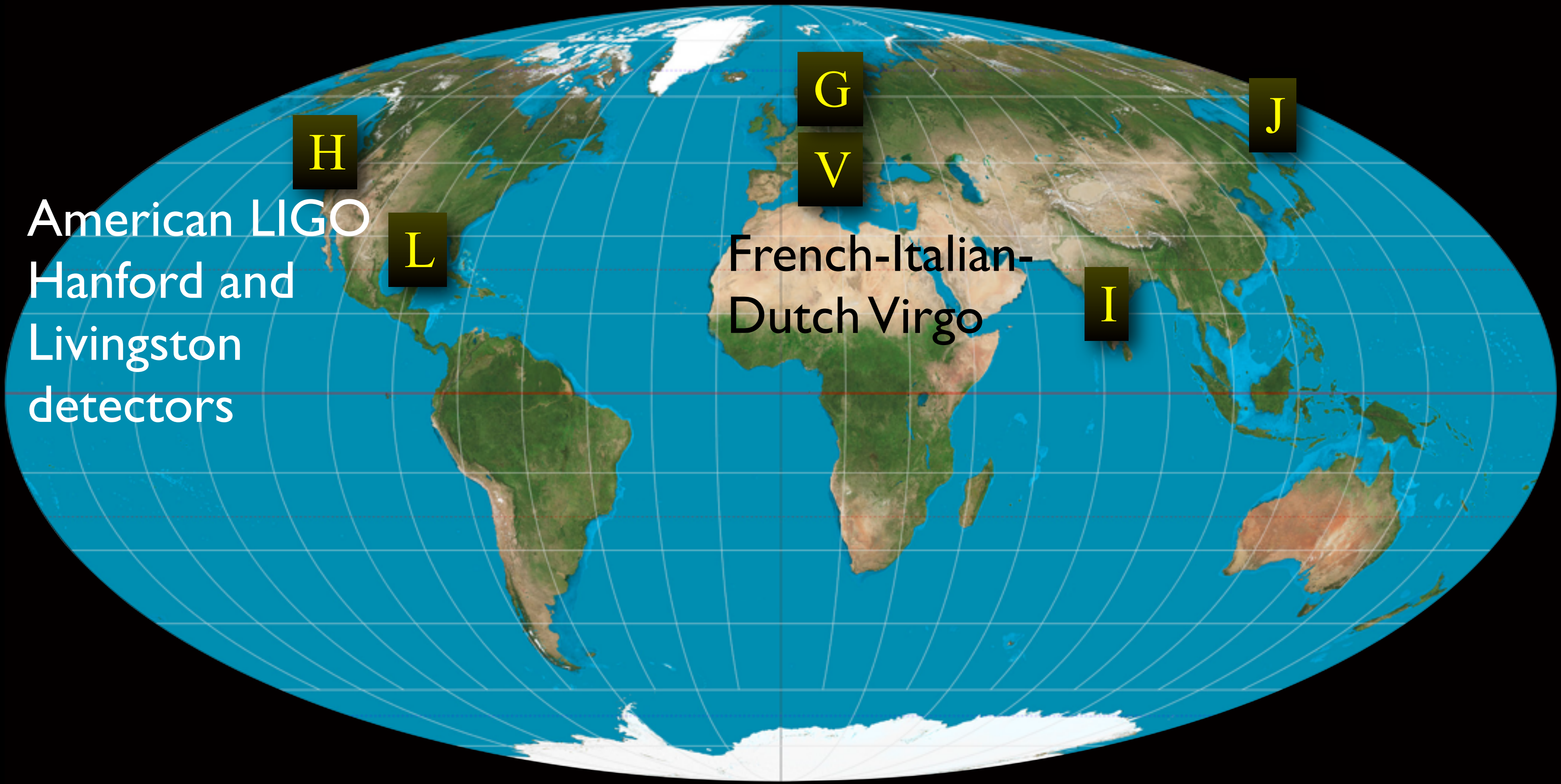

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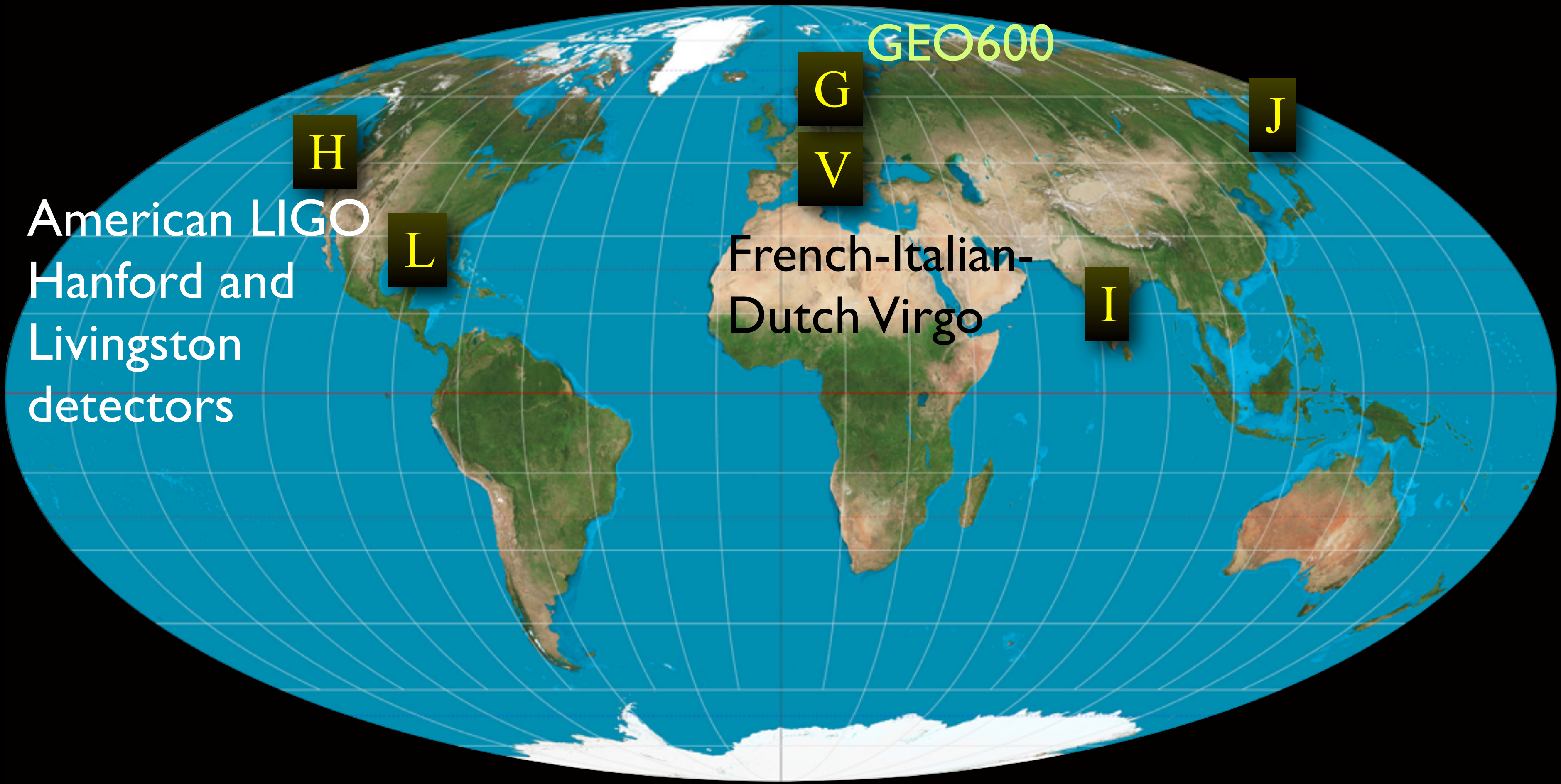

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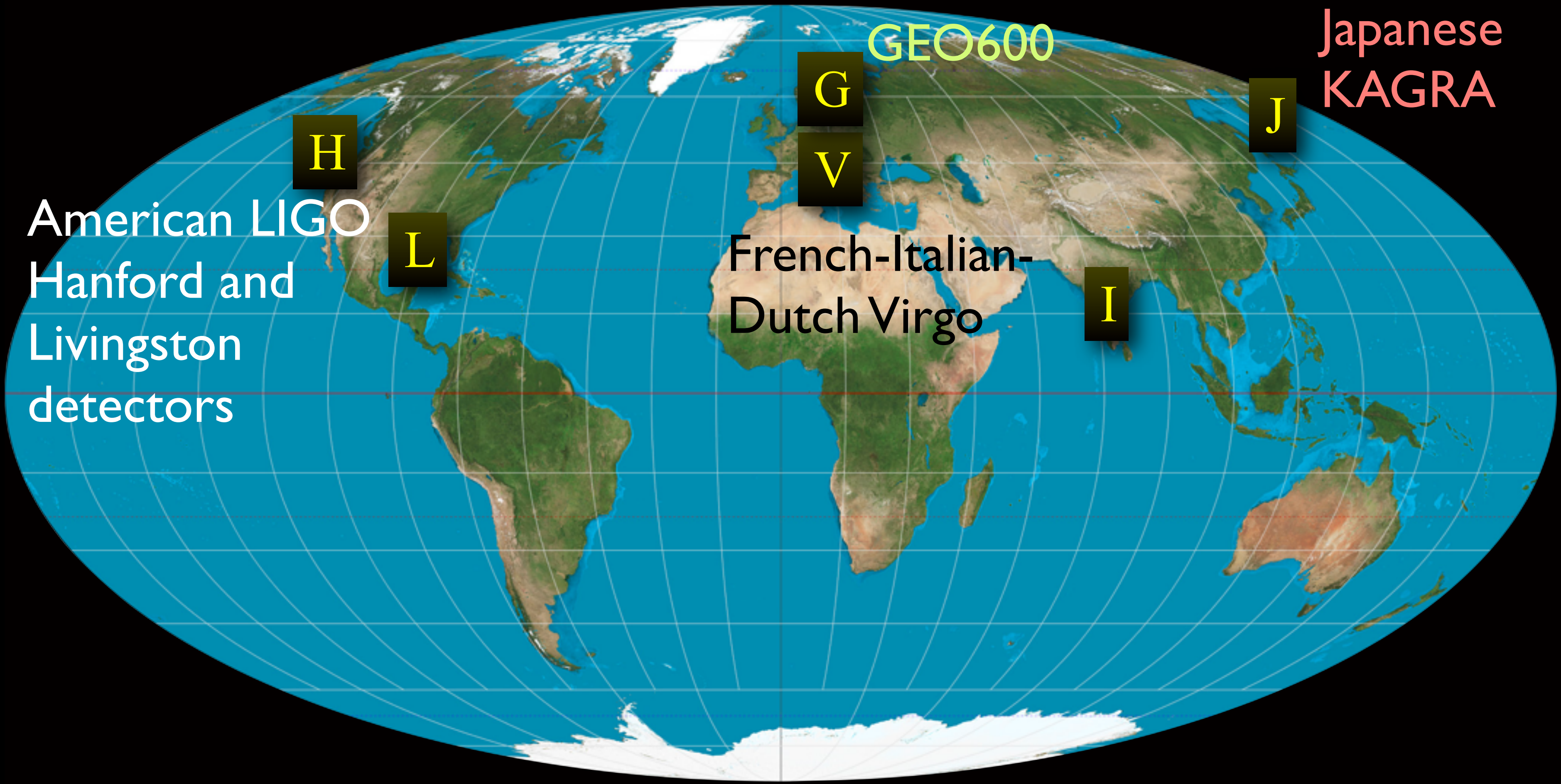

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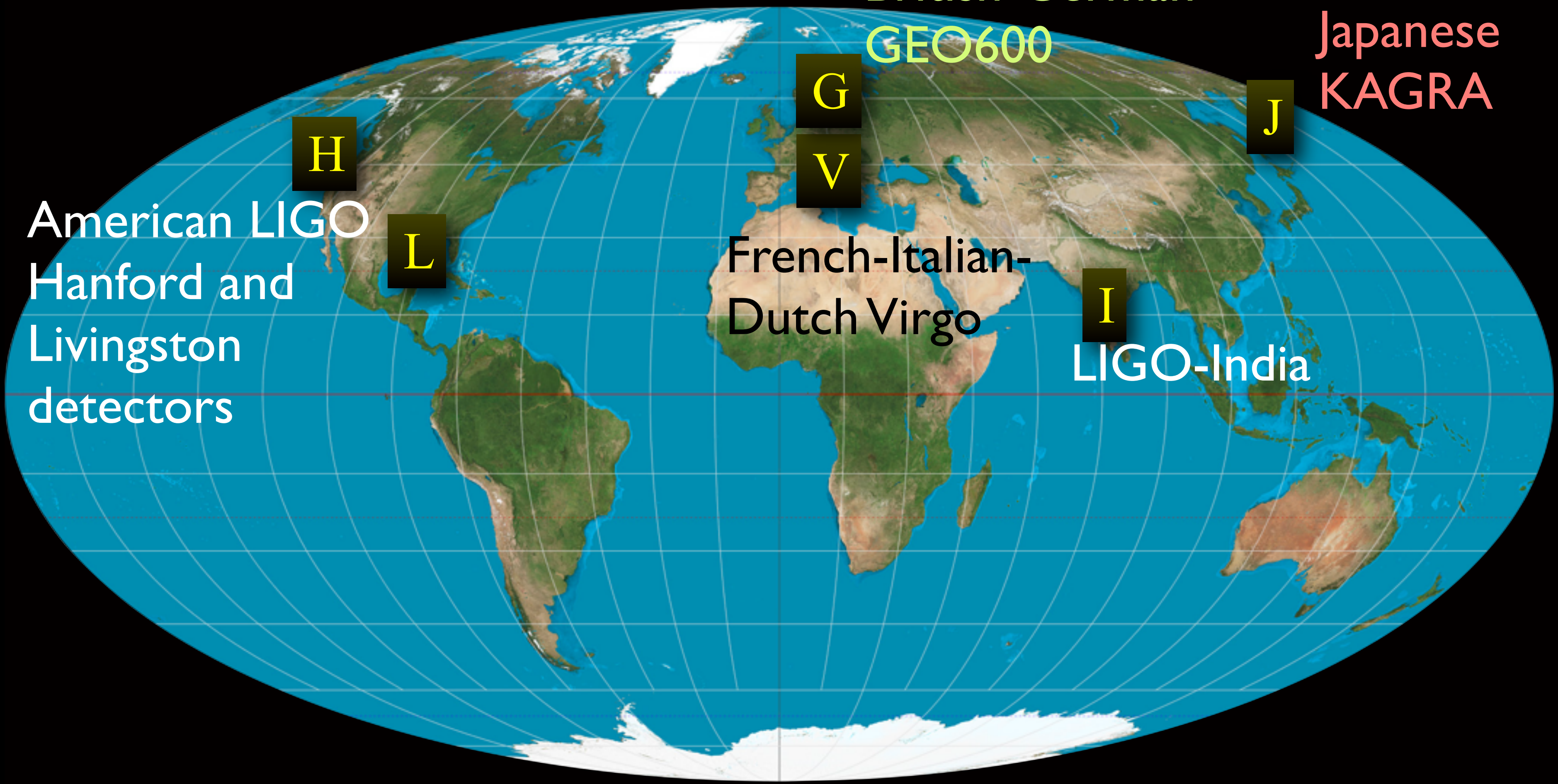

British-German GEO600

Japanese KAGRA

American LIGO Hanford and Livingston detectors

French-Italian-Dutch Virgo

LIGO-India

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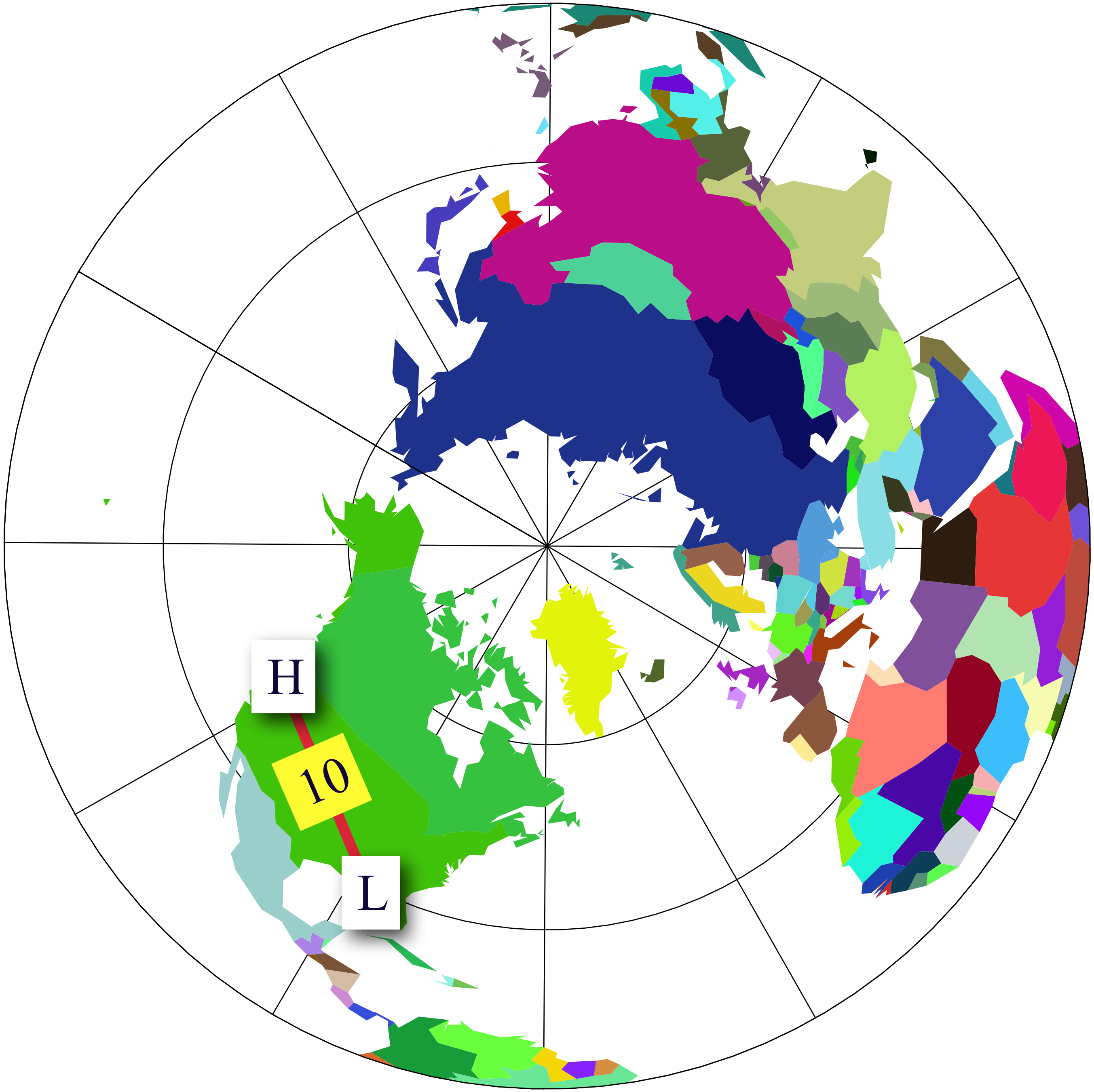
Advanced Detectors:

