DEVELOPING THE SCIENCE CASE FOR THE NEXT GENERATION OF GRAVITATIONAL WAVE DETECTORS

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WITH INPUT FROM

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OVERVIEW

- 2G, 2G+ Science
  - what can we expect advanced detectors to have accomplished by 2030
    - assume 2G+ can have x3 sensitivity of advanced detectors
- 3G Science Case
  - what will be the most interesting problems in 2030?
    - what would still be interesting?
  - what is the ultimate science goals for ground-based detectors
- Possible configurations of future networks
  - is there a role for 3-4 km instruments in the 3G era?
  - mixed 2G+ and 3G observatories
  - is it enough to have 1 3G detector or do we need a 3+ network
- What are the future actions in this area?

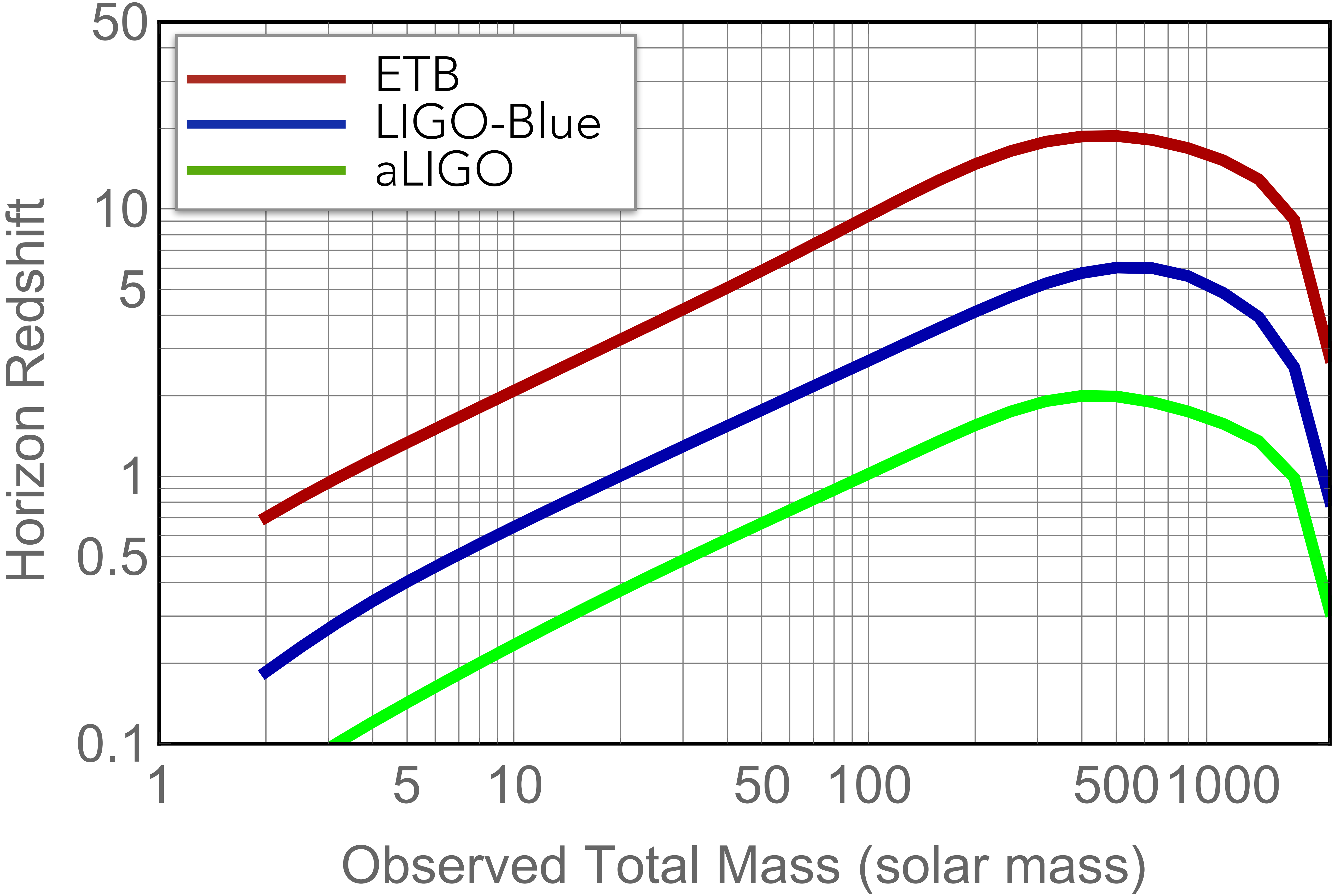
MOST RESULTS ARE FOR ET-B BUT RESULTS WILL NOT BE DIFFERENT WITH ANY 3G DETECTORS

Detector Sensitivities Considered in this Talk

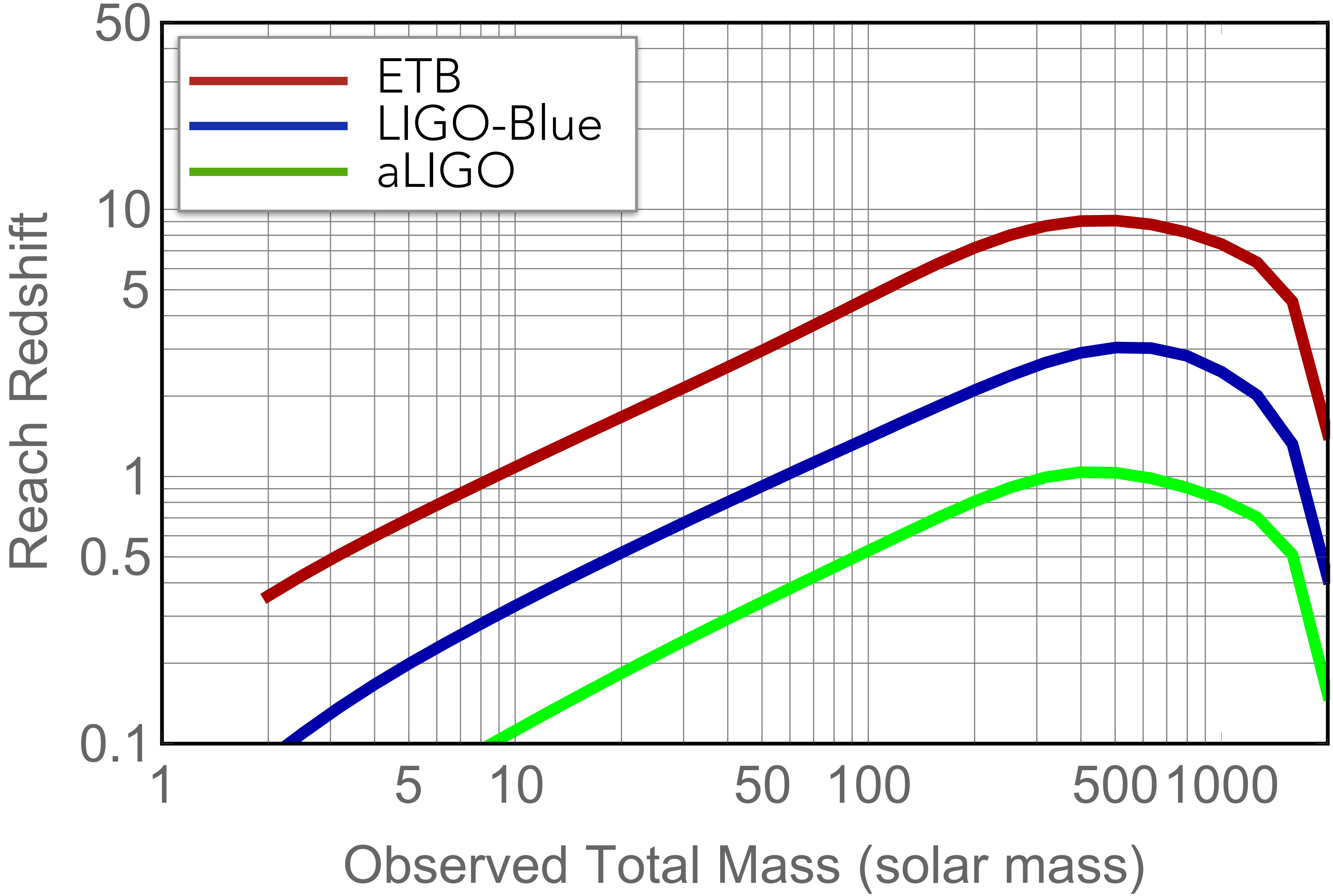
aLIGO (BNS optimised), LIGO-Blue and ET-B

