Revisiting the LISA science case

Neil J. Cornish
Montana State University
extreme Gravity Institute

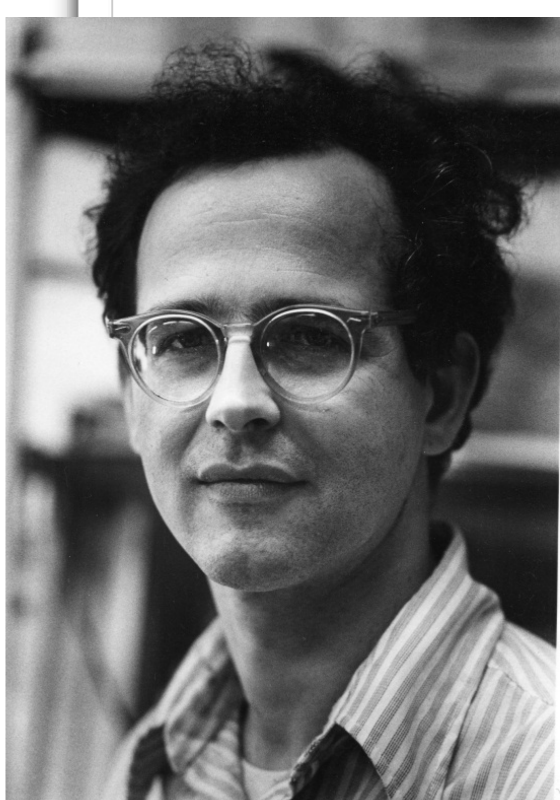
The Weiss Report: 1975

MANAGEMENT AND OPERATIONS

WORKING GROUP FOR SHUTTLE ASTRONOMY

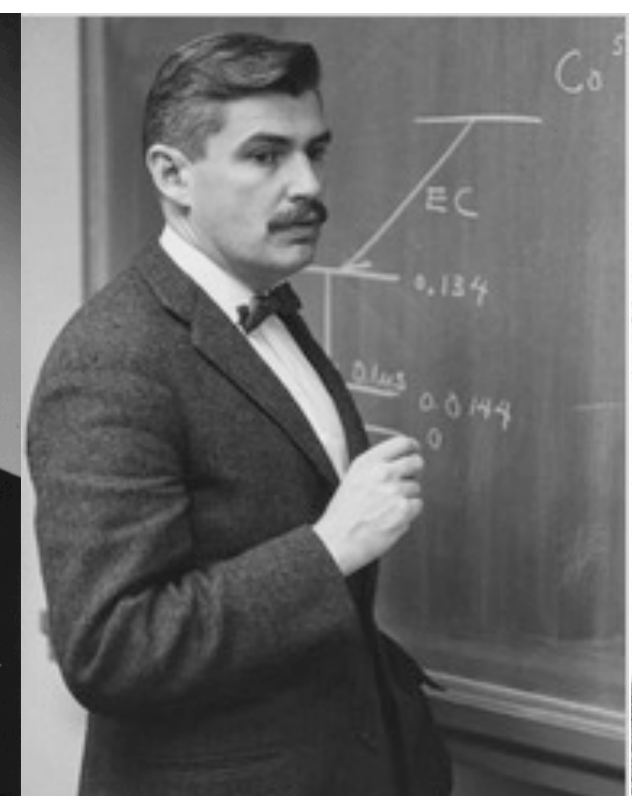
REPORT OF THE SUB-PANEL ON RELATIVITY AND GRAVITATION

Weiss

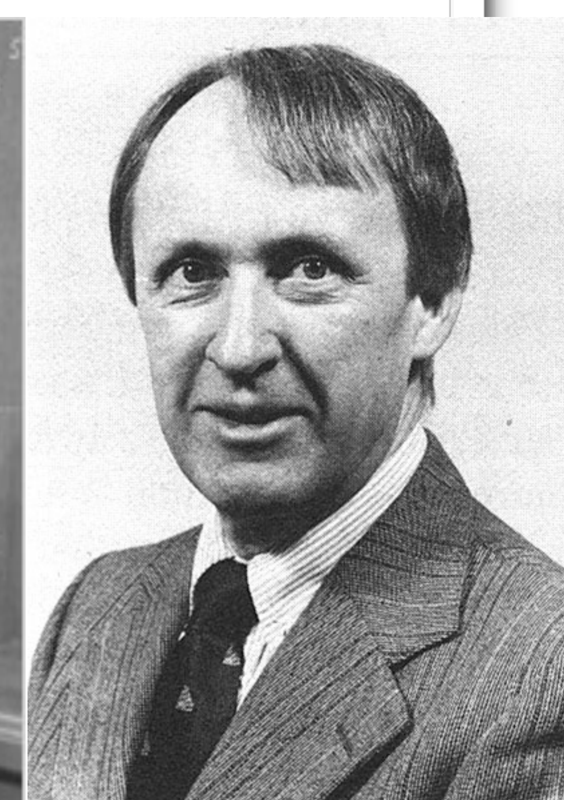


Bender

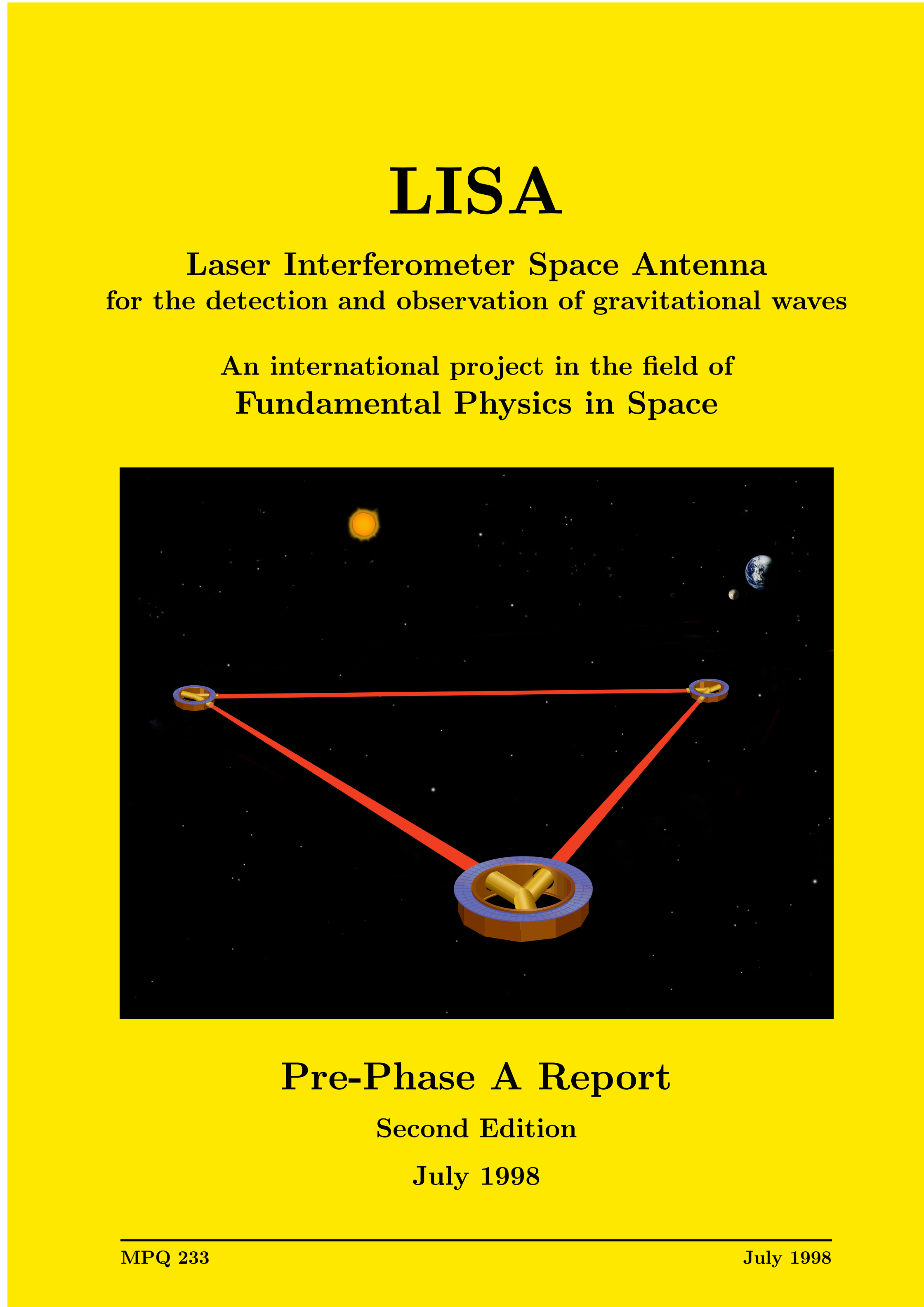
Pound



Misner



Laser Interferometer Space Antenna (LISA)



