GRAVITATIONAL WAVE ASTRONOMY WITH COMPACT BINARIES: LOCALISATION AND LATENCY

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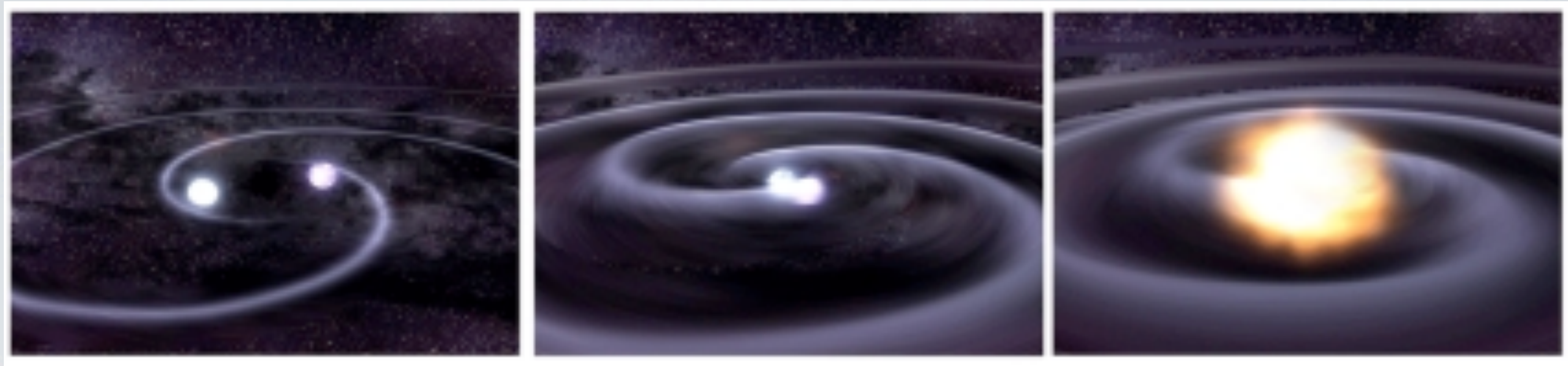
LIGO-G1200760

Refs: arXiv:0908.2356; 1010.6192; 1205.6611

THE ROYAL SOCIETY
CELEBRATING 350 YEARS

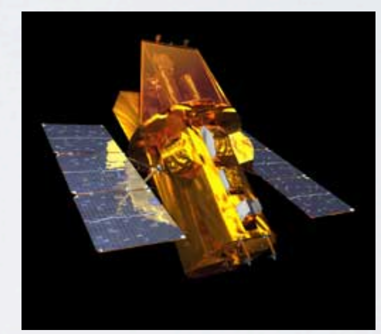
twenty ten and beyond | 350 years of excellence in science

And new results, in collaboration with D. Brown and P. Sutton

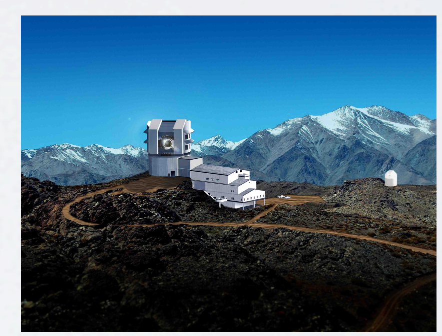


Gravitational Wave

Gamma Ray, X-ray

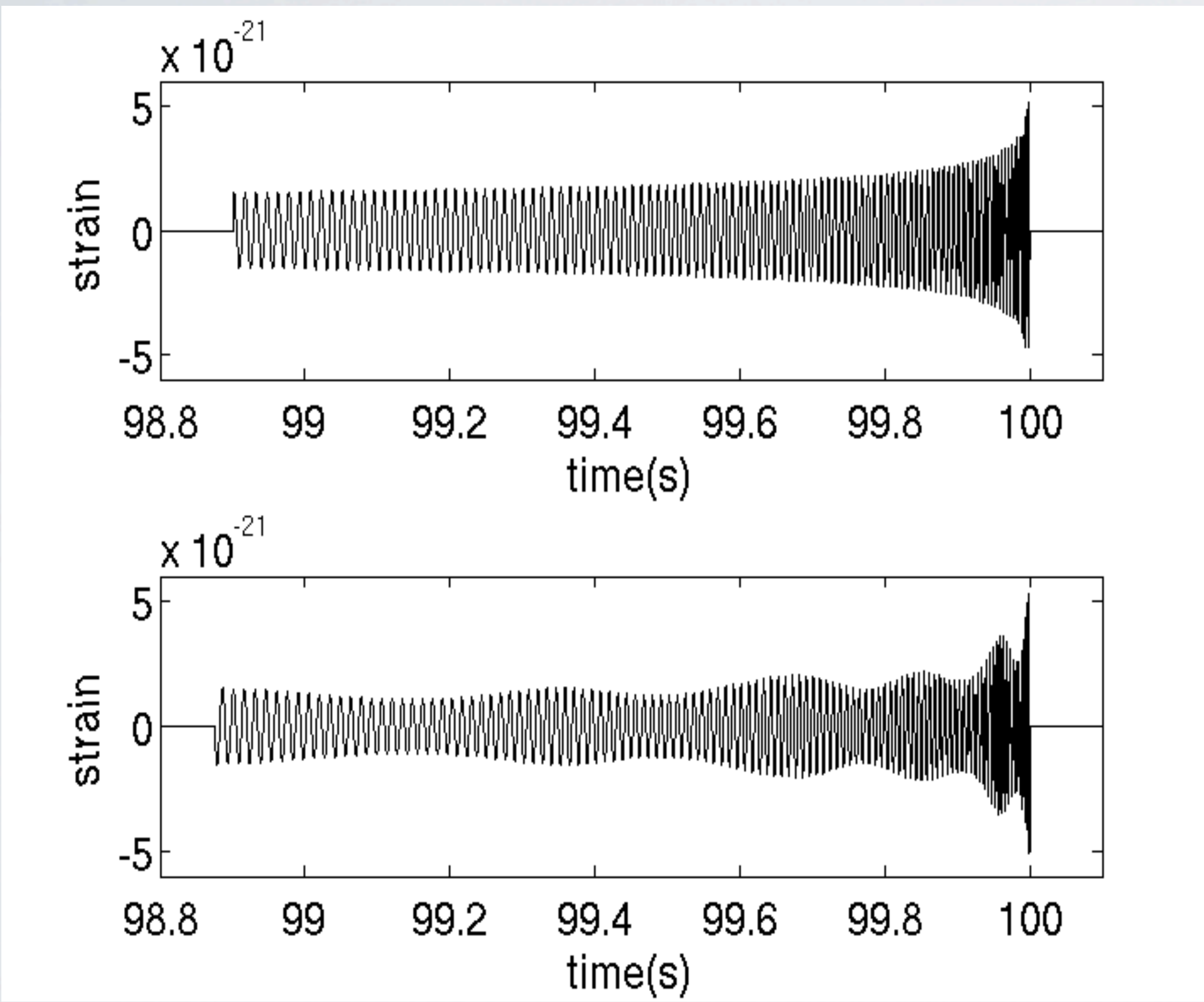


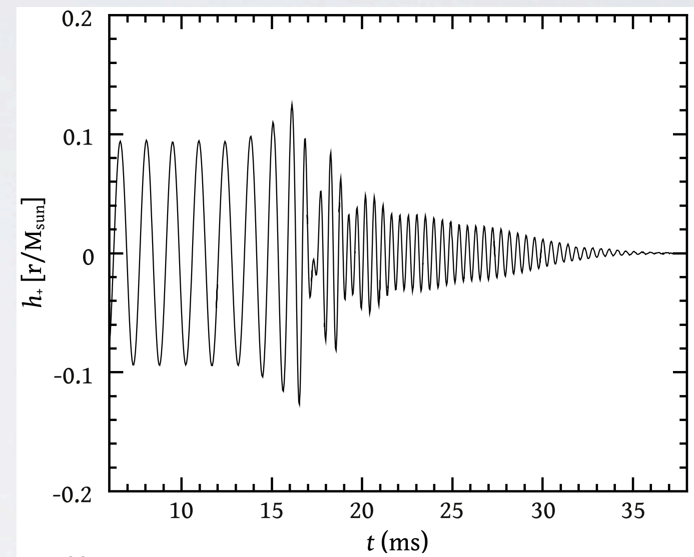
Optical



Radio

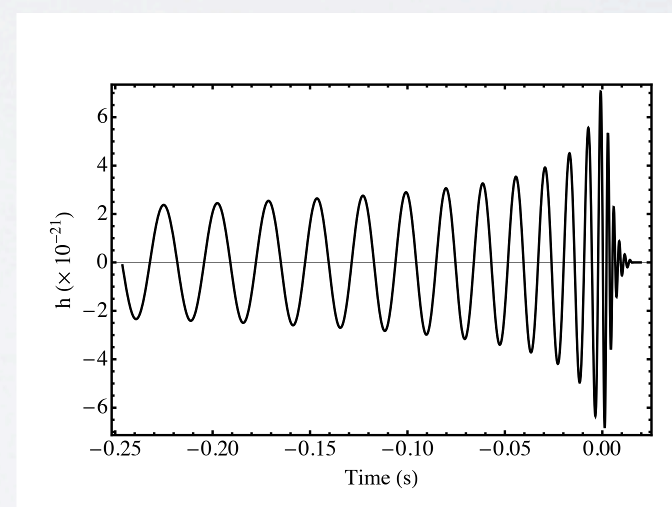
BINARY COALESCENCE WAVEFORMS





BNS Merger

Stergioulas et. al. arXiv 1105:0368



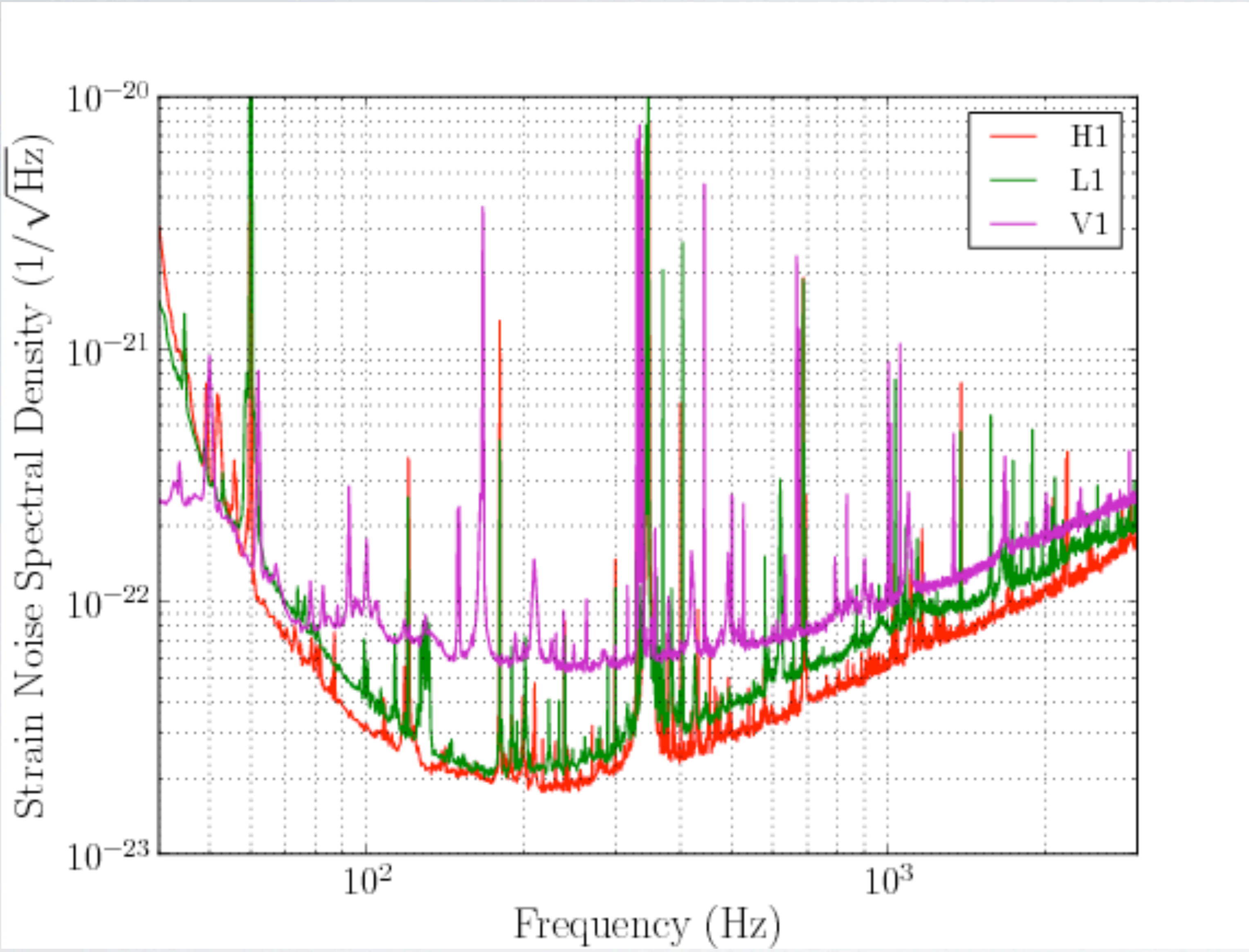
BBH Merger

Hannam et. al. arXiv0901:2437

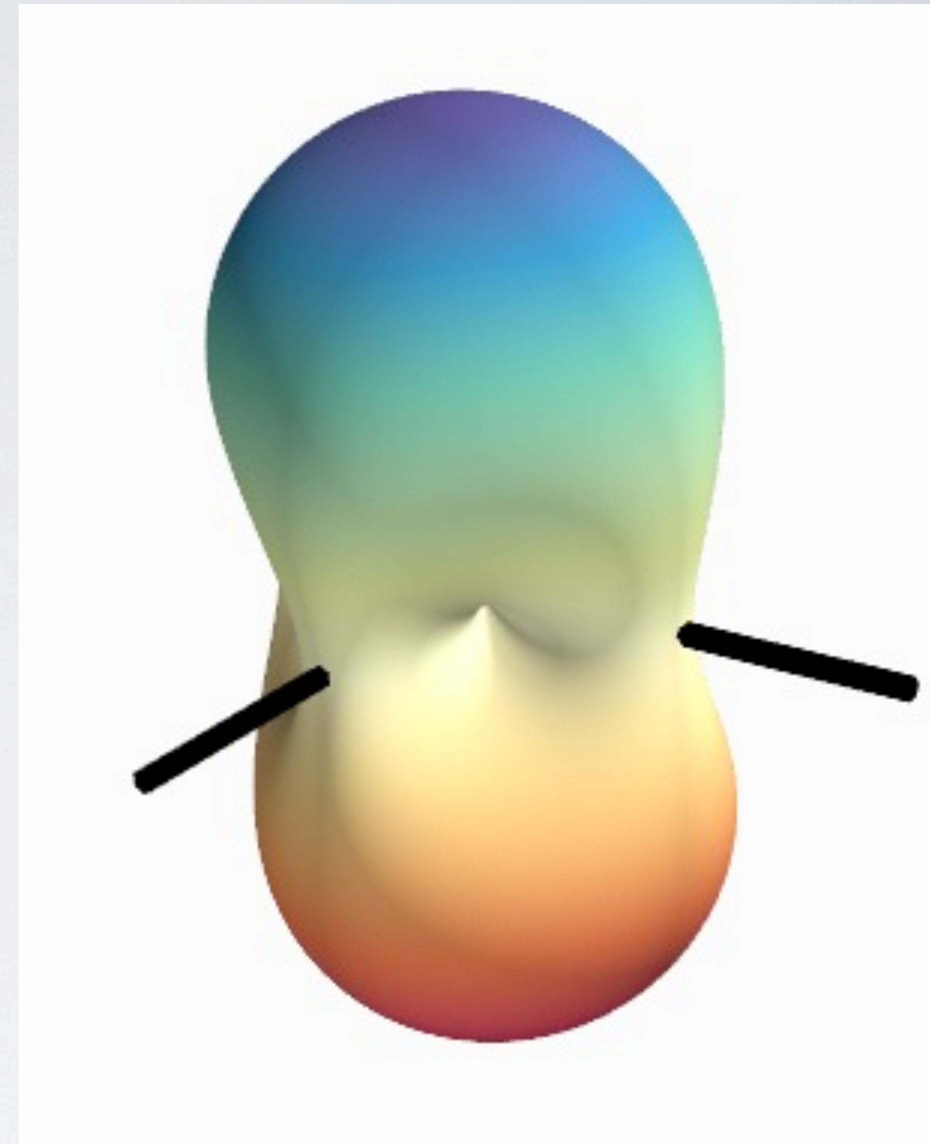
Post-Newtonian Inspiral

Numerical Merger

2009-10 Sensitivity (S6-VSR2/3)