GW ASTRONOMY BY 2030

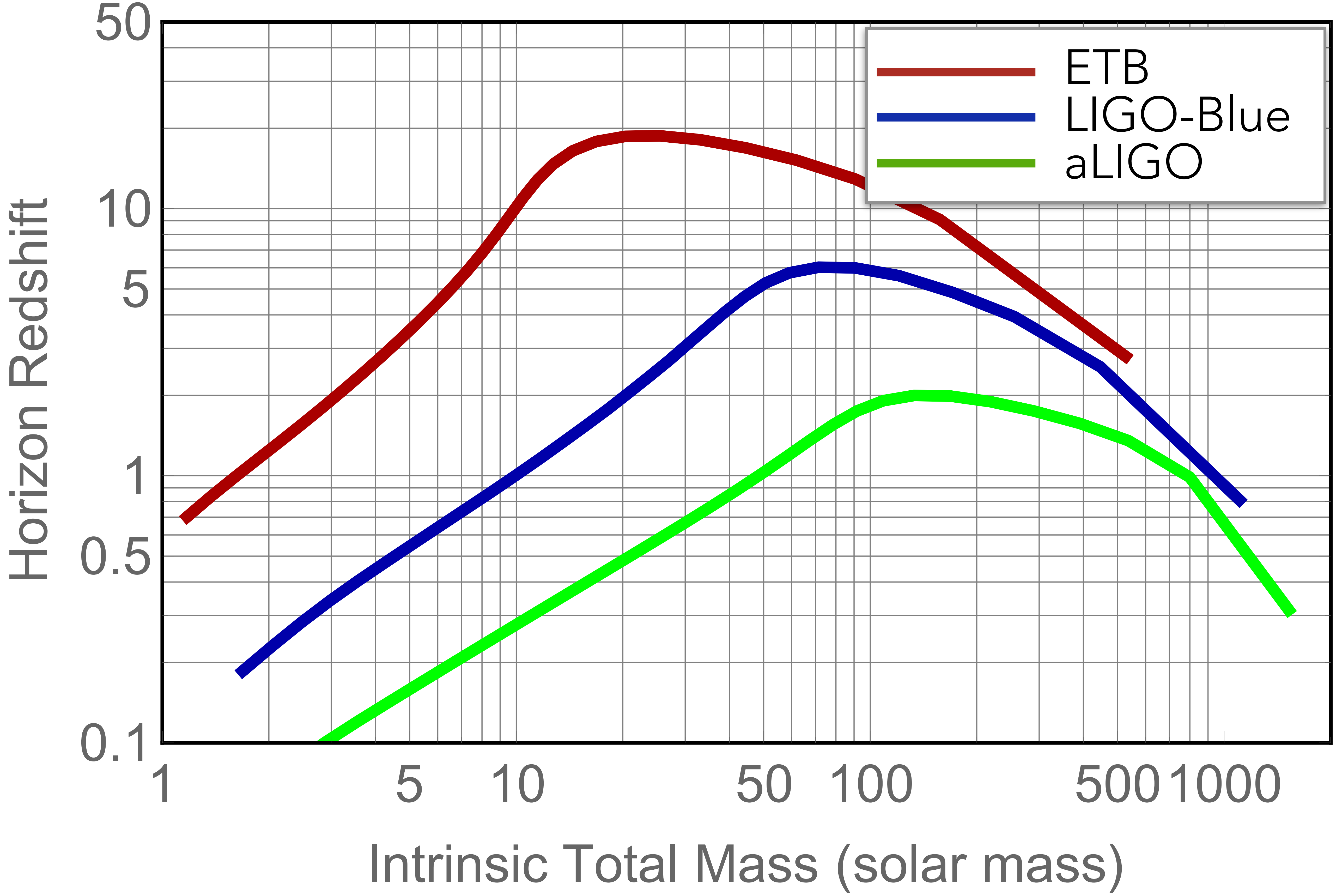
HORIZON REDSHIFT VS. OBSERVED MASS



RANGE REDSHIFT VS. OBSERVED MASS



HORIZON REDSHIFT VS. INTRINSIC MASS



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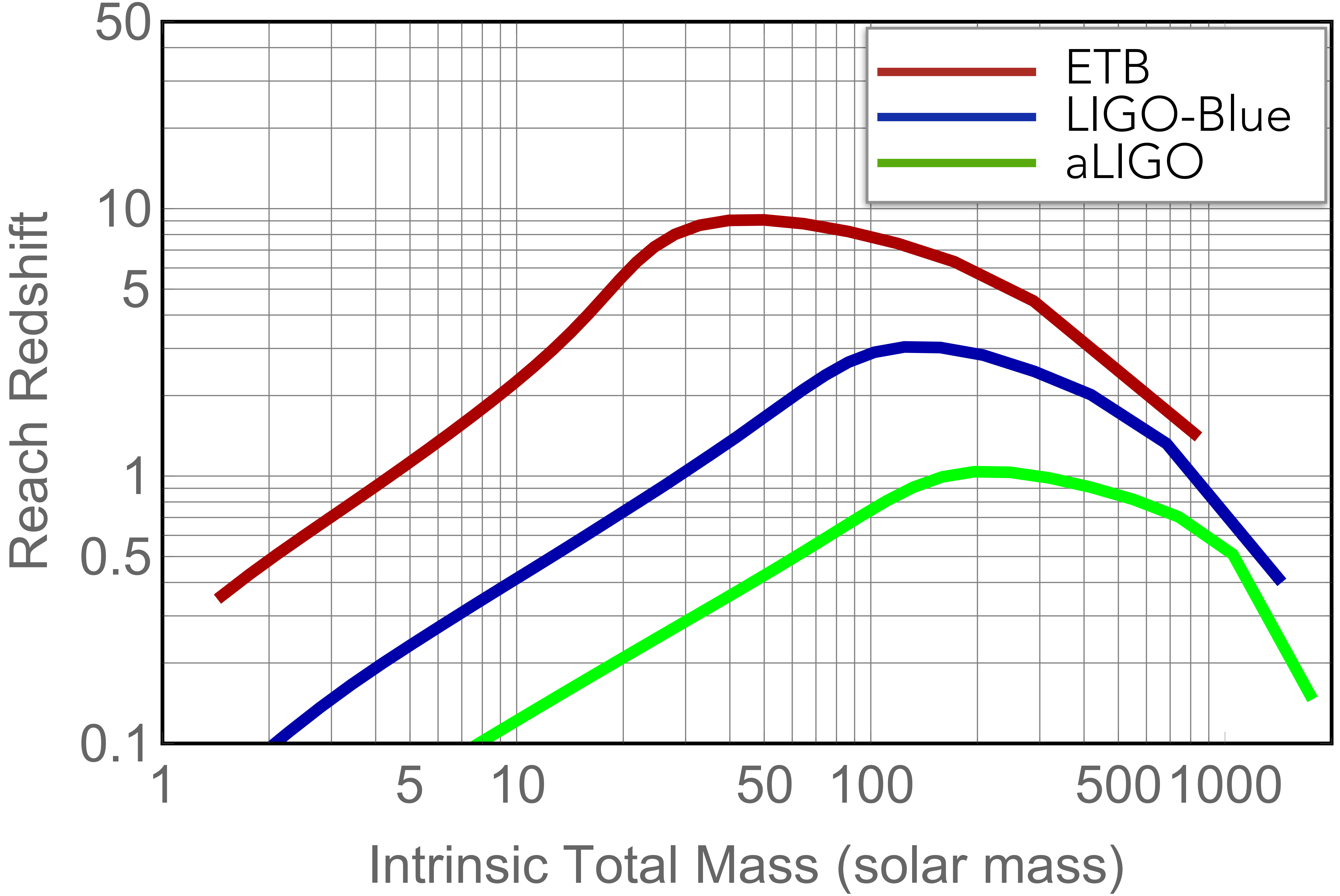


GW ASTRONOMY BY 2030

- Astrophysics by 2030
- we would have measured the rate, confirmed the existence of BBH/NSBH, confirmed GRB progenitors, but probably not much else
  - astrophysical modelling would require a large sample of events: different spins, mass ratios
- it is unlikely that advanced or A+ detectors would detect supernovae or magnetars
- NS ellipticities could be really low $< 10^{-8}$: might need to go beyond A+

GW ASTRONOMY BY 2030

- Fundamental physics by 2030
- equation of state of neutron stars would require 20-30 events (or one within 50 Mpc) - possible within advanced detector era or BB
  - ET would constrain the radius to within 500 m
- dark energy equation of state - would require thousands of BNS or even 10^5 sources, will only be possible with ET
- testing gravity would require 100's or even 1000's of events, again in the ET
- black hole no-hair theorem requires 10's of sources in ET

GW ASTRONOMY BY 2030

- Cosmology and Cosmography
  - Advanced LIGO and Virgo and LIGO-Blue would observe black holes when the universe was about 3-8 billion years old
- ET will take a census of black holes when the Universe was a mere 650 million years old

3G STRATEGY

- it is best to focus on a few very strong messages
  - too many goals will fail to send a strong and clear message about what we want from 3G detectors
- identify what gravitational wave detectors can do best and put that in our chief science goals
  - organise current science goals under 3 or 4 main headings
- identify 3 most important problems that can only be addressed and understood by 3G detectors

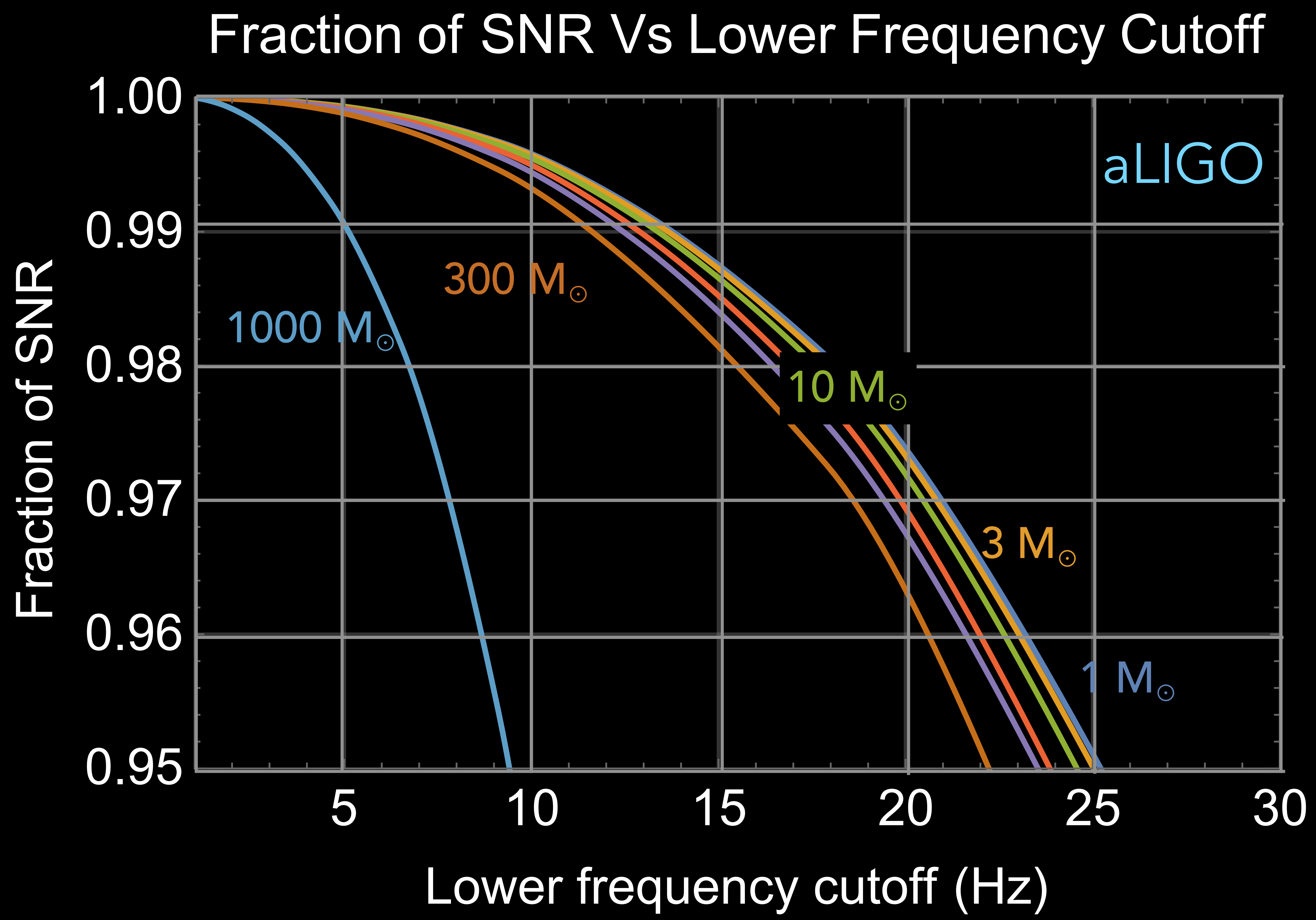
3G SCIENCE CASE

- *extremes of physics*
- *black holes through cosmic history*
- *explosive phenomena*