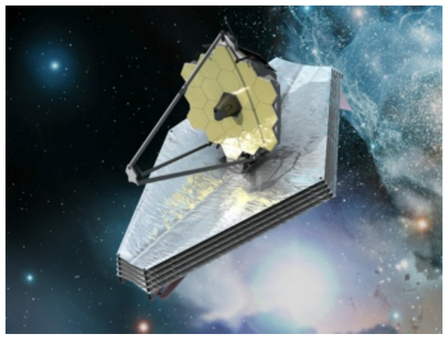
NASA/ESA joint study1996, Yellow Book 1998

Classic LISA Science Case

- Massive (10^5- 10^7 $M_\odot$) Black Hole mergers to high z as tracers of BH-galaxy co-evolution
- Extreme Mass Ratio Inspirals (EMRIs) for tests of GR and as probes of galactic cusps
- Galactic binaries for stellar evolution and galactic structure
- Stochastic backgrounds from early Universe

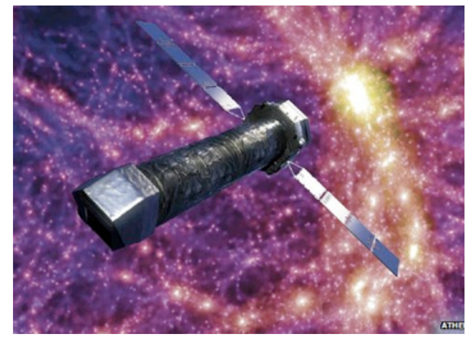
Astrophysics in the 2034

Post JWST



Post WFIRST

Post Athena

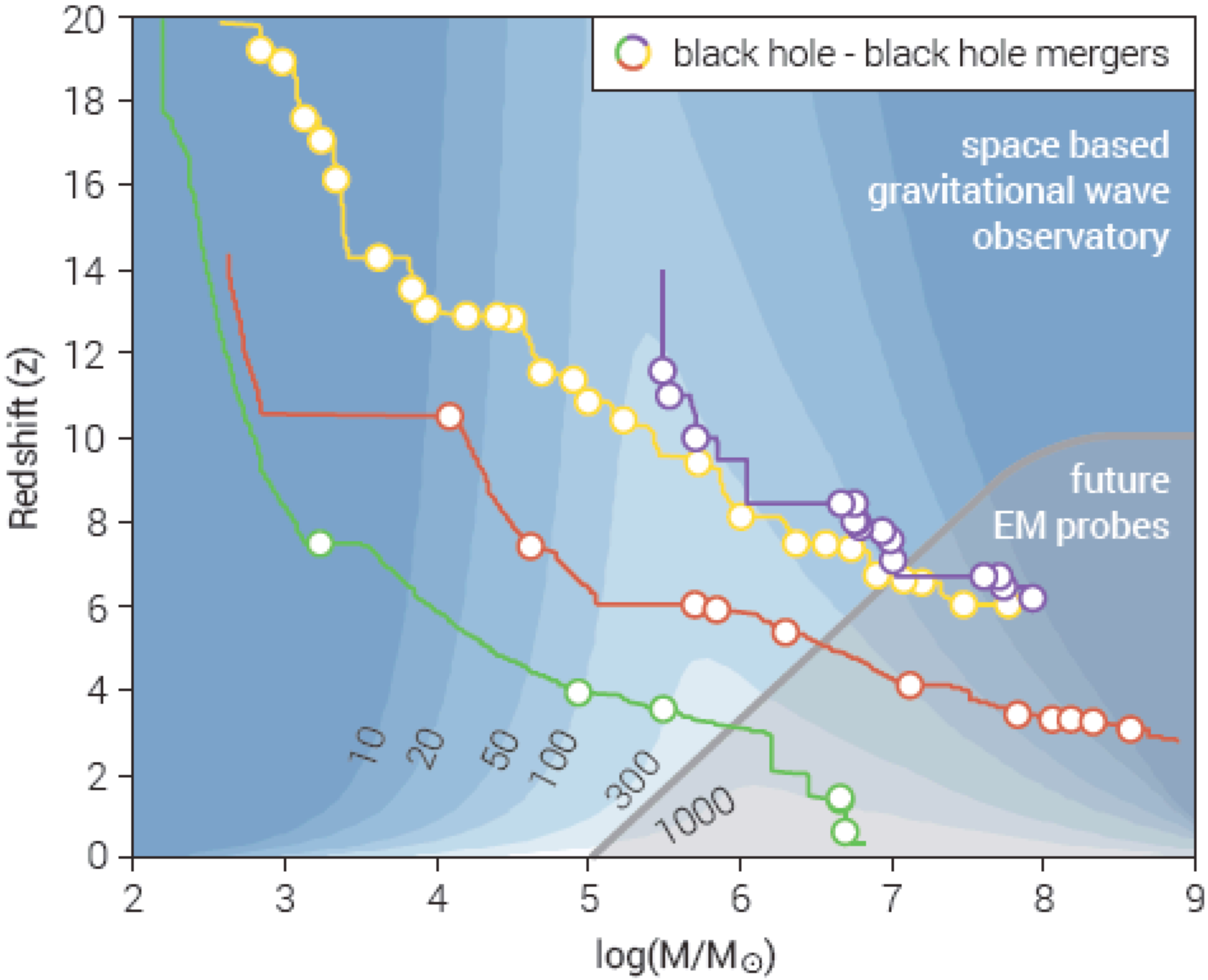


Post aLIGO+

Post IPTA

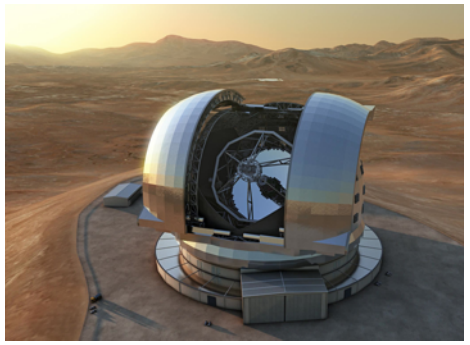
- Assembly and growth of first galaxies observed by JWST
- Expansion history & distance scale to better than 1% from WFIRST
- High SNR (100+) gravitational wave signals detected by LIGO
- EM counterparts of LIGO sources detected
- Athena will have detected many IMBHs
- Supermassive Black Holes observed to high redshift (z~8) by Athena
- Gravitational waves from supermassive black hole binaries discovered by IPTA