Directional Sensitivity



Abadie et al
arXiv:1203.2674

DETECTOR SENSITIVITY

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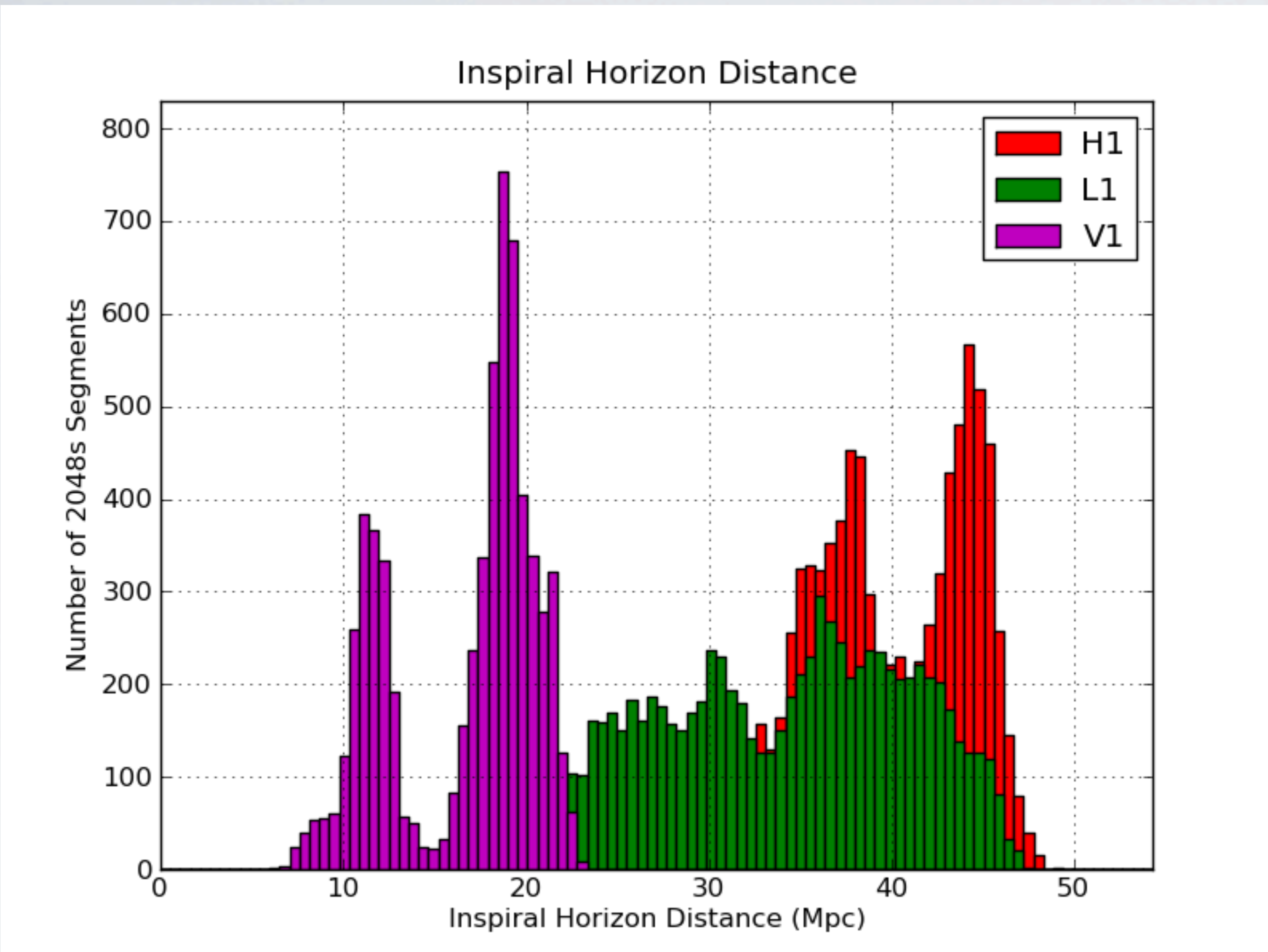
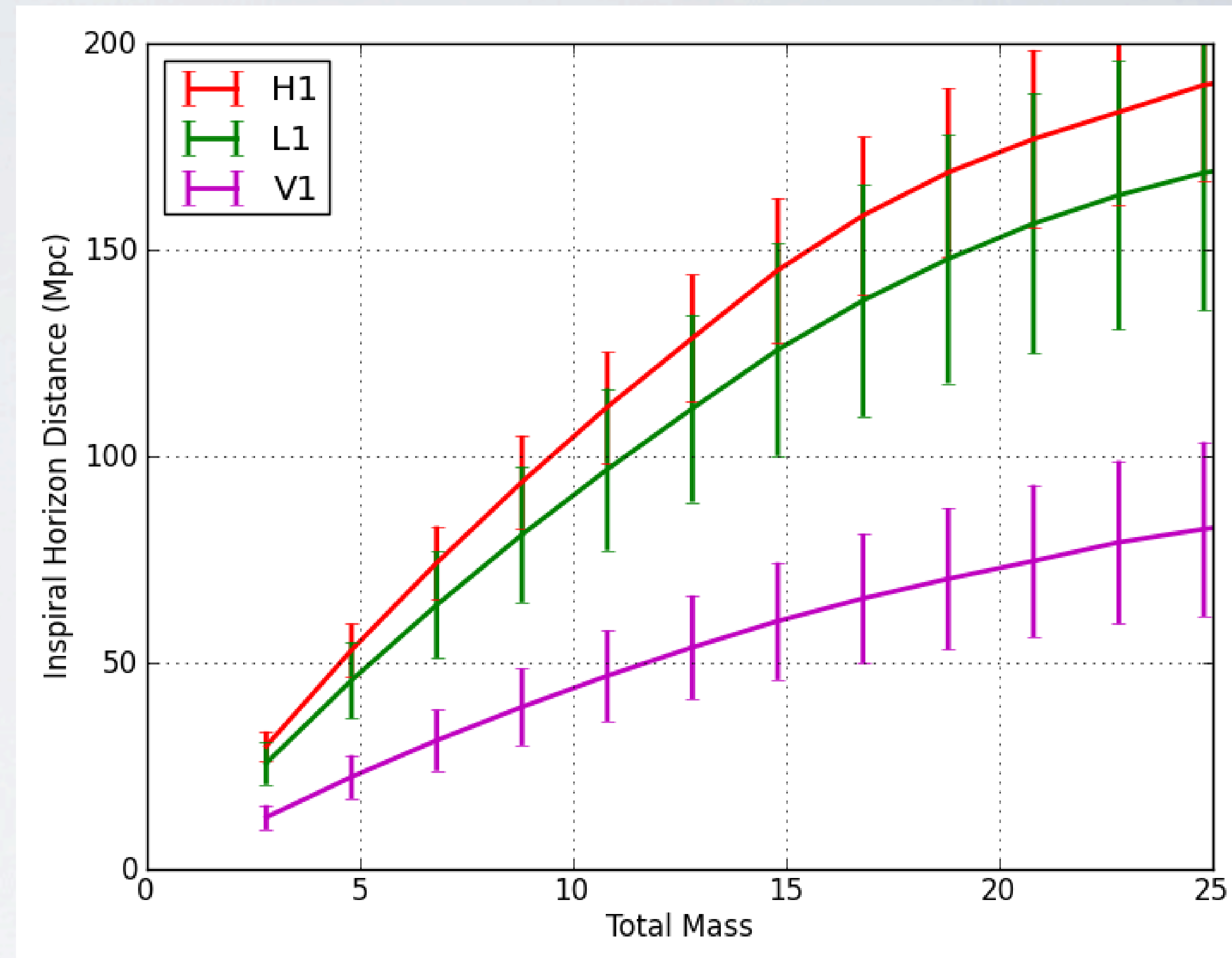
BNS Horizon



Horizon = 2.26 x Average Range

Horizon vs Mass



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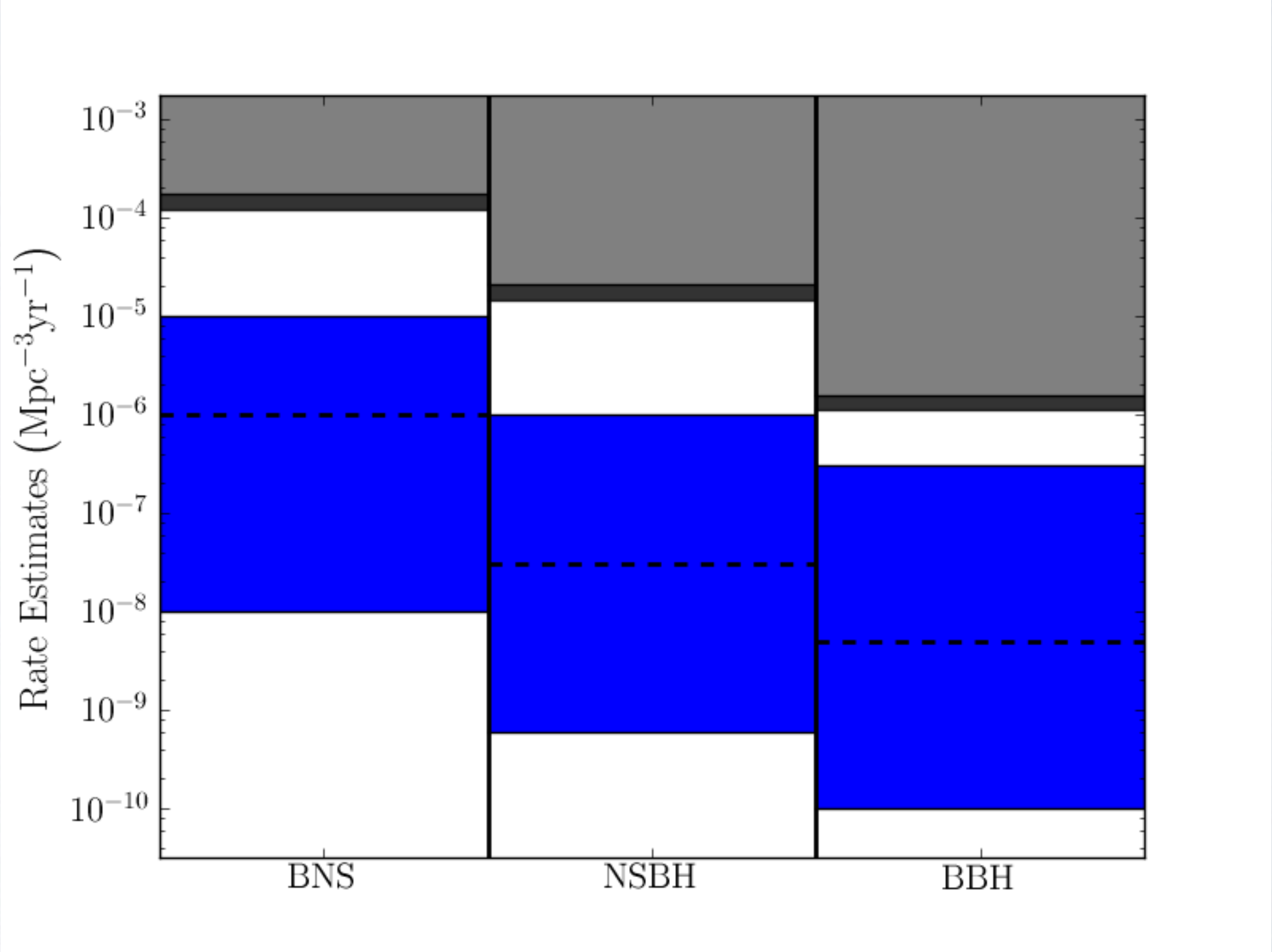
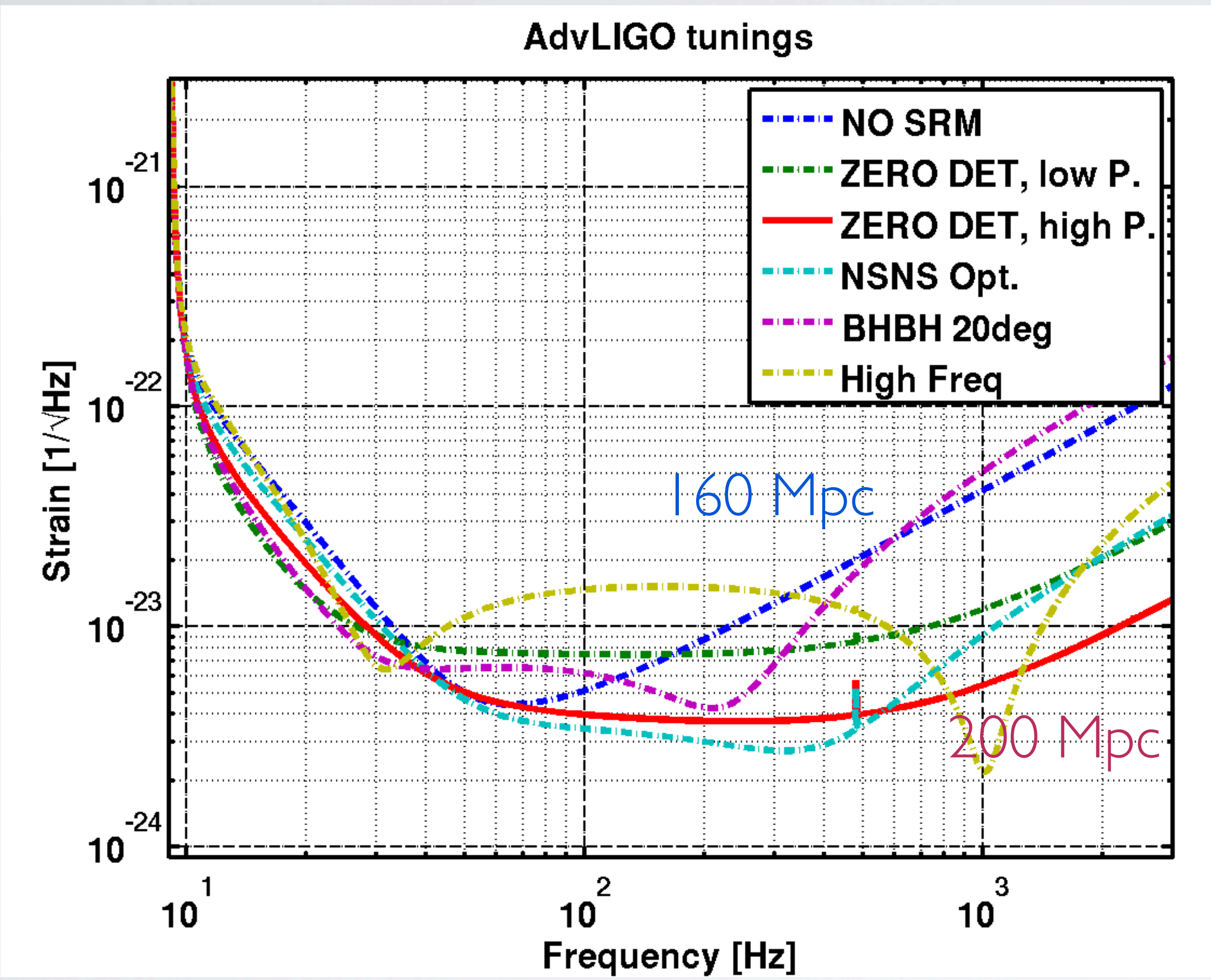
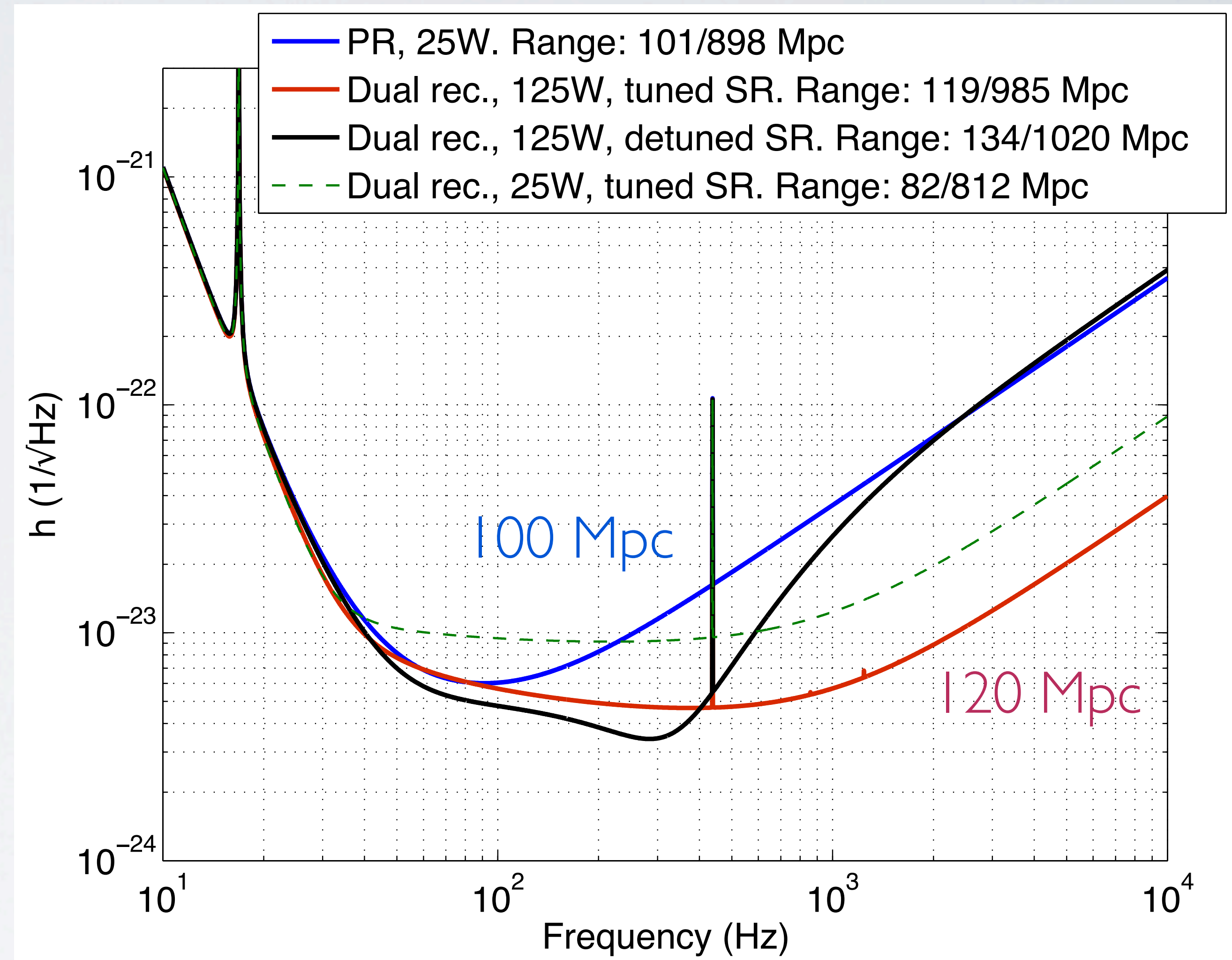
COALESCENCE RATES