3G SCIENCE CASE

- *extremes of physics*
  - structure and dynamics of neutron stars
  - physics of extreme gravity
- *black holes through cosmic history*
  - formation, evolution and growth of black holes and their properties
- *explosive phenomena*
  - gamma ray bursts, gravitational collapse and supernovae, flaring and bursting neutron stars

LOW-FREQUENCY CUTOFF



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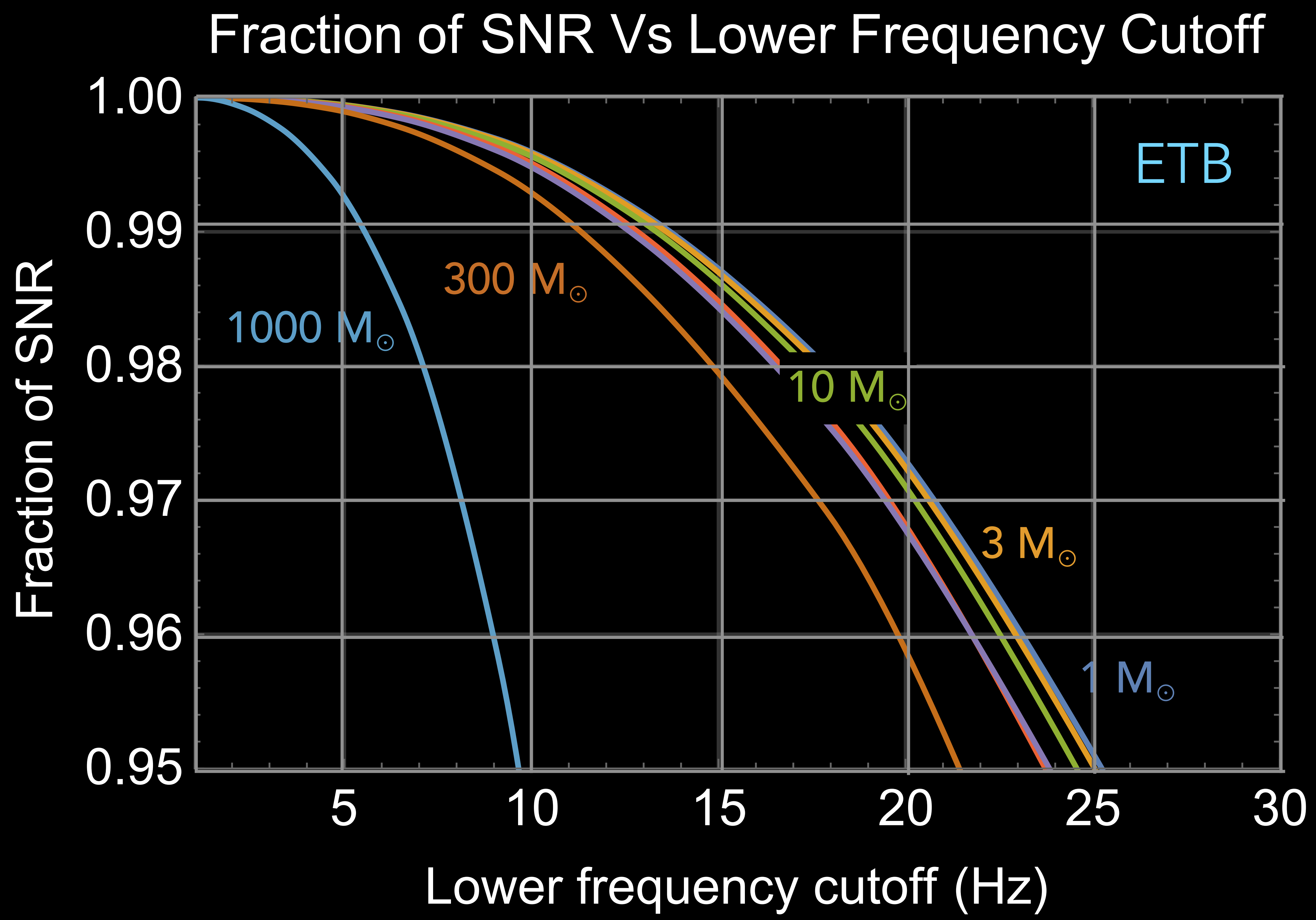
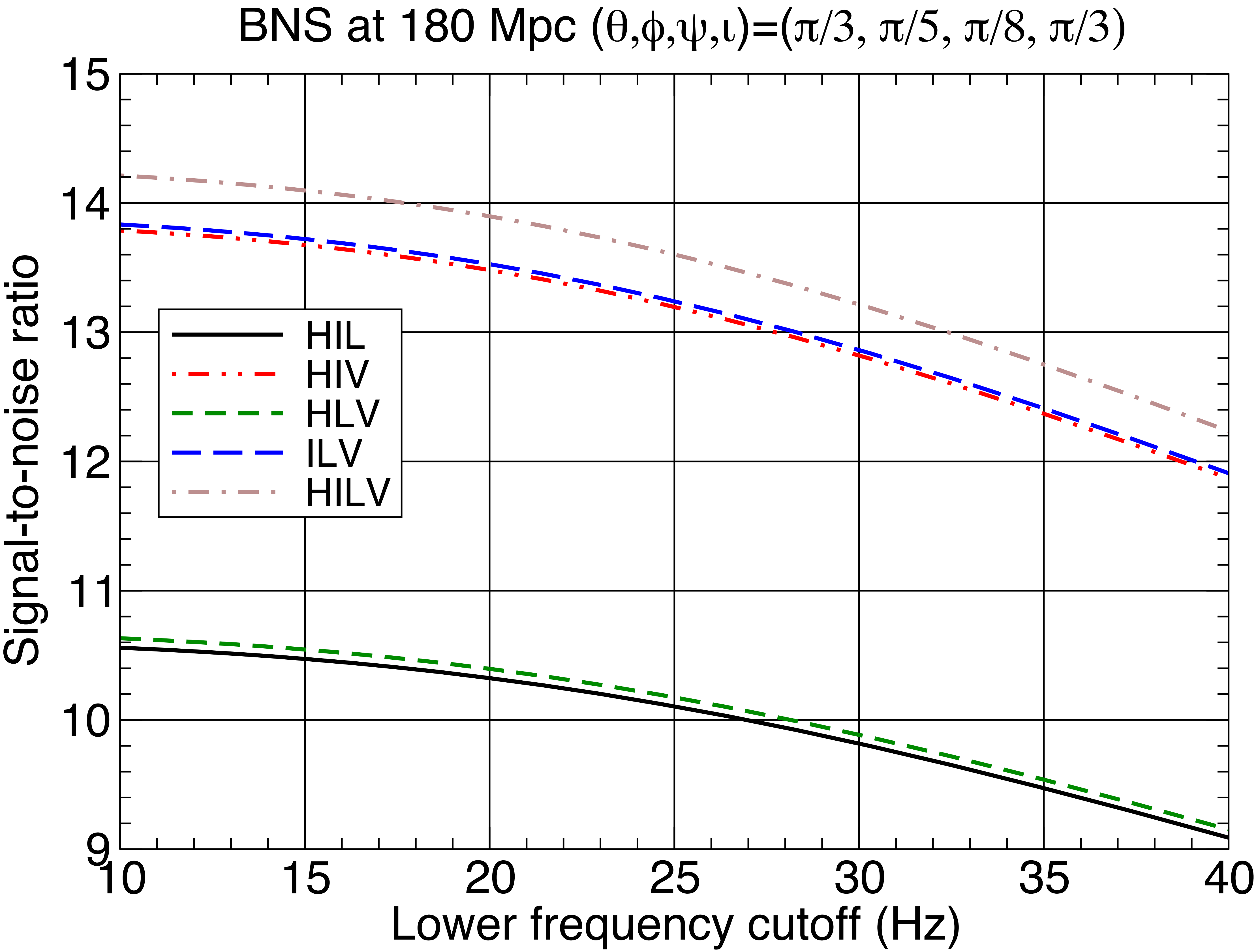
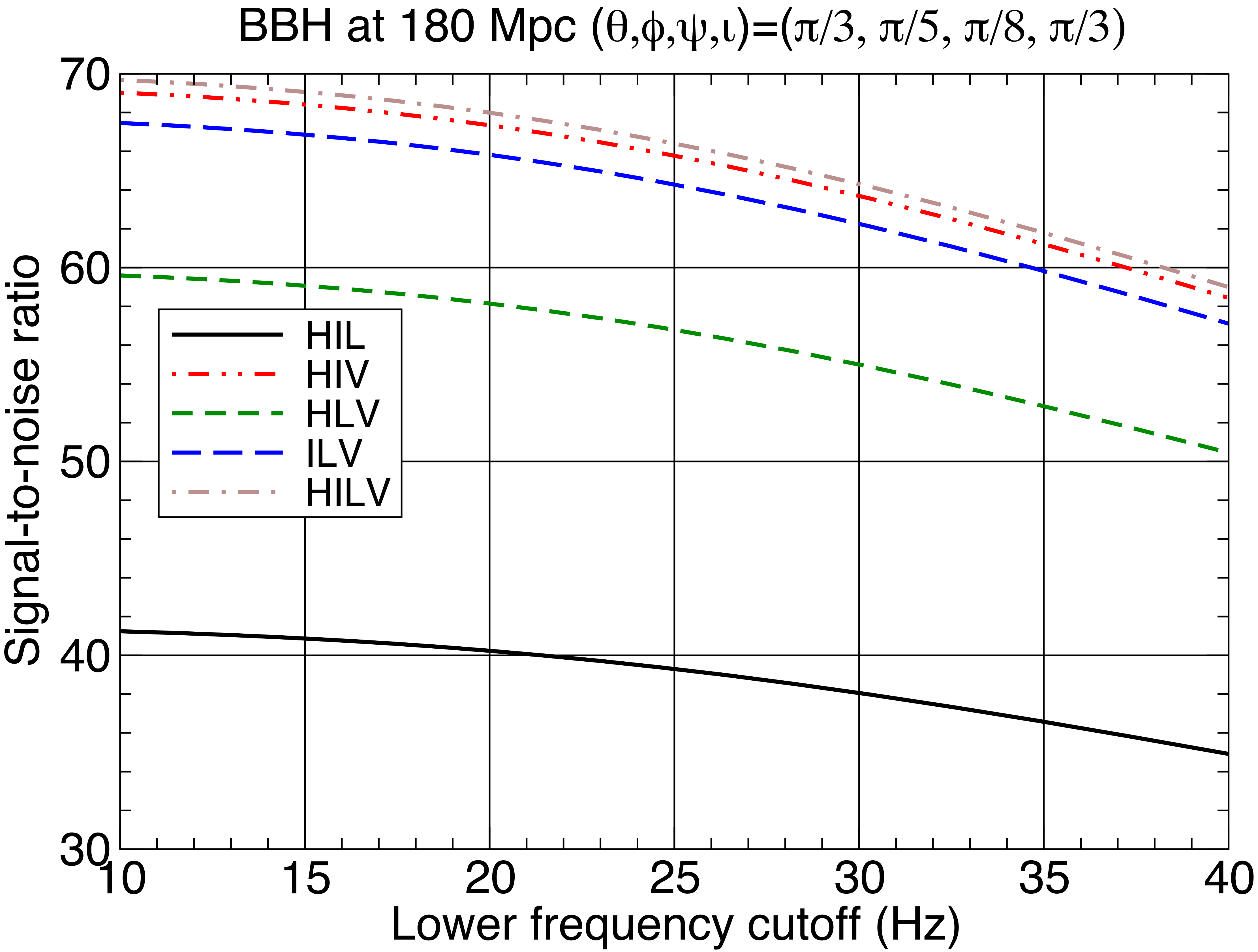