LISA - charting the BH merger history



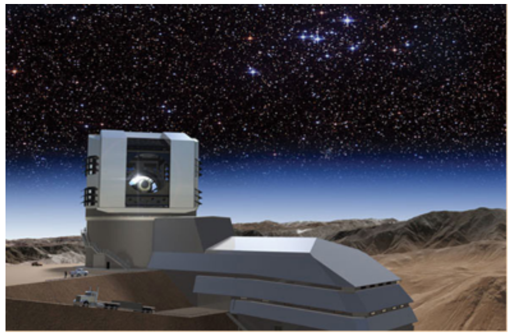
Astrophysics in the 2034

Post EELT



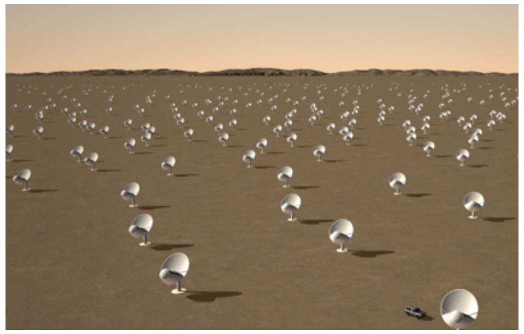
Post GAIA

Post LSST



Post GRAVITY

Post SKA



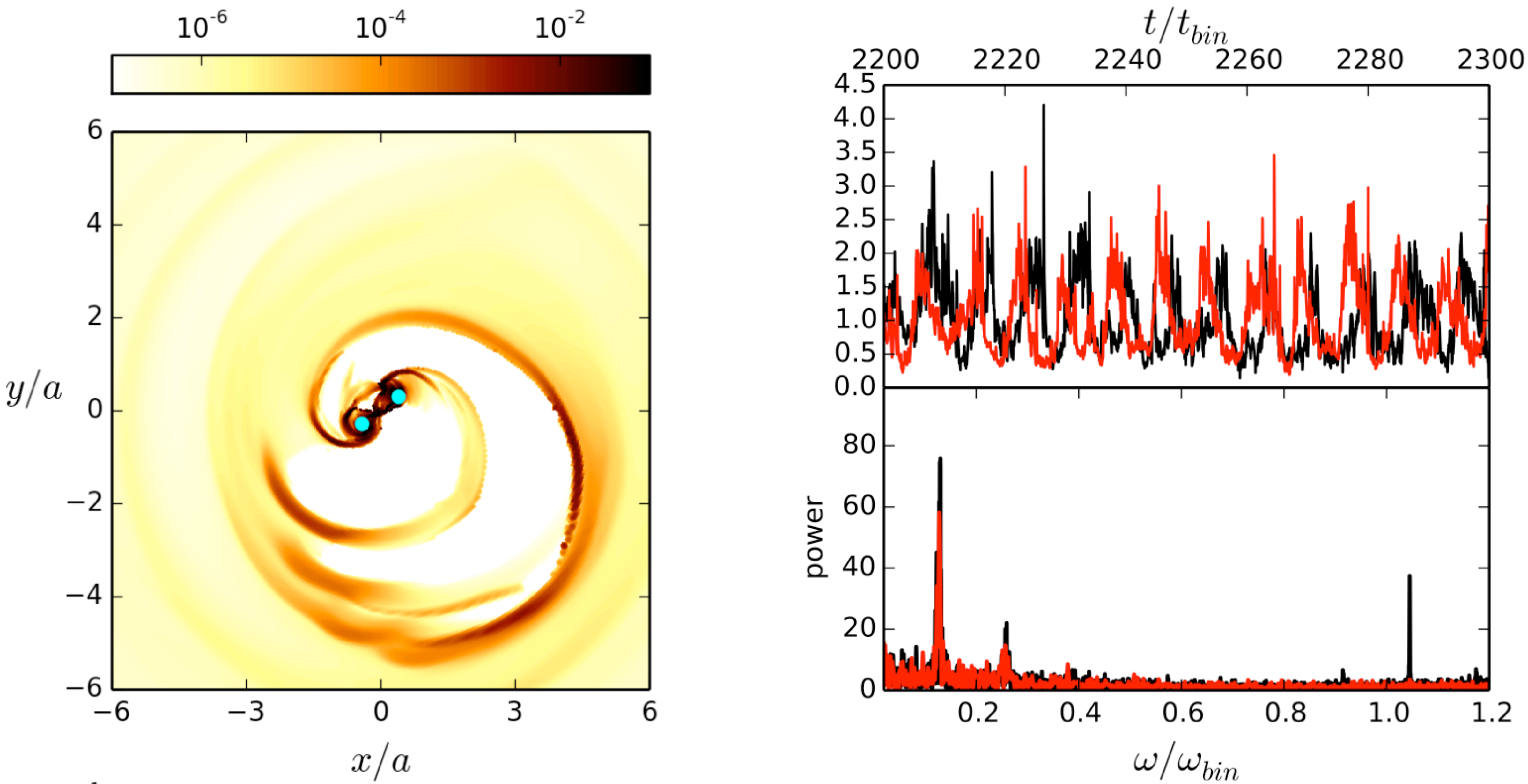
- EELT will observe first stars in Universe and early black holes
- Census of IMBH masses from stellar velocities in clusters from EELT
- GAIA catalog will include several hundred short period eclipsing WD binaries
- SKA will have discovered pulsars at the galactic center giving insight into EMRI rates
- LSST will detect 100's of SMBH stellar tidal disruption events per year and give insight into EMRI populations
- GRAVITY and its successors will have found stars with < year orbits around Sgr A* yielding insight into EMRI rates

Evolved LISA Science Case

- Classic LISA science case +
- Prompt and pre-cursor EM counterparts
- Intermediate mass black holes (10^2-10^4 $M_\odot$)
- Stellar remnant BHs (GW150914-like)
- IMRIs (mass ratios 100-1000)
- EMRI resonances
- WD resonances, detonations
- Unmodeled Bursts

Electromagnetic Counterparts

Old picture likely wrong - there will be significant pre and post merger EM counterparts to SMBHBs

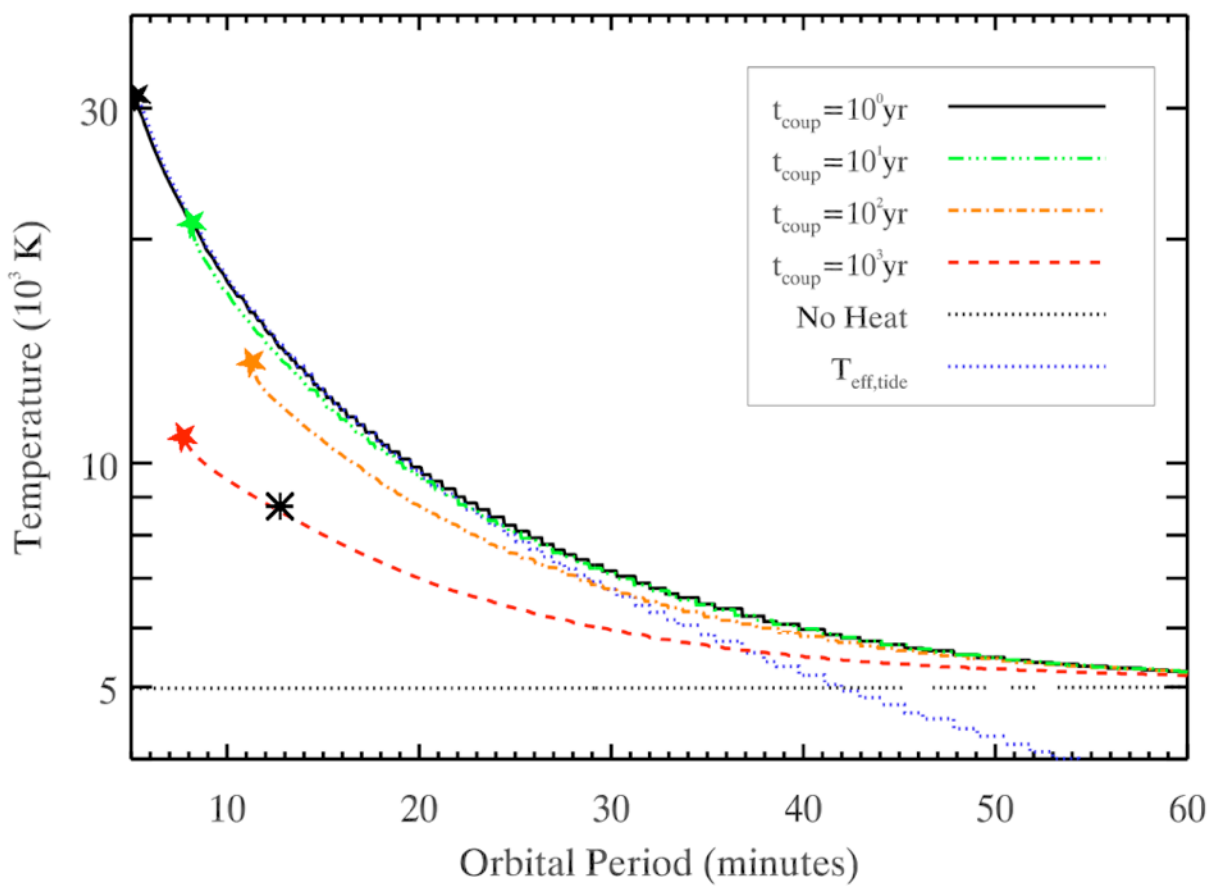


(Farris et al. 2015 a,b)