- Latest rate exclusions from LIGO-Virgo data
  Abadie et al PRD (2012)
- Astrophysical predictions
  See, e.g. Abadie et al CQG (2010)
- A range of about 100 Mpc likely to provide events



ADVANCED DETECTORS





Advanced LIGO design

LIGO-M060056-v2

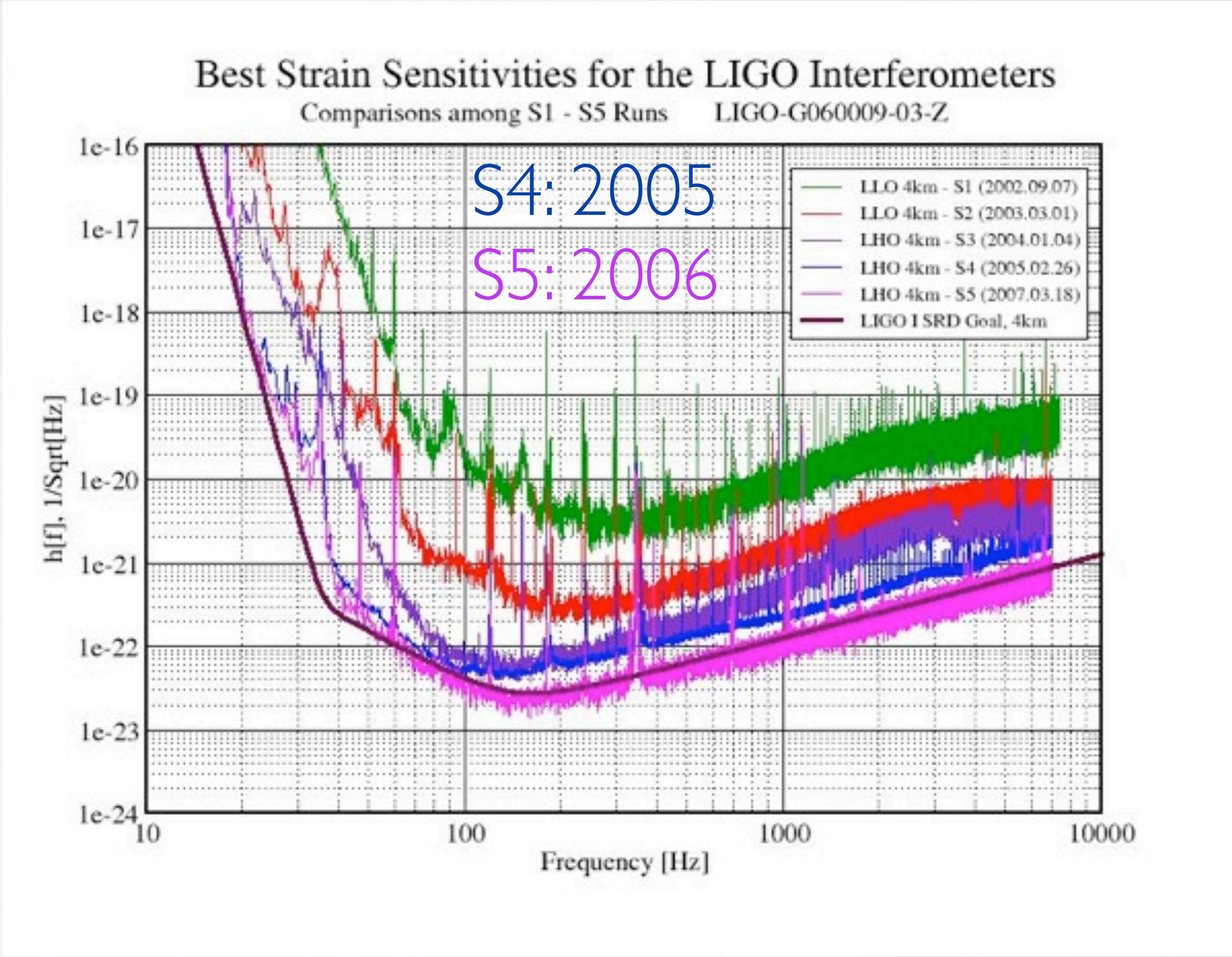
Advanced Virgo design

VIR-0128A-12

SENSITIVITY EVOLUTION

- Advanced detectors: first lock in 2014
- Will take several years to achieve design sensitivity
- Commissioning & Observing roadmap in preparation
- For now, take lessons from initial detectors ...

LIGO: first lock 2000



SENSITIVITY EVOLUTION

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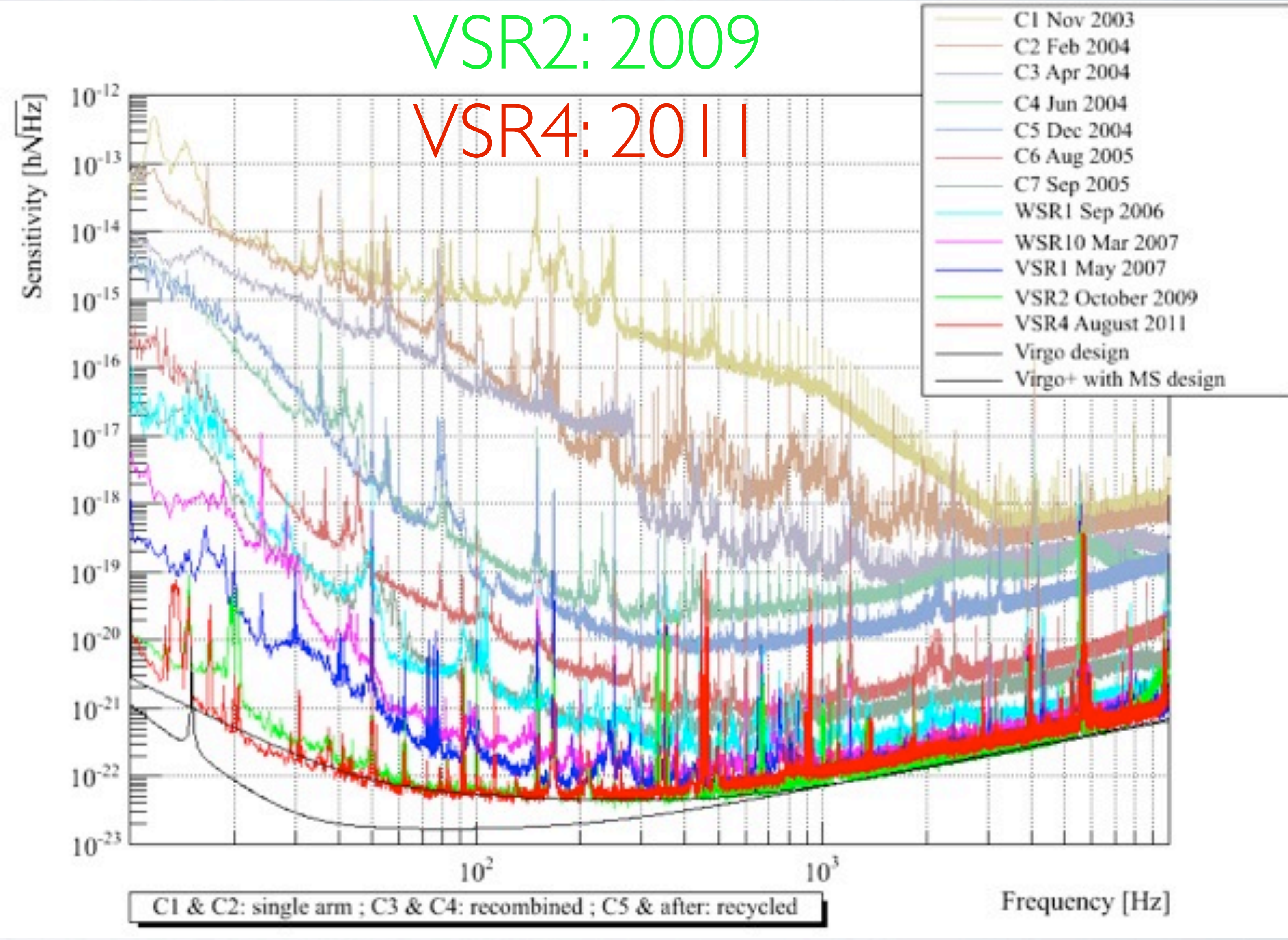
Virgo: first lock 2004

VSR2: 2009

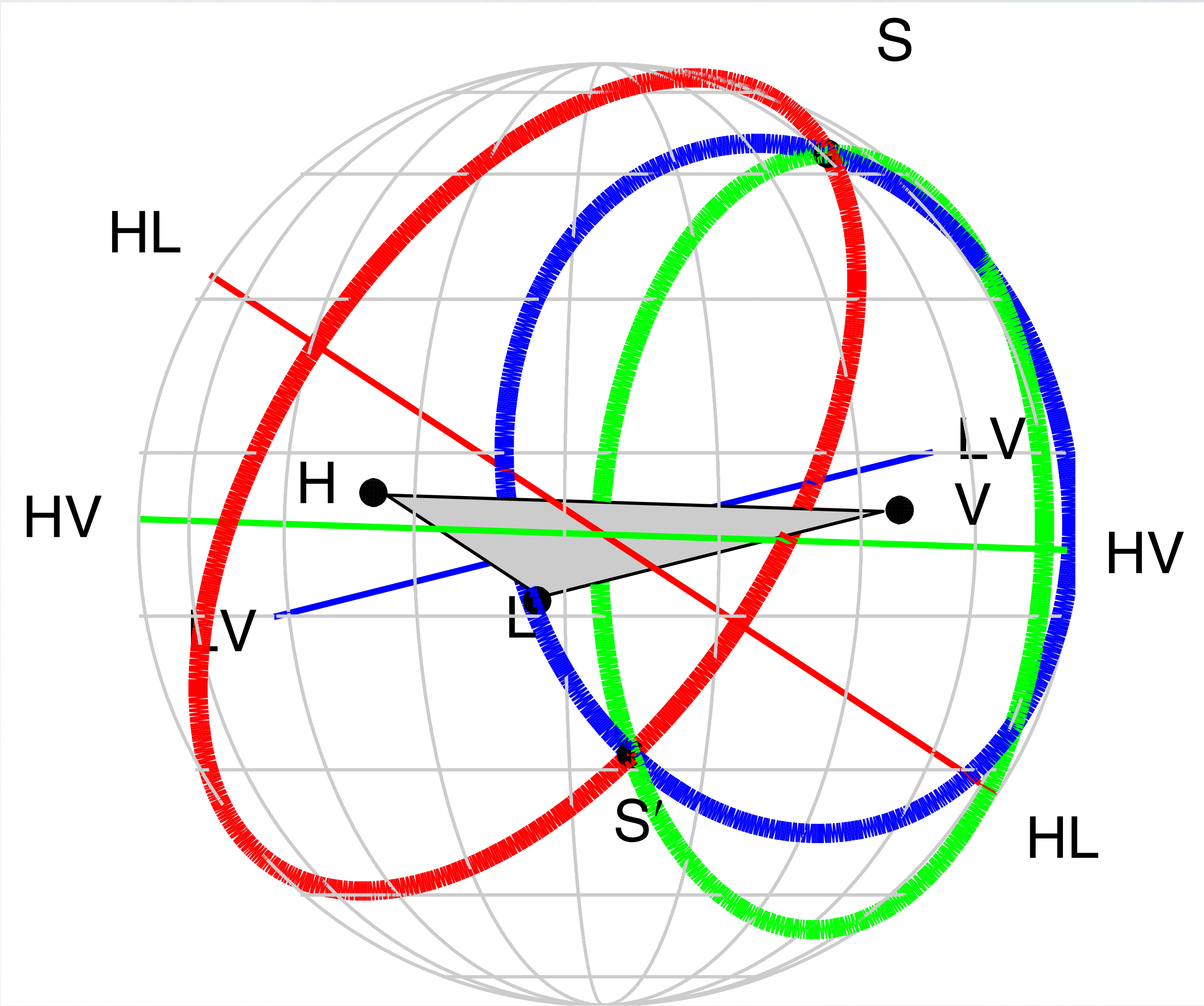
VSR4: 2011



LOCALISATION

LOCALISATION FROM TIMING

- A pair of detectors localises to a ring on the sky



LOCALISATION FROM TIMING

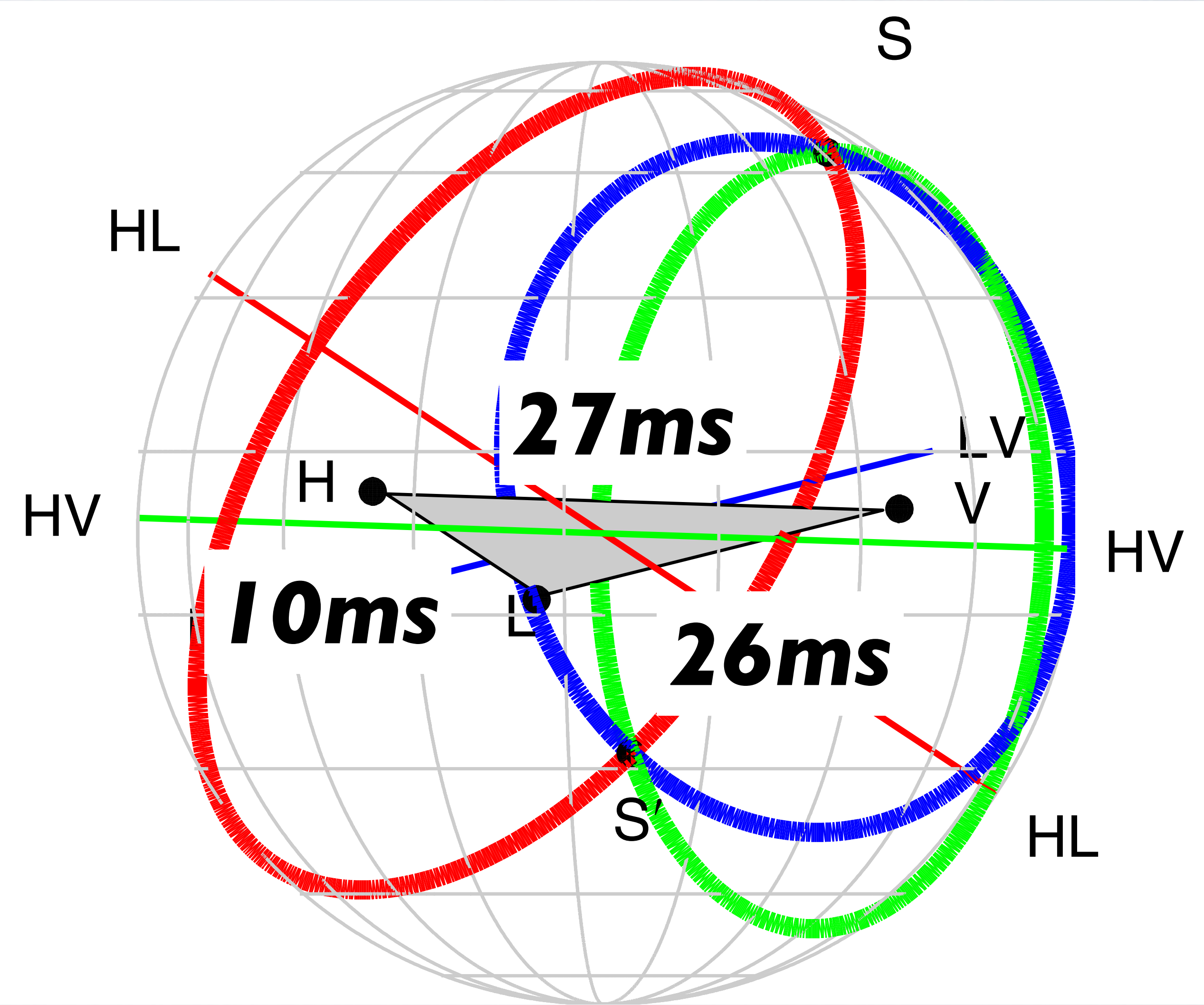
- A pair of detectors localises to a ring on the sky