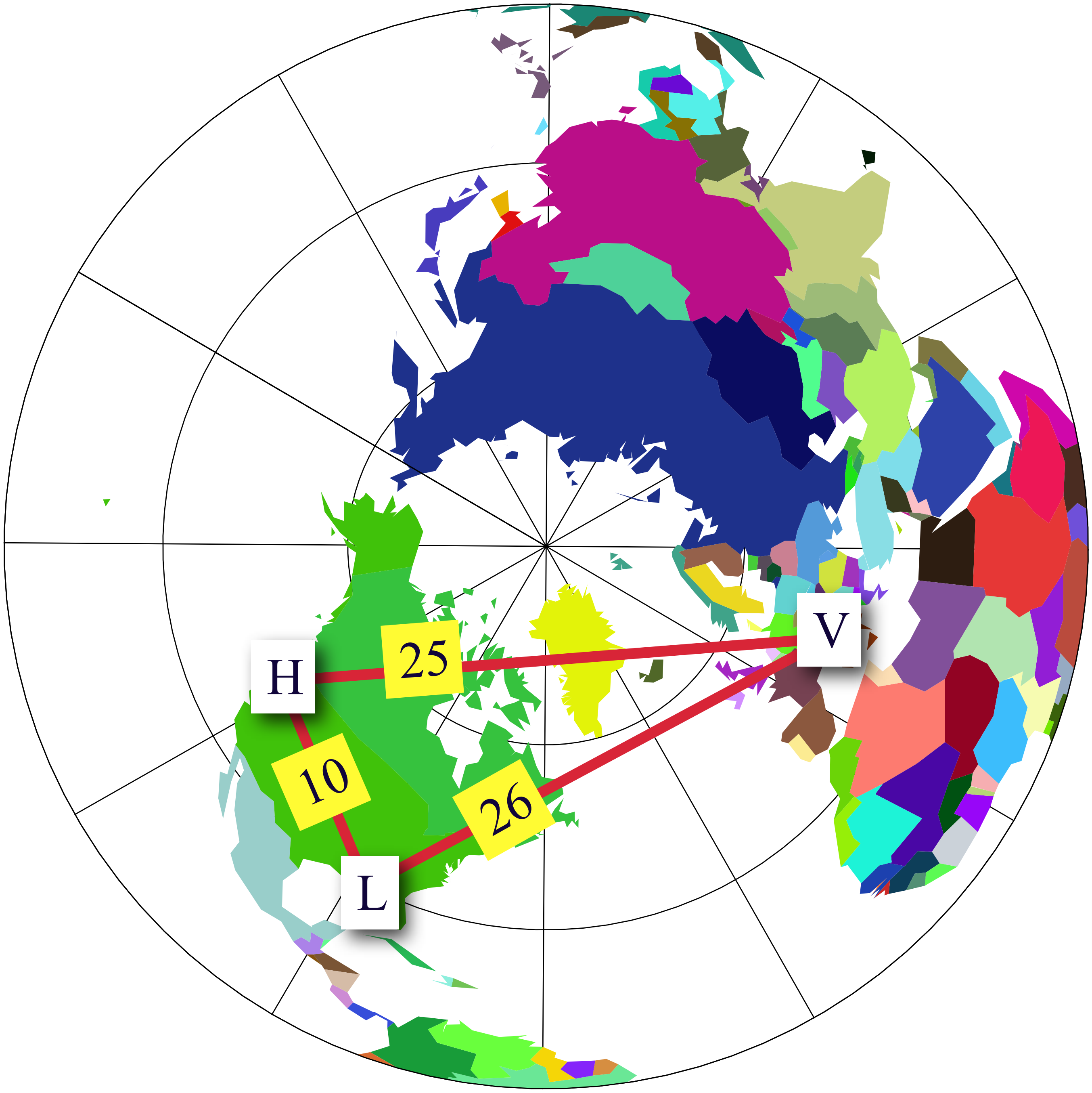
Ca 2015–2025



Detector Networks 2015-

Baselines

in light travel time (ms)



Detector Networks 2016-

Baselines

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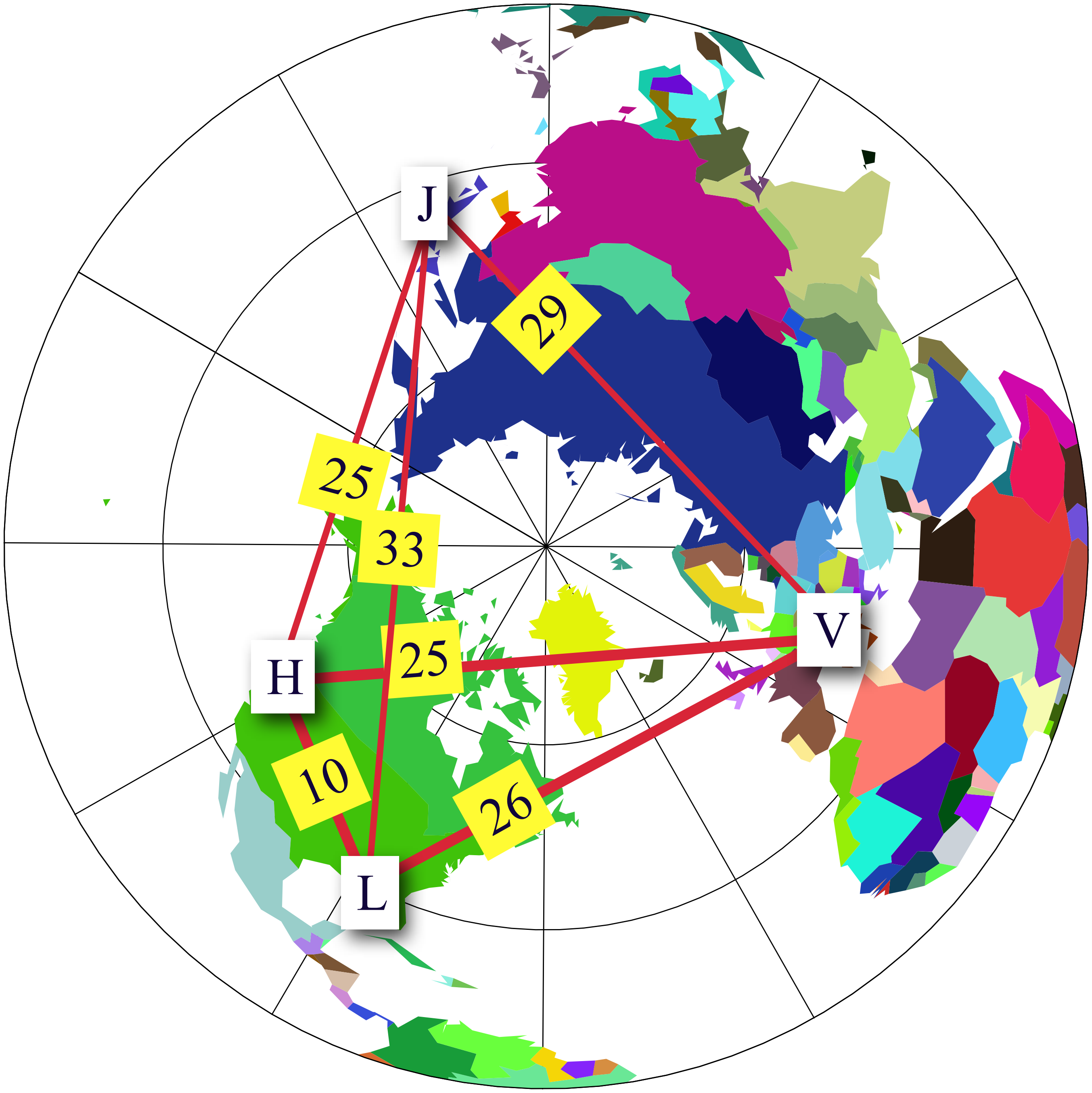
Detector Networks 2018-



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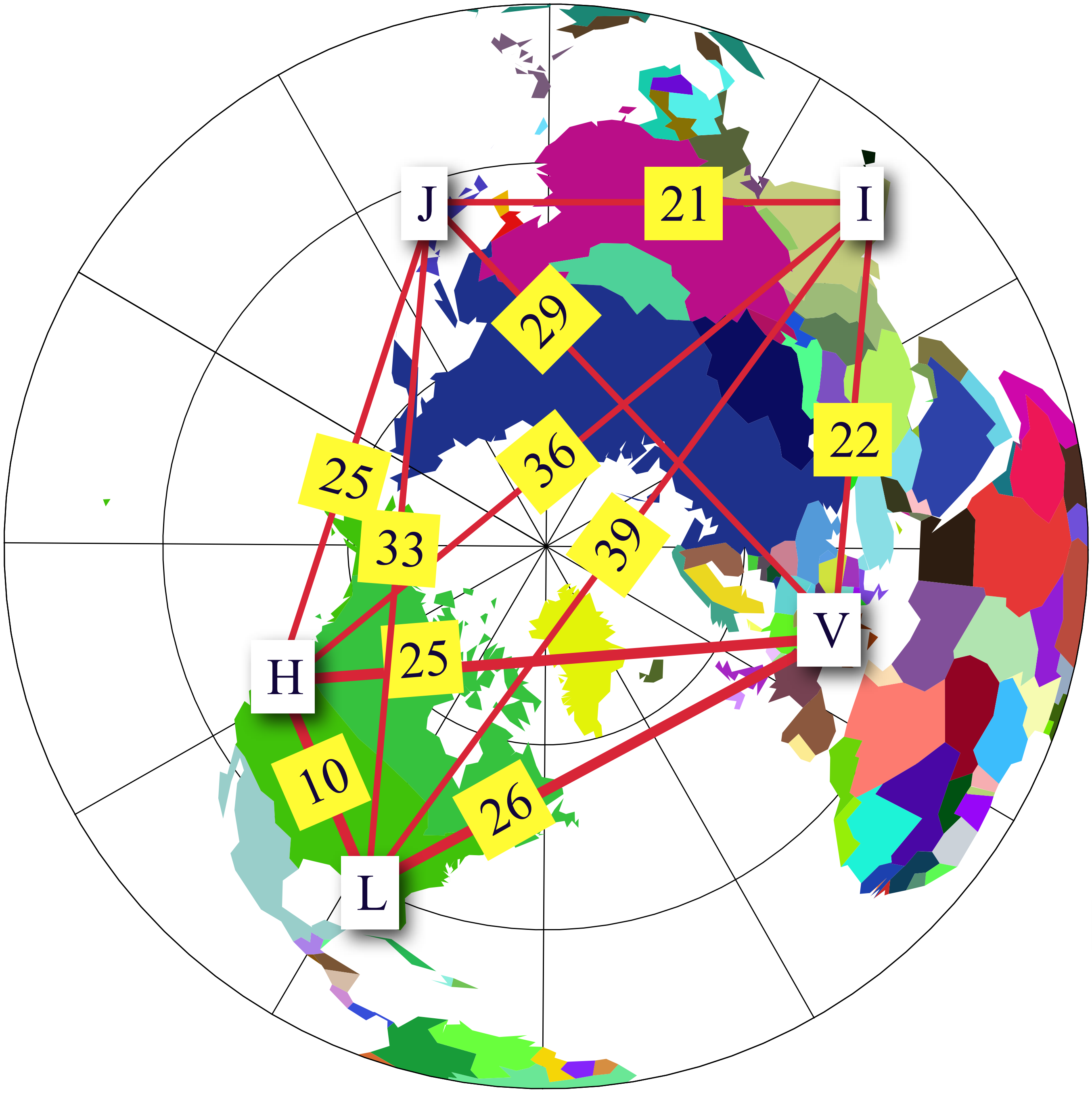


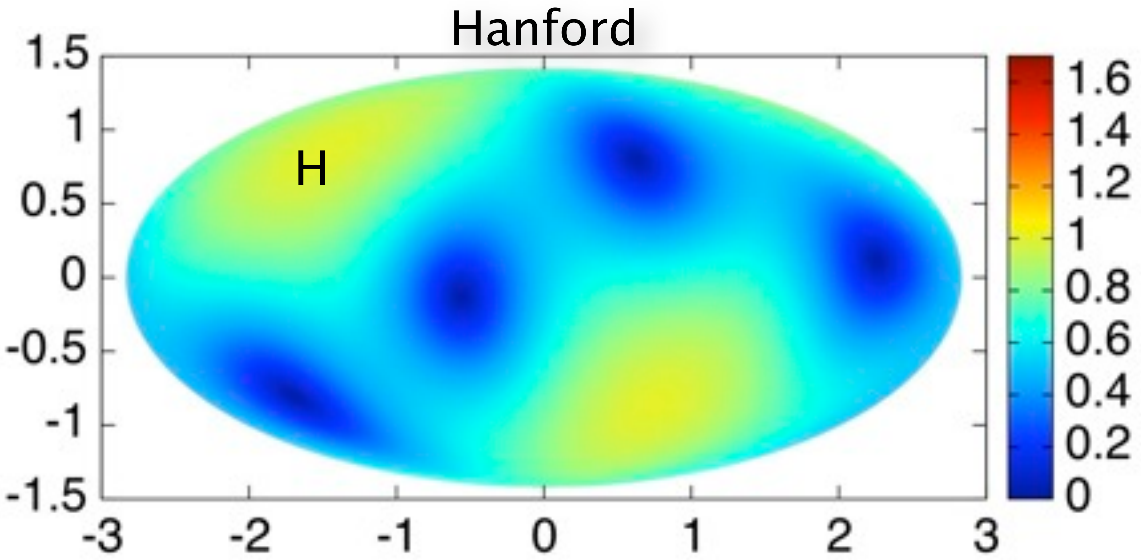
Detector Networks 2022-

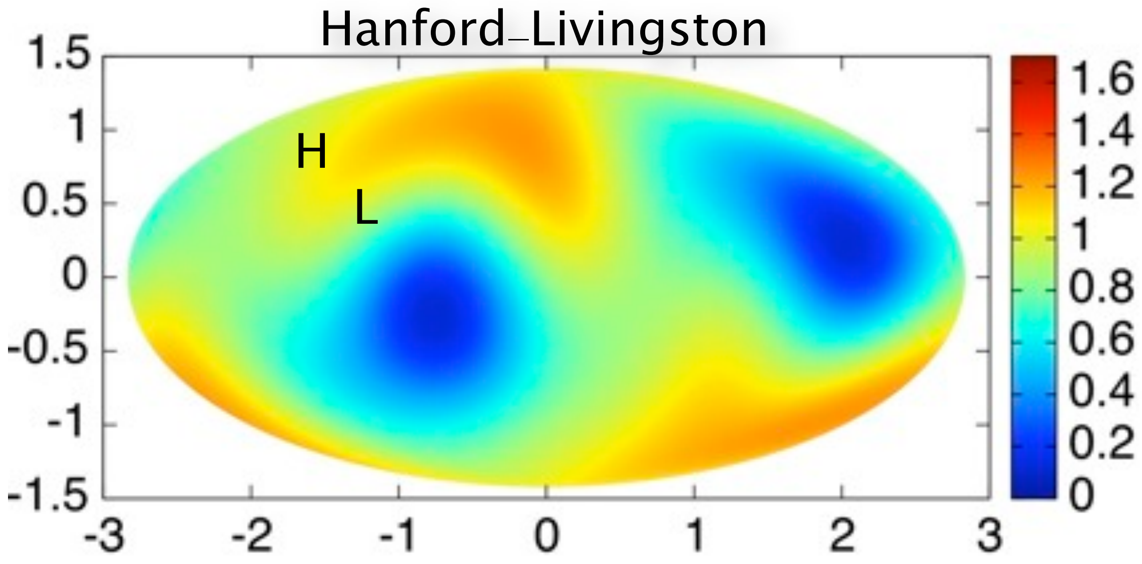
Baselines

in light travel time (ms)

Detector Beam Pattern Function

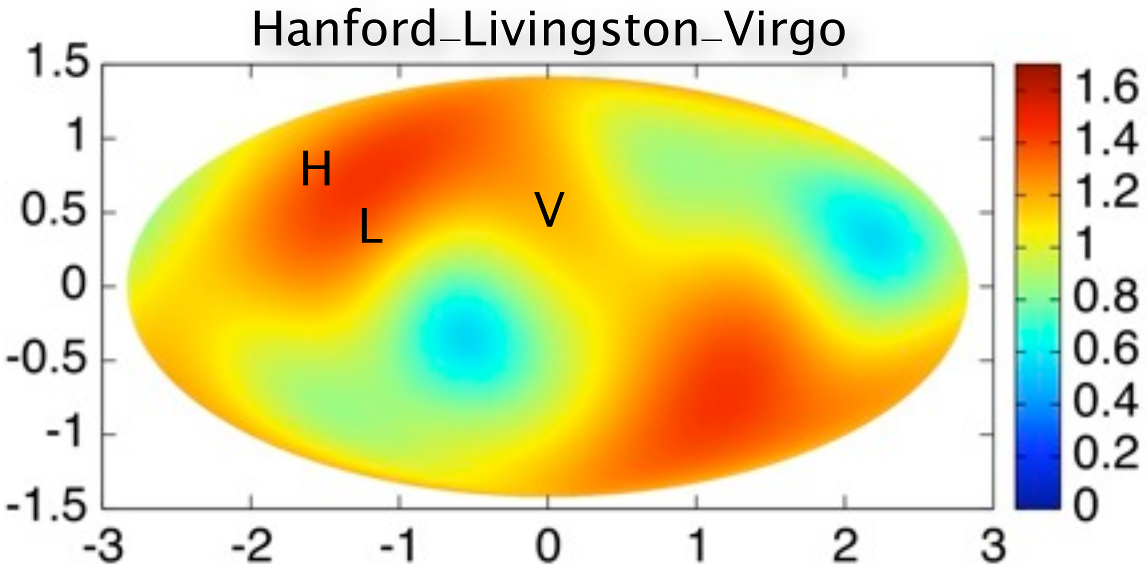
- Gives the sensitivity of a detector to sources at different parts of the sky
- For a single detector the beam is a quadrupole
- For a network of 5 or more globally distributed detectors the pattern can essentially become isotropic