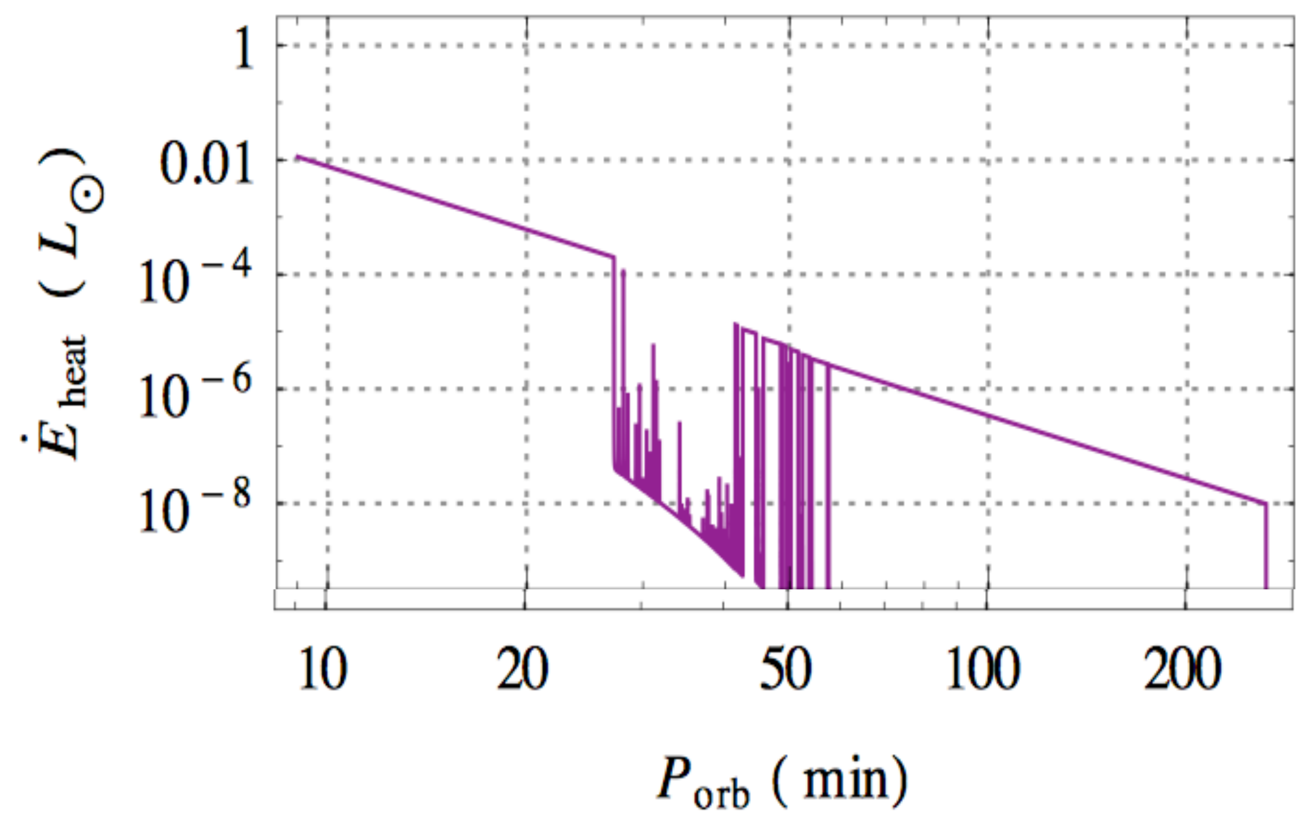
Electromagnetic Counterparts

Tidally heated white dwarfs in binaries

(Fuller & Lai 2014)

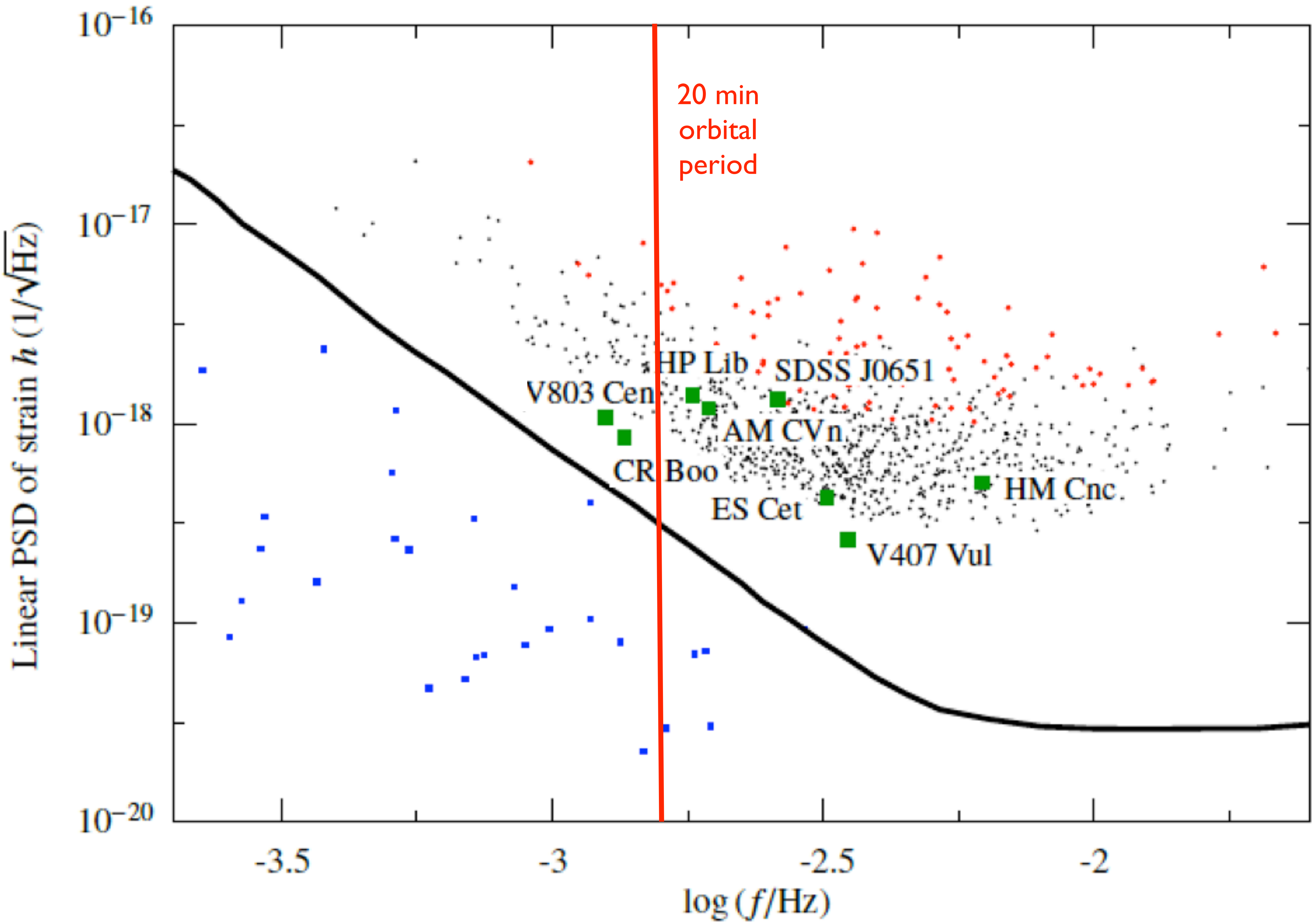


(Burkart et al. 2013)



(Iben et al. 1998; Witte & Savonjie1999; Cooray et al. 2003; Rathore et al. 2005; Fuller & Lai 2012; Weinberg et al. 2012; Burkart et al. 2013; Fuller & Lai 2014; Burkart et al. 2014)