- Width of rings given by

$$\sin\theta\, d\theta = \frac{\sqrt{\sigma_1^2 + \sigma_2^2}}{\Delta t}$$

- where $\sigma_t = \frac{1}{2\pi\rho\sigma_f}$

Δt detector baseline



SNR AND BANDWIDTH

Ajith et al arXiv:1201.5319

- Timing accuracy:

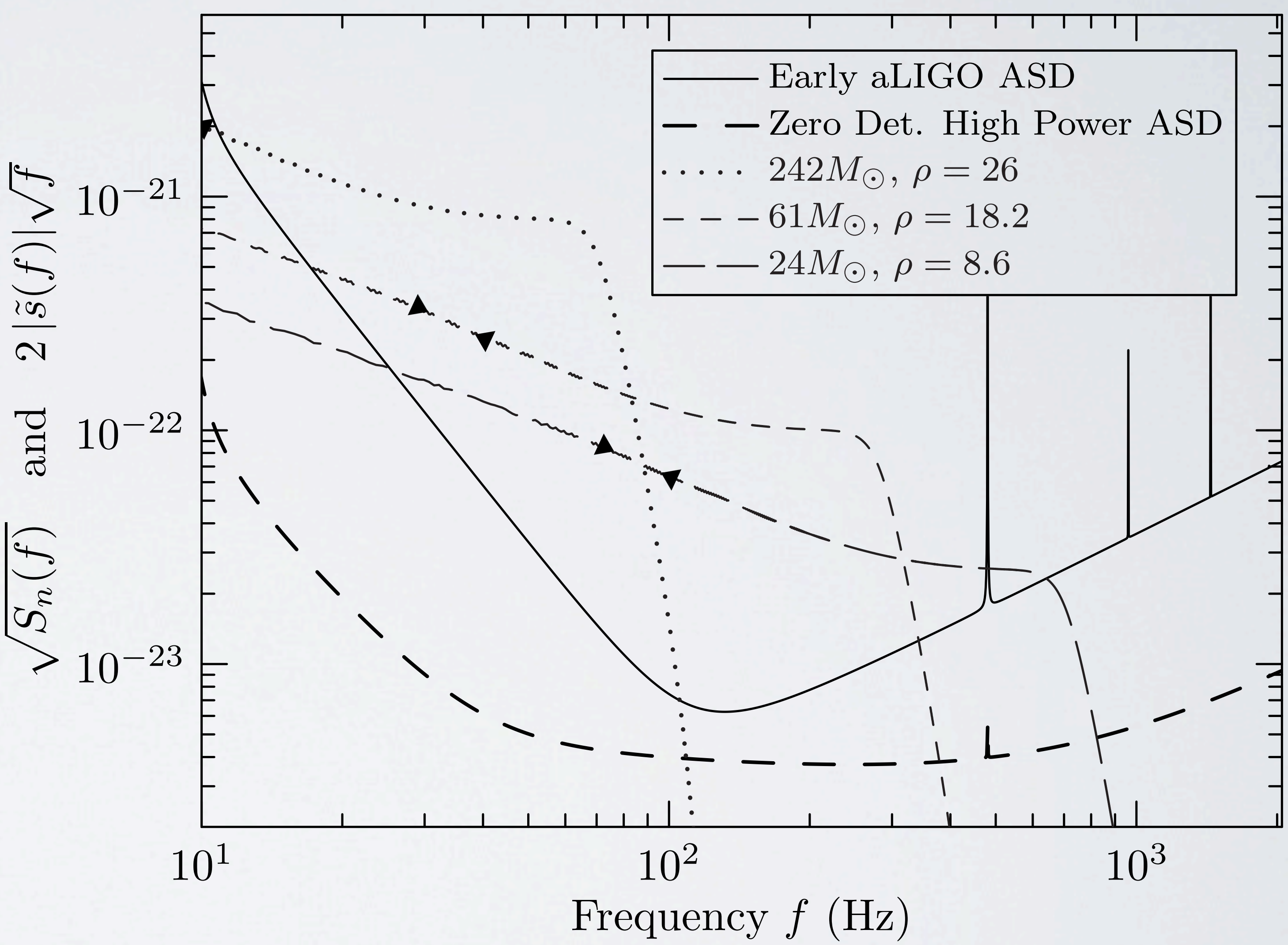
$$\sigma_t = \frac{1}{2\pi\rho\sigma_f}$$

- SNR:

$$\rho^2 = 4\int_0^\infty \frac{|h(f)|^2}{S(f)} df\,,$$

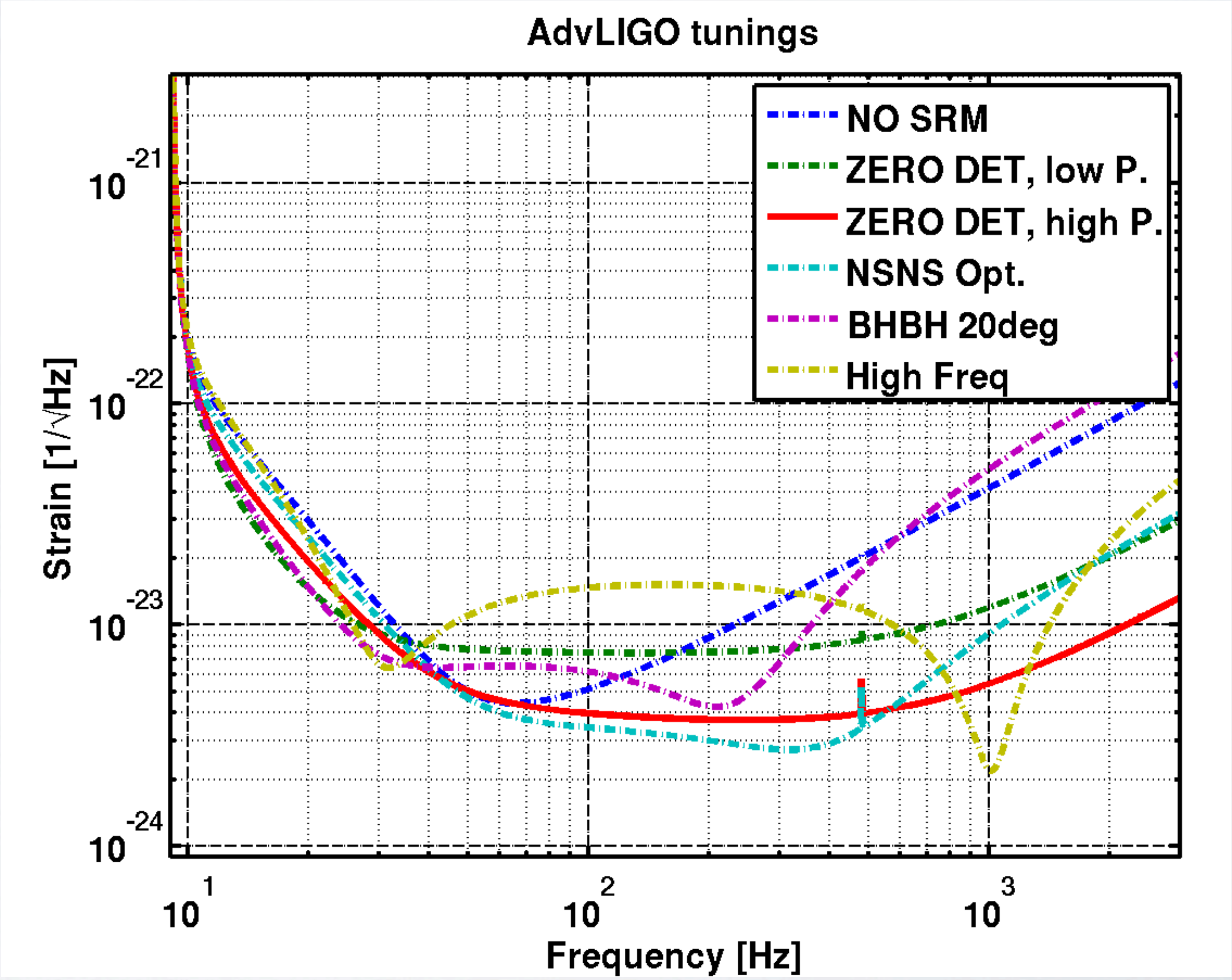
- Bandwidth:

$$\sigma_f^2 = \left(\frac{4}{\rho^2}\int_0^\infty f^2\frac{|h(f)|^2}{S(f)}df\right) - \left(\frac{4}{\rho^2}\int_0^\infty f\,\frac{|h(f)|^2}{S(f)}df\right)^2,$$



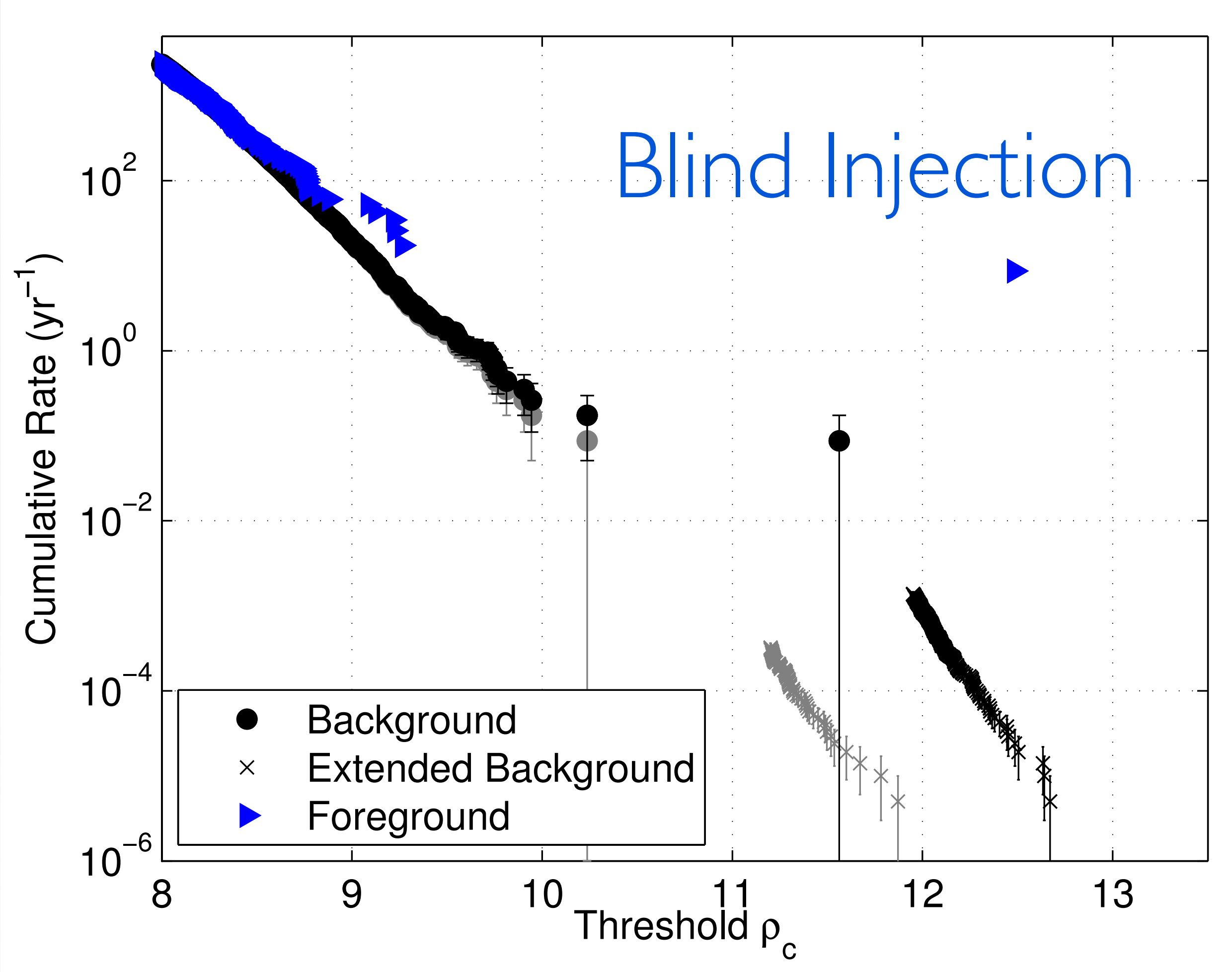
FREQUENCY BANDWIDTH

- 100 Hz as a rule of thumb
- Does depend upon high frequency sensitivity
  - No SRM: 60 Hz
  - Zero Det, High P: 120 Hz
- Significant impact on localisation



NOISE BACKGROUND

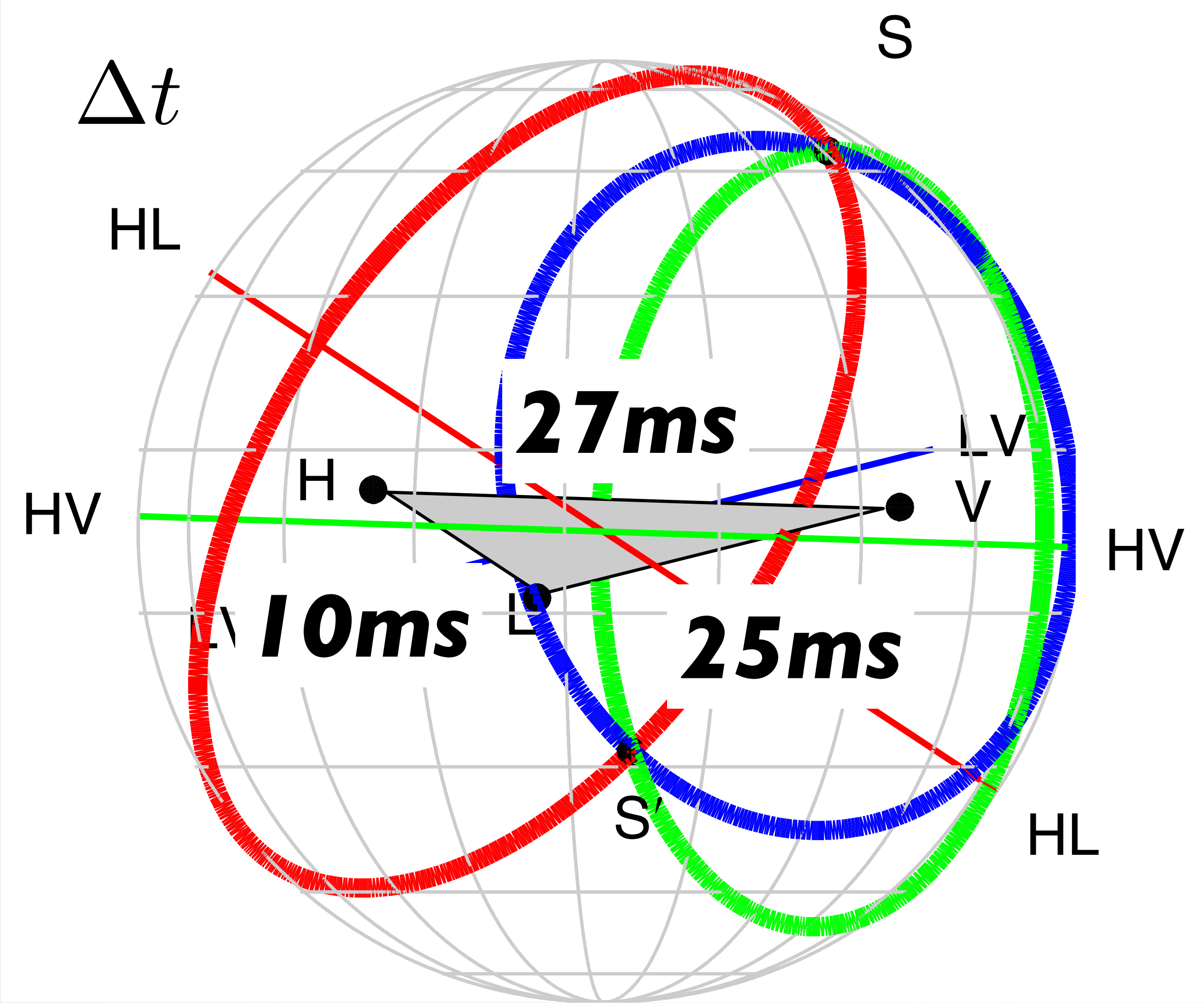
- Noise background falls off rapidly at high SNR, due to sophisticated analysis pipeline
  Babak et al, arXiv:1208
  - Matched filtering analysis
  - Signal consistency tests
  - Data quality cuts
- For following examples:
  - Require combined SNR > 12 for detection
  - SNR > 5 in two detectors
  - SNR > 3 to contribute to localisation