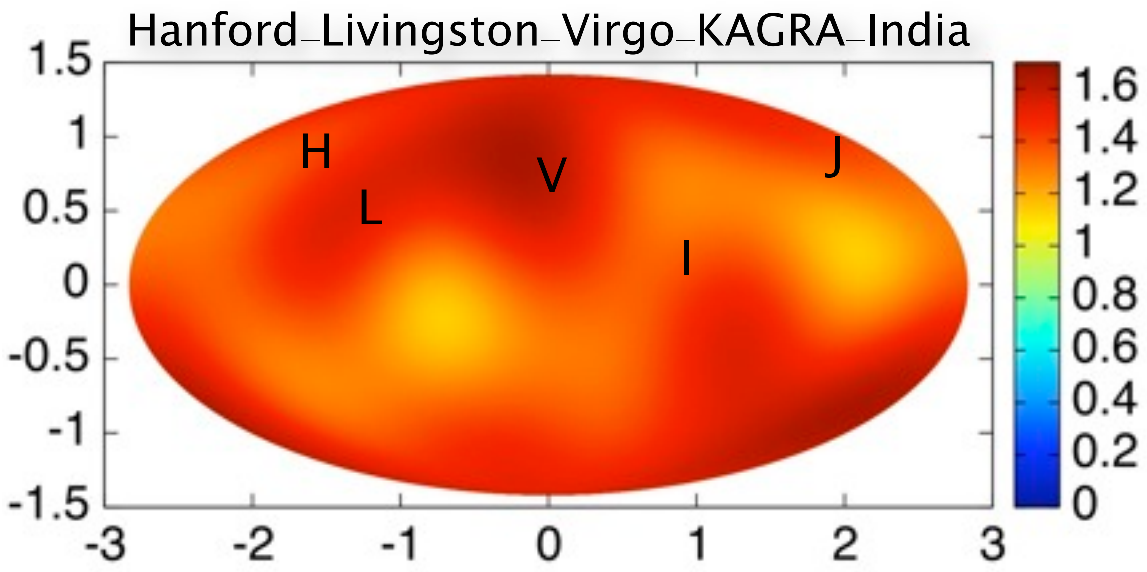




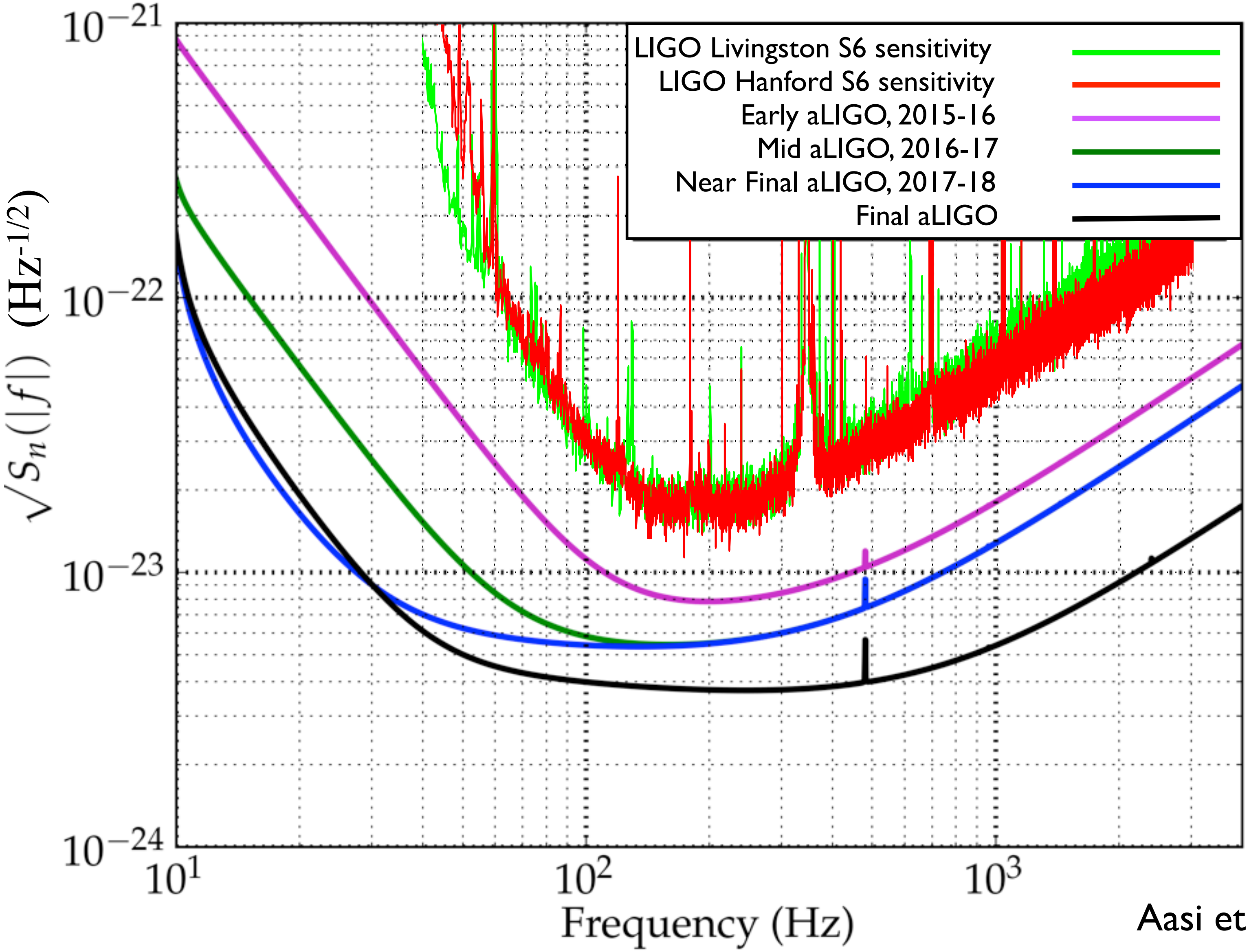
Challenge of Gravitational Wave Searches

- A network of gravitational wave detectors is always on and sensitive to most of the sky
- Signals can be milliseconds long or last for years
- Multiple signals could be in band but with different amplitudes
- We can integrate and build SNR by coherently tracking signals in phase



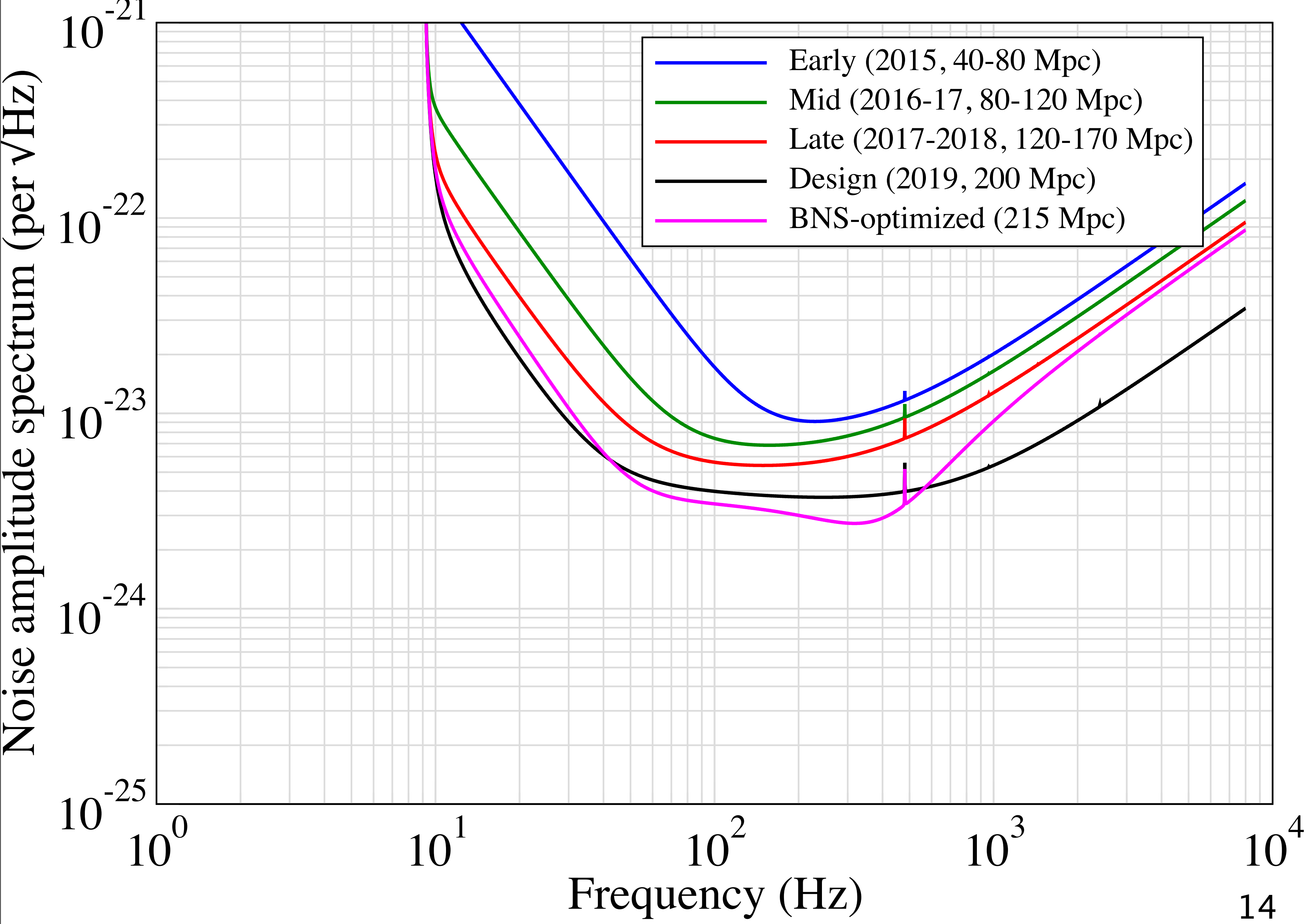


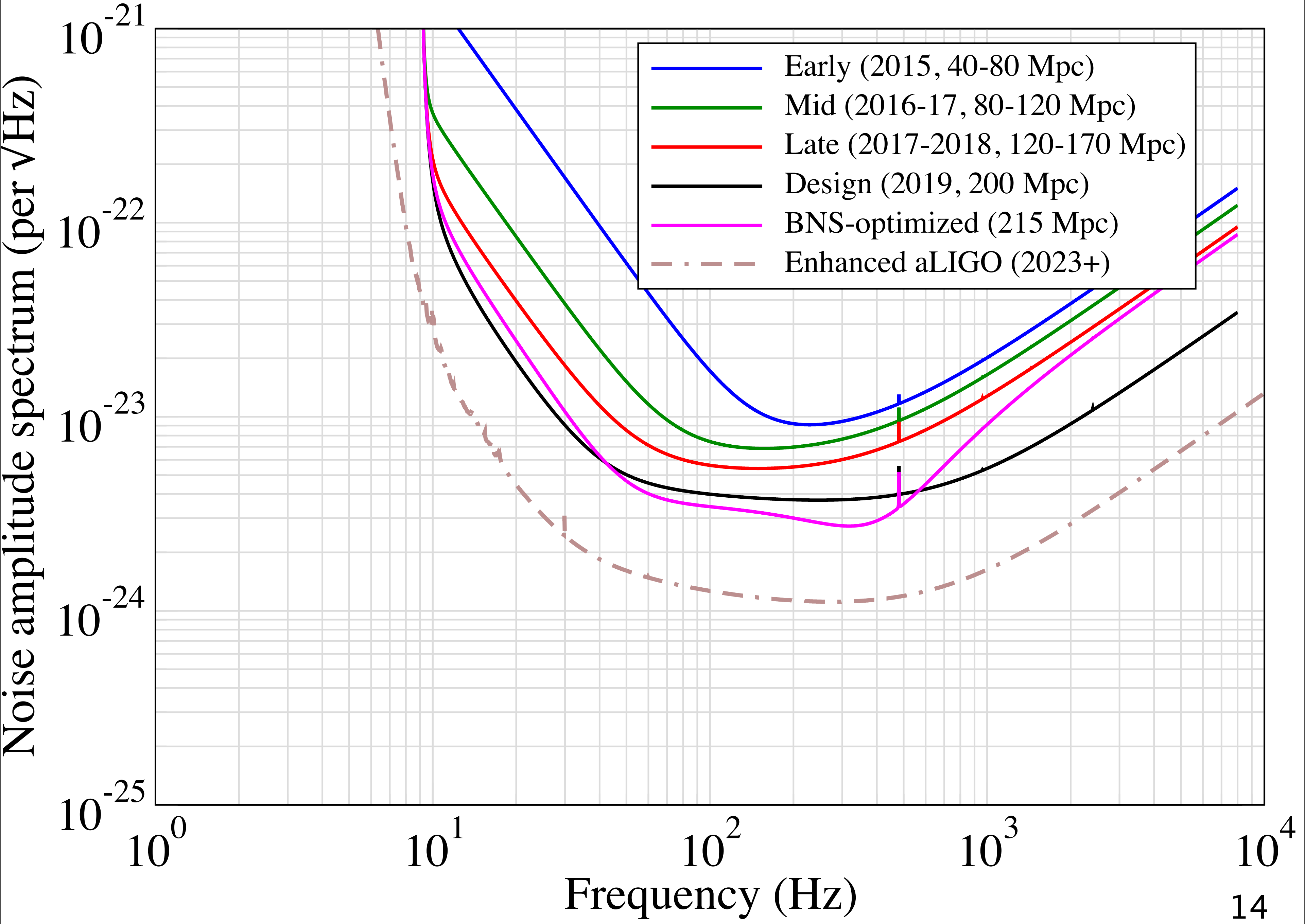
Advanced LIGO Sensitivity



Aasi et al 2013

Beyond Advanced Detectors:
2G+ and Einstein Telescope


Early (2015, 40-80 Mpc)
Mid (2016-17, 80-120 Mpc)
Late (2017-2018, 120-170 Mpc)
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)
Noise amplitude spectrum (per √Hz)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)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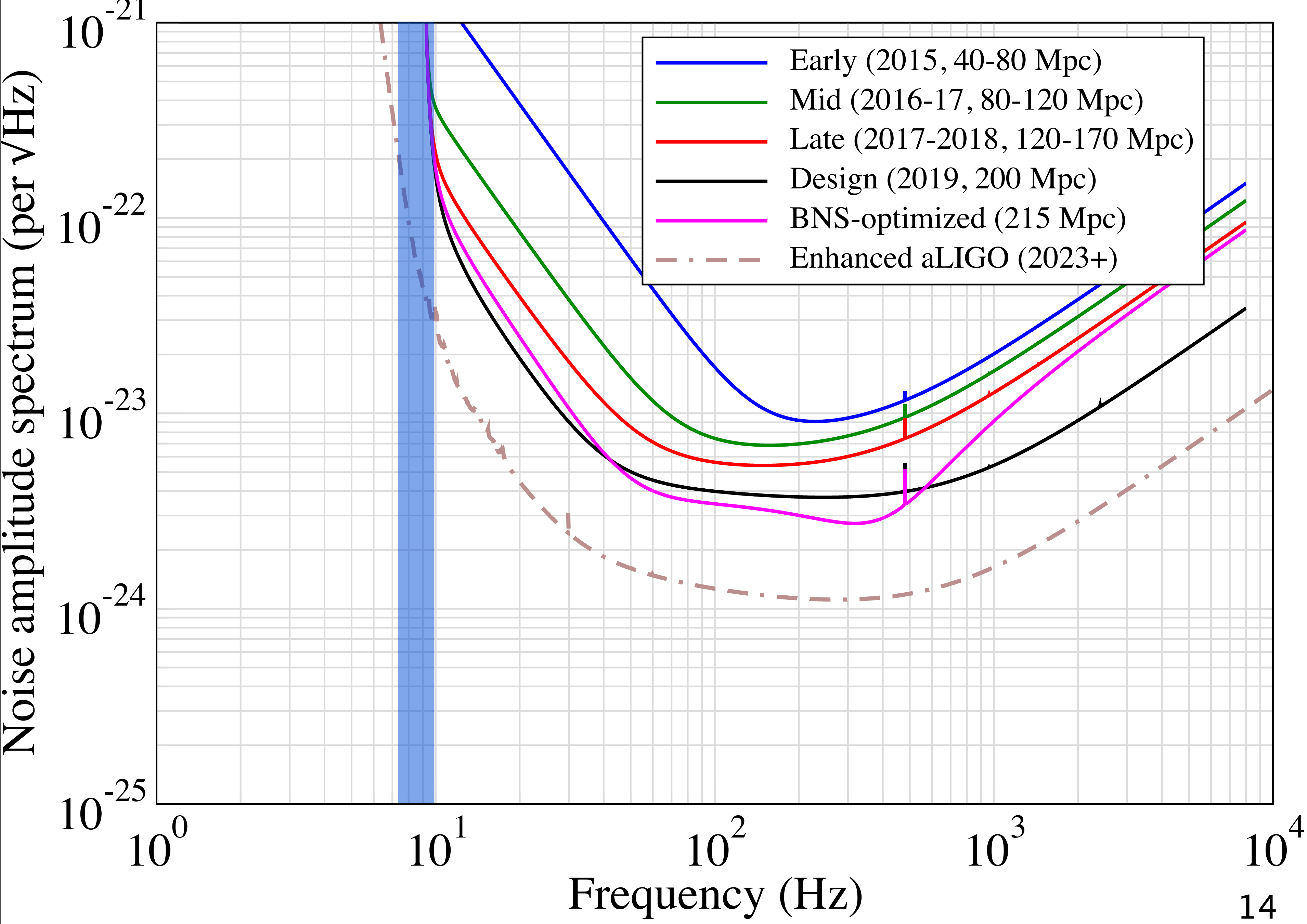

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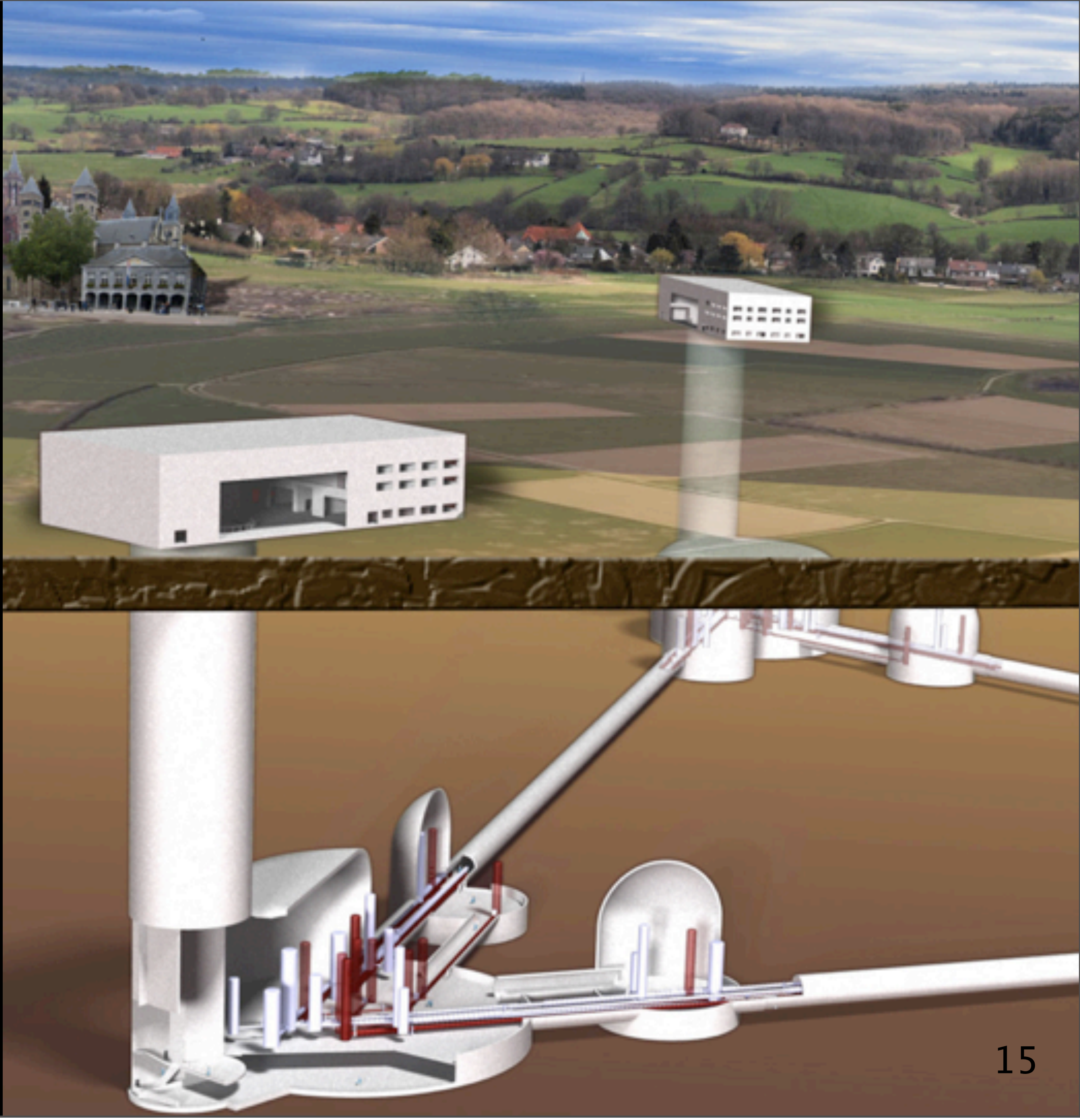
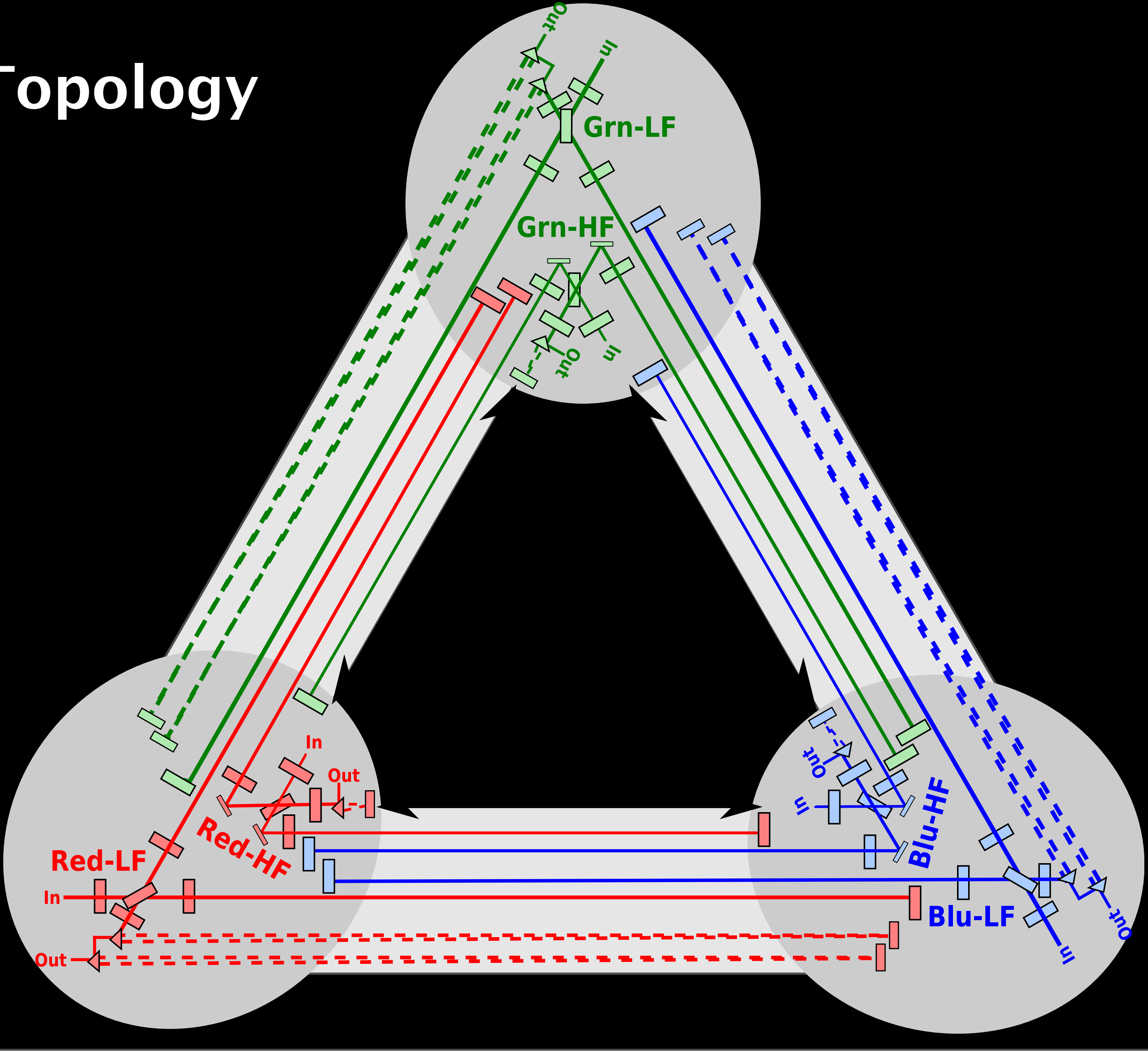
2008–2011
European
Conceptual
Design Study