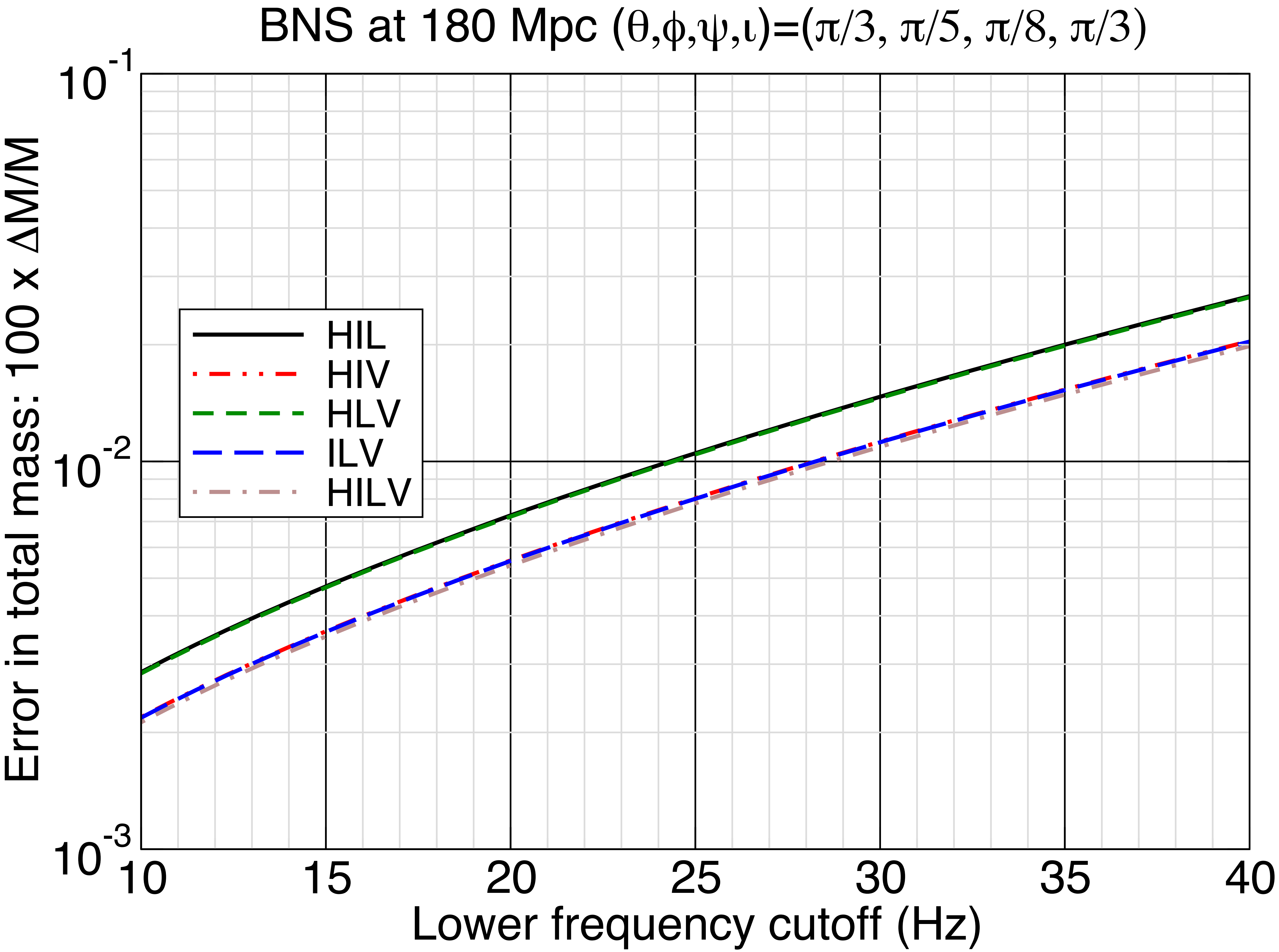
S N R


BNS at 180 Mpc (θ,φ,ψ,ι)=(π/3, π/5, π/8, π/3)
Signal-to-noise ratio
Lower frequency cutoff (Hz)
9
10
11
12
13
14
15
10
15
20
25
30
35
40
HIL
HIV
HLV
ILV
HILV

S N R


BBH at 180 Mpc (θ,ϕ,ψ,ι)=(π/3, π/5, π/8, π/3)
Signal-to-noise ratio
30
40
50
60
70
10
15
20
25
30
35
40
Lower frequency cutoff (Hz)
HIL
HIV
HLV
ILV
HILV

ERROR IN TOTAL MASS



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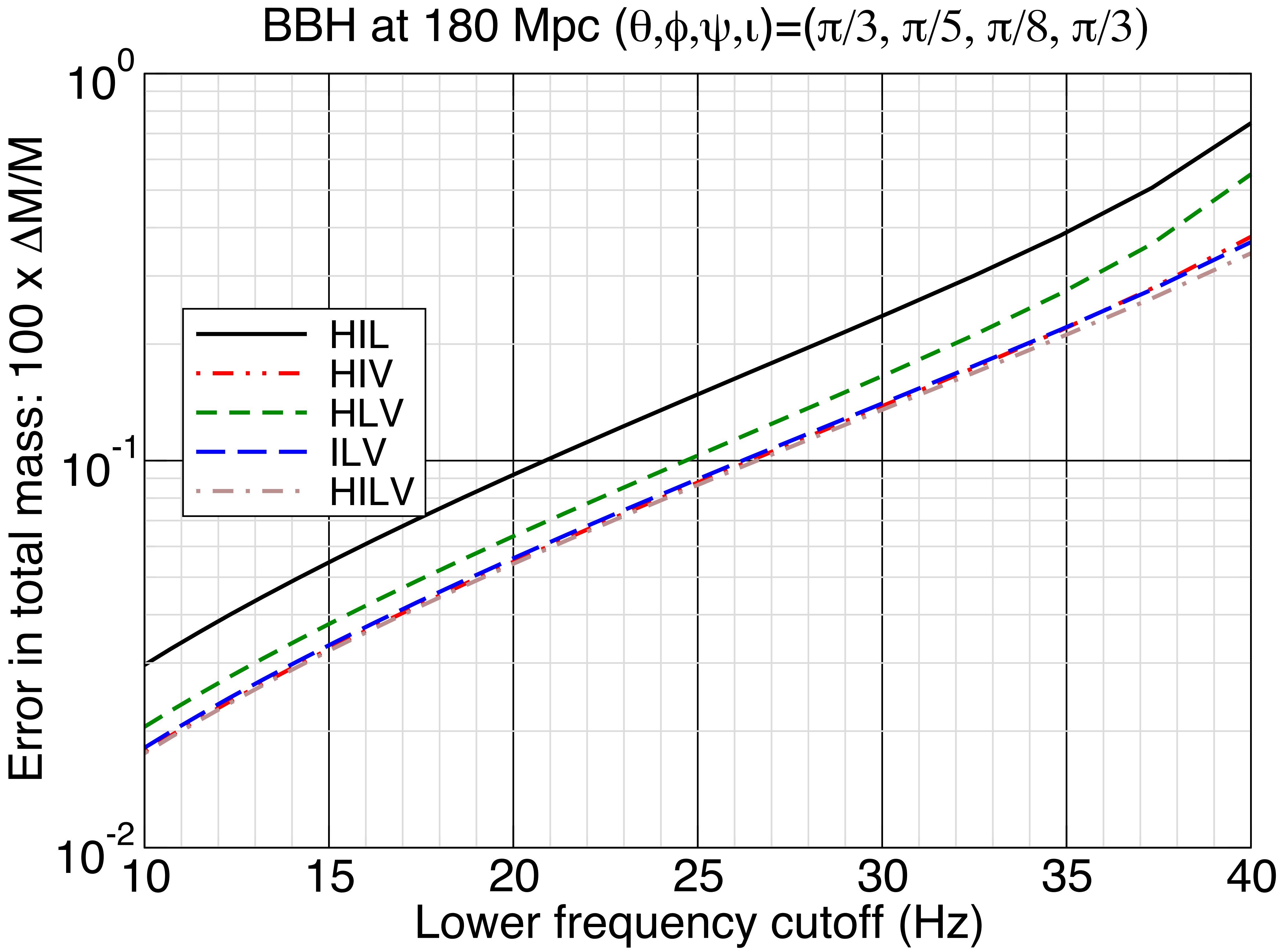
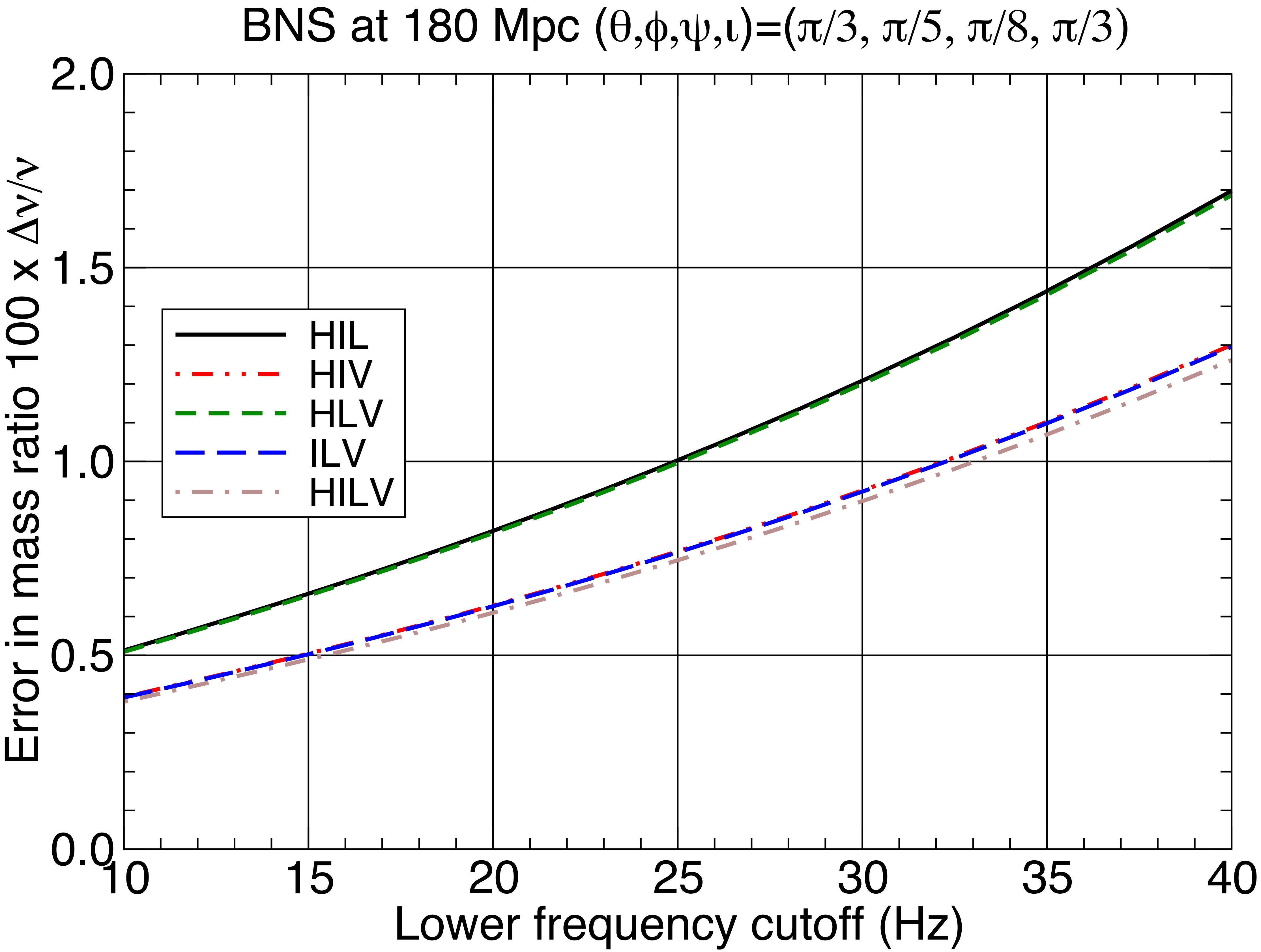