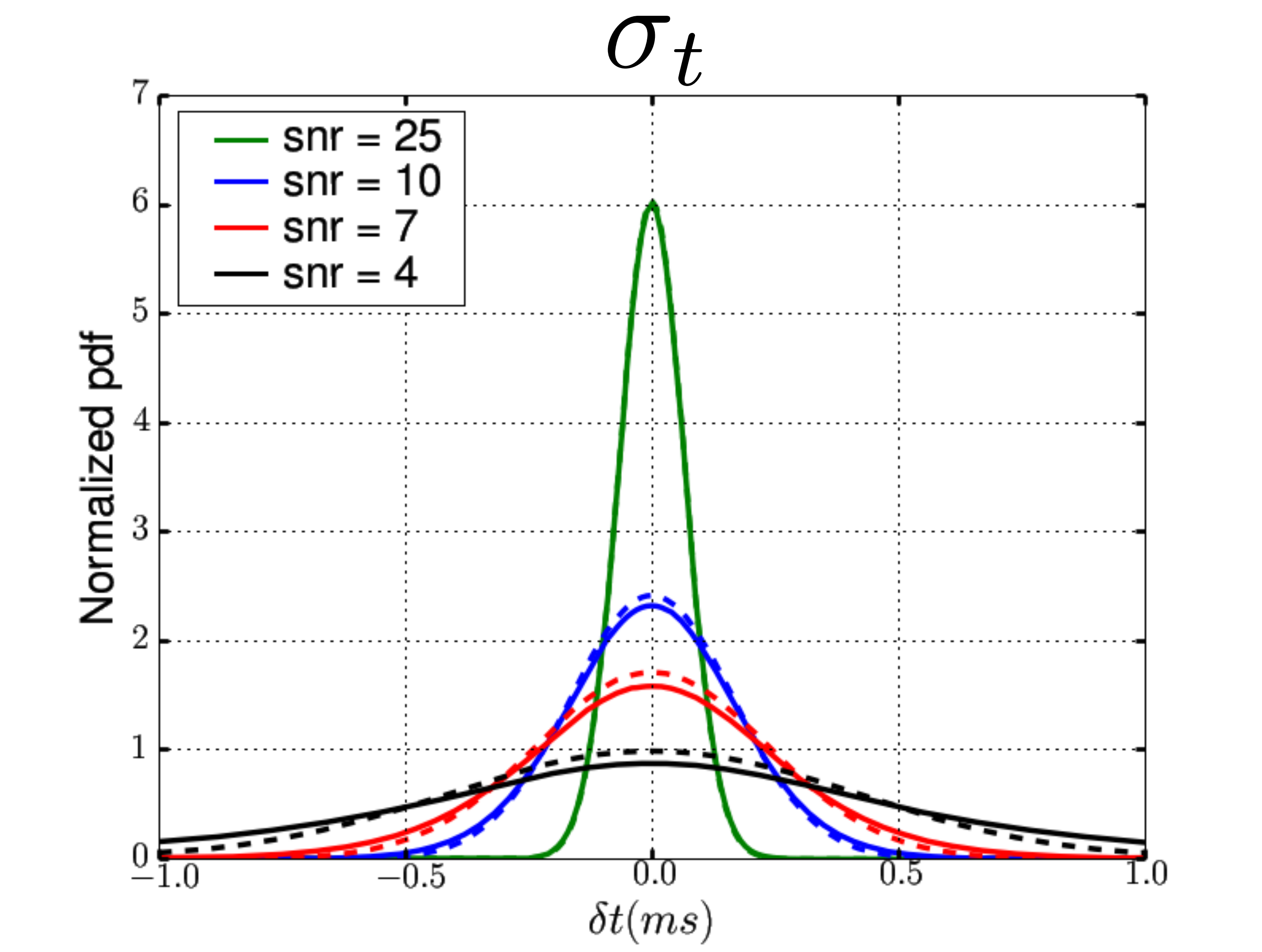


Abadie et al PRD (2012)

LOCALISATION FROM TIMING

$$\sin\theta\, d\theta = \frac{\sqrt{\sigma_1^2 + \sigma_2^2}}{\Delta t} \sim \frac{10^{-4}s}{10^{-2}s}$$





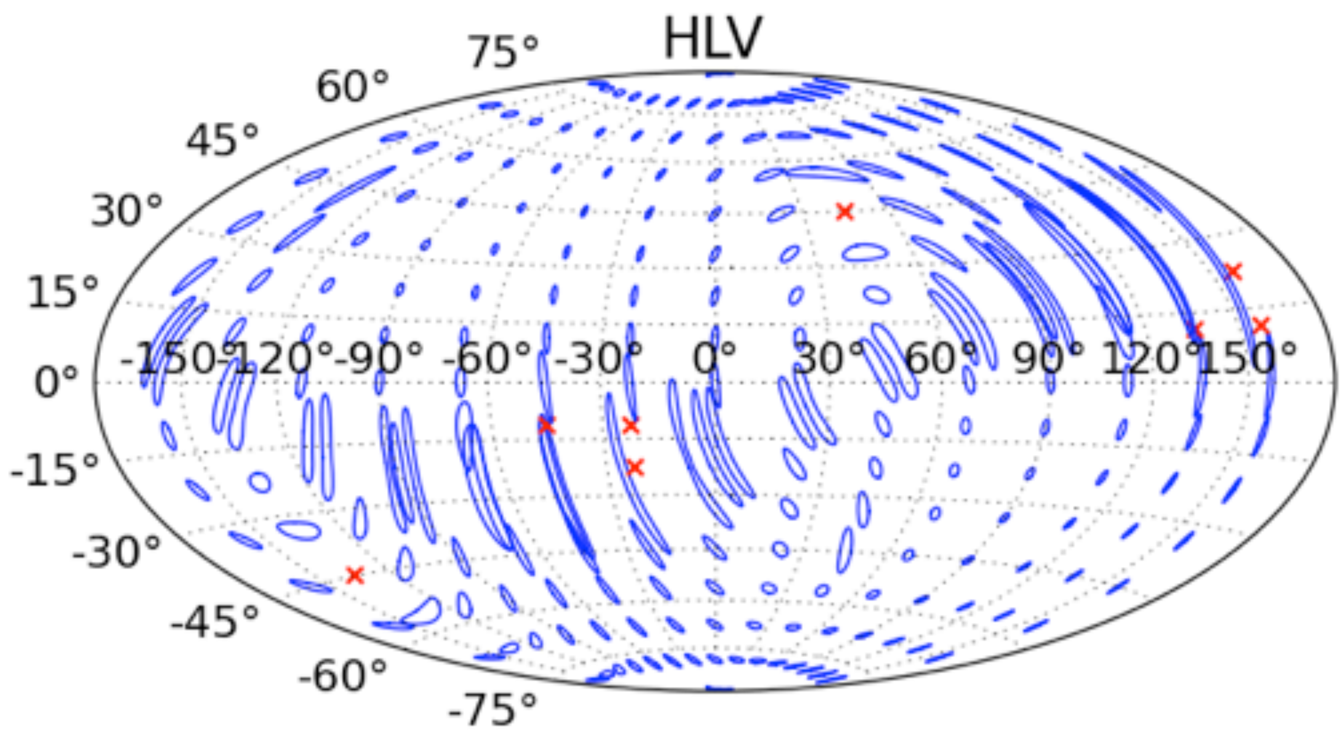
CAVEATS

- Results use only timing information, but assuming can break reflection degeneracy for 3 sites [Veitch talk]
- Use Gaussian approximation to localisation (breaks down at low SNR)
- Have neglected effects of discrete "template bank"
- Have neglected spin (precession) effects [Harry, Raymond talks]

LIGO-VIRGO AT DESIGN

- LIGO 200 Mpc
- Virgo 120 Mpc
- Assume 80% duty cycles
- 0.2 - 200 BNS signals per year

Face on BNS @ 160 MPc



90% confidence regions

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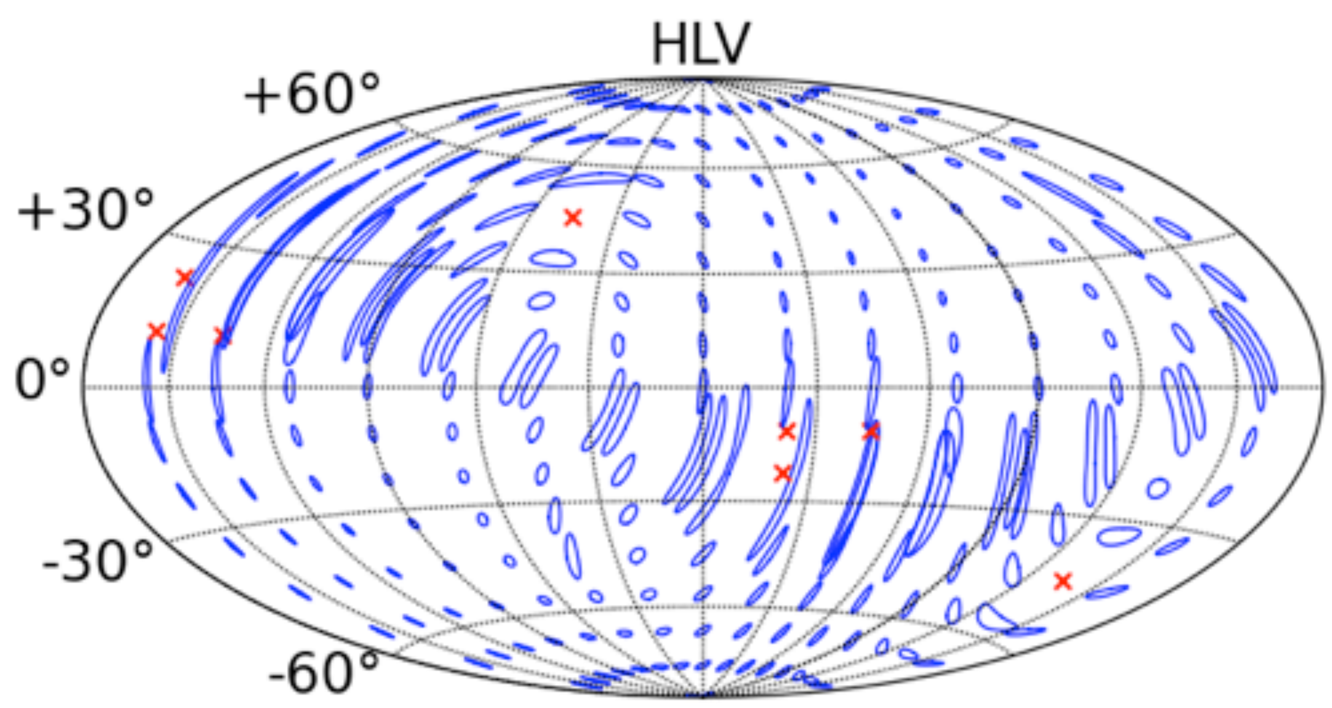

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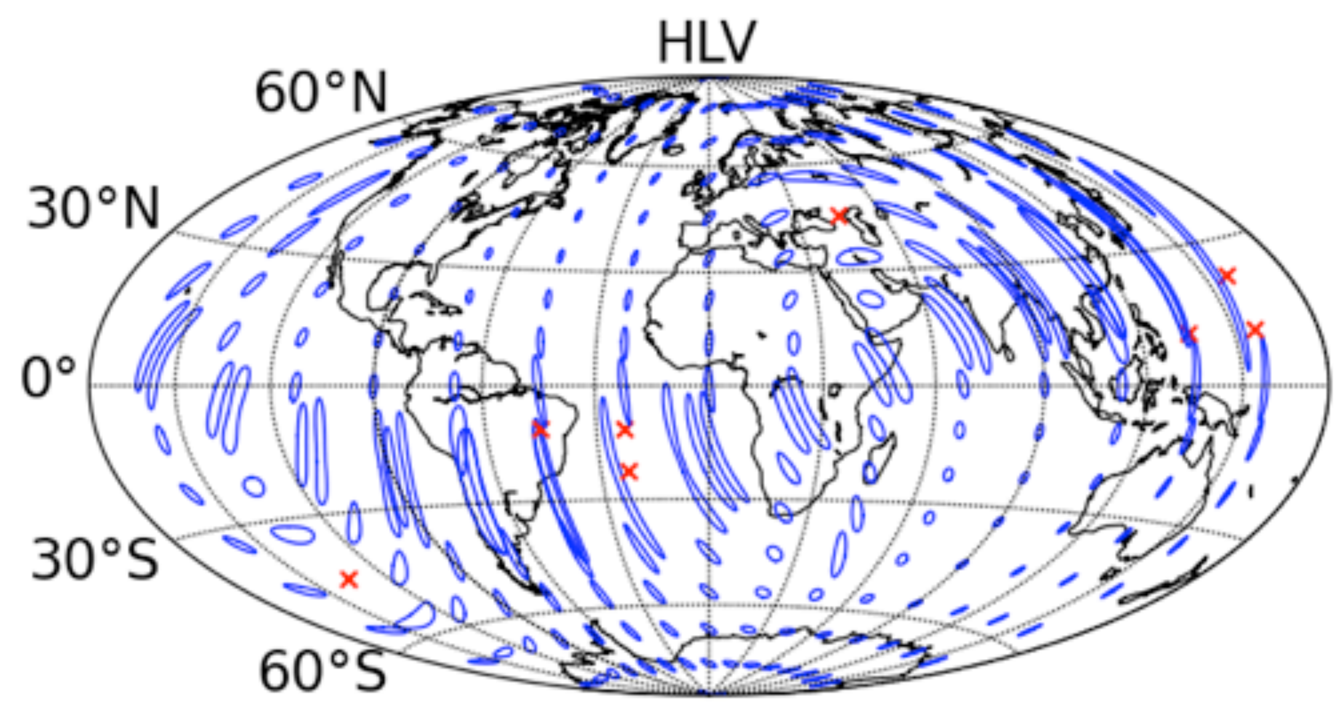
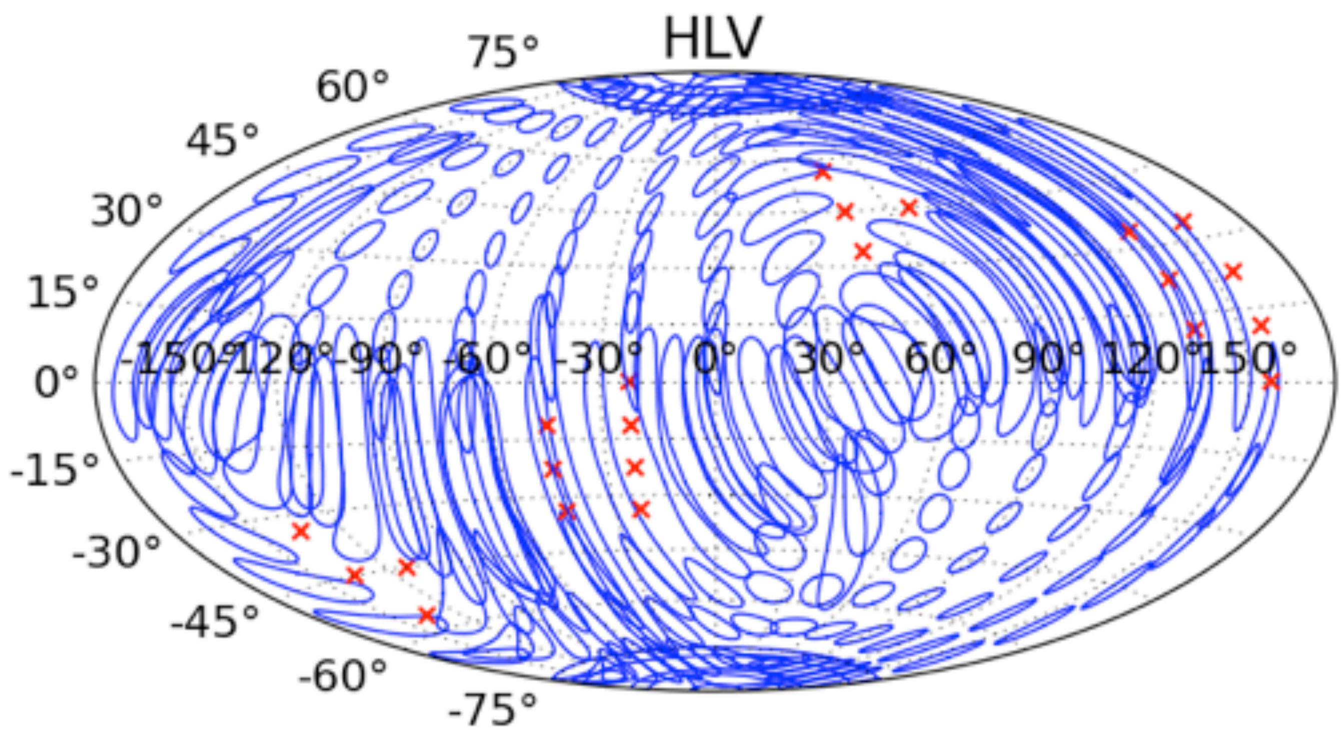