2013–2016
ET R&D

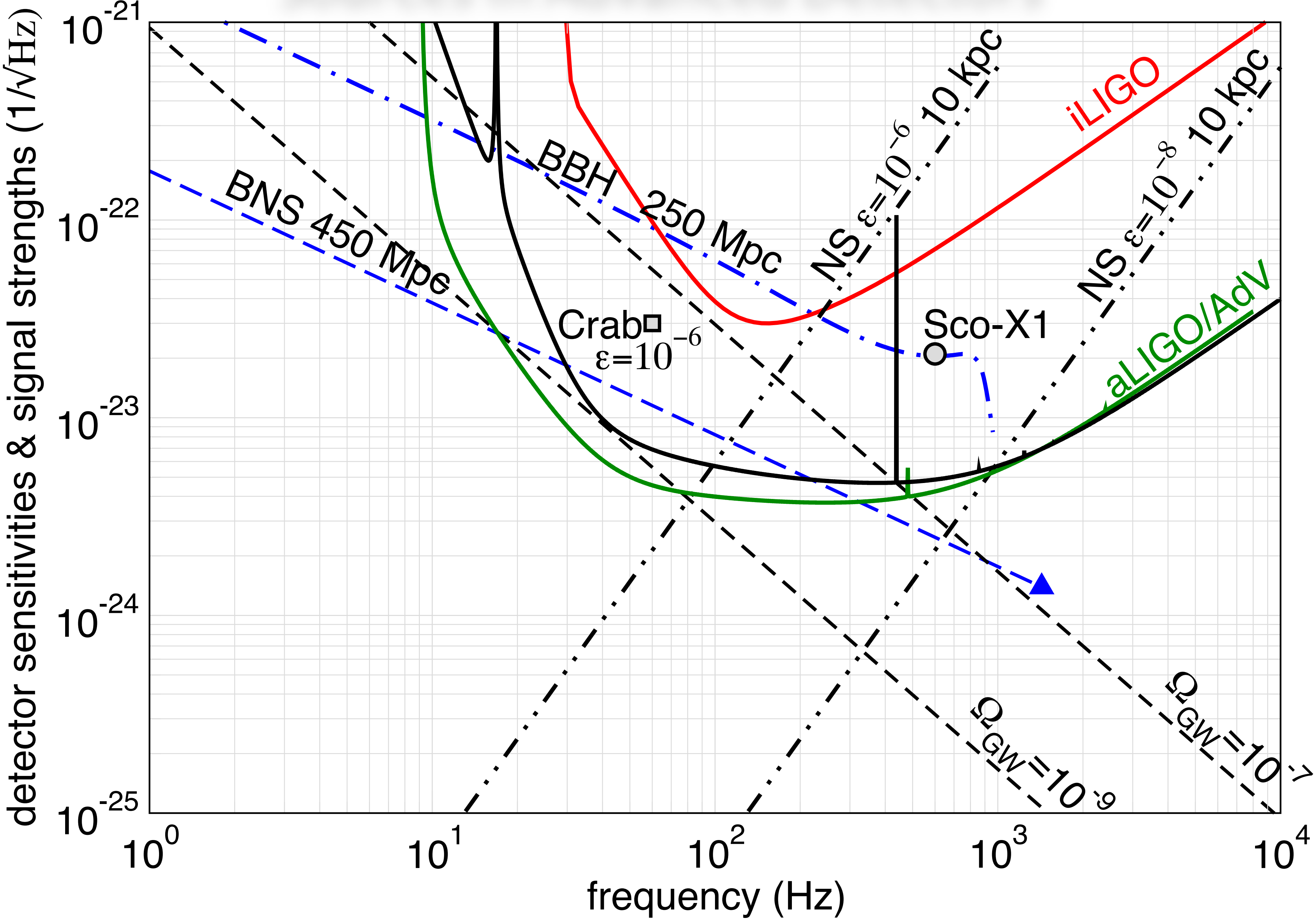
Underground
detectors
should have
Significant
reduction in
GG



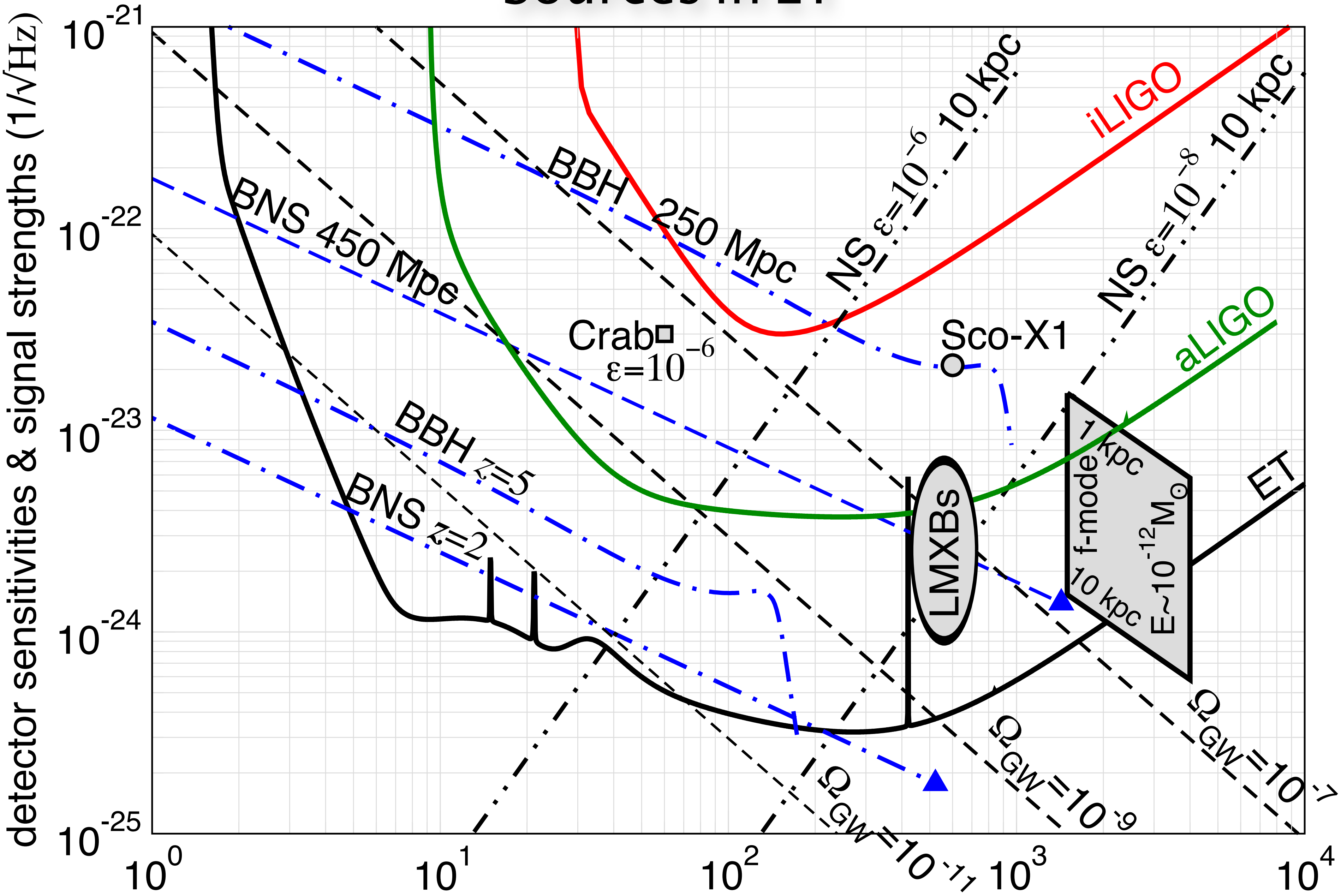
ET Topology


Out
In
Grn-LF
Grn-HF
Out
In
In
Out
Out
In
Red-LF
Red-HF
In
Out
Out
In
Blu-HF
Blu-LF
Out
In

Sources in Advanced Detectors



Sources in ET



Tuesday, 1 July 2014

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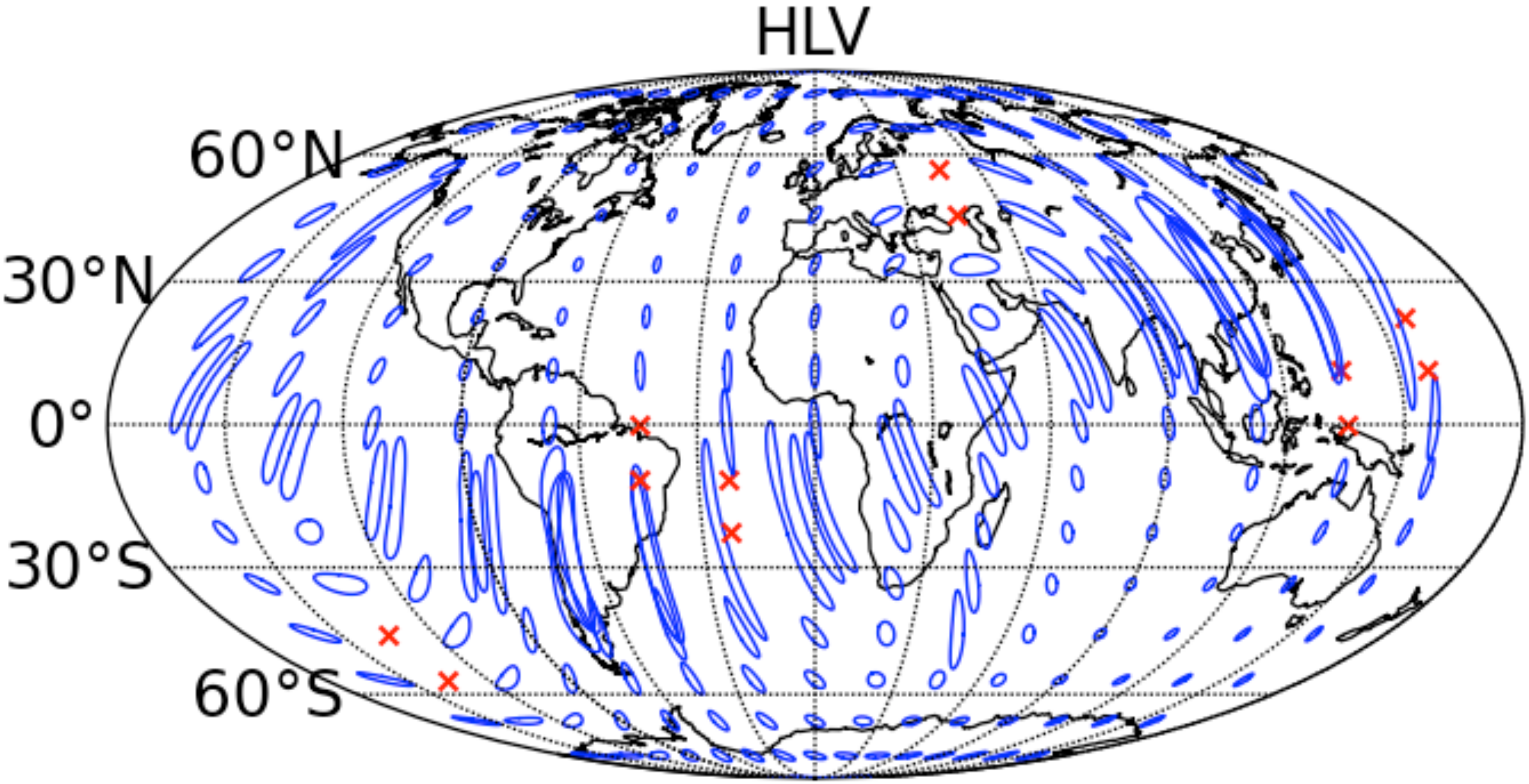
- **Source Distance** can be inferred if the signal model is accurate

Sky Localization Error Ellipses:

Binary Neutron Stars at 160 Mpc; Uses only Timing Information



Red crosses denote regions where the network has blind spots

Fairhurst 2011

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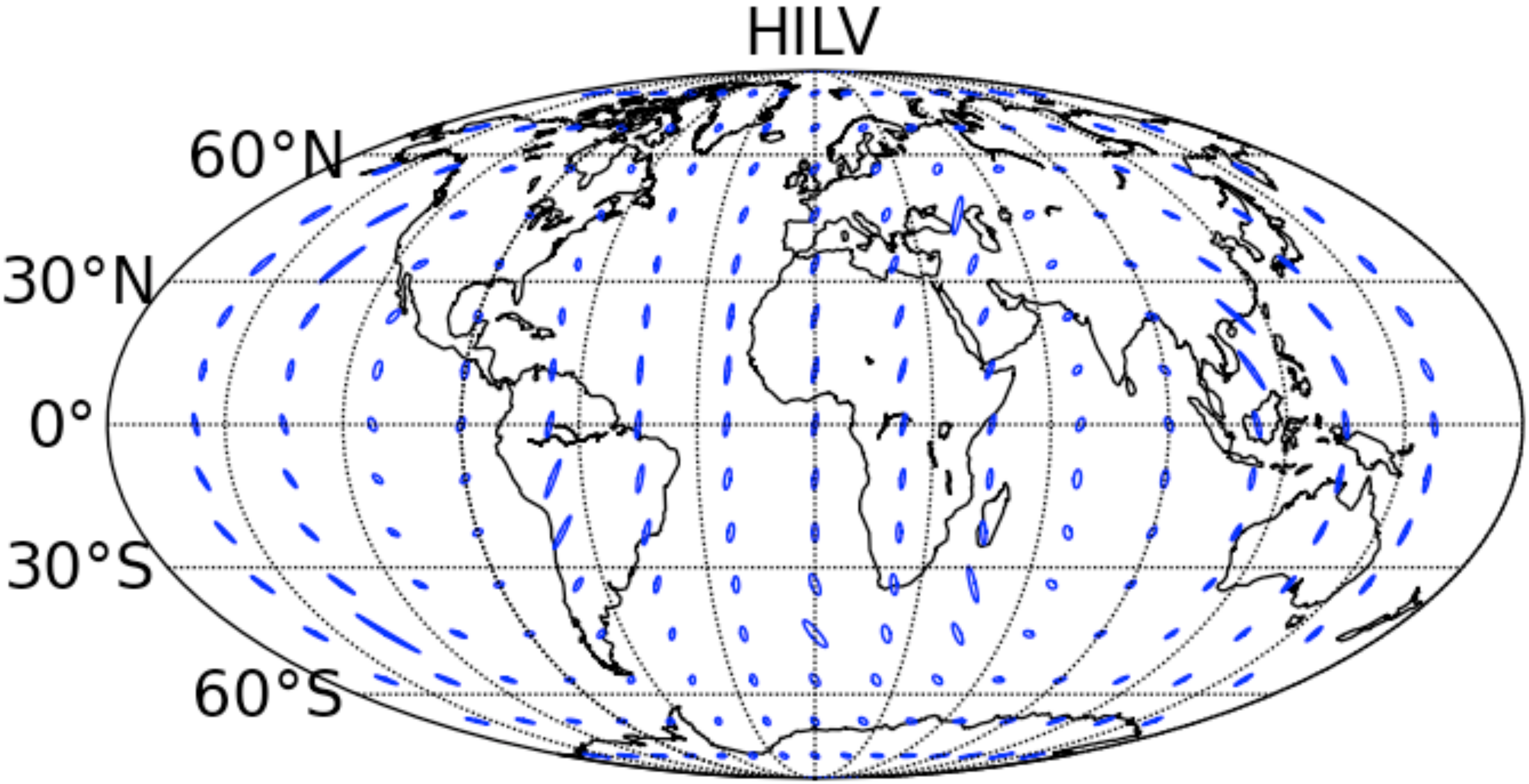