ERROR IN MASS RATIO



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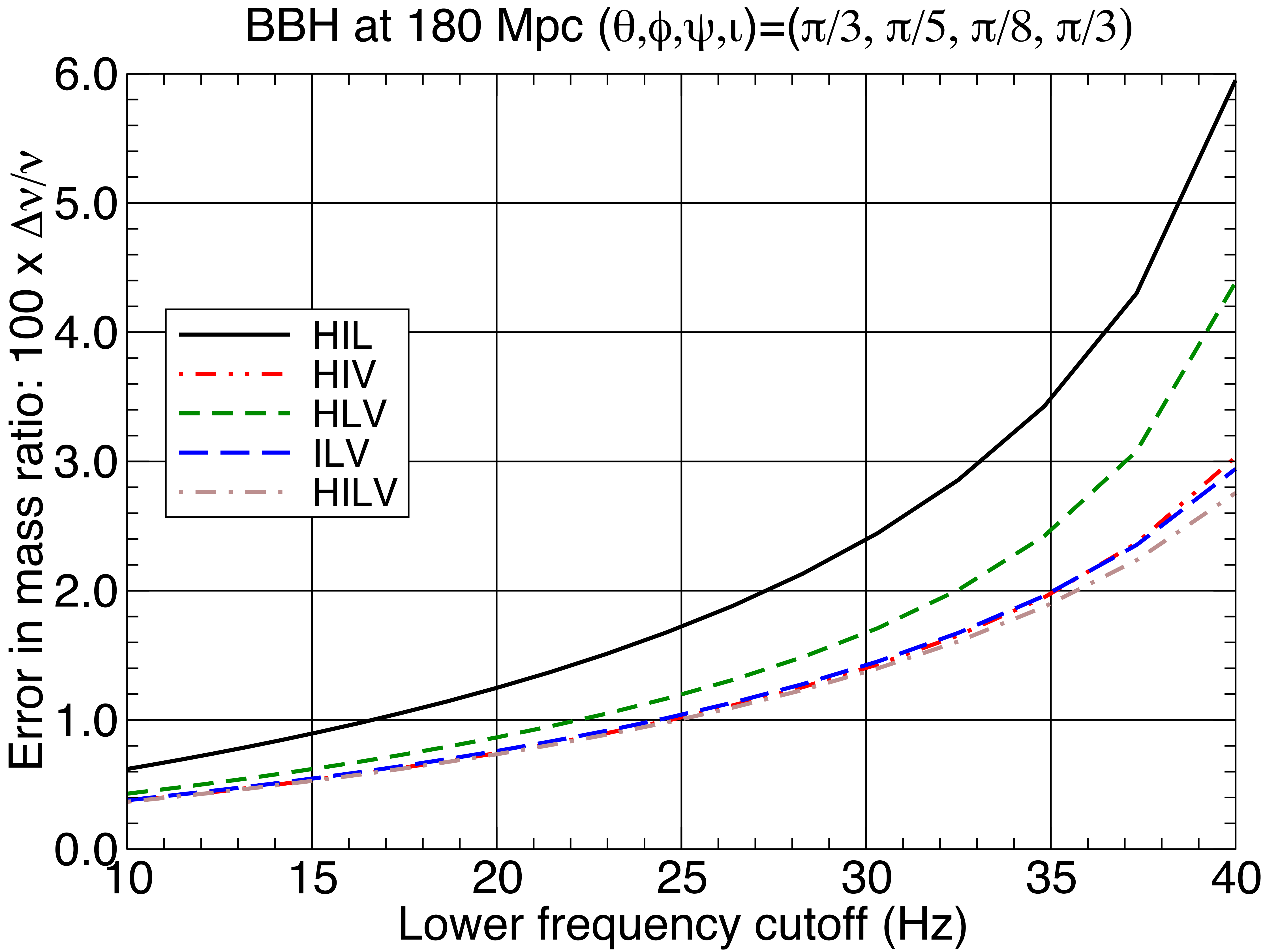
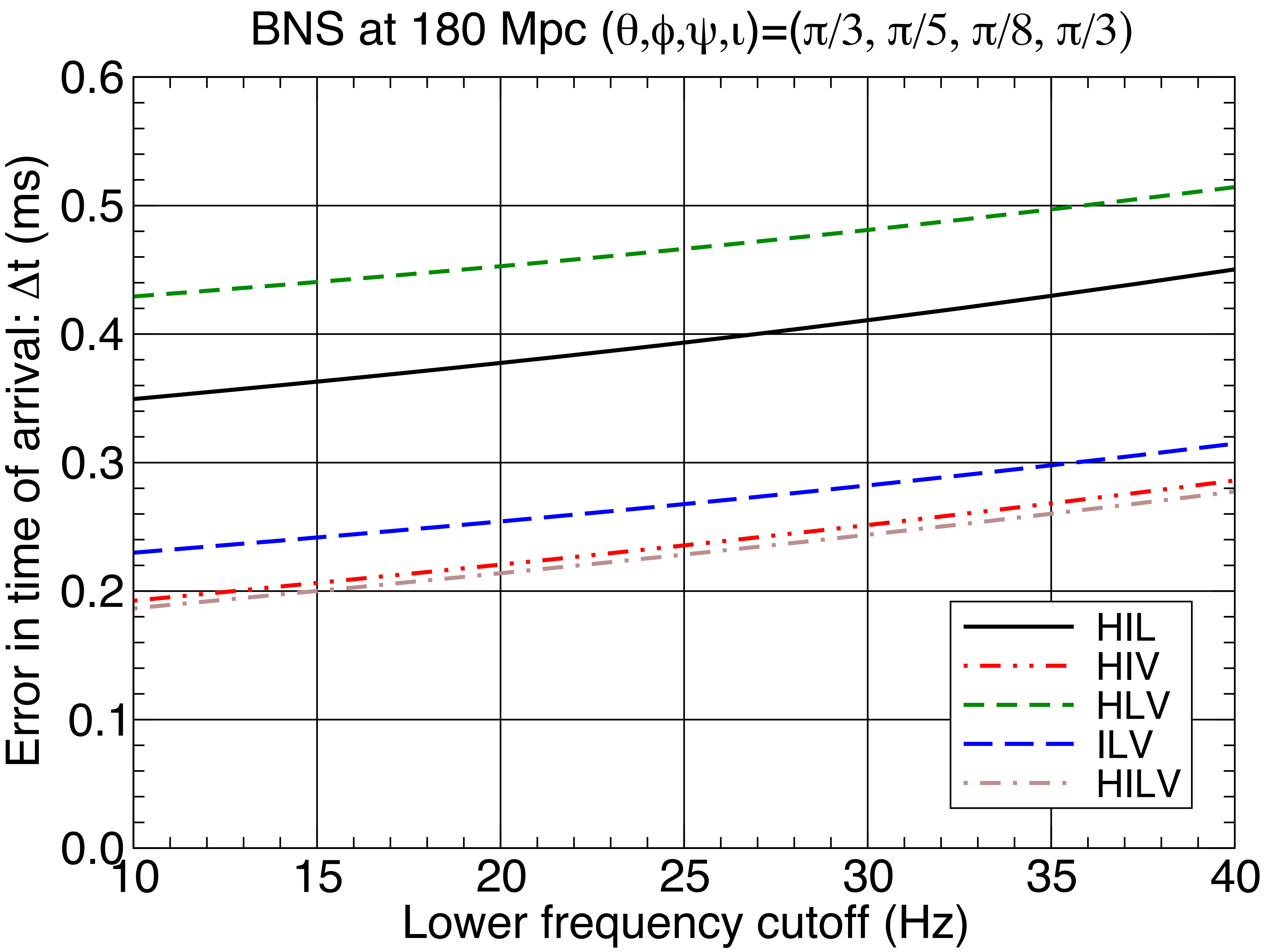