90% confidence regions

NO SIGNAL RECYCLING

- LIGO 160 Mpc
- Virgo 100 Mpc
- Assume 80% duty cycles
- 0.1 - 100 BNS signals per year

Face on BNS @ 160 MPc

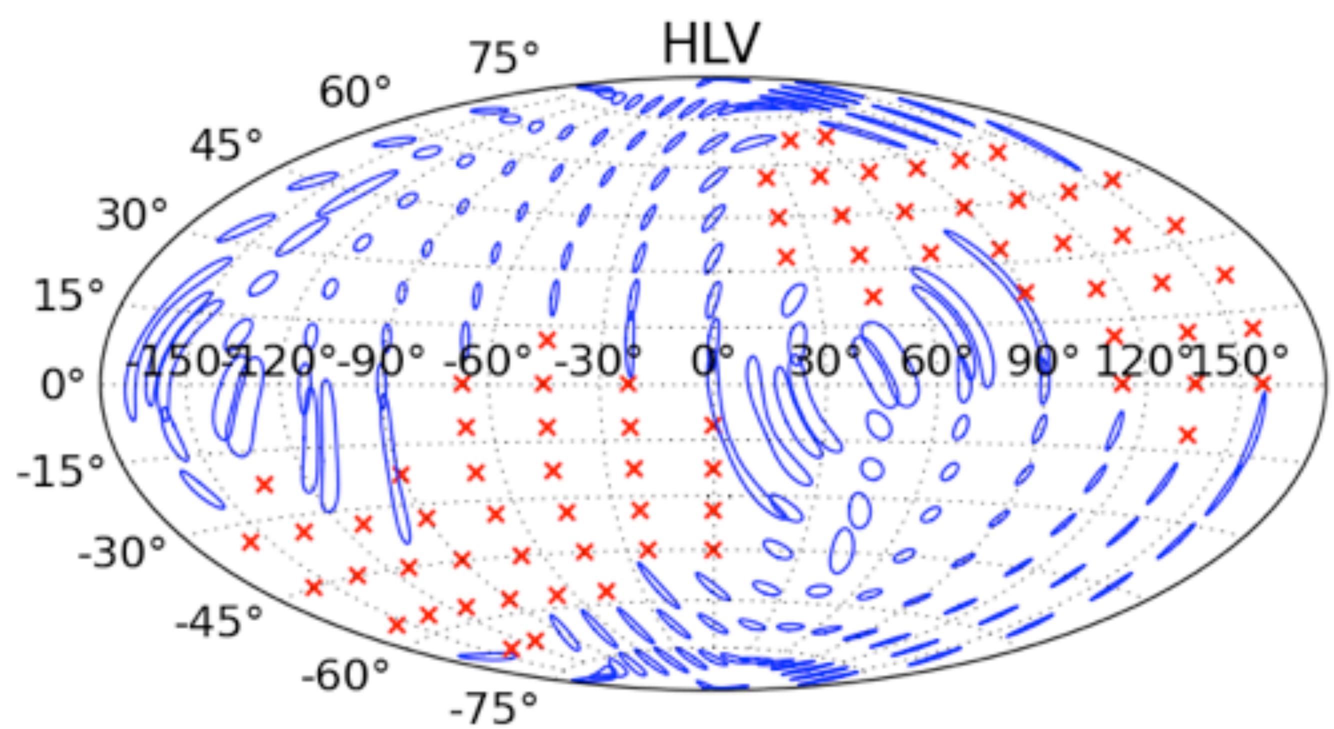


90% confidence regions

LIGO (half commissioned) -VIRGO

- LIGO ~~200 Mpc~~ 100 Mpc
- Virgo 120 Mpc
- Assume 80% duty cycles
- 0.05 - 50 BNS signals per year

Face on BNS @ 160 MPc

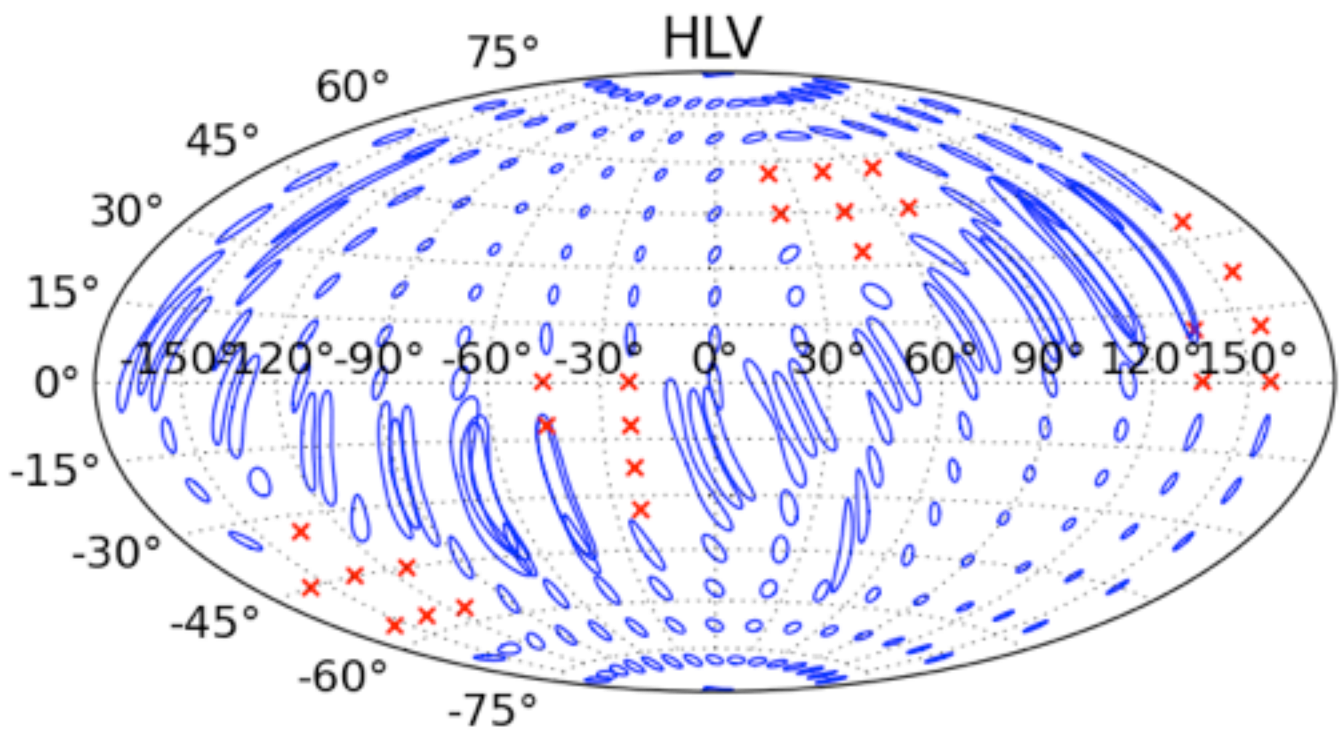


90% confidence regions

LIGO-VIRGO (half commissioned)

- LIGO 200 Mpc
- Virgo ~~120 Mpc~~ 60 Mpc
- Assume 80% duty cycles
- 0.2 - 200 BNS signals per year

Face on BNS @ 160 MPc



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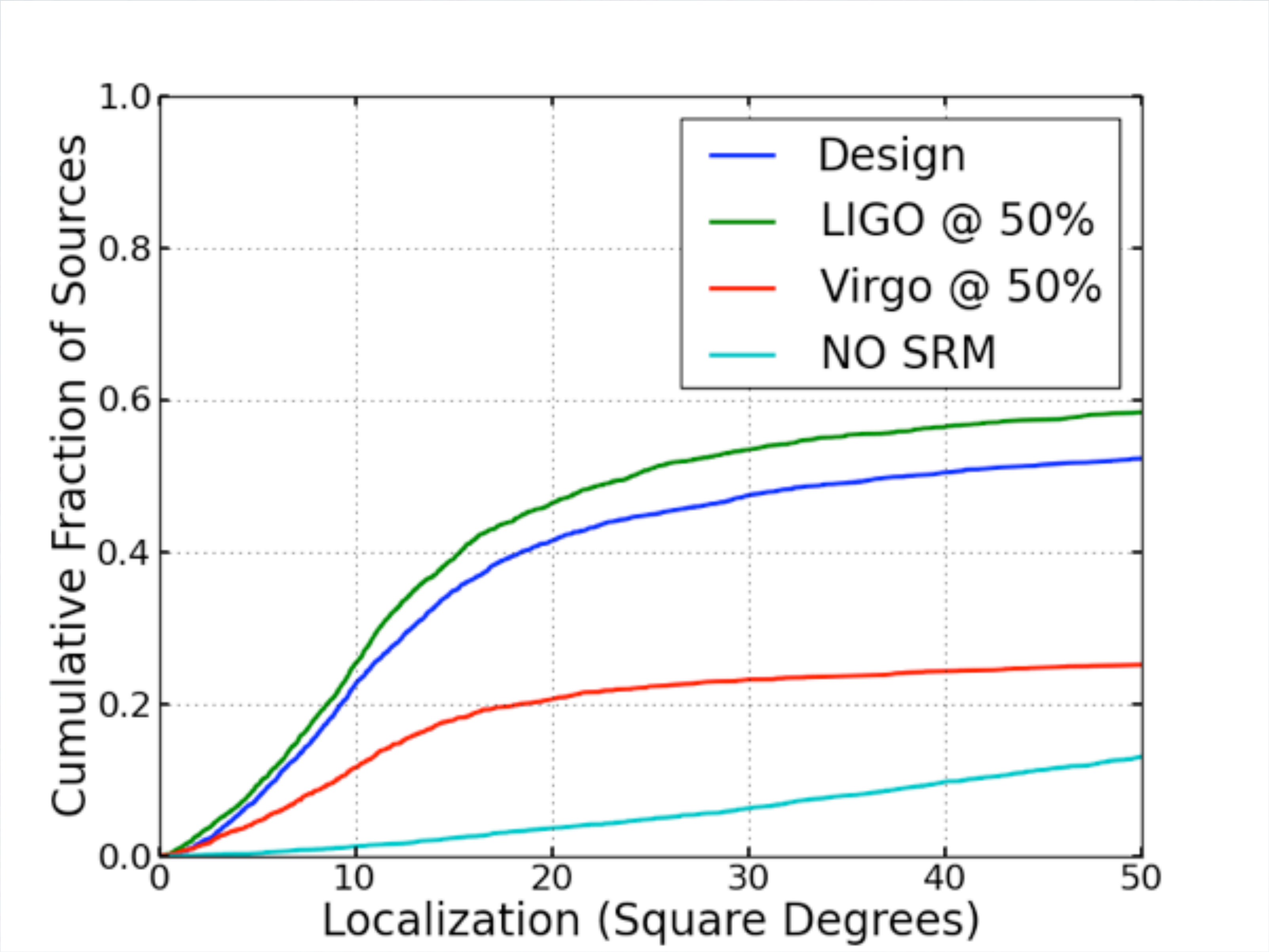
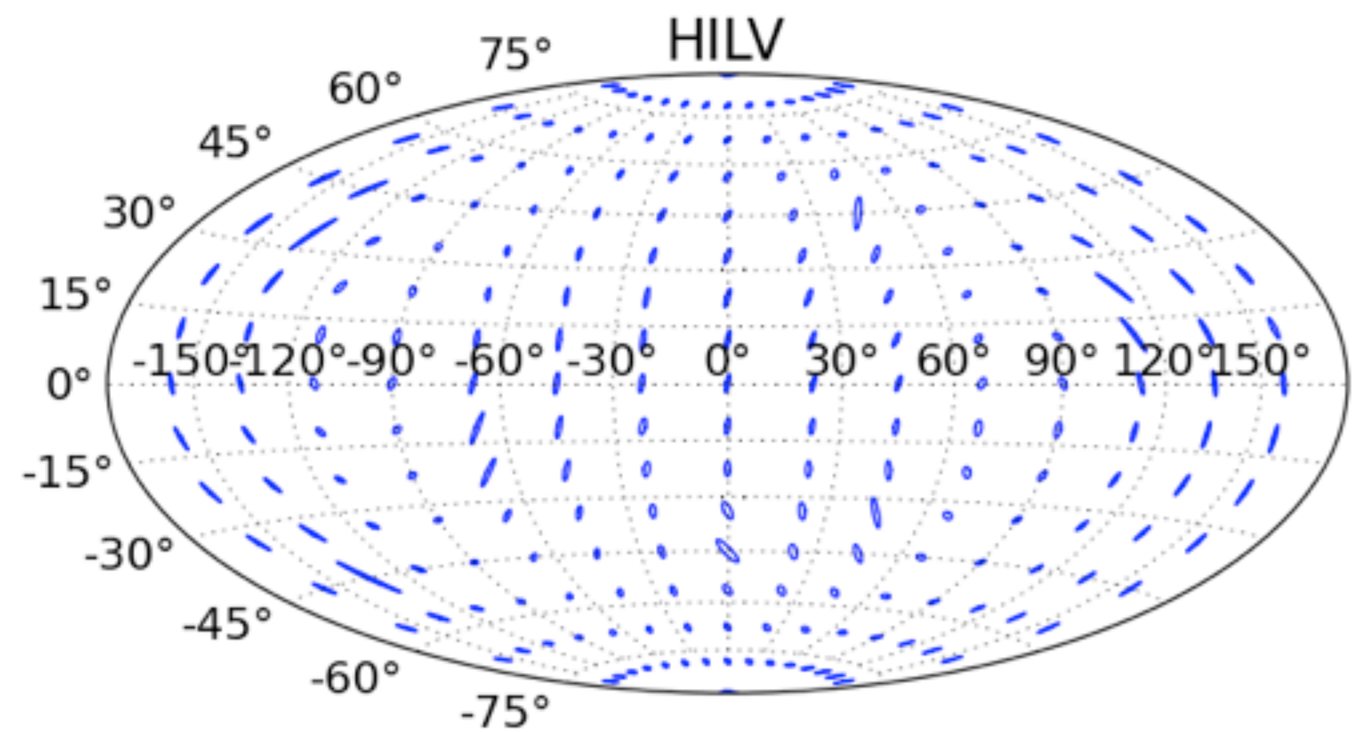


LOCALISATION OF SOURCES

WITH LIGO INDIA

- LIGO (inc India) 200 Mpc
- Virgo 120 Mpc
- Assume 80% duty cycle
- 0.4 -400 BNS signals per year

Face on BNS @ 160 MPc

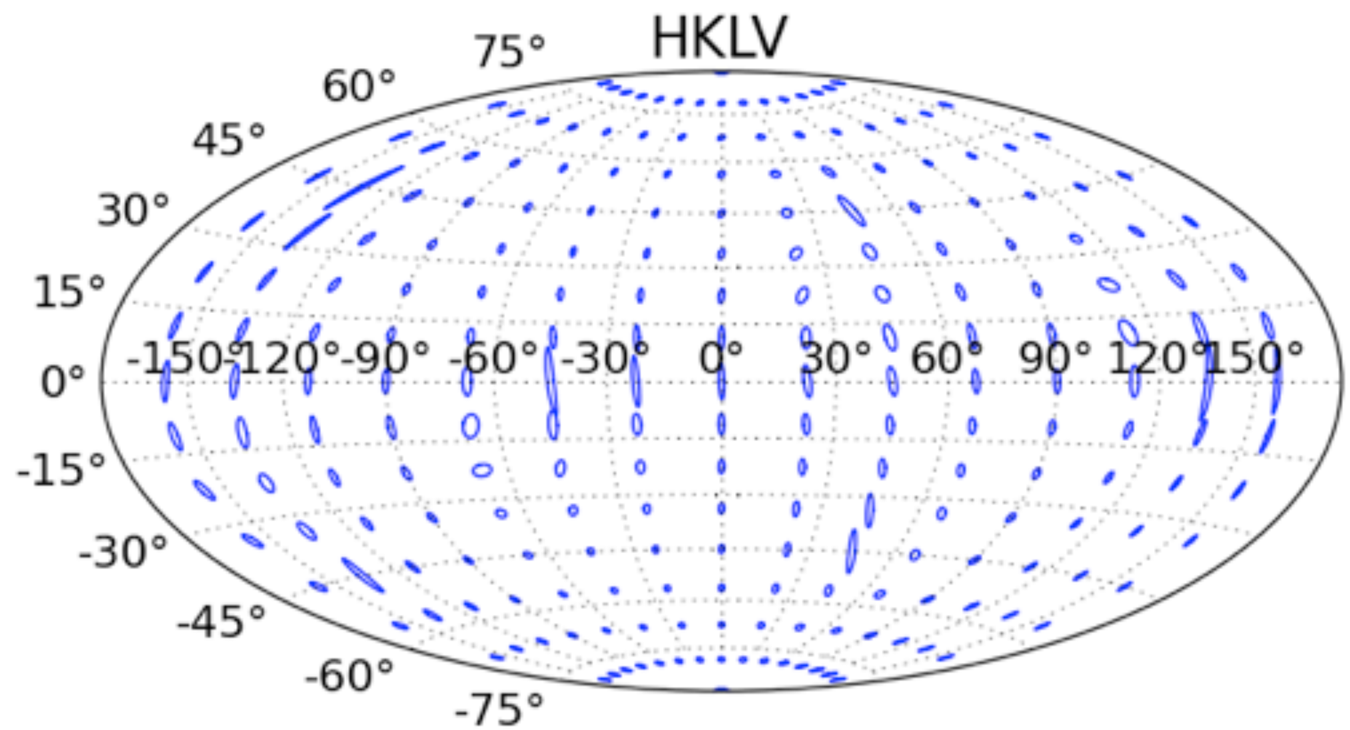


90% confidence regions

WITH KAGRA

- LIGO 200 Mpc
- Virgo 120 Mpc
- KAGRA 160 Mpc
- Assume 80% duty cycle
- 0.3-300 BNS signals per year