Fairhurst 2011

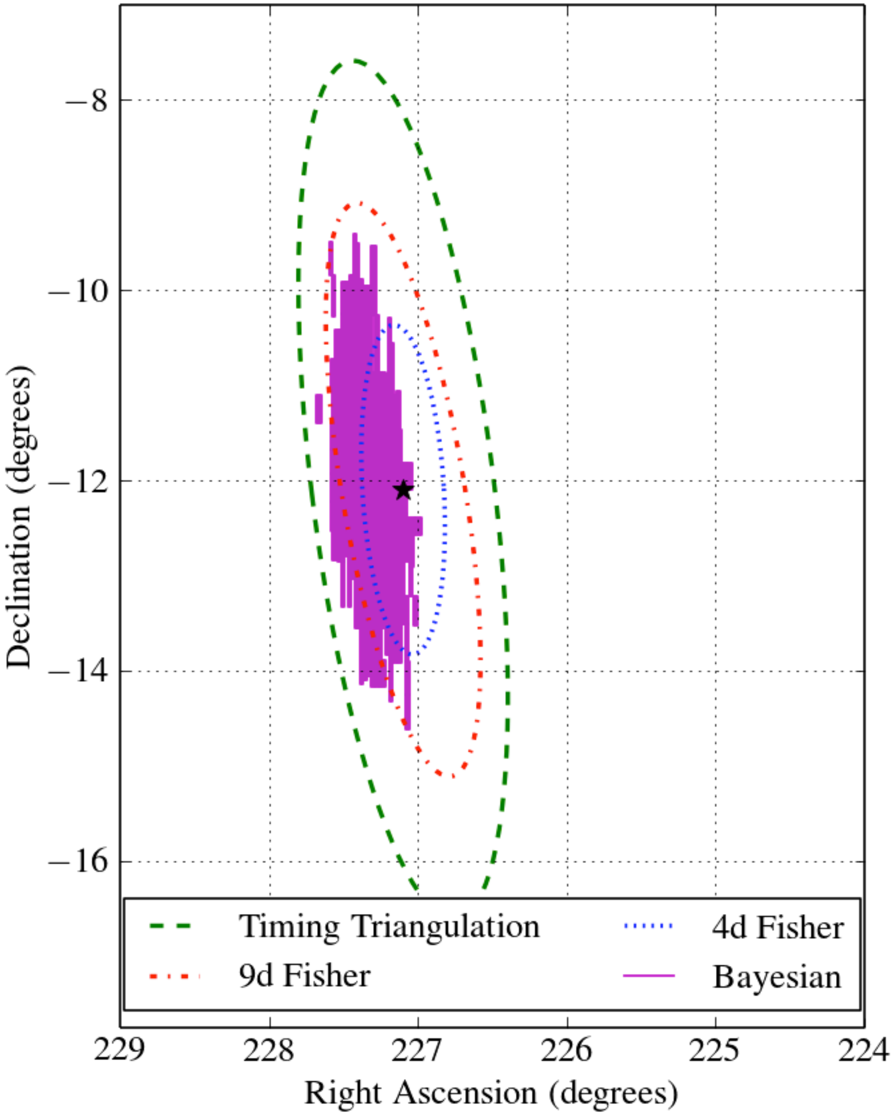
Comparison of Gravitational Wave Detector Network Sky Localization Approximations

K. Grover,[1] S. Fairhurst,[2] B. F. Farr,[3,1] I. Mandel,[1] C. Rodriguez,[3] T. Sidery,[1] and A. Vecchio[1]

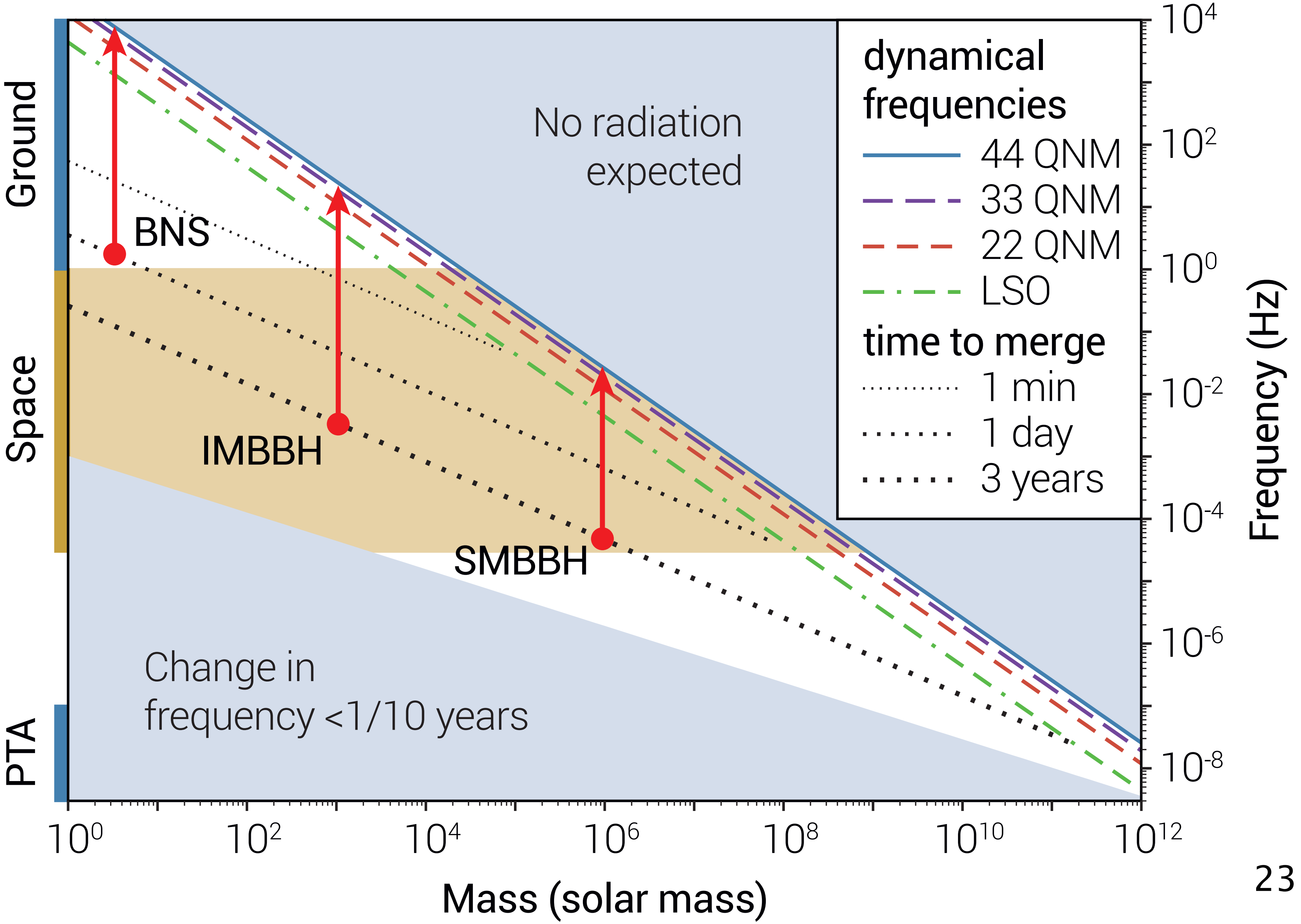
Sky Localization Improves when all the information is included:

A factor 3 better than was thought before

Median size of patches could be as small as about 2.5 Sq Degrees with LIGO–Virgo network



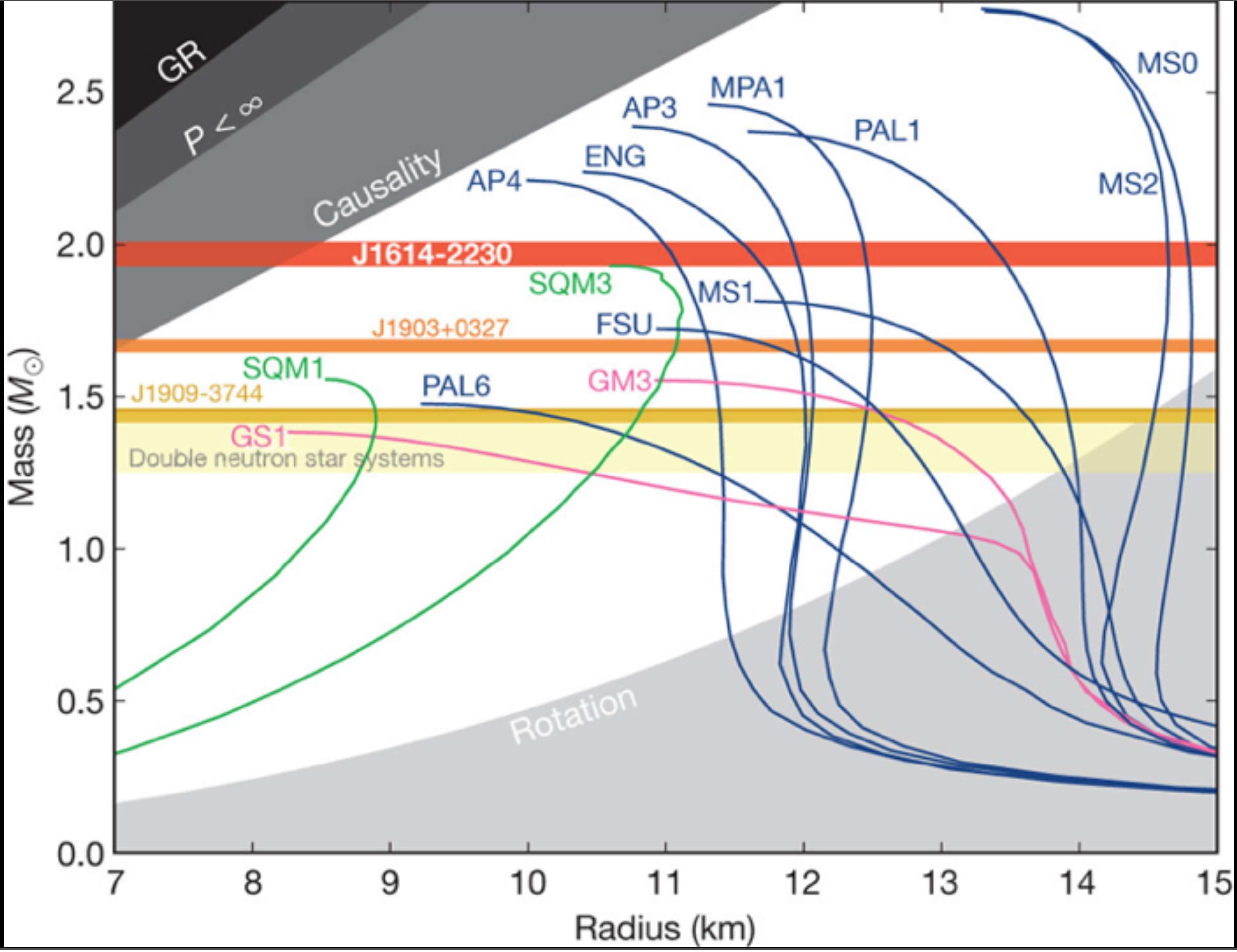
How long do BNS signals last in our detectors?



NS Equation_of_State

Maximum Mass of a Neutron Star and Mass Gap

- Heaviest known neutron star has a mass of 2 solar masses
  - Although many equations of state are ruled out by this model many more remain
- Finding heavier neutron stars is not likely to fix the problem
  - Many EoS predict heavier neutron stars with exotic cores
- Measuring both NS mass and Radius is the key
  - If radius can be measured to within a few km then EoS will be very tightly constrained
- Advanced detectors would go someway but ET will be critical to resolving the issues



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Effect of tides in BNS inspiral

K. G. Arun, B. R. Iyer, B. S. Sathyaprakash, and P. A. Sundararajan, Phys. Rev. D, **71**, 084008 (2005), arXiv:gr-qc/0411146.

$$\Psi_{PP}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta x^{5/2}} \sum_{k=0}^{N} \alpha_k x^{k/2}$$

T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D, **81**, 123016 (2010), arXiv:0911.3535 [astro-ph.HE].

$$\Psi^{\rm tidal}(f) = \sum_{a=1,2} \frac{3\lambda_a}{128\eta}\left[-\frac{24}{\chi_a}\left(1+\frac{11\eta}{\chi_a}\right)\frac{x^{5/2}}{M^5} \right. \qquad (3)$$

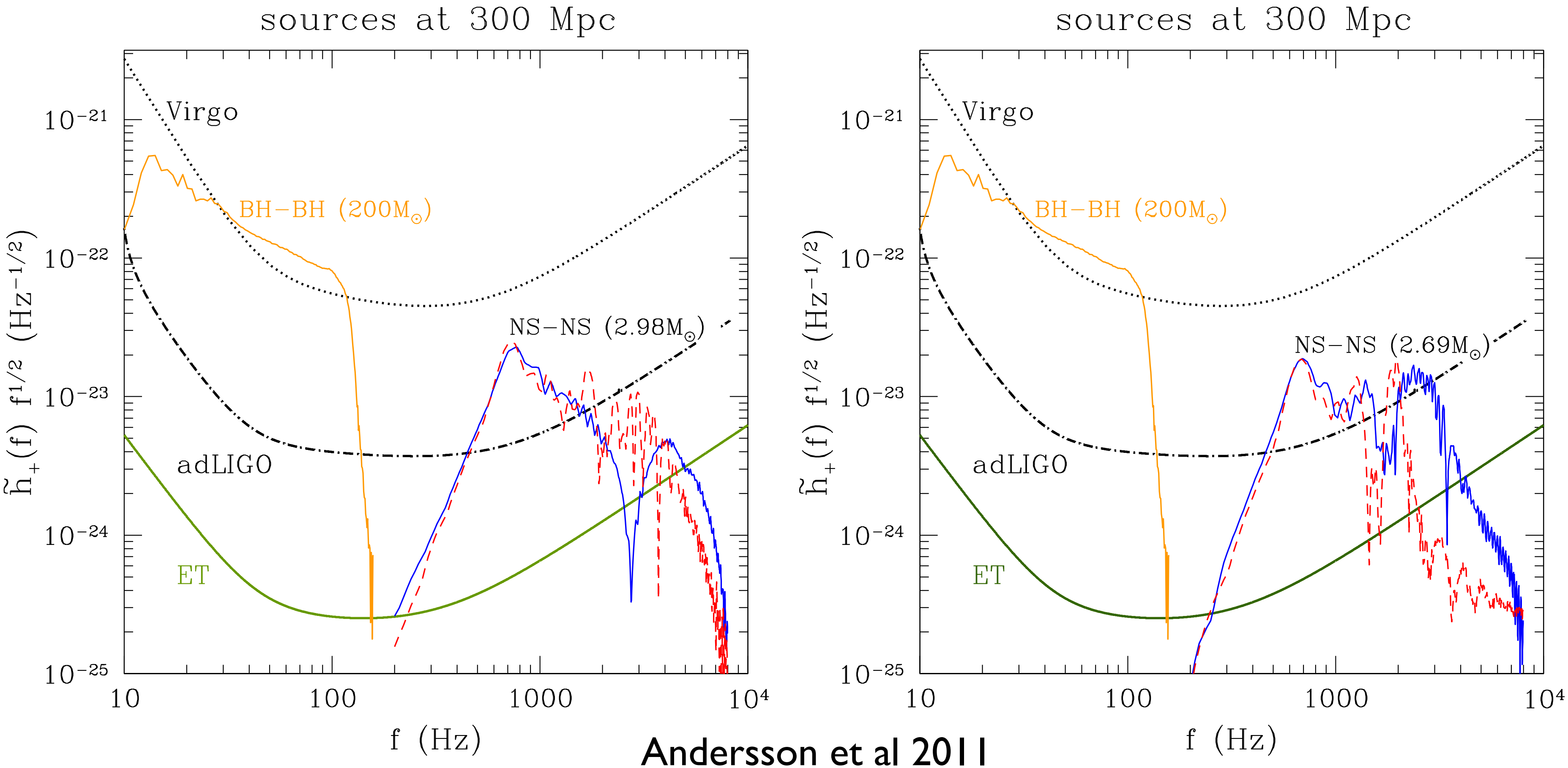
$$\left. -\frac{5}{28\chi_a}\left(3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3\right)\frac{x^{7/2}}{M^5}\right]$$

$$x = (\pi M f)^{2/3}$$

$$\lambda = (2/3) R_{\rm ns}^5 k_2$$

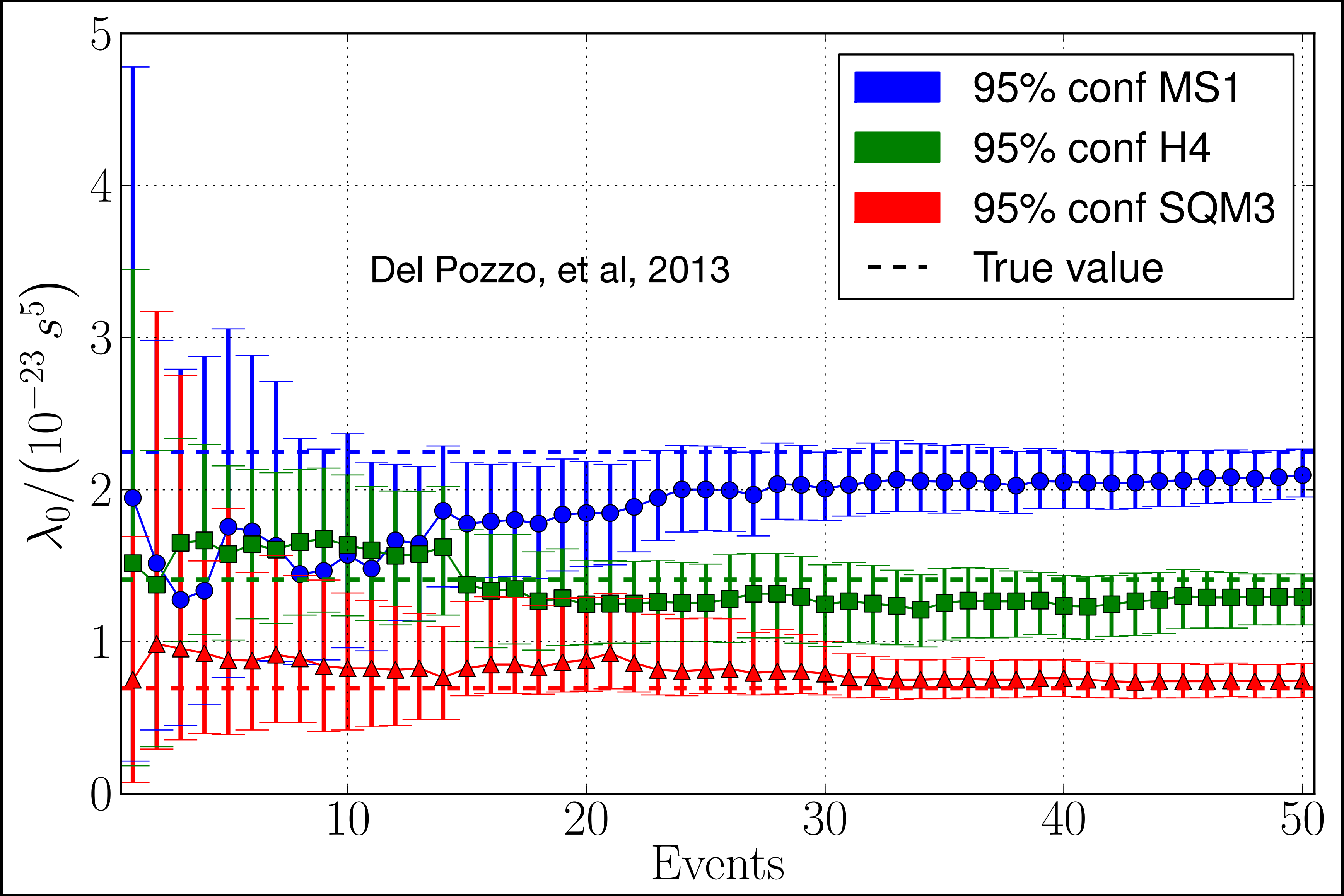
BNS mergers and equation of state of NS

- Spectrum of gravitational radiation from black hole binaries is featureless
- Radiation from binary neutron star mergers carries an imprint of the star's mass and equation of state



Andersson et al 2011

NS EoS with a population of BNS mergers: Advanced detectors, ~25 merger events



Dark Energy Equation_of_State

Why are BNS signals standard sirens?