ERROR IN TIME OF ARRIVAL



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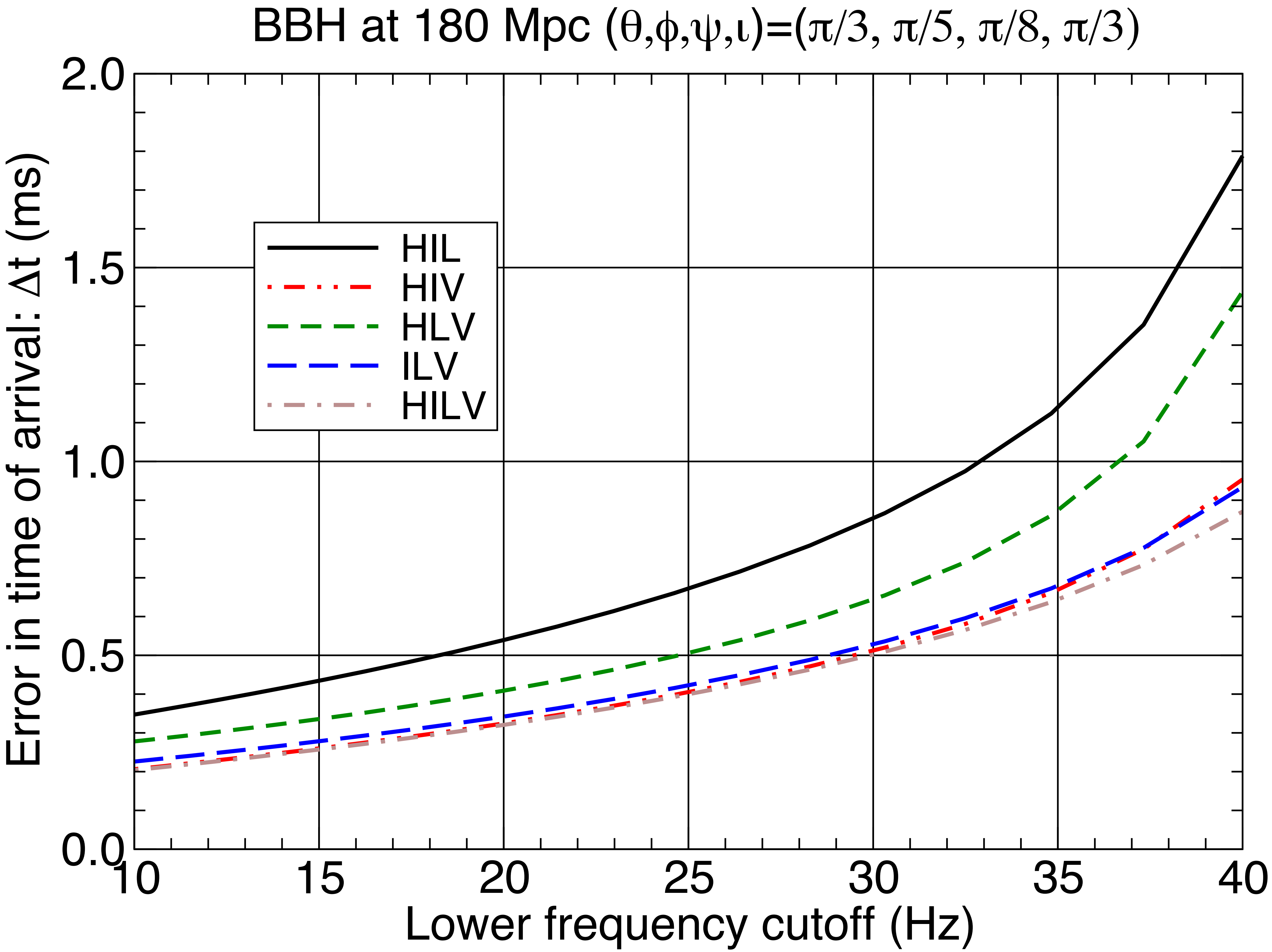
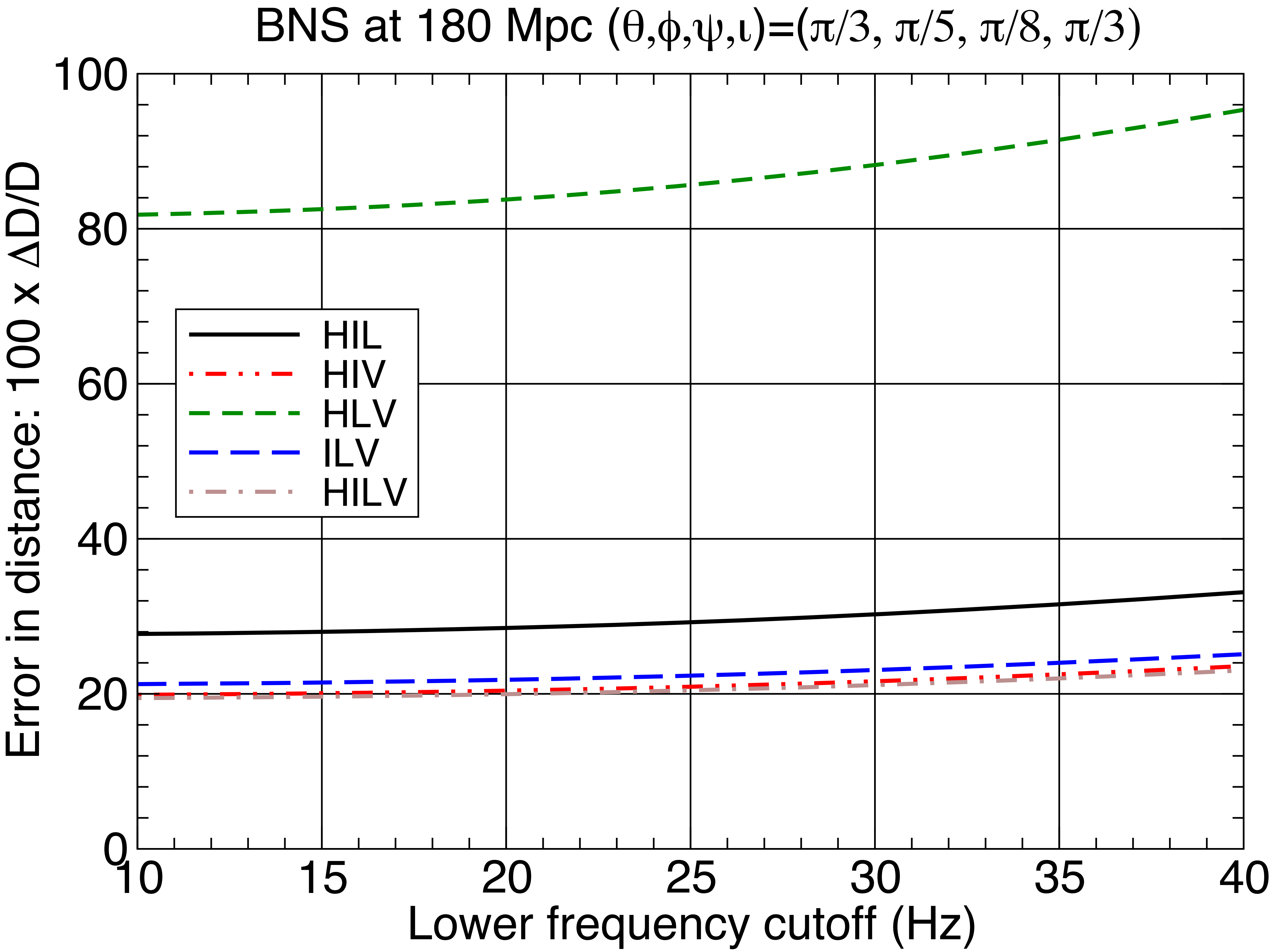