Guaranteed Sources: Galactic Binaries

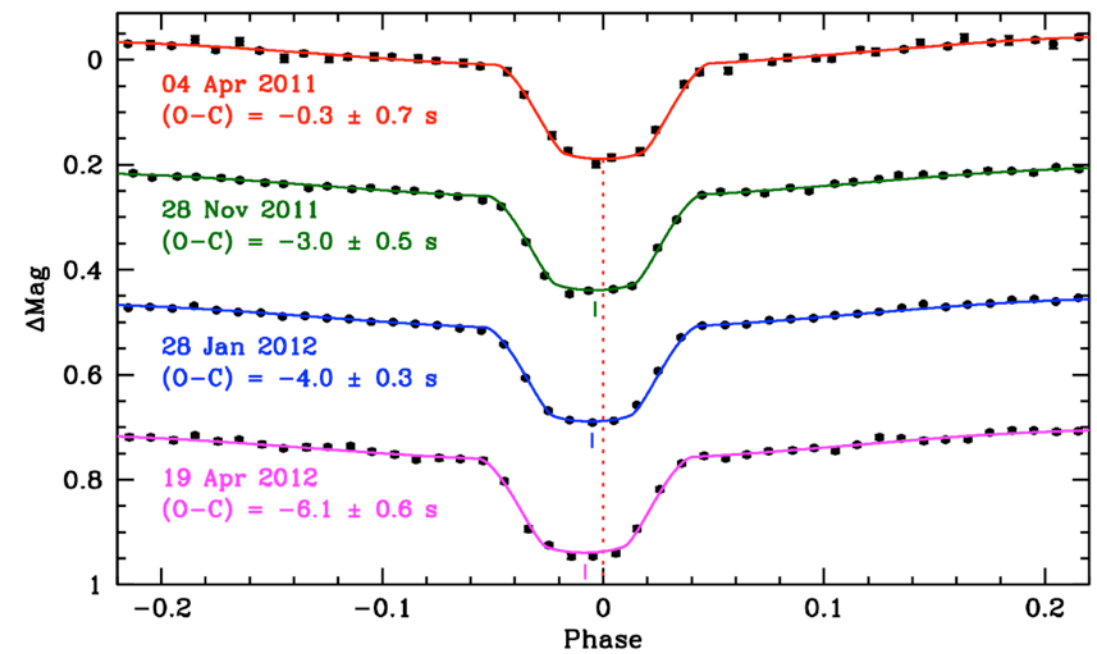


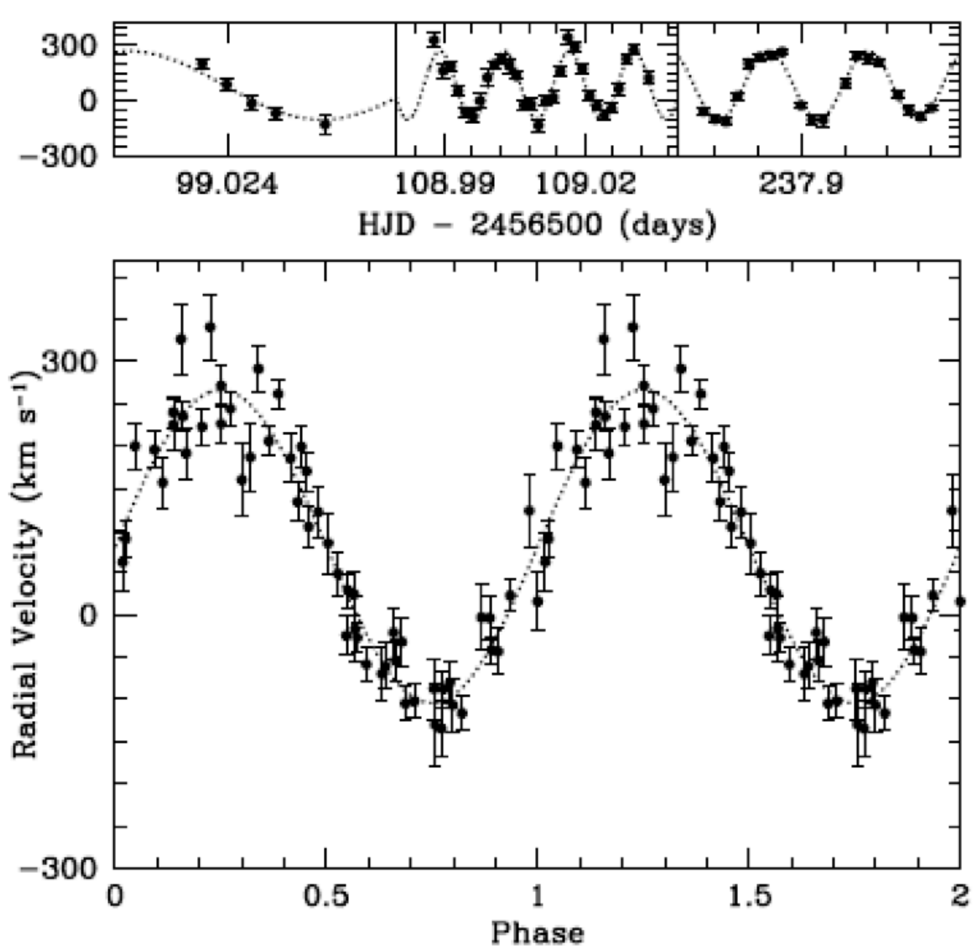
New, loud verification binaries

SDSS J0651+2844 (Brown et al. 2011)

12 minute eclipsing WD-WD binary

$$f_{GW} = 2.78 \text{ mHz}$$





WD0931+444 (Kilic et al. 2014)

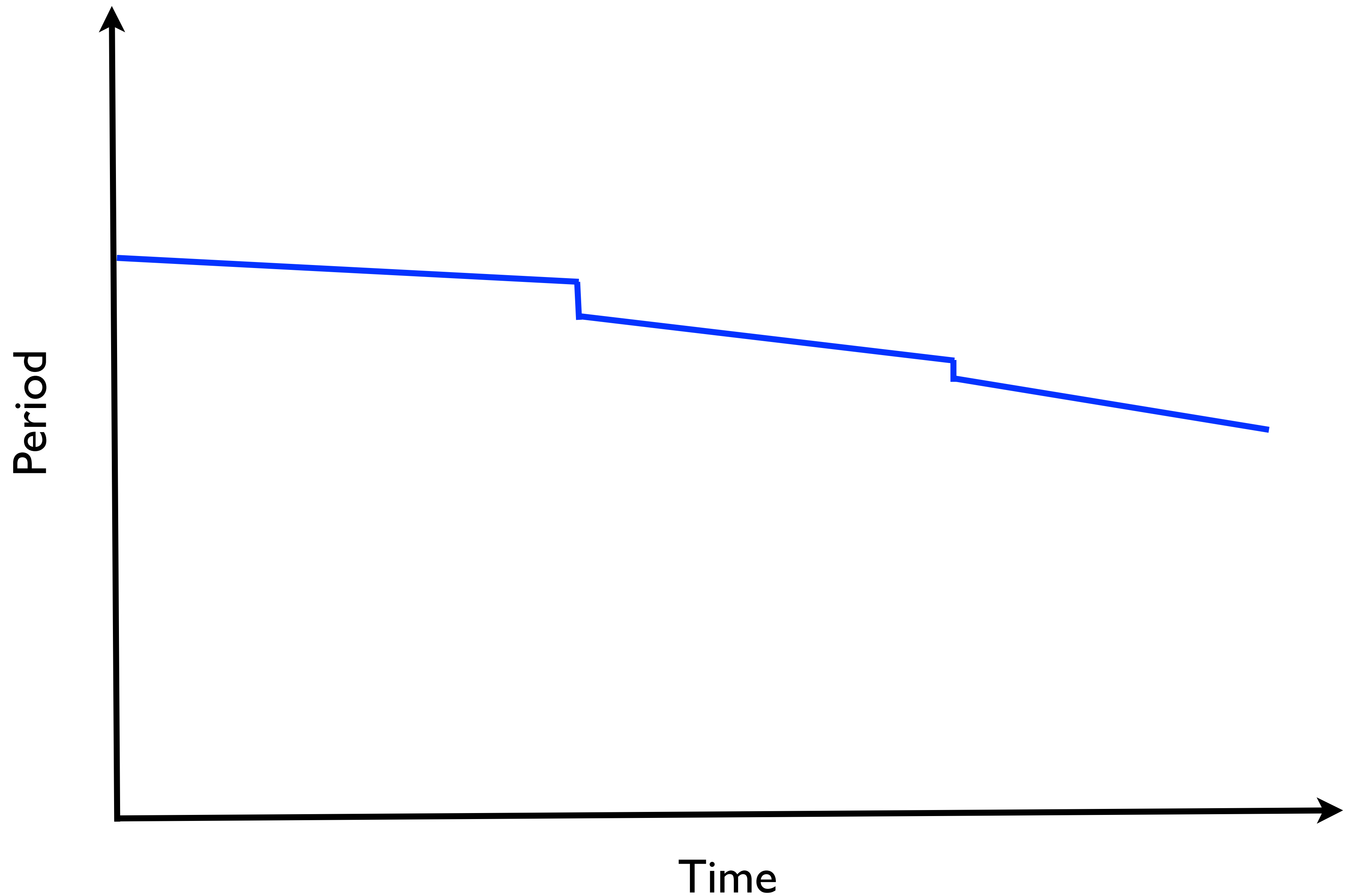
20 minute detached WD-WD binary

$m_1 = 0.32 M_\odot, \quad m_2 \geq 0.14 M_\odot$ 660 pc

$$f_{GW} = 1.68 \text{ mHz}$$

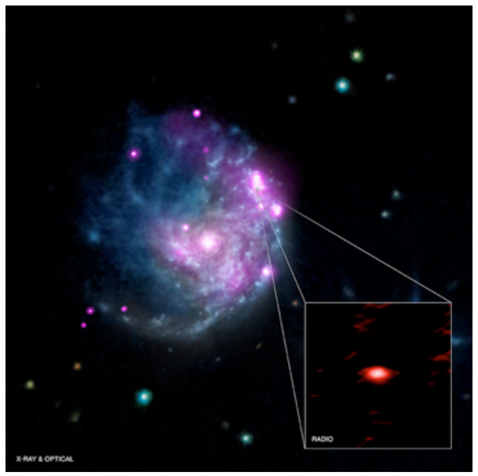
$$h \sim 10^{-22} \to 10^{-21}$$

WD orbital resonances



(Witte & Savonjie1999; Rathore et al. 2005; Fuller & Lai 2012;Weinberg et al. 2012;Burkart et al. 2013; Fuller & Lai 2014; Burkart et al. 2014)