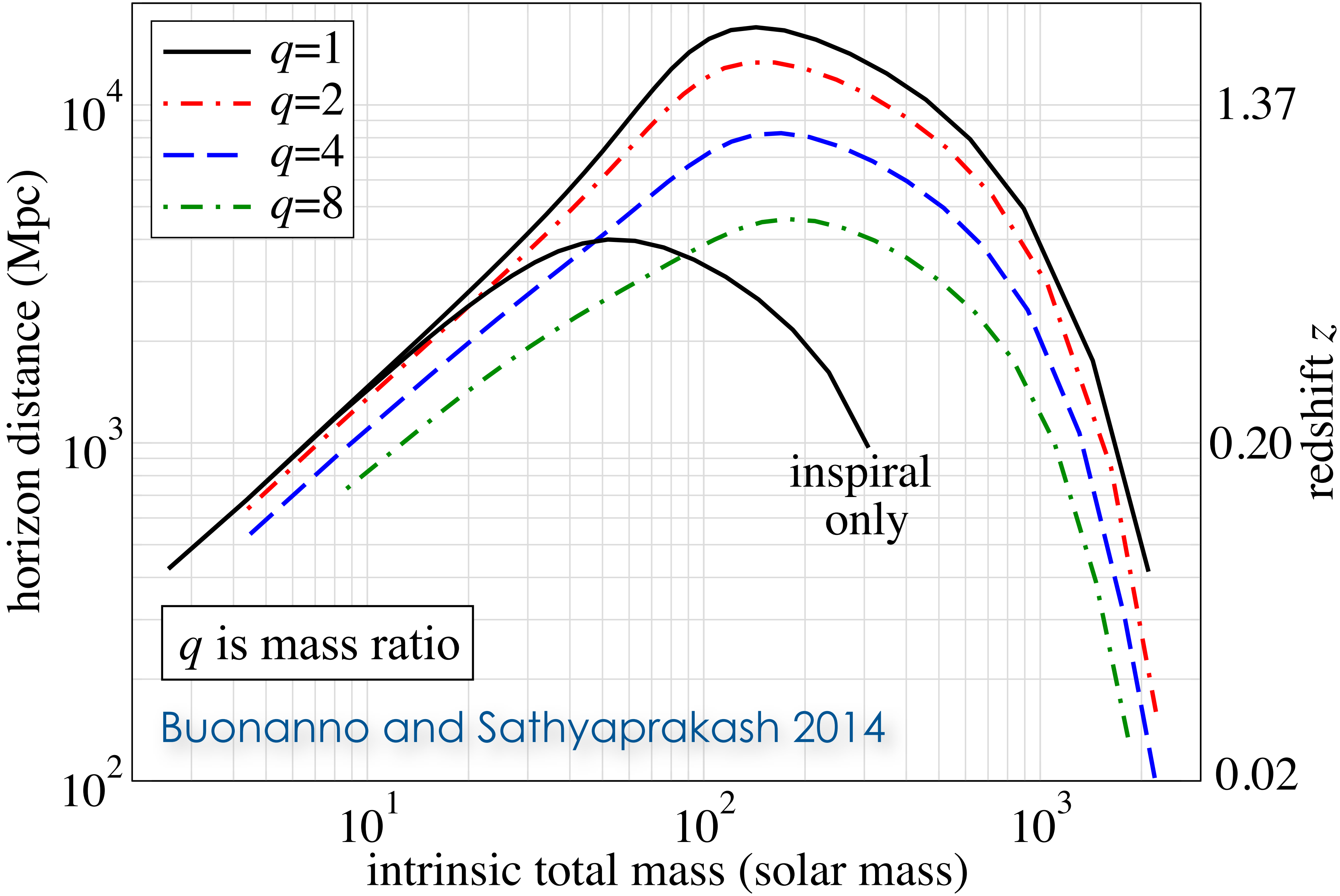
- Luminosity distance D can be inferred if one can measure:
  - the flux of radiation F and
  - absolute luminosity L

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

Schutz Nature1986

- Flux of gravitational waves determined by amplitude of gravitational waves measured by our detectors
- Absolute luminosity can be inferred from the rate $\dot{f}$ at which the frequency of a source changes
  - Not unlike Cephied variables except that $\dot{f}$ is completely determined by general relativity
- Therefore, compact binaries are self_calibrating standard sirens

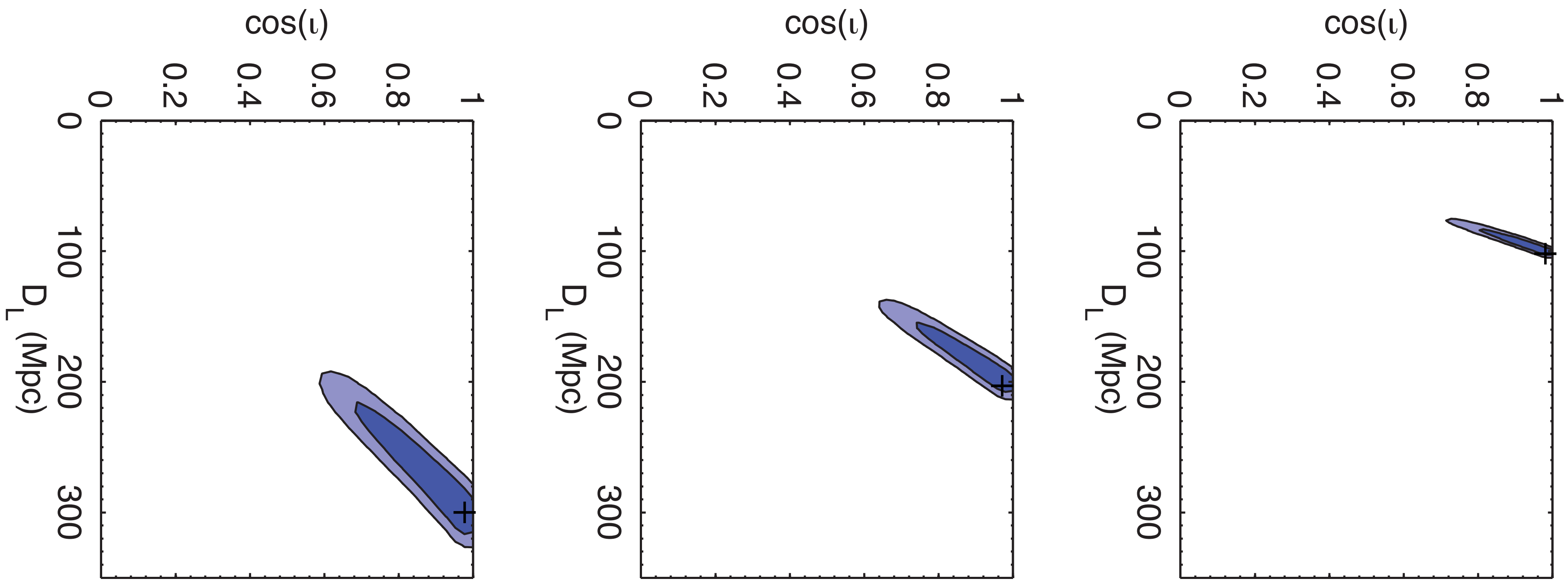
Advanced LIGO Distance Reach to Binary Coalescences



Buonanno and Sathyaprakash 2014

Hubble Constant from Advanced Detectors Assuming short_hard_GRBs are binary neutron stars

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,



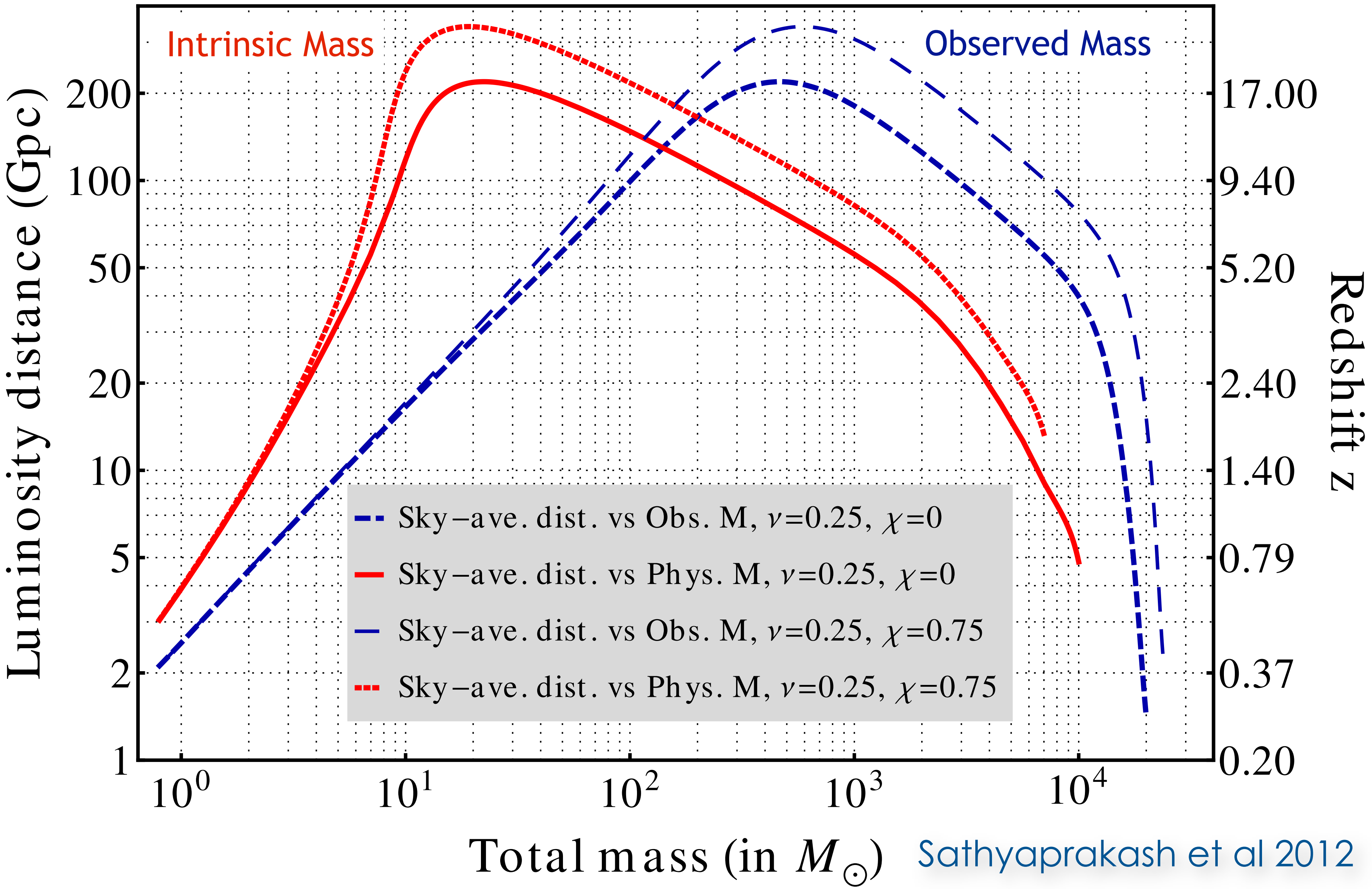
Nissanke et al 2009

Hubble Constant from Advanced Detectors without EM counterparts

- 25 events:
  - H_0= 69 ± 3 km s^{-1} Mpc^{-1} (~4% at 95% confidence)
- 50 events:
  - H_0= 69 ± 2 km s^{-1} Mpc^{-1} (~3% at 95% confidence)
- WMAP7+BAO+SnIa (Komatsu et al.,2011):
  - H_0= 70.2 ± 1.4 km s^{-1} Mpc^{-1} (~2% at 68% confidence)