ERROR IN DISTANCE



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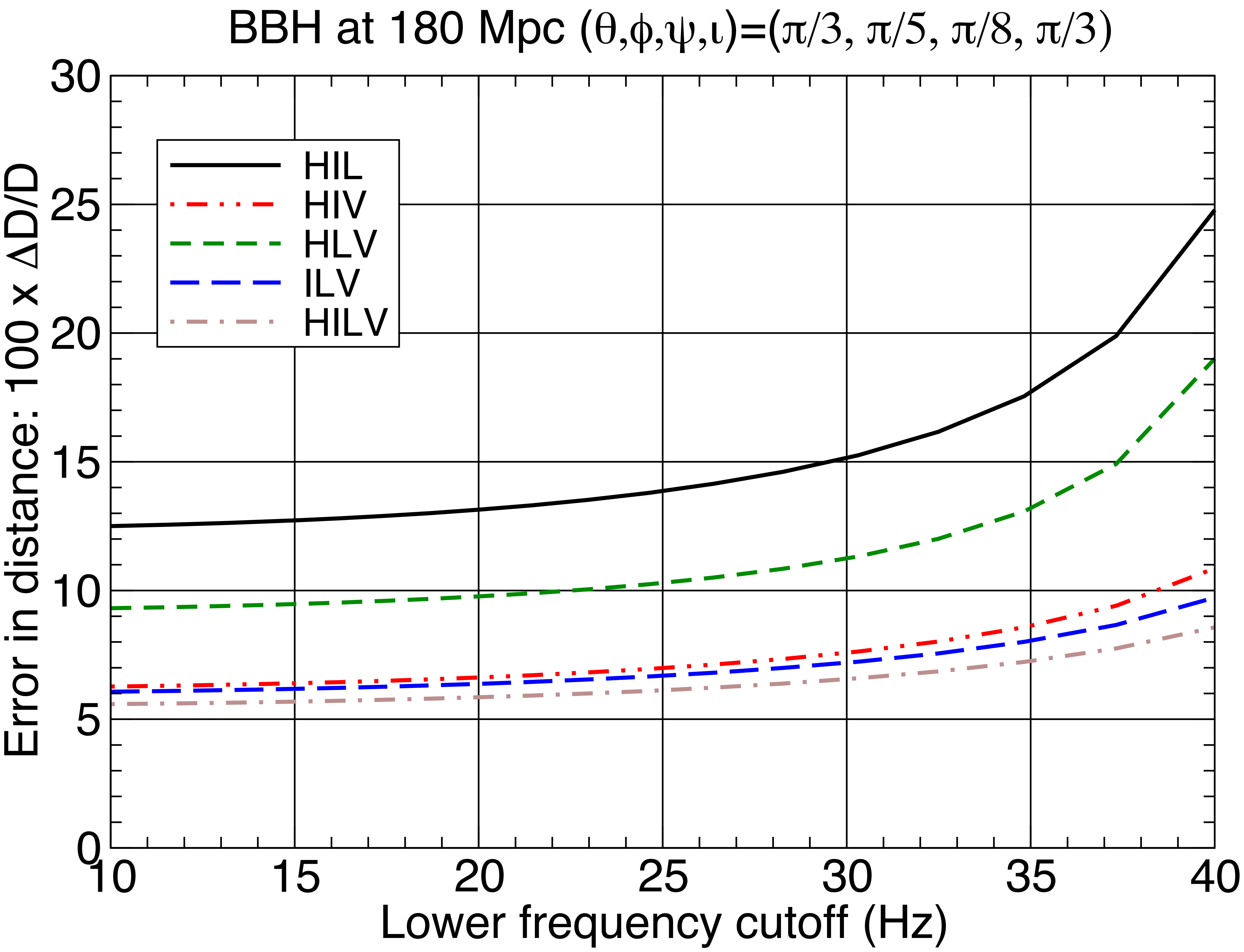
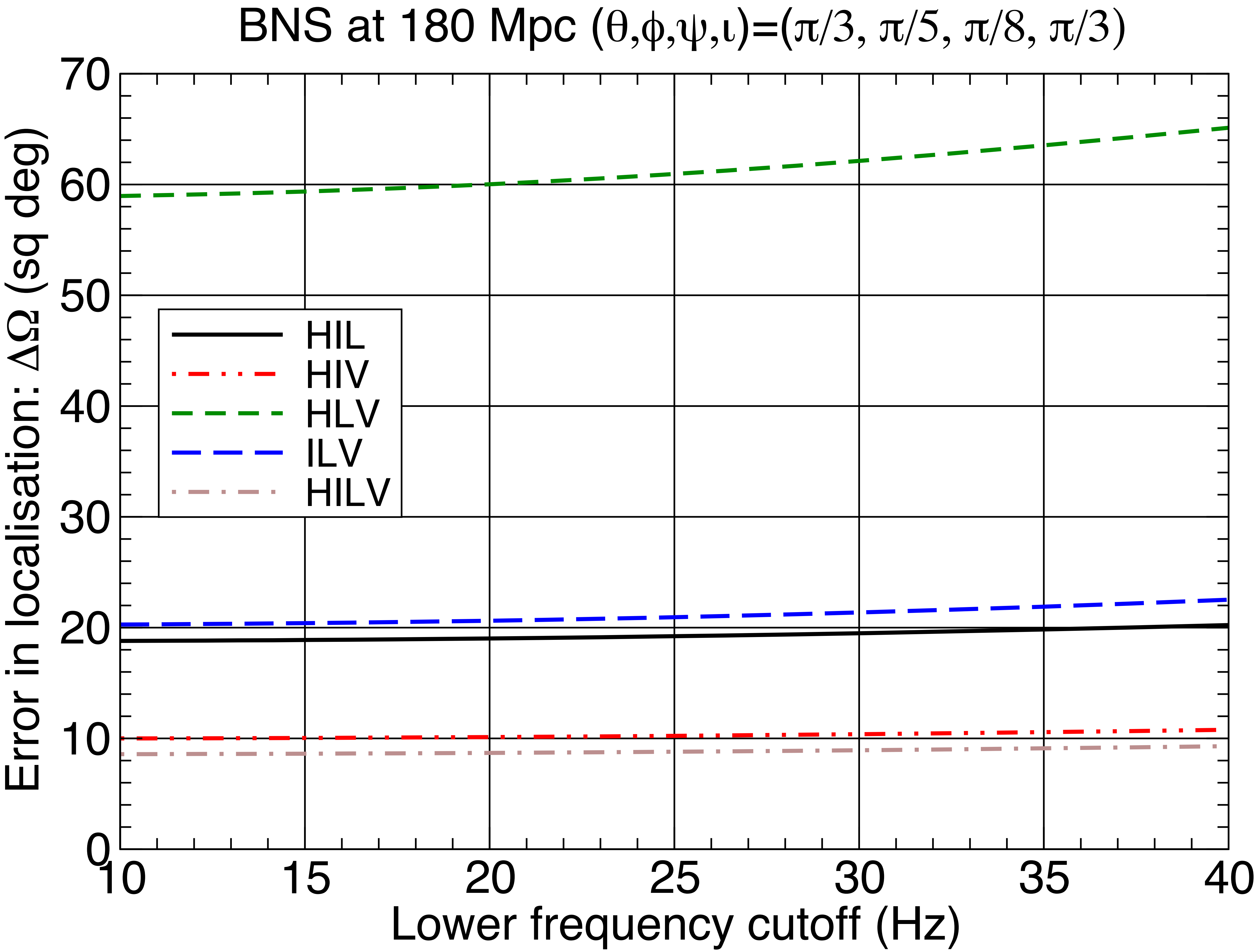


ERROR IN SKY LOCALISATION



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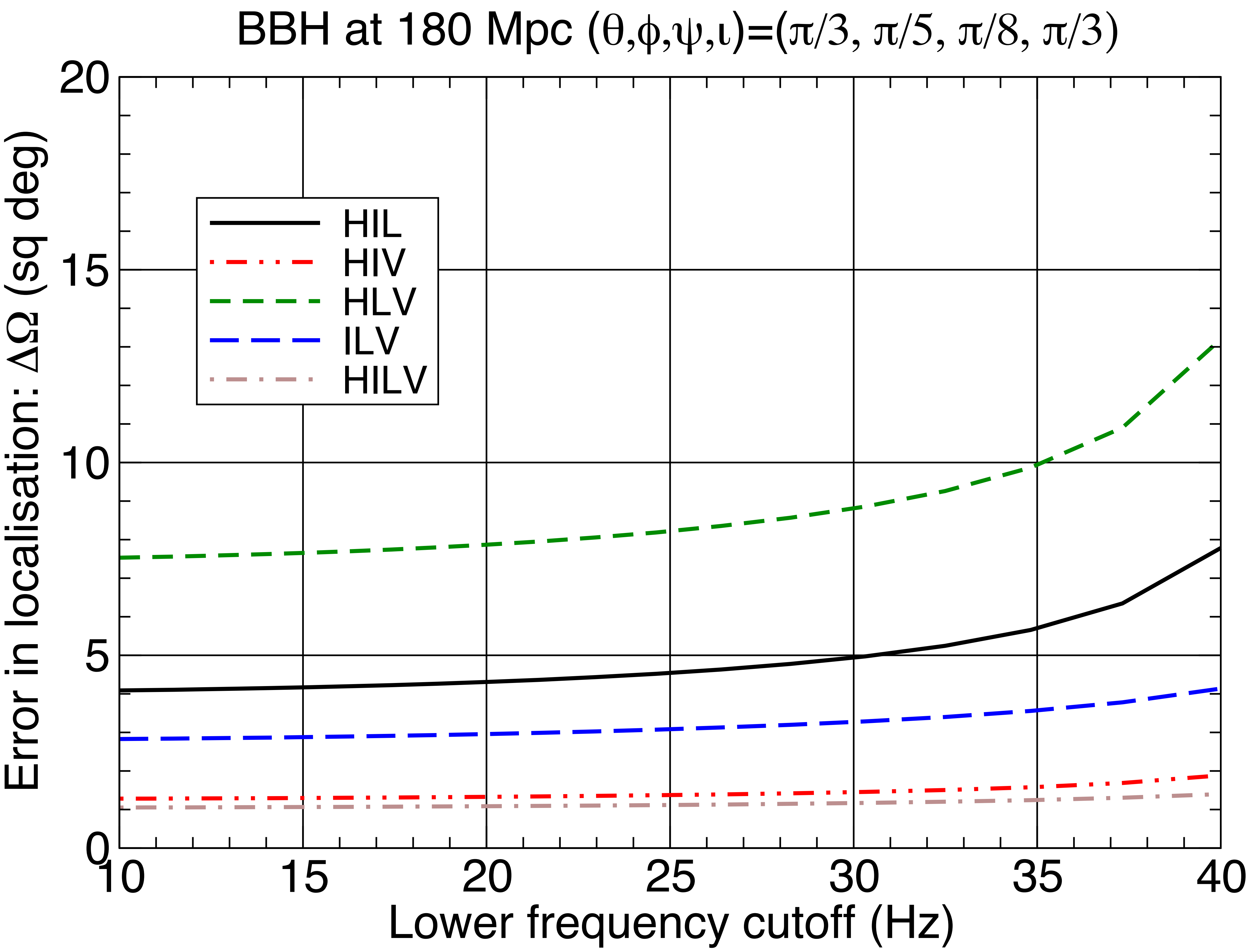


CAPABILITIES OF A 2G+/3G NETWORK

NEED NETWORK OF 3G DETECTORS?

PARAMETER ESTIMATION - ANGULAR RESOLUTION: (1.38+1.42) BNS, ARBITRARY LOCATION AND ORIENTATION

$$\theta = \pi/6,\ \varphi = \pi/5,\ \psi = \pi/8,\ \iota = \pi/3,\ D = 3\,\mathrm{Gpc}$$

- At their distance reach each of these networks perform equally well

	SNR	SKY $\Delta\Omega$ DEG^2	INC. ΔI DEG	DIST ΔD/D	CHIRP MASS (PPM)	EPOCH ΔT (MS)
3XBB (800 MPC)	12	**43**	23	75%	50	0.47
3XETB	12.85	**55**	23	78%	60	0.52
3XALIGO (200 MPC)	10	56	27	62%	30	0.52

PARAMETER ESTIMATION - IMPORTANCE LOW FREQUENCY: (12+8) BBH (NO SPIN), ARBITRARY LOCATION AND ORIENTATION

$$\theta = \pi/6,\ \varphi = \pi/5,\ \psi = \pi/8,\ \iota = \pi/3,\ D = 7\,\mathrm{Gpc}$$

- Same as before but for black hole sources

	SNR	SKY ΔΩ DEG^2	INC. ΔI DEG	DIST ΔD/D	CHIRP MASS	EPOCH ΔT (MS)
3XBB (2.5 GPC)	21	86	21	55%	0.22%	1.4
3XETB	30	53	14	51%	**0.065%**	0.94
3XALIGO (1 GPC)	10	260	37	130%	0.19%	1.9

PARAMETER ESTIMATION: RELEVANCE OF LOW FREQUENCY (1.38+1.42) BNS, ARBITRARY LOCATION AND ORIENTATION

$$\theta = \pi/6,\ \varphi = \pi/5,\ \psi = \pi/8,\ \iota = \pi/3,\ D = 3\,\mathrm{Gpc}$$

- For ETD assumed a lower cutoff of 5 Hz (to answer effect of low-frequency cutoff on parameter estimation)
- Chirp mass is equivalent to the most dominant PN term: It gets determined a factor of 8 better in ETD

	SNR	SKY ΔΩ DEG^2	INC. ΔI DEG	DIST ΔD/D	CHIRP MASS (PPM)	EPOCH ΔT (MS)
3XBB (800 MPC)	12	43	23	53%	50	0.47
3XETB **3XETD**	12.85 12.86	55 52	23 22	78% 72%	**60** **8**	0.52 0.52
3XALIGO (200 MPC)	10	56	27	62%	30	0.52