Intermediate Mass Black Holes making news

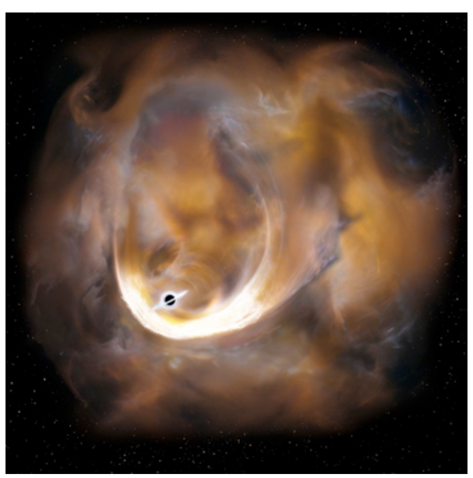


NGC 2276, $5 \times 10^4\ M_\odot$
Mezcua 2015

"Rare 'Missing Link' Black Hole Apparently Found"
Space.com 2015

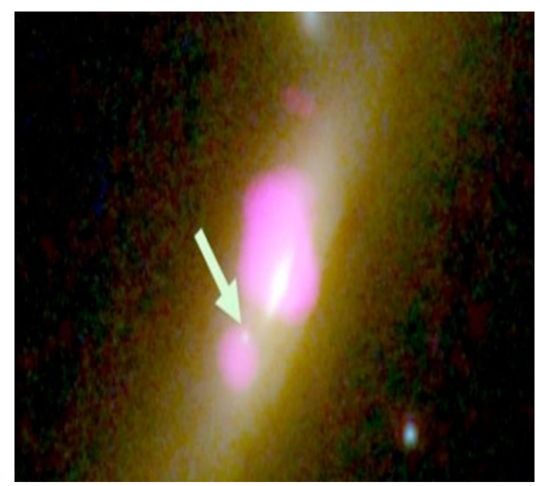
M82 X-1, $428 \pm 105\ M_\odot$
Pasham 2014

"It's Confirmed! Black Holes Do Come in Medium Sizes"
Space.com 2014



Milky Way, $10^5\ M_\odot$
Oka 2016

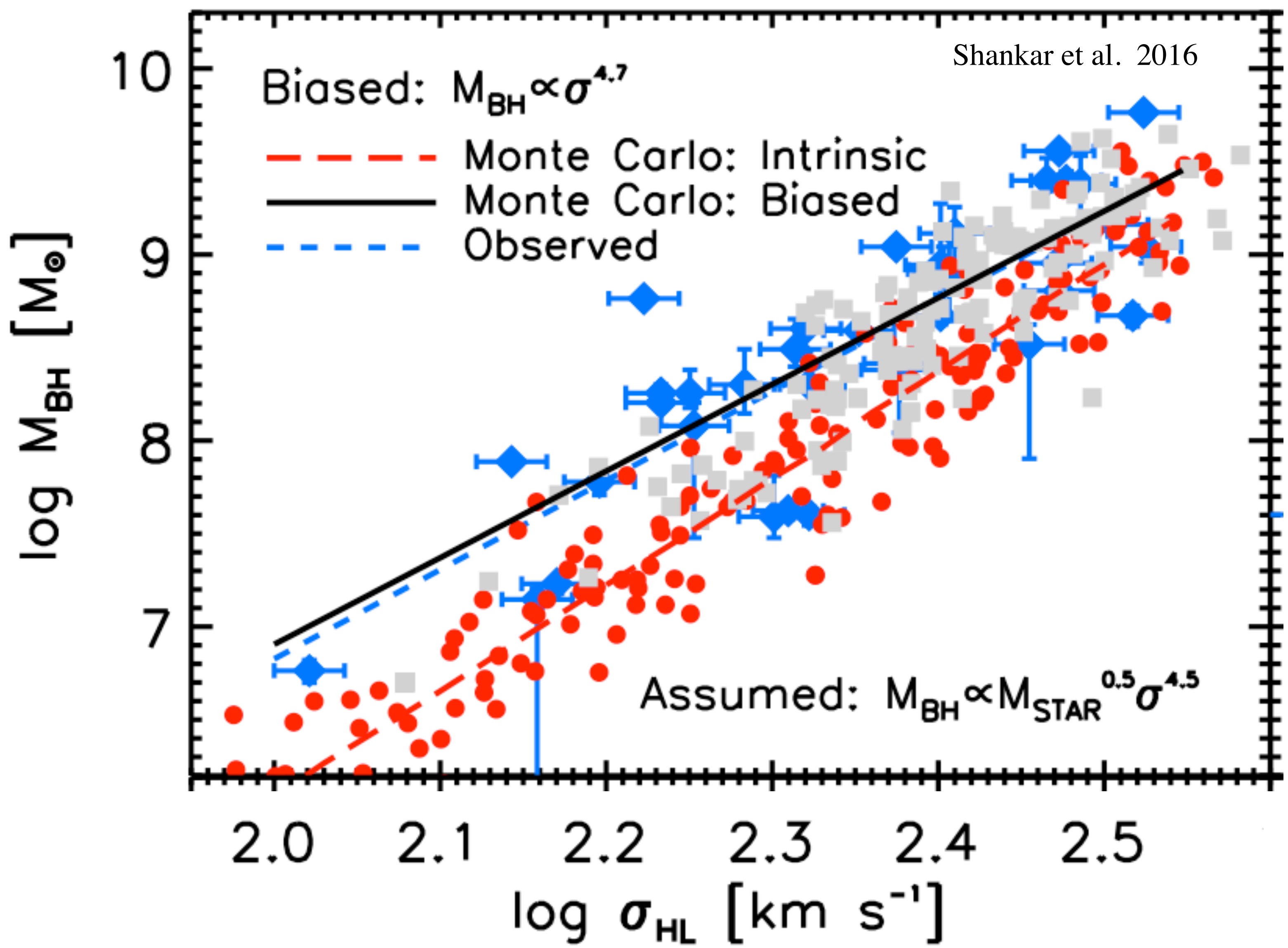
"Signs of second largest black hole in the Milky Way",
astronomy.com 2016



SDSS J1126+2944, $10^2 \rightarrow 10^6\ M_\odot$
Comerford 2016

"'Stripped' black hole could be a rarely seen phenomenon, study says"
La Times 2016

Rescaling of M-sigma relation?

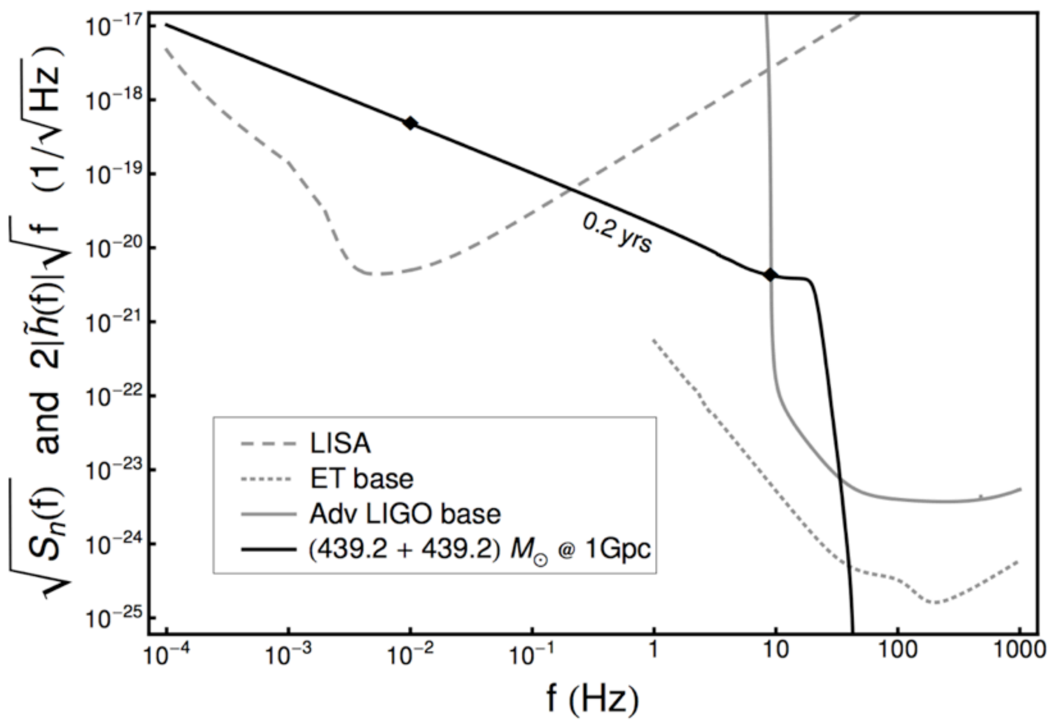


Selection bias in galaxies with measured BH masses. Typical galaxies have BHs 3 times smaller