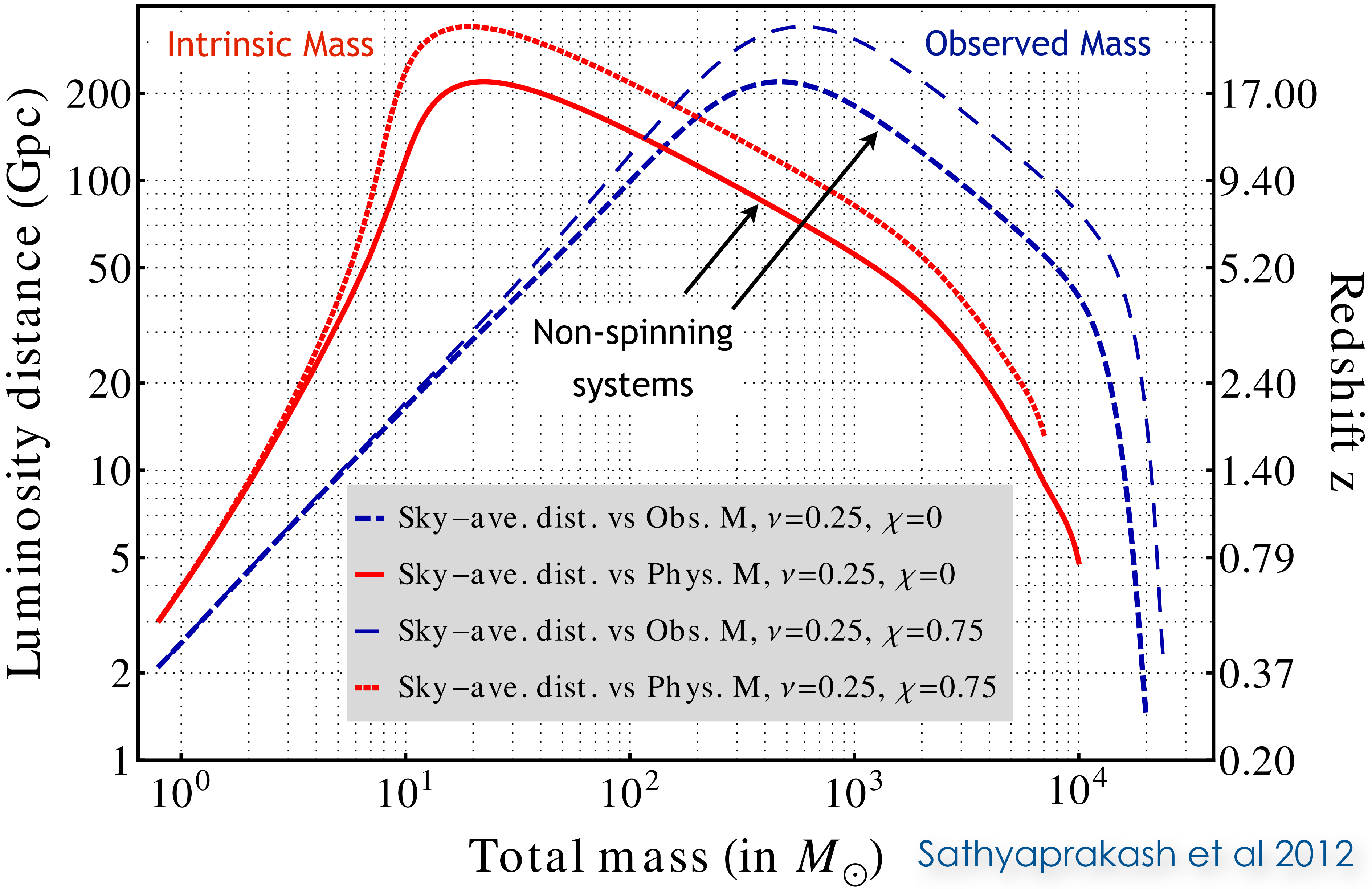
Del Pozzo, 2011

ET Distance Reach to Coalescing Binaries



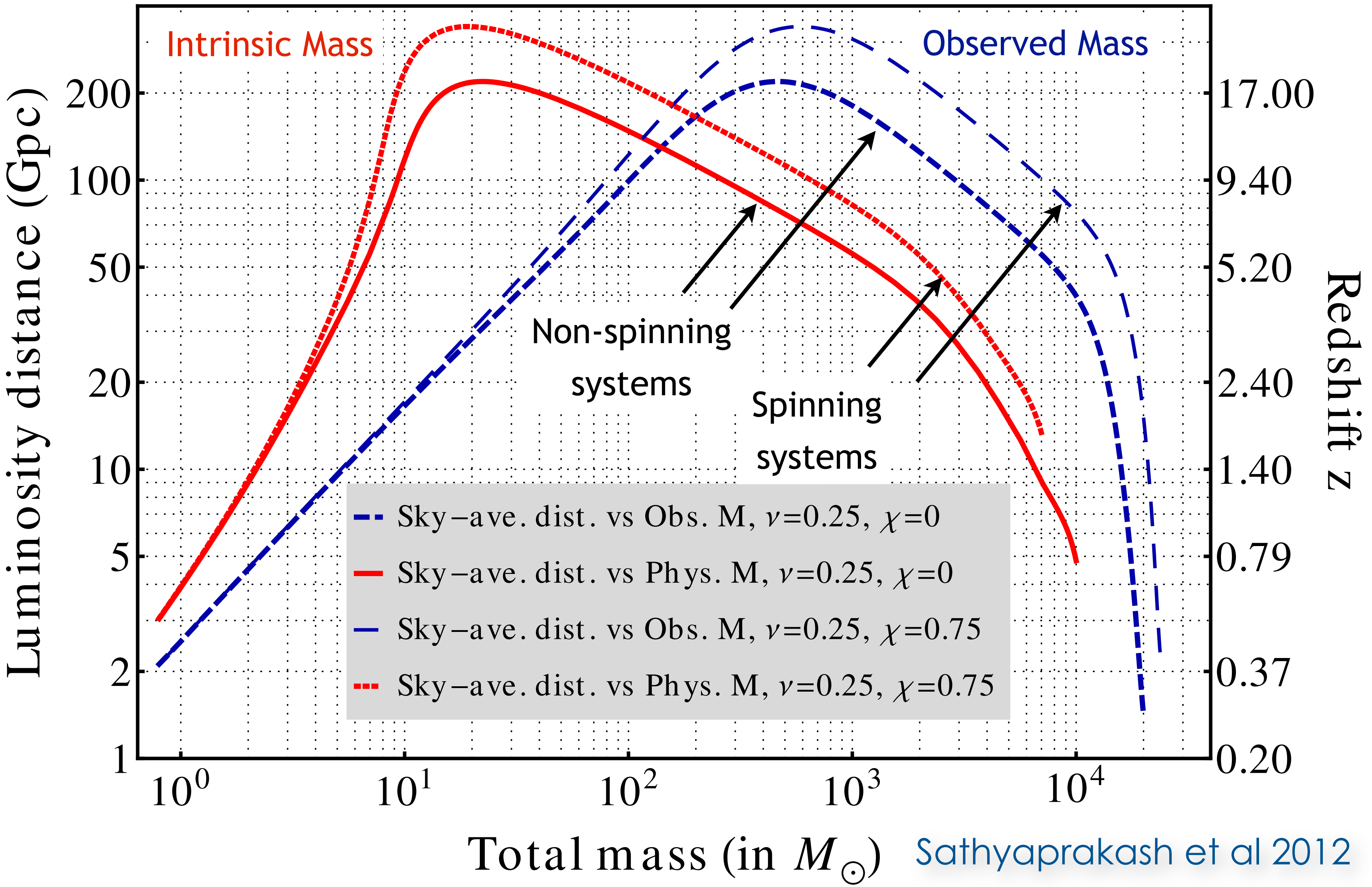
Sathyaprakash et al 2012

ET Distance Reach to Coalescing Binaries



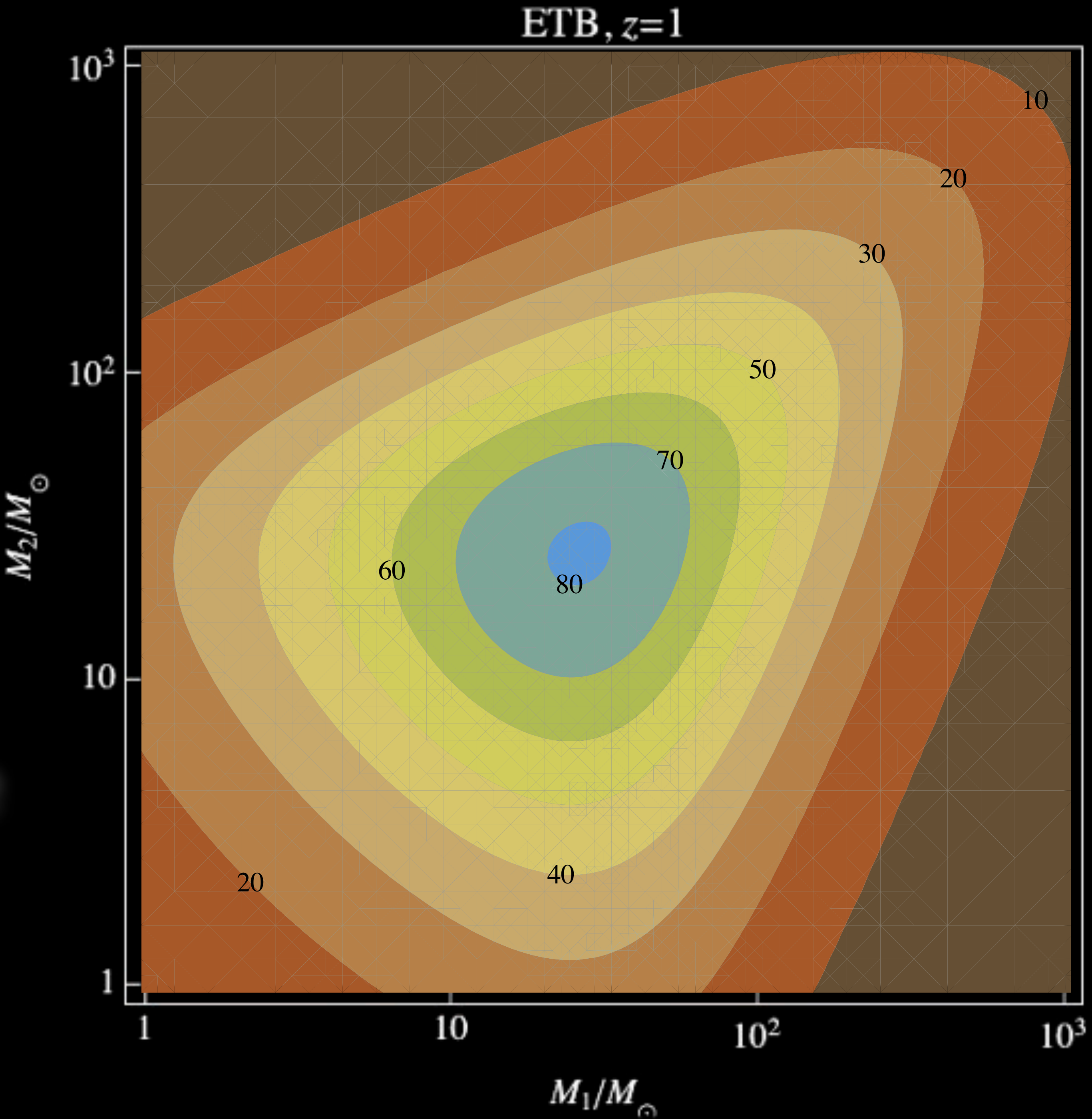
Sathyaprakash et al 2012

ET Distance Reach to Coalescing Binaries



Sathyaprakash et al 2012

Visibility of Binary Inspirals in Einstein Telescope

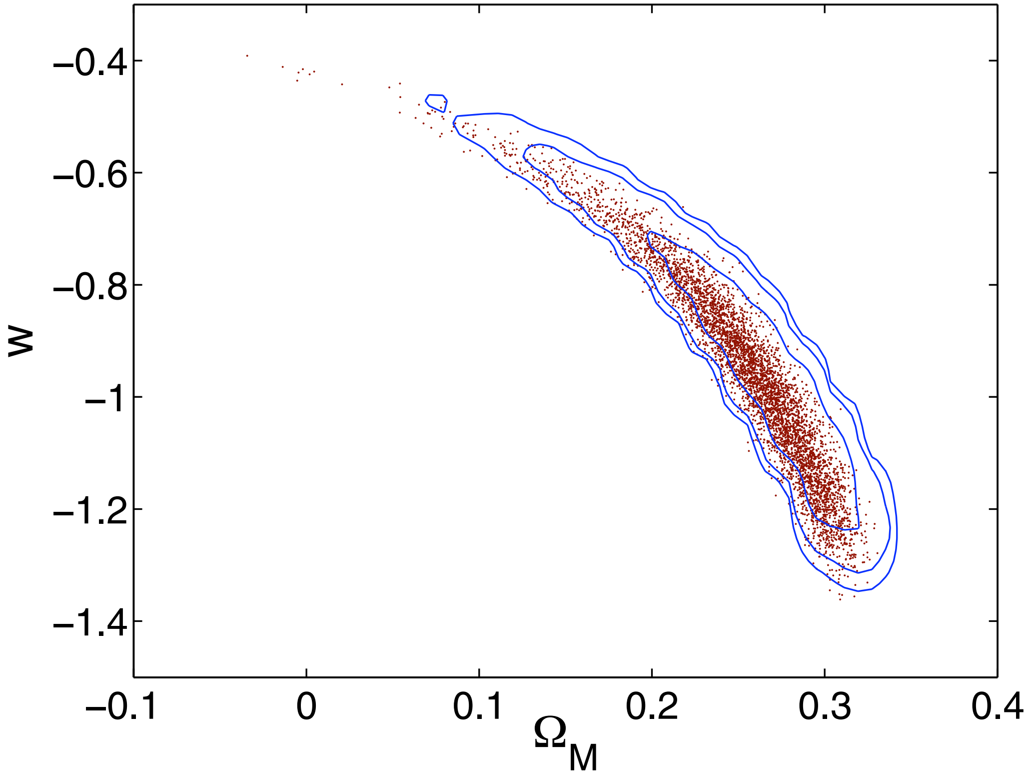


ET: Measuring Dark Energy and Dark Matter

- 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

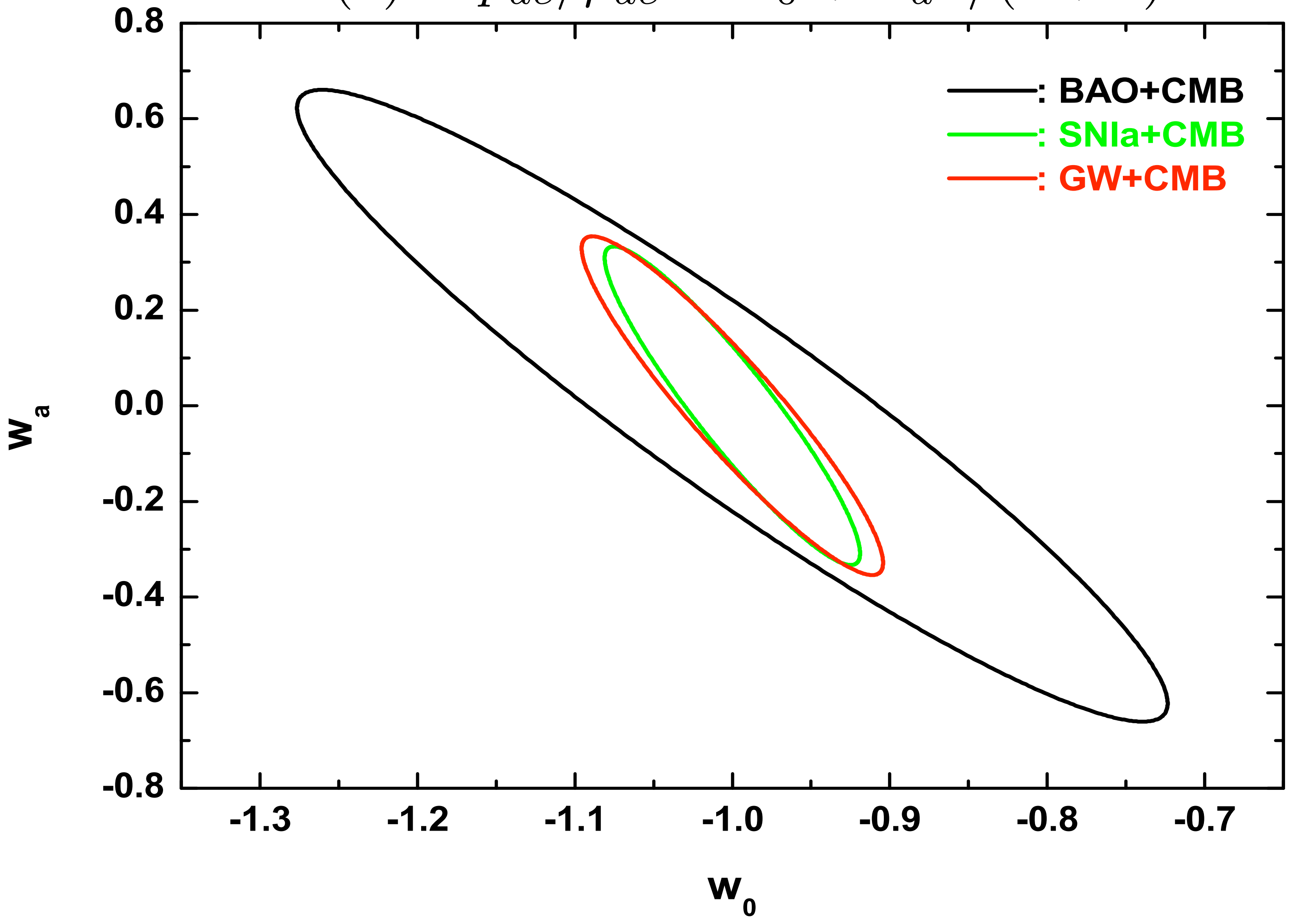
Sathyaprakash et al 2010

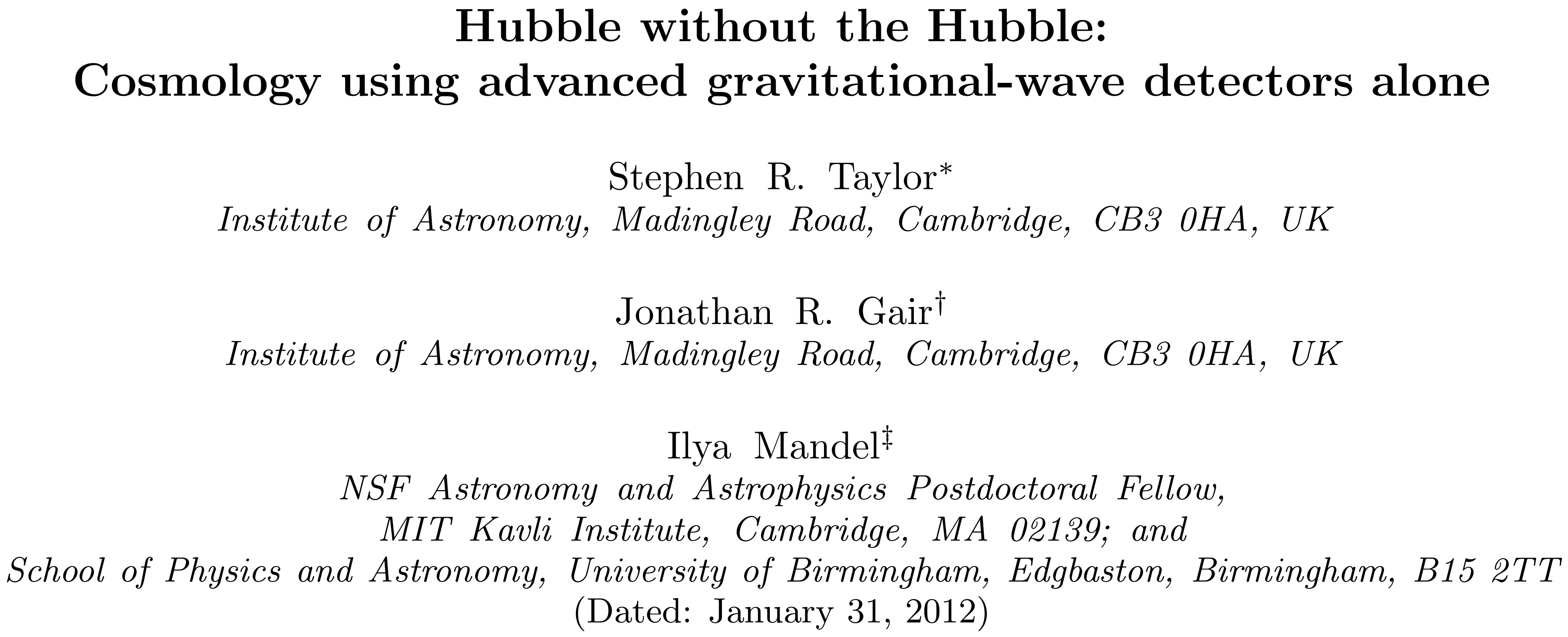


Measuring w and its variation with z

Baskaran, Van Den Broeck, Zhao, Li, 2011

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





Hubble without the Hubble: Cosmology using advanced gravitational-wave detectors alone

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MIT Kavli Institute, Cambridge, MA 02139; and
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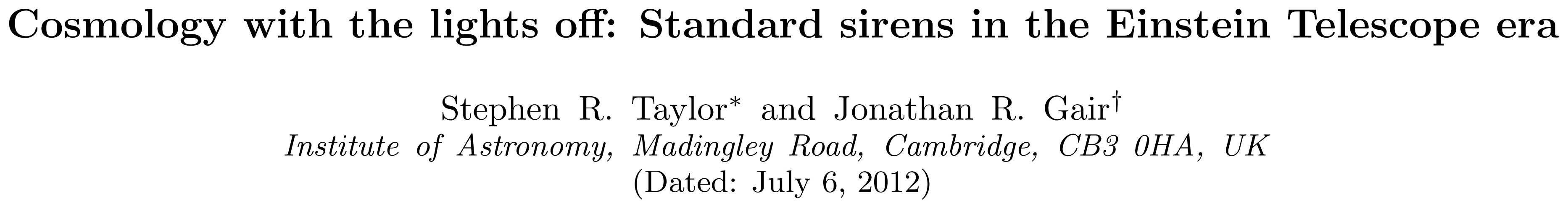
(Dated: January 31, 2012)



Cosmology with the lights off: Standard sirens in the Einstein Telescope era

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Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

(Dated: July 6, 2012)

Cosmology without EM Counterparts

- Distribution of Chirp Mass

$$\mathcal{M} \sim N(\mu_c, \sigma_c^2),$$

$$\mu_c \approx 2(0.25)^{3/5}\mu_{\rm NS}, \quad \sigma_c \approx \sqrt{2}(0.25)^{3/5}\sigma_{\rm NS},$$

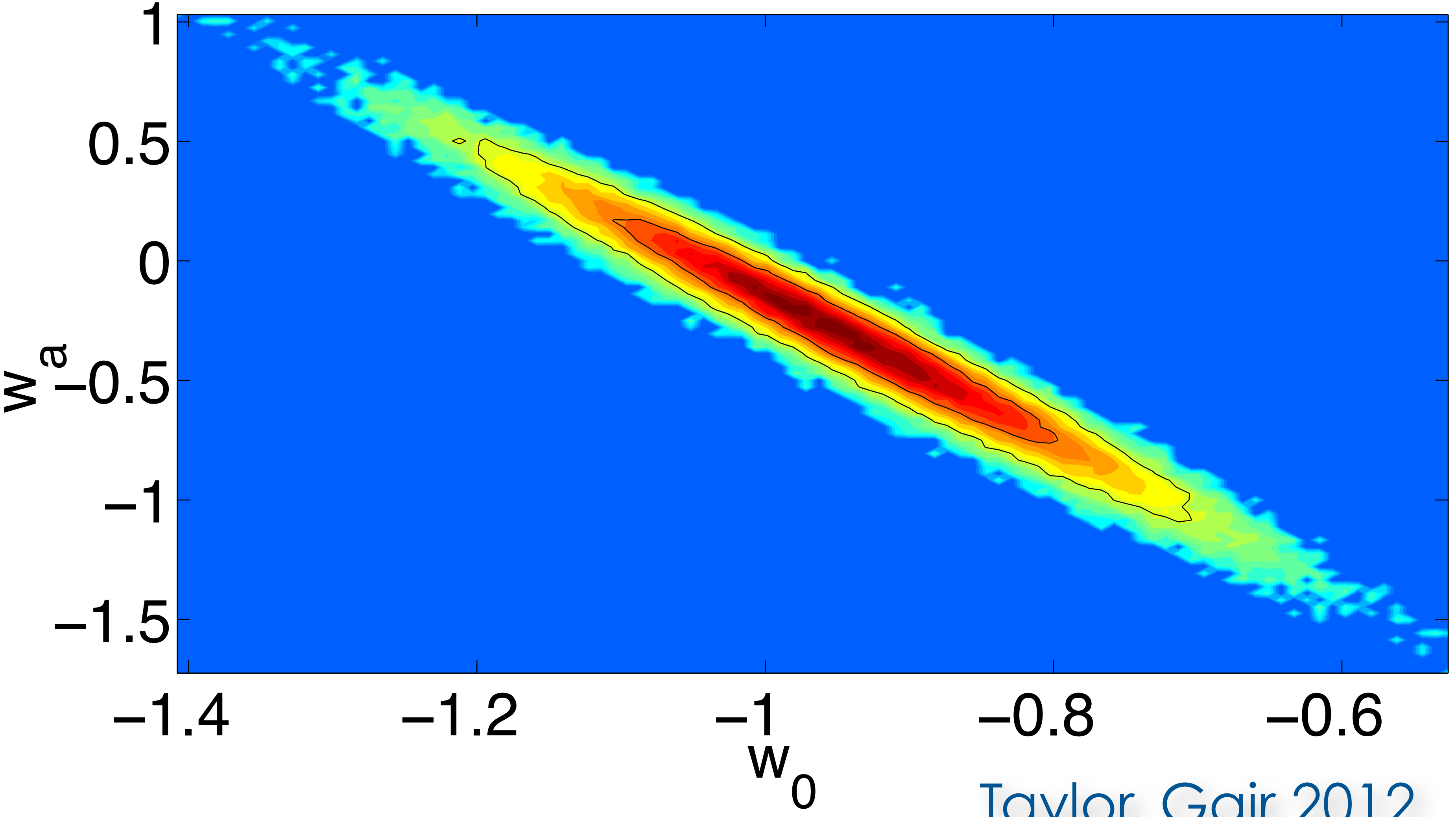
$$\mu_{\rm NS} \in [1.0, 1.5]M_\odot, \; \sigma_{\rm NS} \in [0, 0.3]M_\odot$$

$$w(a) = w_0 + w_a(1-a),$$

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right).$$

Taylor, Gair 2012

Measuring dark energy EoS and its variation with redshift



Taylor, Gair 2012

Measuring red_shift from GW observations alone

Messenger–Read method to measure redshift makes use of the post–Newtonian tidal term

K. G. Arun, B. R. Iyer, B. S. Sathyaprakash, and P. A. Sundararajan, Phys. Rev. D, **71**, 084008 (2005), arXiv:gr-qc/0411146.

$$\Psi_{PP}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta x^{5/2}} \sum_{k=0}^{N} \alpha_k x^{k/2}$$

T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D, **81**, 123016 (2010), arXiv:0911.3535 [astro-ph.HE].