Face on BNS @ 160 MPc

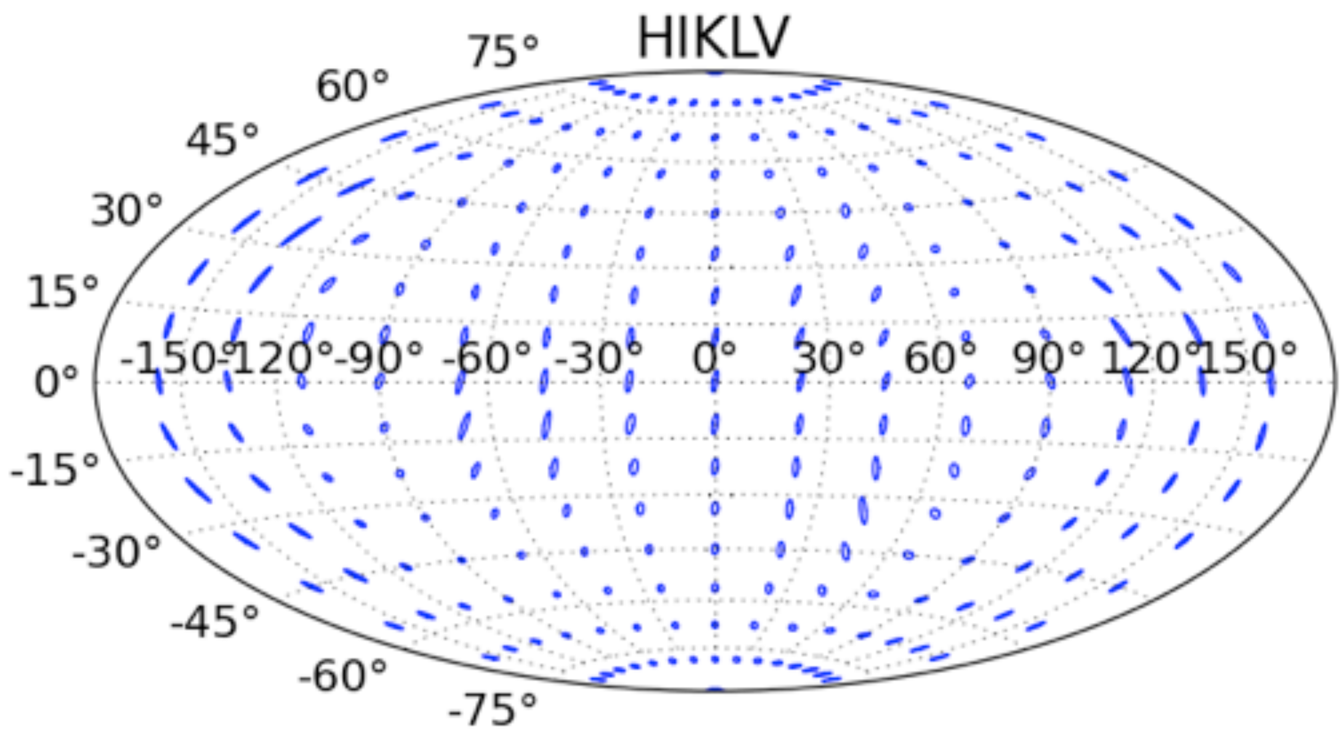


90% confidence regions

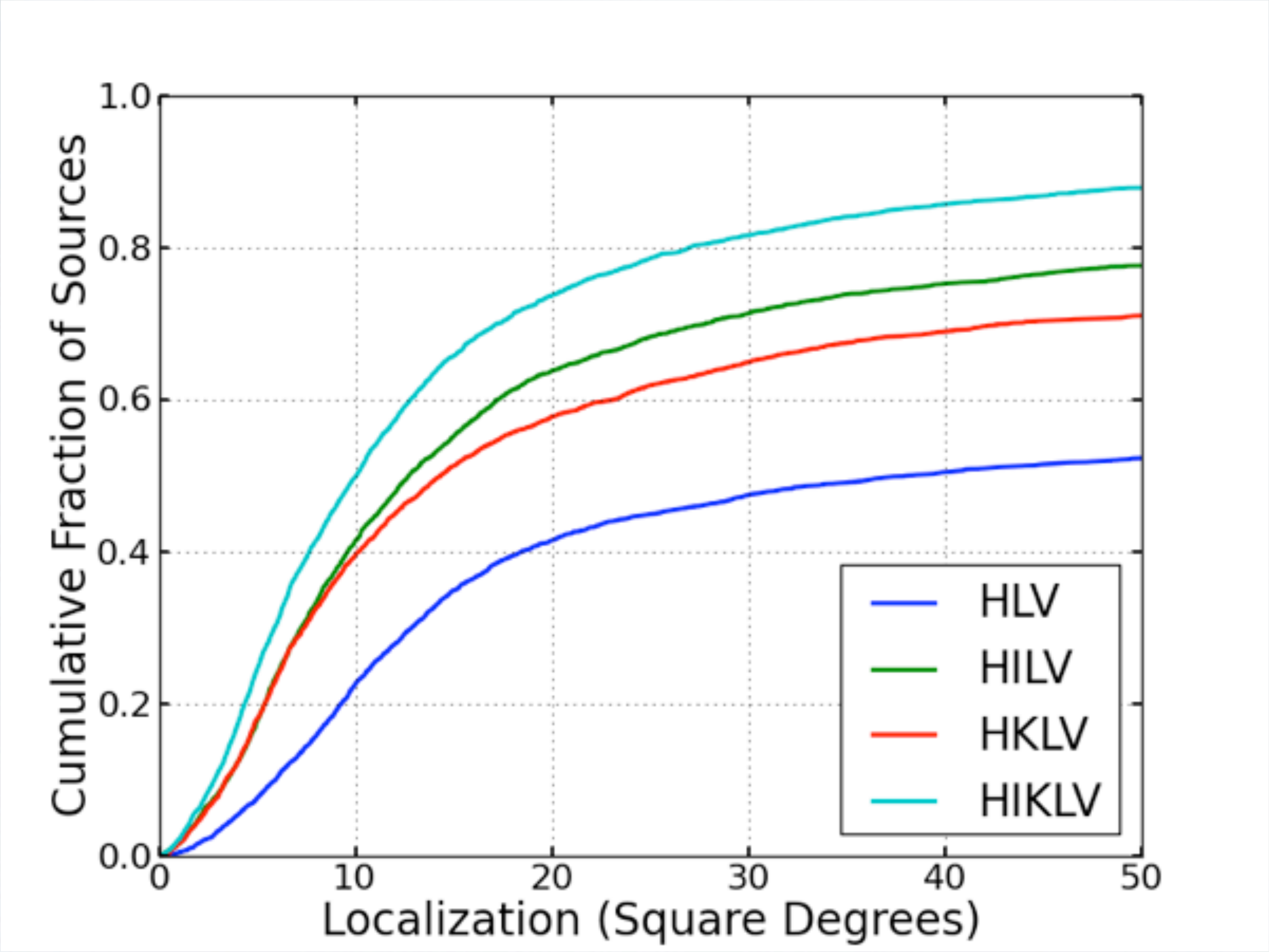
5 SITES

- LIGO (inc India) 200 Mpc
- Virgo 120 Mpc
- KAGRA 160 Mpc
- Assume 80% duty cycle
- 0.5-500 BNS signals per year

Face on BNS @ 160 MPc



90% confidence regions



LOCALISATION OF SOURCES

WAVEFORMS AND CALIBRATION

- Phase error introduces a timing systematic

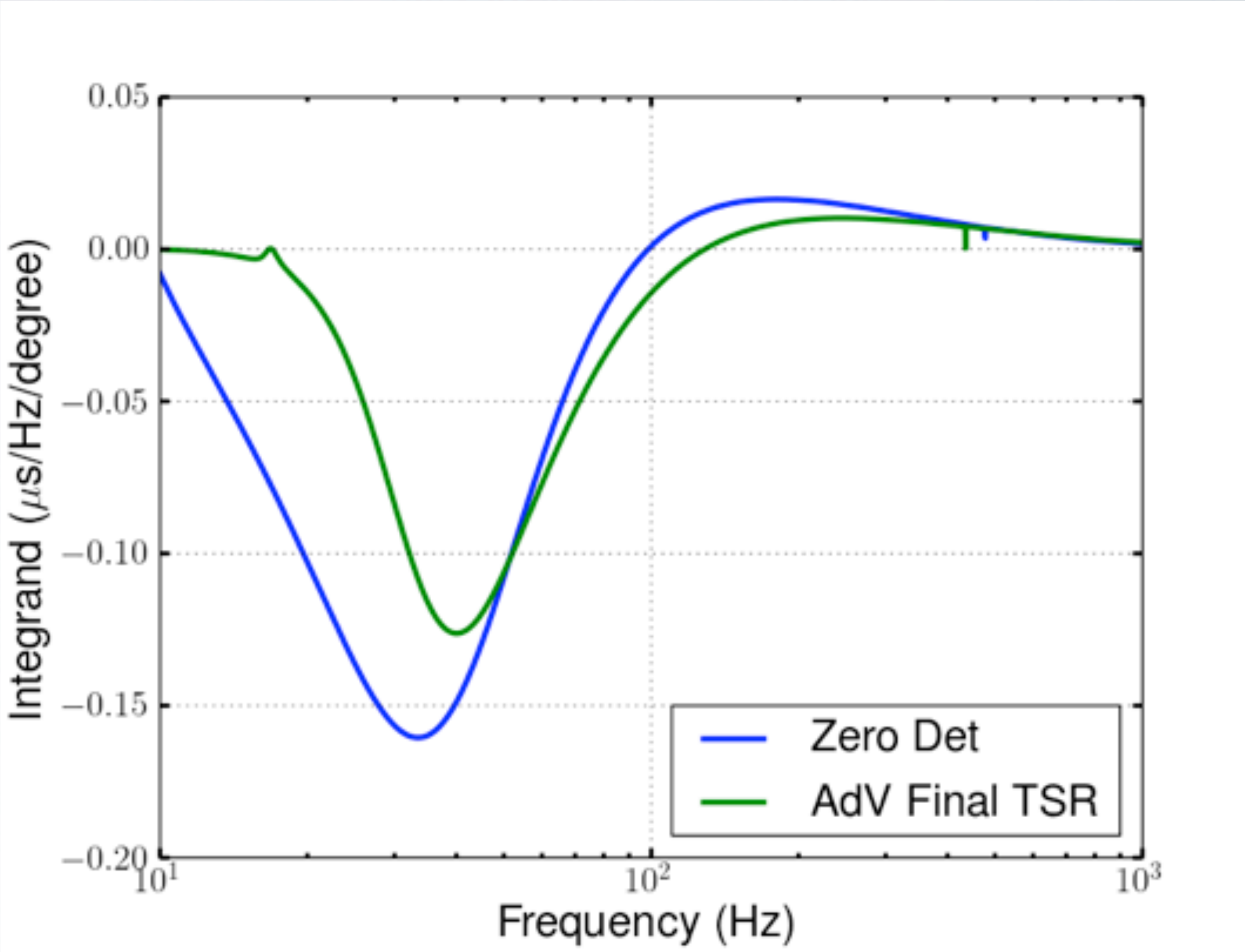
$$|\delta t| \leq \frac{1}{\sigma_f}\left[\frac{\delta\phi_{\max}}{2\pi}\right]$$

  - True for all PSDs; for realistic ones, typically factor of 2 better

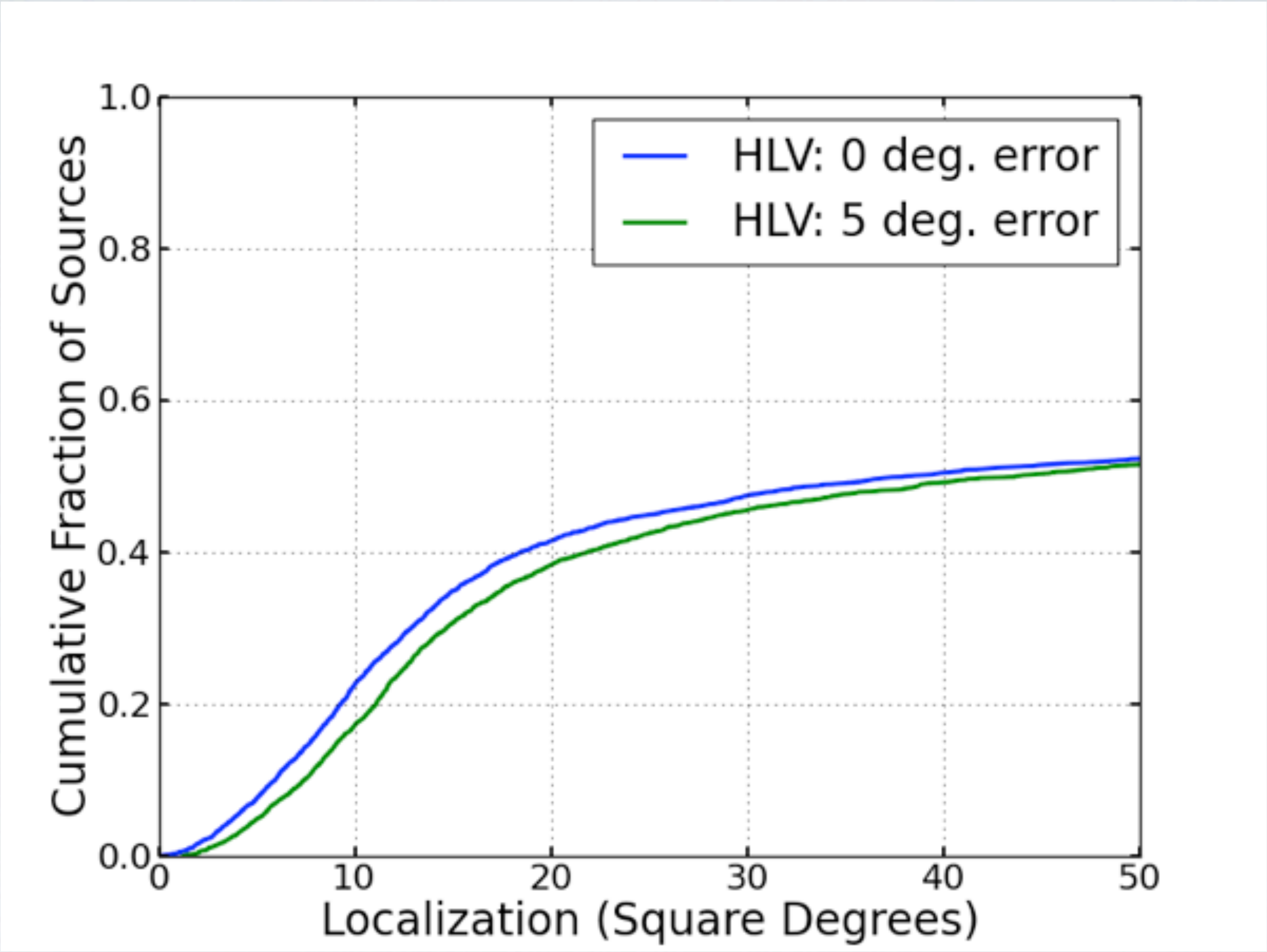
- Compare to statistical error

$$\sigma_t = \frac{1}{2\pi\rho\sigma_f}$$

- 5° systematic subdominant below SNR of 20



Contribution to phase error
(multiply by δϕ and integrate)