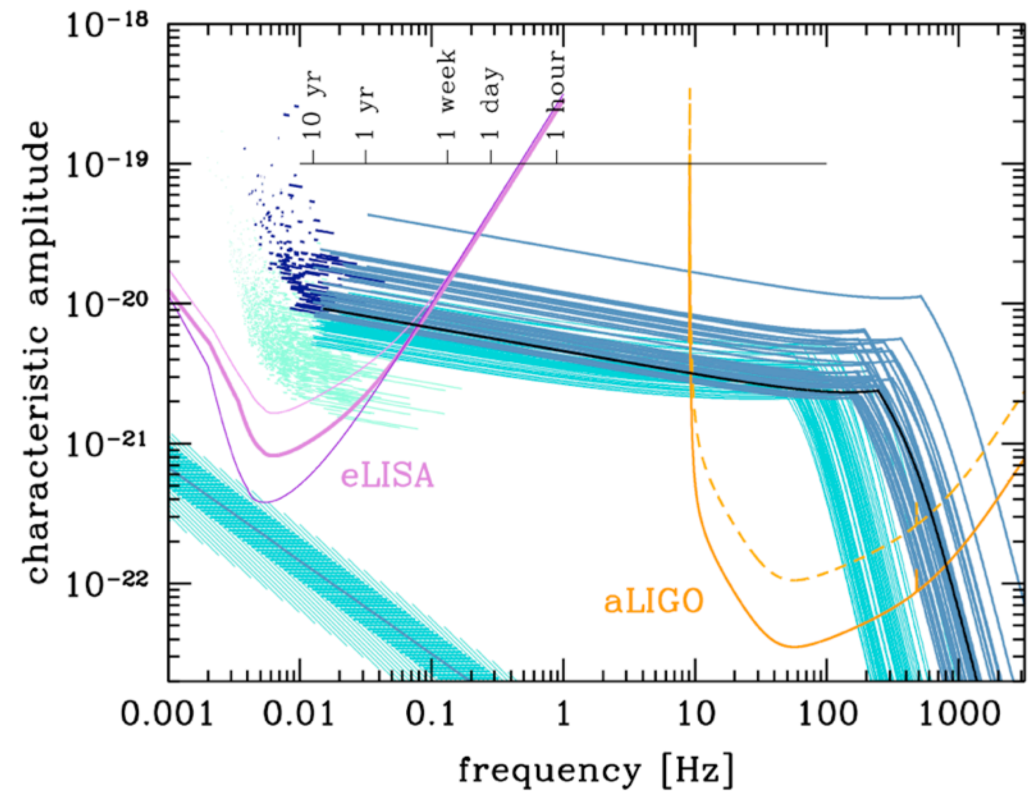
Suggest more IMBHs. Also no need for massive seeds (inferred large masses at high z not so large after all)

Multi-Band Observations

(Amaro-Seoane & Santamaria 2010)

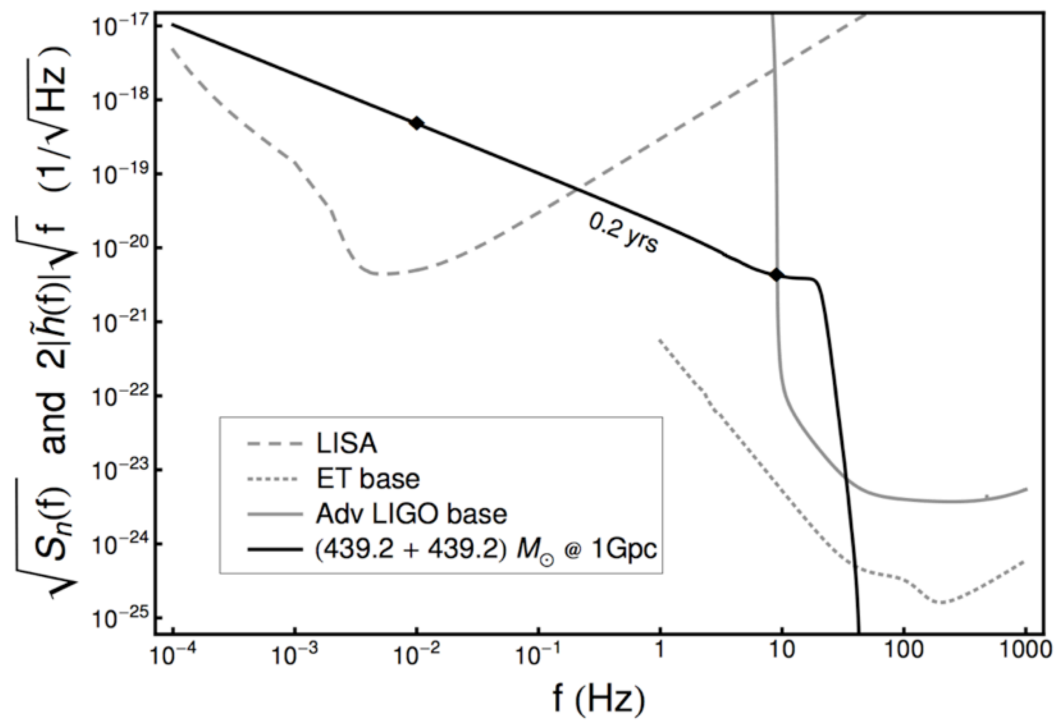


(Sesana 2016)