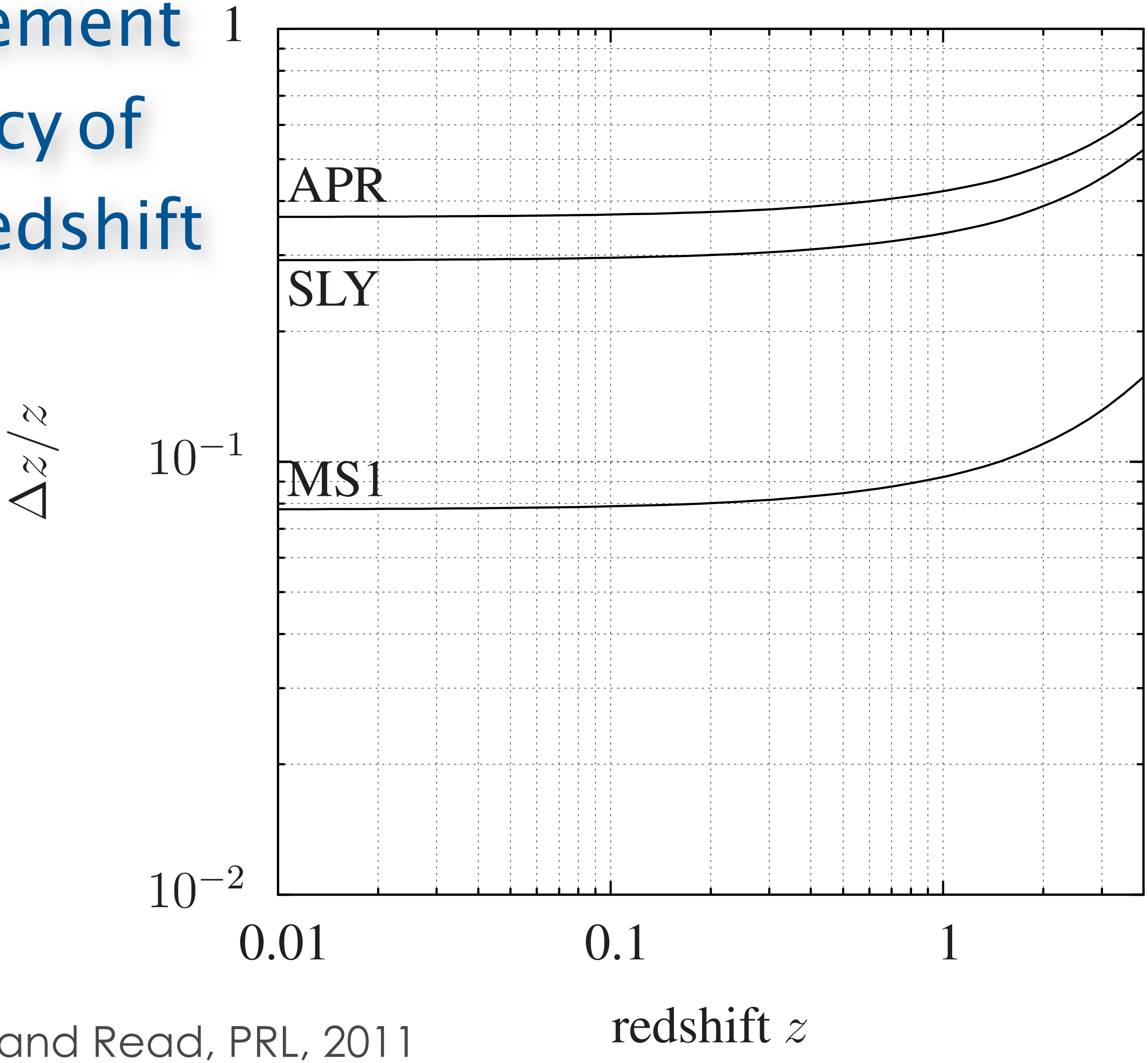
$$\Psi^{\rm tidal}(f) = \sum_{a=1,2} \frac{3\lambda_a}{128\eta} \left[-\frac{24}{\chi_a}\left(1 + \frac{11\eta}{\chi_a}\right)\frac{x^{5/2}}{M^5} \right. \qquad (3)$$

$$\left. -\frac{5}{28\chi_a}\left(3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3\right)\frac{x^{7/2}}{M^5} \right]$$

$$x = (\pi M f)^{2/3}$$

$$\lambda = (2/3) R_{\rm ns}^5 k_2$$

Measurement accuracy of source redshift

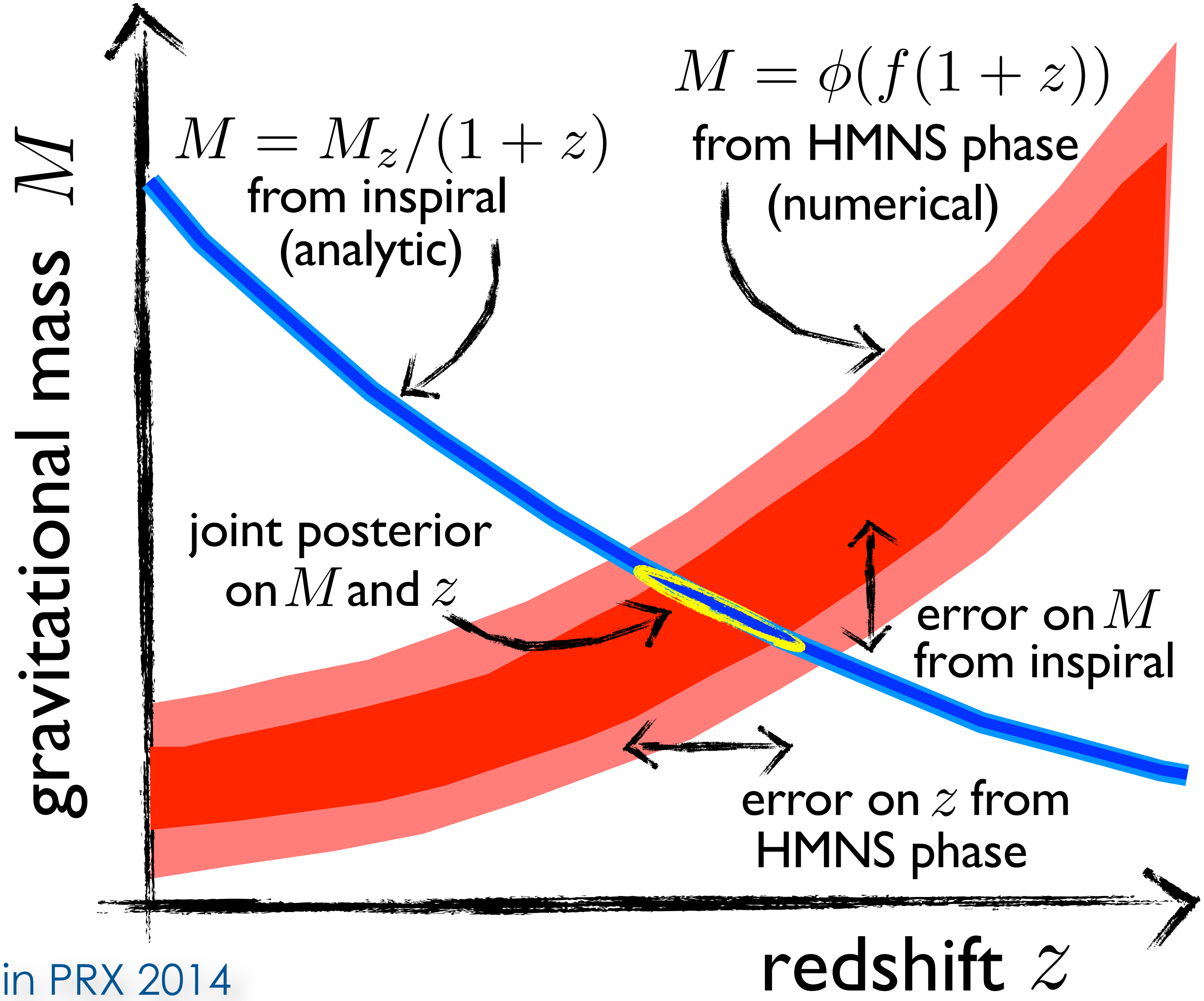


Messenger and Read, PRL, 2011

Host redshifts from gravitational wave observations

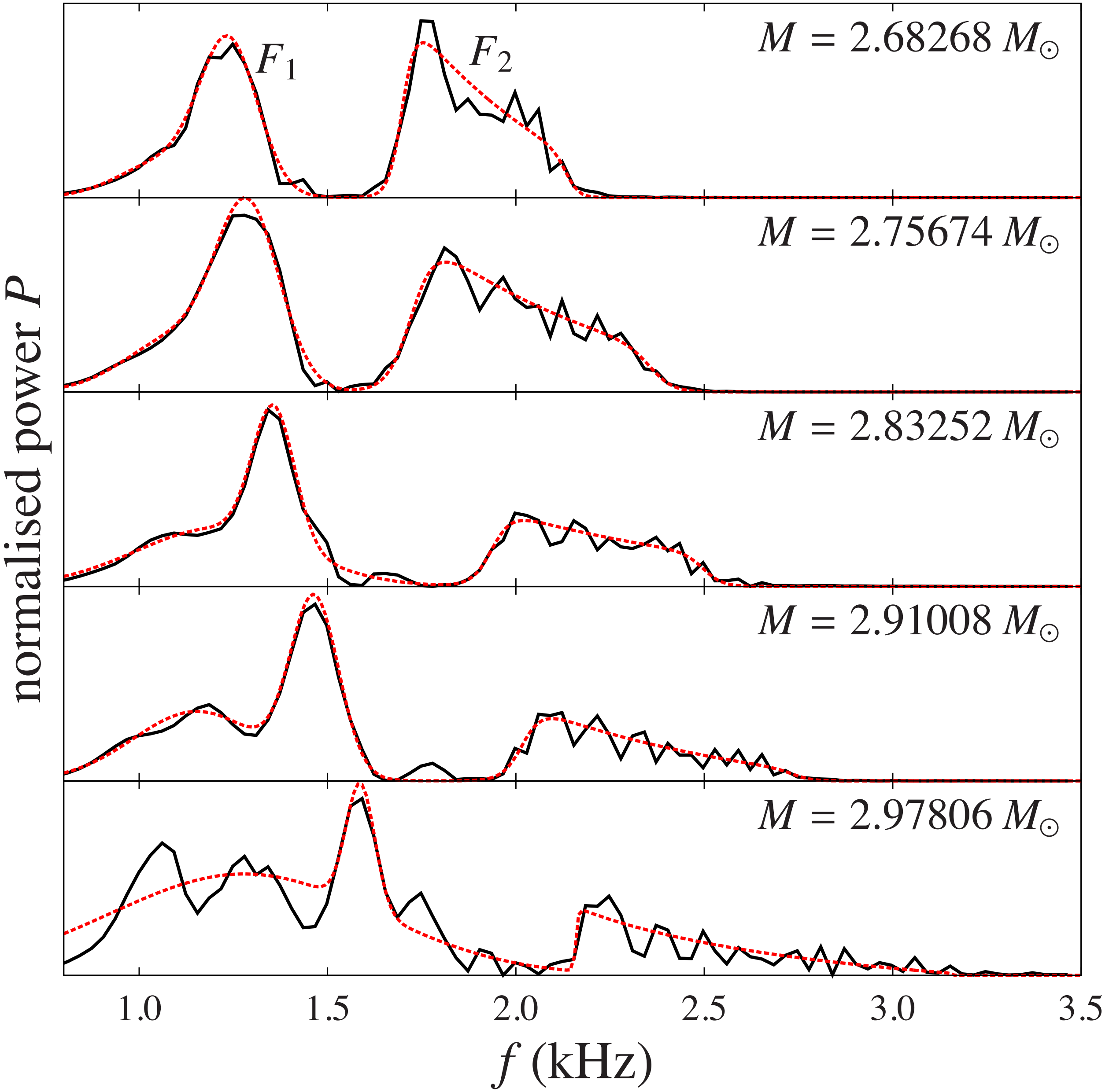
Host-galaxy redshifts from gravitational-wave observations of binary neutron star mergers

C. Messenger,[1] Kentaro Takami,[2,3] Sarah Gossan,[4] Luciano Rezzolla,[3,2] and B. S. Sathyaprakash[5]

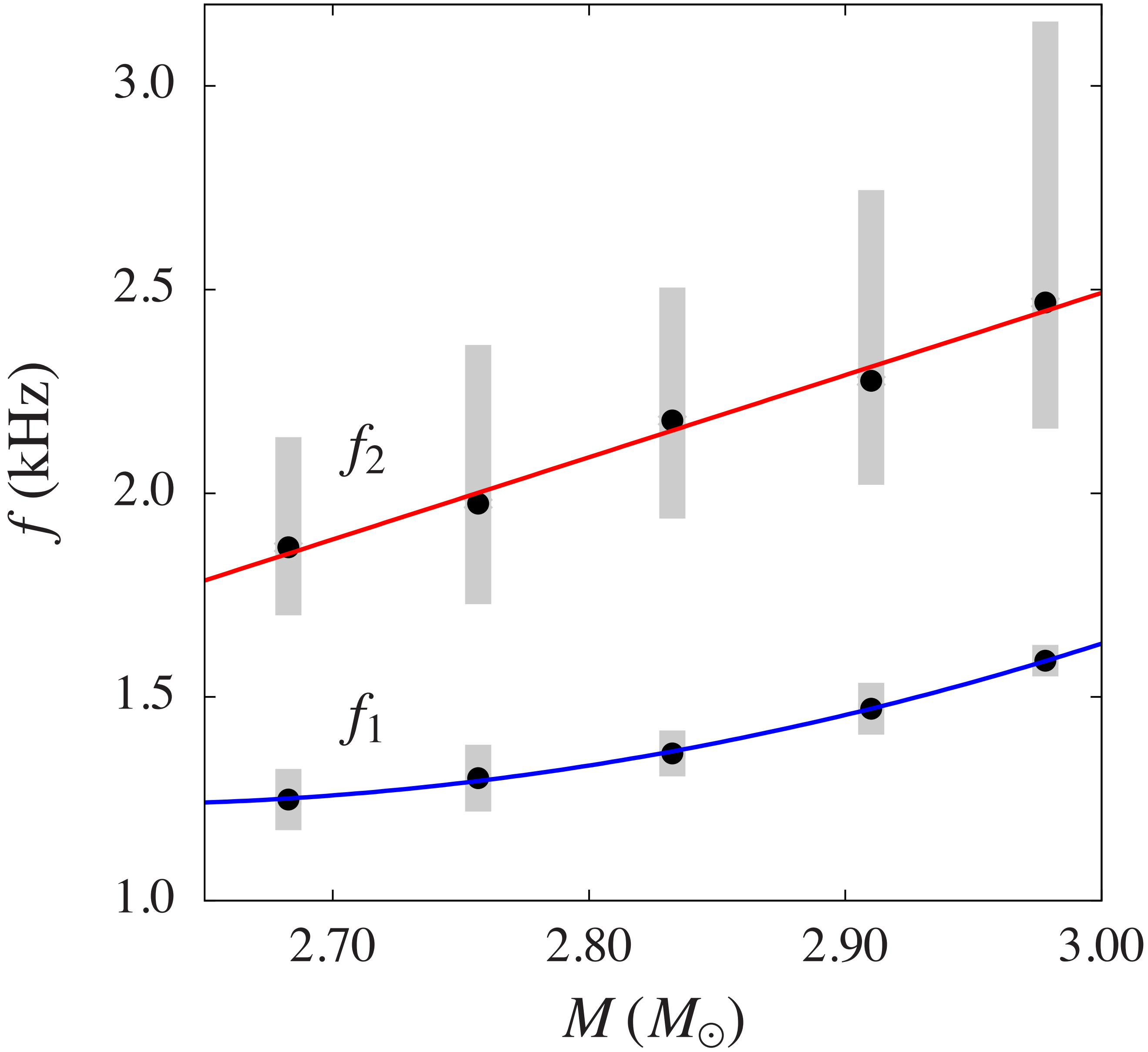


to appear in PRX 2014

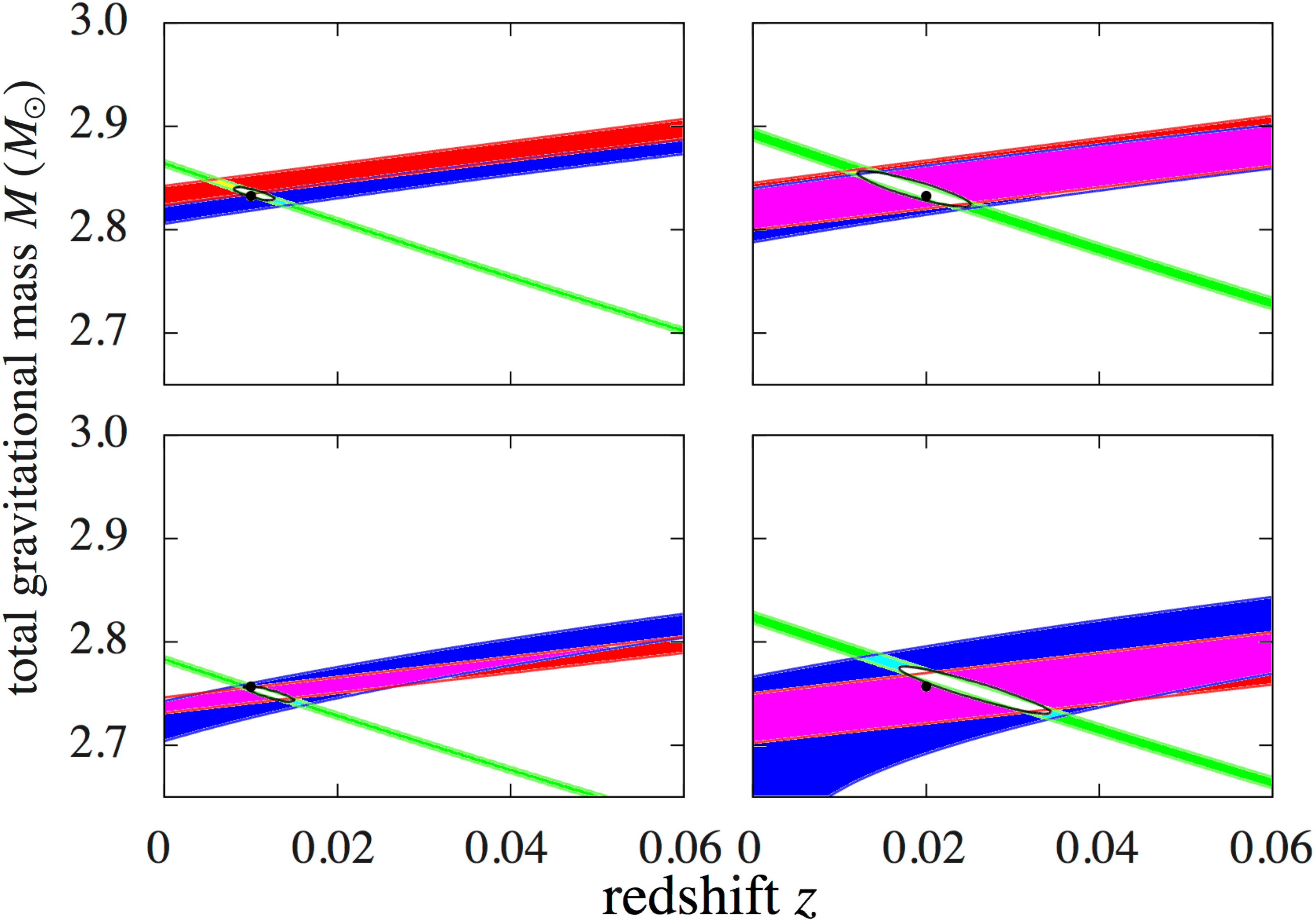
Binary Neutron Star GW Spectrum – post Merger



Measurement Accuracies of Char. Frequencies



How well can we measure z?



Topics for discussion

- Missing post-Newtonian terms
  - Tidal terms are at 5 and 5.5 PN order; unknown terms at 4 and 4.5 PN severely bias the estimation of parameters
  - What progress can be made in computing 4 and 4.5 PN terms?
  - Are there other ways of mitigating the effect of unknown PN terms?
- Signal from the merger phase and bar mode instability
  - Would it be possible to build a complete analytic model for the signal emitted during and post-merger?
- Effect of strong magnetic fields, high spins, multi-component fluid, ...
  - How far away are we from "realistic" BNS simulations?
  - How good are these simulations: stability and convergence?