PARAMETER ESTIMATION: HETEROGENOUS DETECTORS (1.38+1.42) BNS, ARBITRARY LOCATION AND ORIENTATION

- Compare performance of 3 x ET vs 2 x BB+ET
- In a such a network error in chirp mass not severely compromised: only marginally worse
  - This should help test of GR etc.
- But sky localisation takes a big hit: a factor of 7 worse compared to a homogeneous network of detectors

$$\theta = \pi/6,\ \varphi = \pi/5,\ \psi = \pi/8,\ \iota = \pi/3,\ D = 800\,\mathrm{Mpc}$$

	SNR	SKY $\Delta\Omega$ DEG^2	INC. ΔI DEG	DIST $\Delta D/D$	CHIRP MASS (PPM)	EPOCH ΔT (MS)
2 X BB + ETB	37	**41**	22	71%	**5.6**	0.41
3 X ETB	39	**5.7**	7.6	25%	**5.2**	0.16
3 X BB	12	**43**	23	75%	**52**	0.47

PARAMETER ESTIMATION - HETEROGENOUS DETECTORS: (12+8) BBH, ARBITRARY LOCATION AND ORIENTATION

$$\theta = \pi/6,\ \varphi = \pi/2,\ \psi = \pi/8,\ \iota = \pi/3,\ D = 2.5\,\mathrm{Gpc}$$

- Even for binary black holes the story is the same: heterogeneous network is good for mass measurements (which also means good for test of GR) but not good for sky resolution

- These studies are for a single source location and orientation, should do exhaustive Monte Carols before concluding anything definitive

	SNR	SKY $\Delta\Omega$ DEG^2	INC. ΔI DEG	DIST ΔD/D	CHIRP MASS	EPOCH ΔT (MS)
2 X BB + ETB	54	**24**	17	50%	**0.02%**	0.41
3 X ETB	68	**2.8**	5.8	17%	**0.02%**	0.16
3 X BB	21	**32**	20	63%	**0.21%**	1.5

FREQUENCY CHOICES

- There are no obvious choices
  - questions addressed by low- and high- frequency improvements are both interesting
  - low frequencies improve measurement but high frequency contains strong field dynamics
- High SNR events are important:
  - for testing general relativity or measuring equation of state; but large number of events can also be used
- Large number of events are important for:
  - measuring cosmological parameters, testing astrophysical models, etc., few SNR events are not of much use
- Rare events might tell us some important physics
  - Supernovae, precessing binaries, magnetar glitches, long GRBs, …

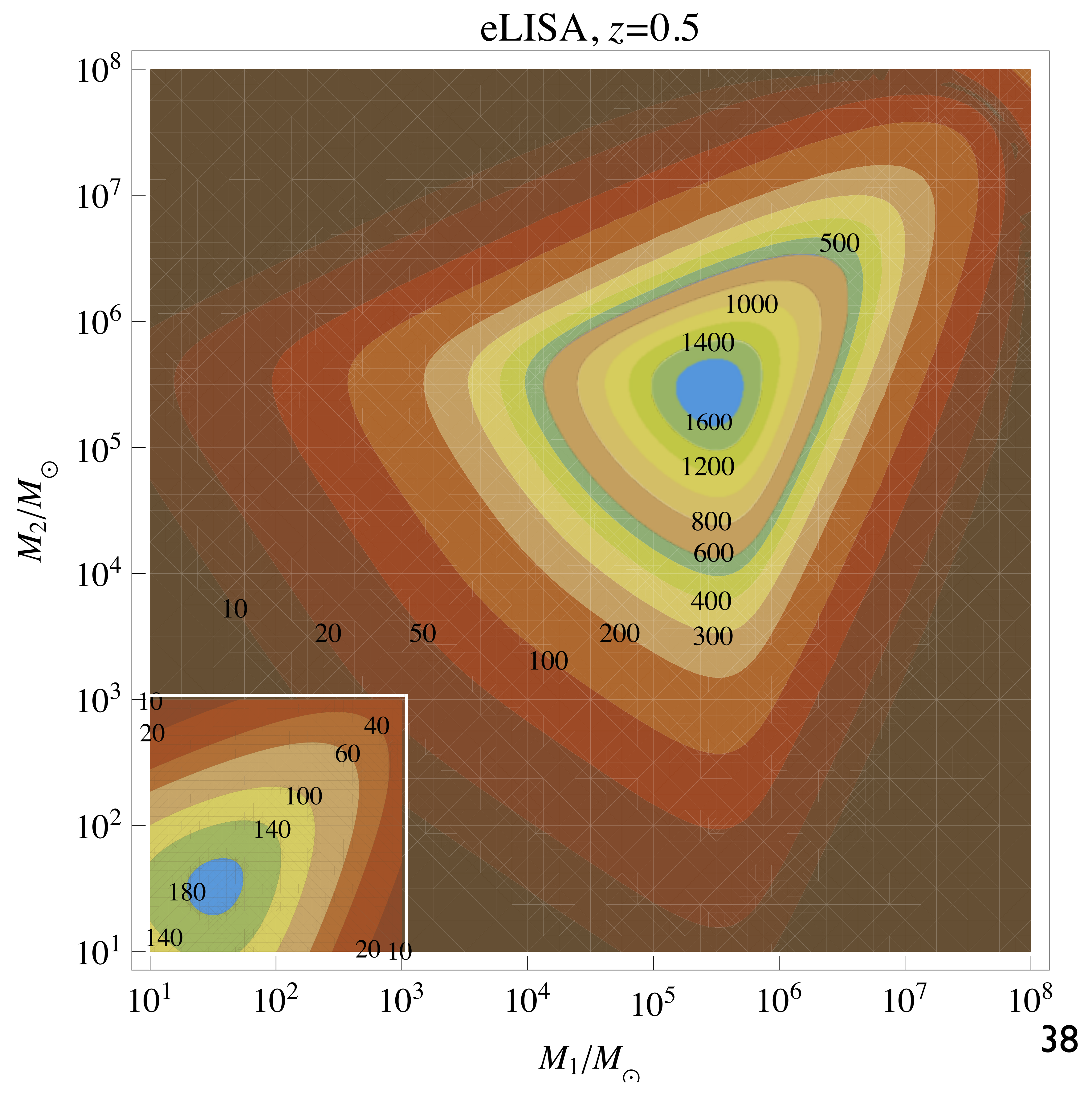
MULTI-MESSENGER ASTRONOMY

- What are the multi-messenger physics problems in 3G scenario, also with LISA?
  - what EM detectors do we expect in the next 10-30 years?
- What actions from GW communities should be taken to facilitate future EM detectors?
  - which EM telescopes/detectors are important to us?
- What GW network capabilities are needed?
  - what are the next action items in this domain?

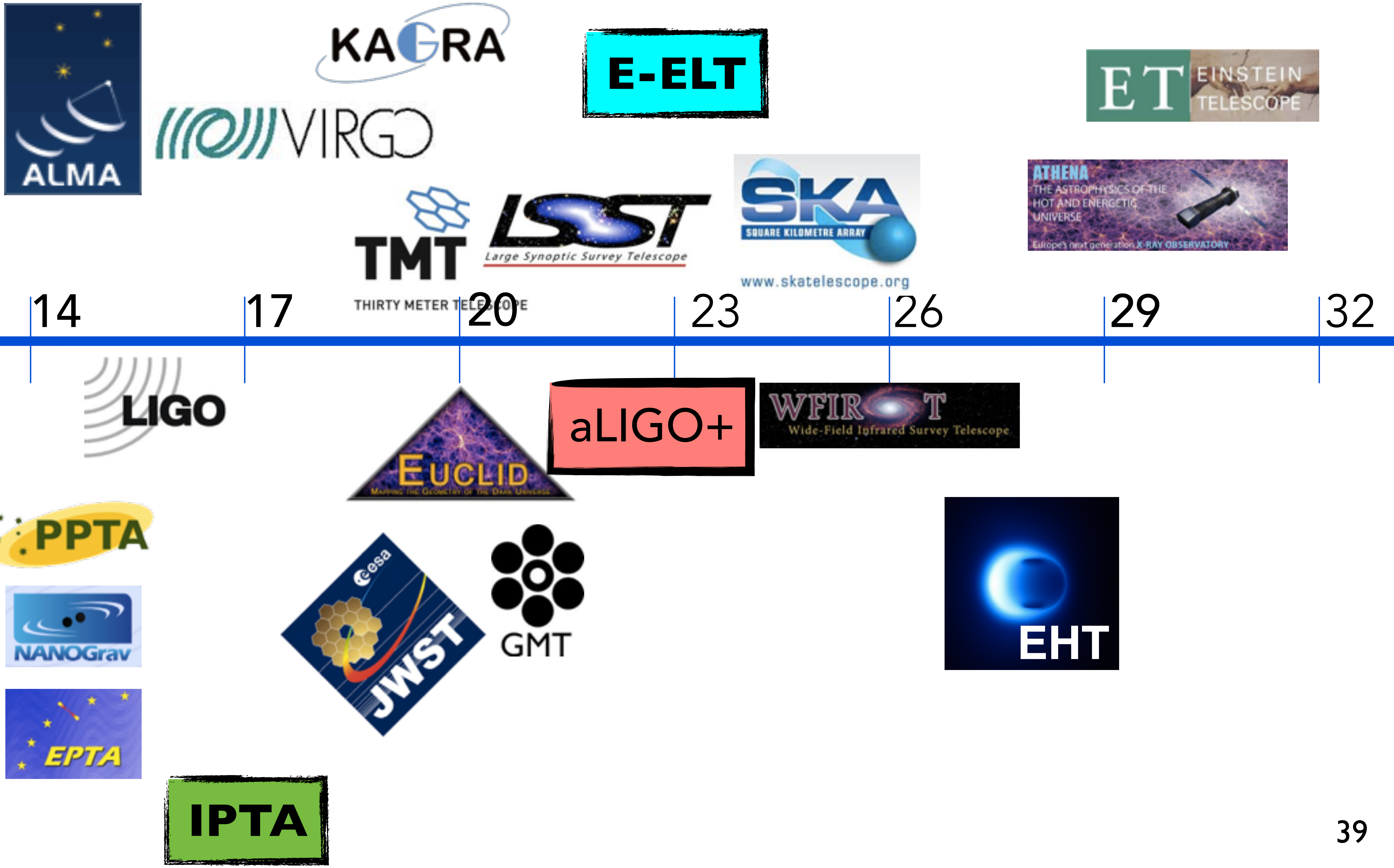
Expected Signal-to-Noise Ratios: ET and eLISA

Some systems observed by eLISA might also be observable by ET

Caution: Only inspiral part is considered when computing the SNR



Timescale of Telescopes, Missions, Surveys



FUTURE ACTIONS

- Develop a blue-book on 3G