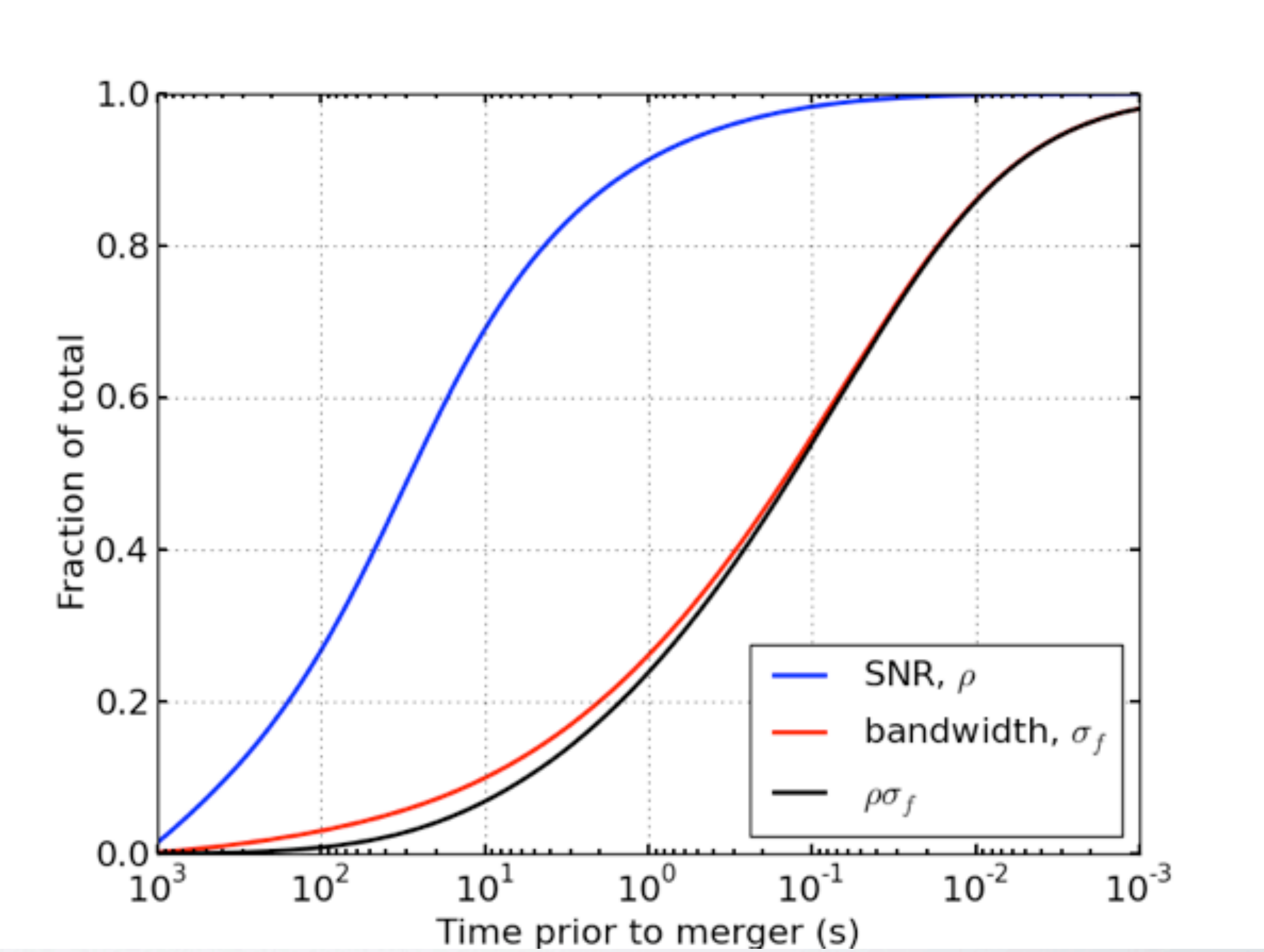


EFFECT ON LOCALISATION

LATENCY

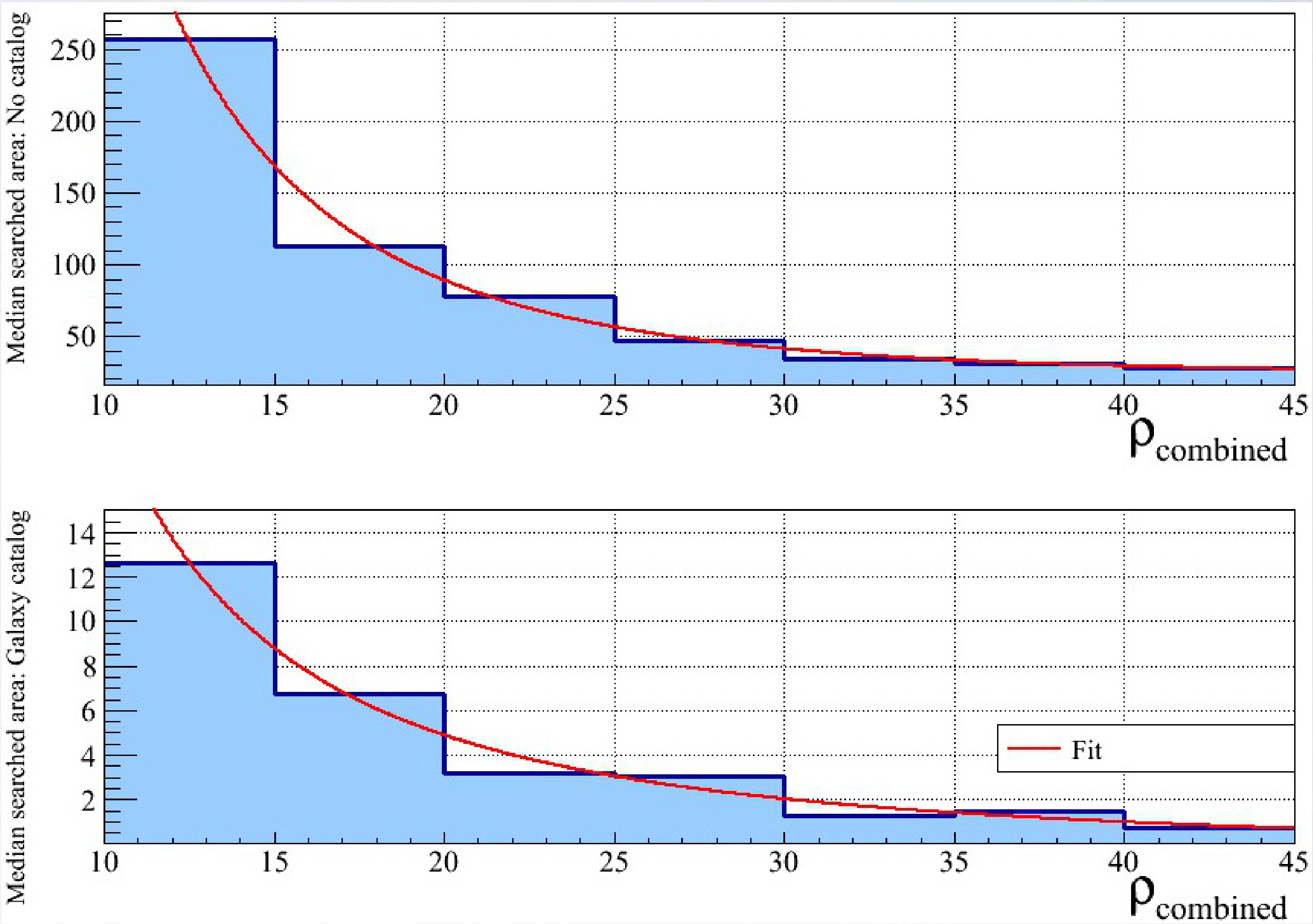
LOCALISATION BEFORE MERGER?

- In advanced detectors, BNS signals spend minutes in band
- Might detect a loud signal a minute ahead.
- But localisation comes in the last second.



S6-VSR3 LOW LATENCY

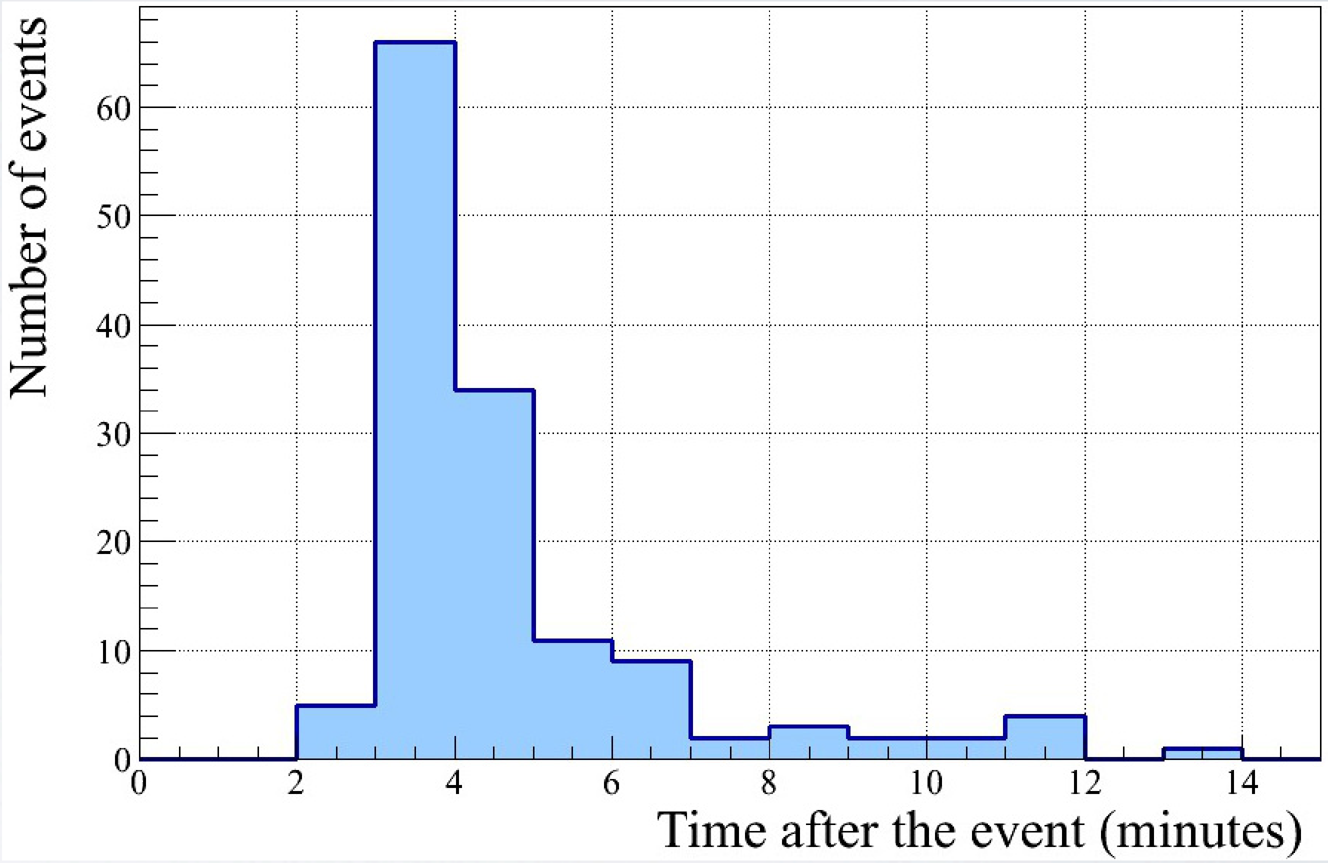
- Low latency search was done in S6-VSR2/3
- Used timing and amplitude information for rapid localisation
- Areas comparable to theoretical predictions



Abadie et al, A&A 2012

S6-VSR3 LOW LATENCY

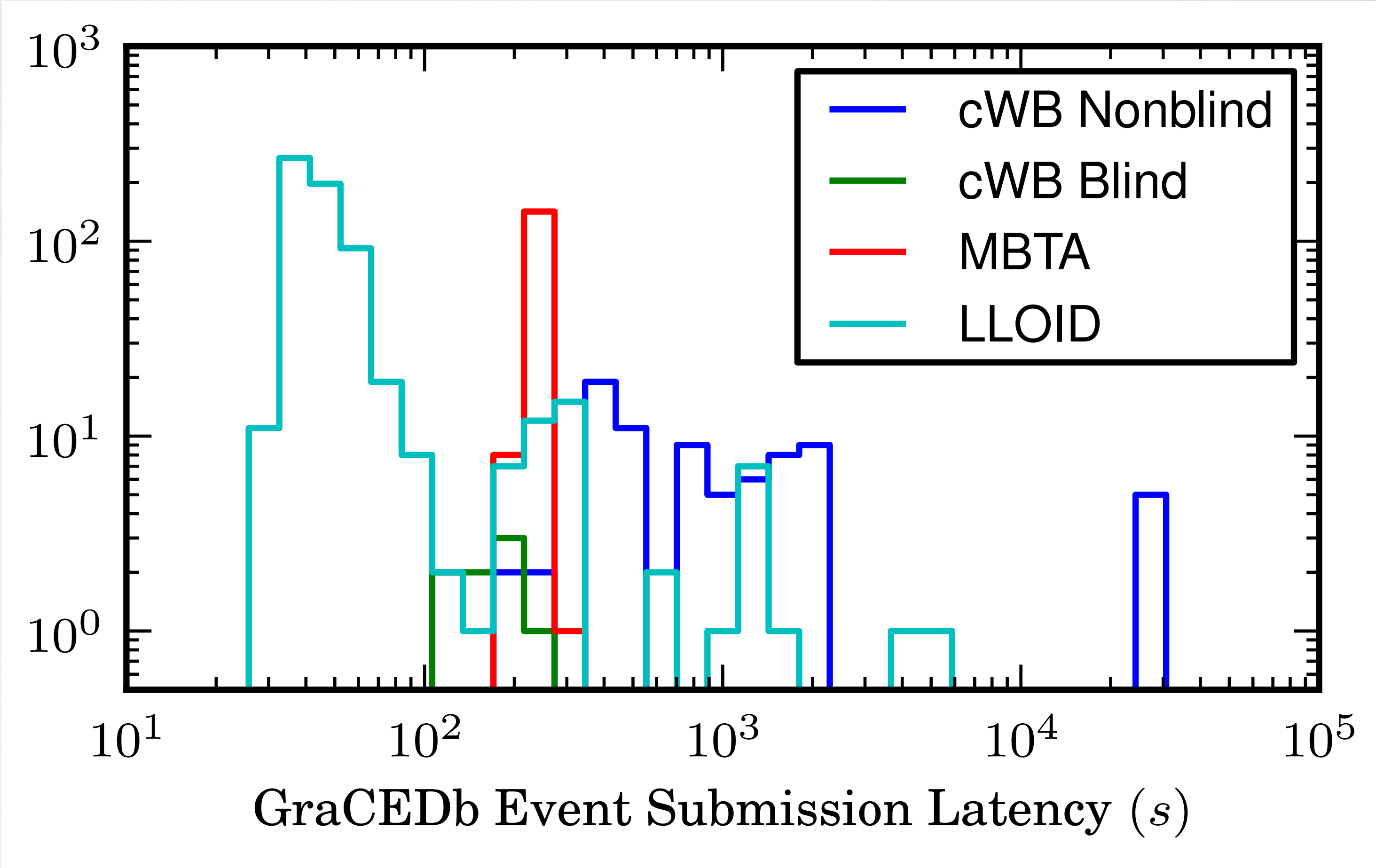
- Latencies of minutes for the analysis were achieved
- There was then a human check of instrumental performance



Abadie et al, A&A 2012

ADVANCED DETECTOR LATENCY

- Low latency much harder
  - 10x longer templates
  - 10x as many templates
- Significant effort to achieve minutes latency
- Achieved in recent "engineering runs" using simulated data at advanced detector design

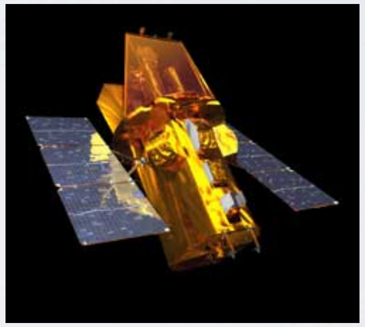


Keppel for the LSC and Virgo, GWPAW 2012 poster

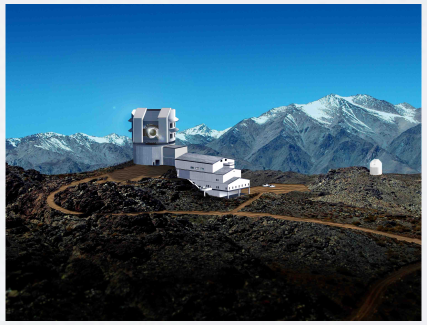
ALTERNATIVE LOCALISATION ROUTE

Gravitational Wave

Gamma Ray, X-ray



Optical



Radio

SUMMARY

- Advanced detectors will approach their design sensitivities toward the end of the decade
- Localisation areas of 10s of deg^2 with three sites
- Additional sites in India and Japan give significant improvement
- Latency of minutes is possible
- Rapid follow up of observed GRBs could give localised GW sources.