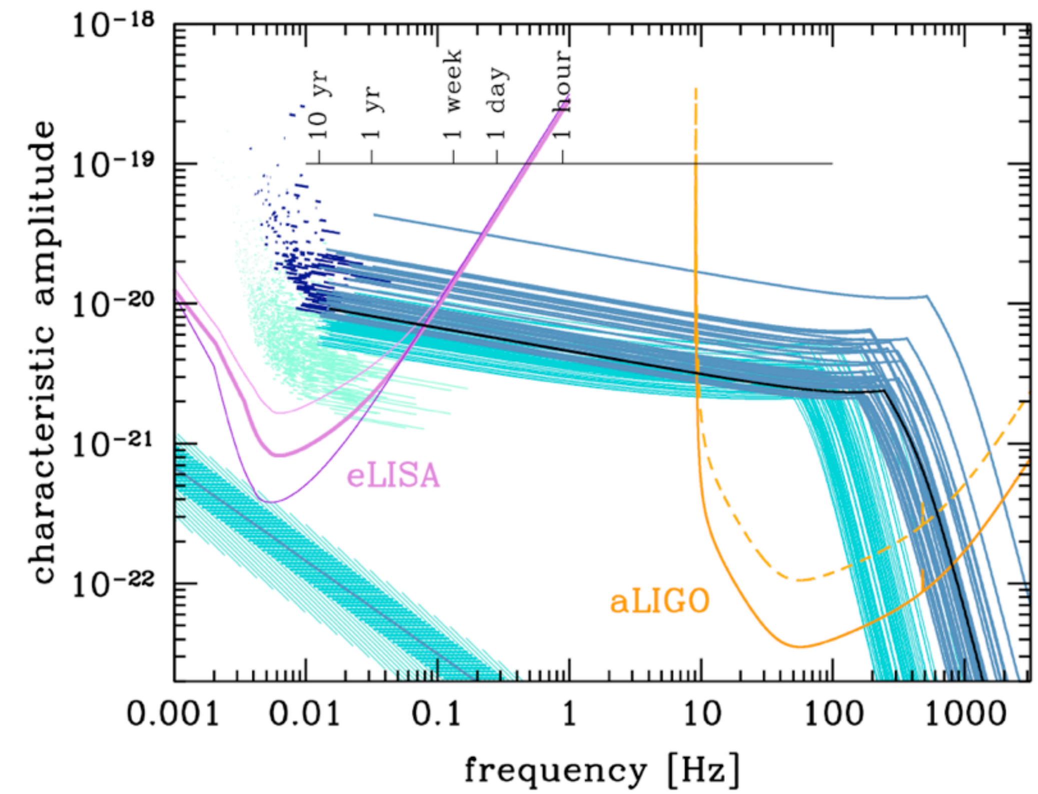


Multi-Band Observations

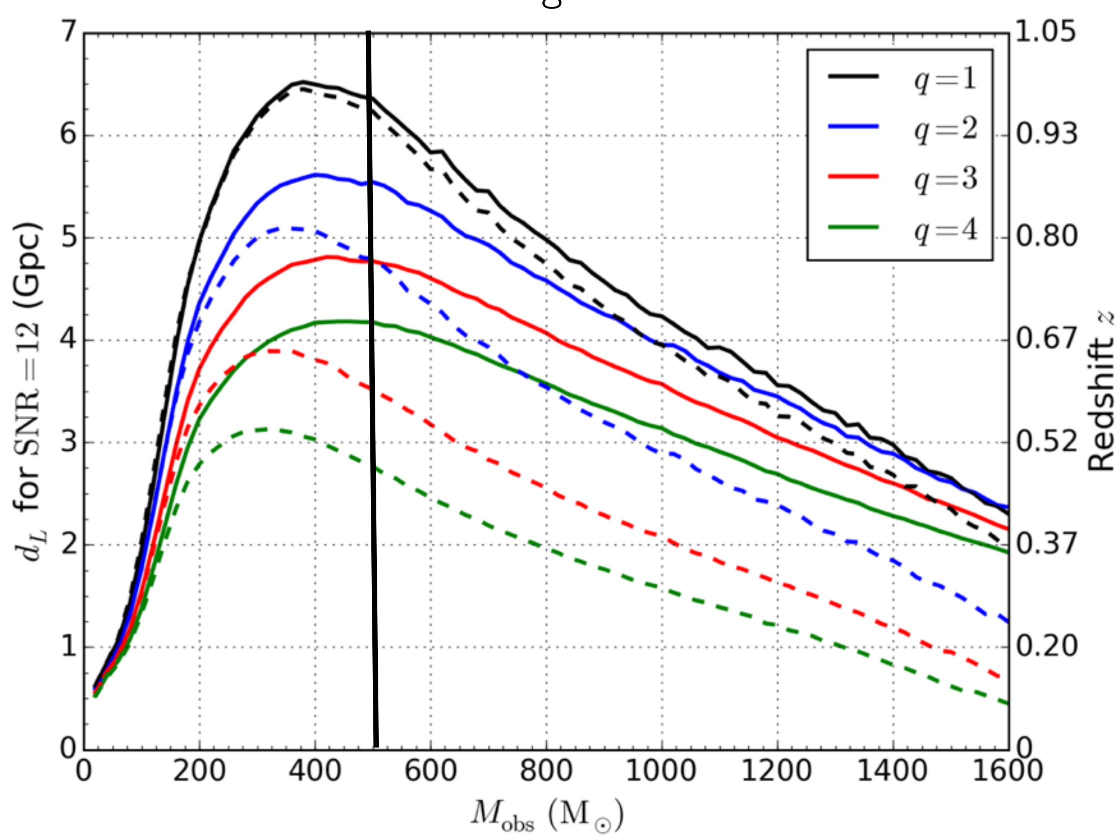
(Amaro-Seoane & Santamaria 2010)



(Sesana 2016)

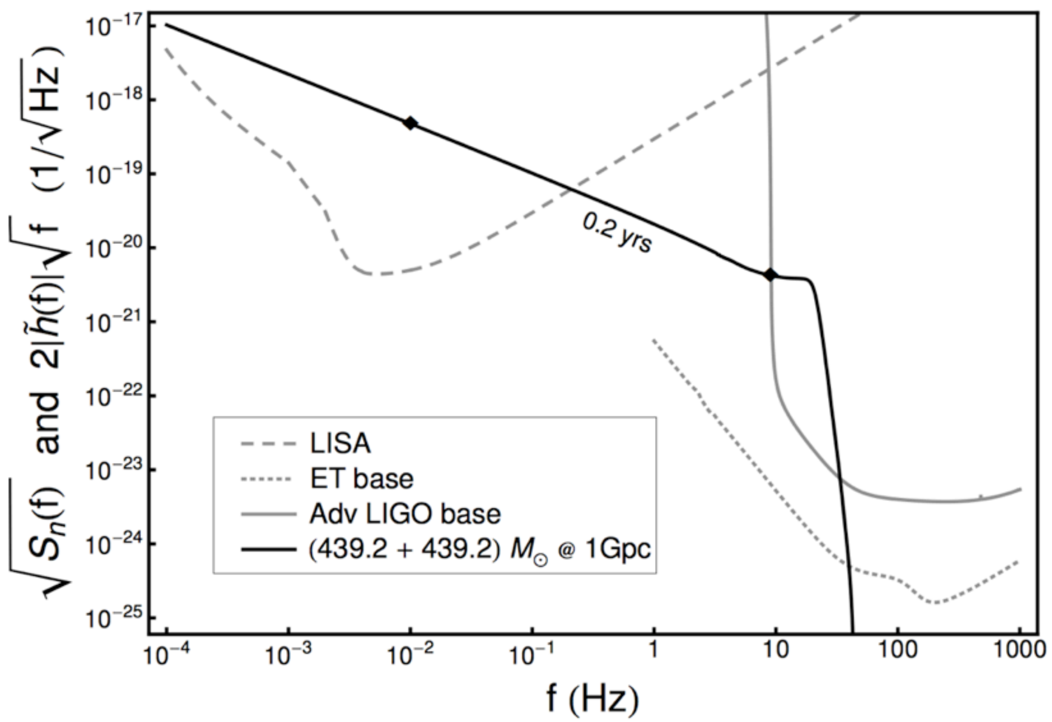


aLIGO/aVirgo Horizon

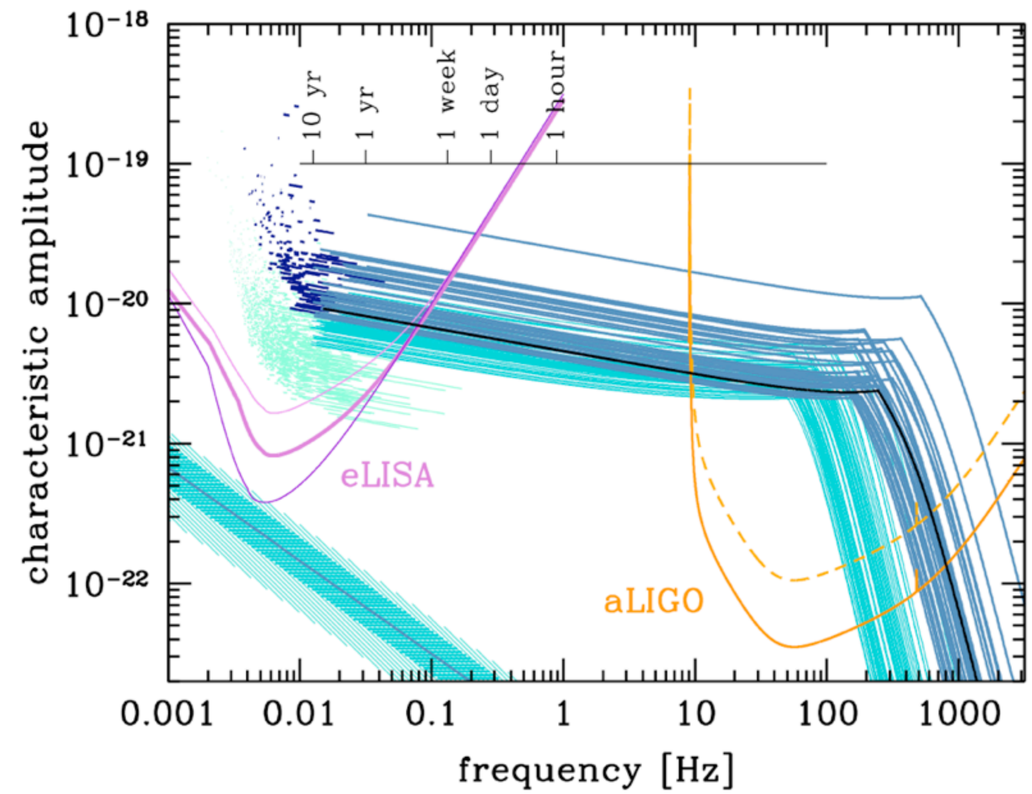


Multi-Band Observations

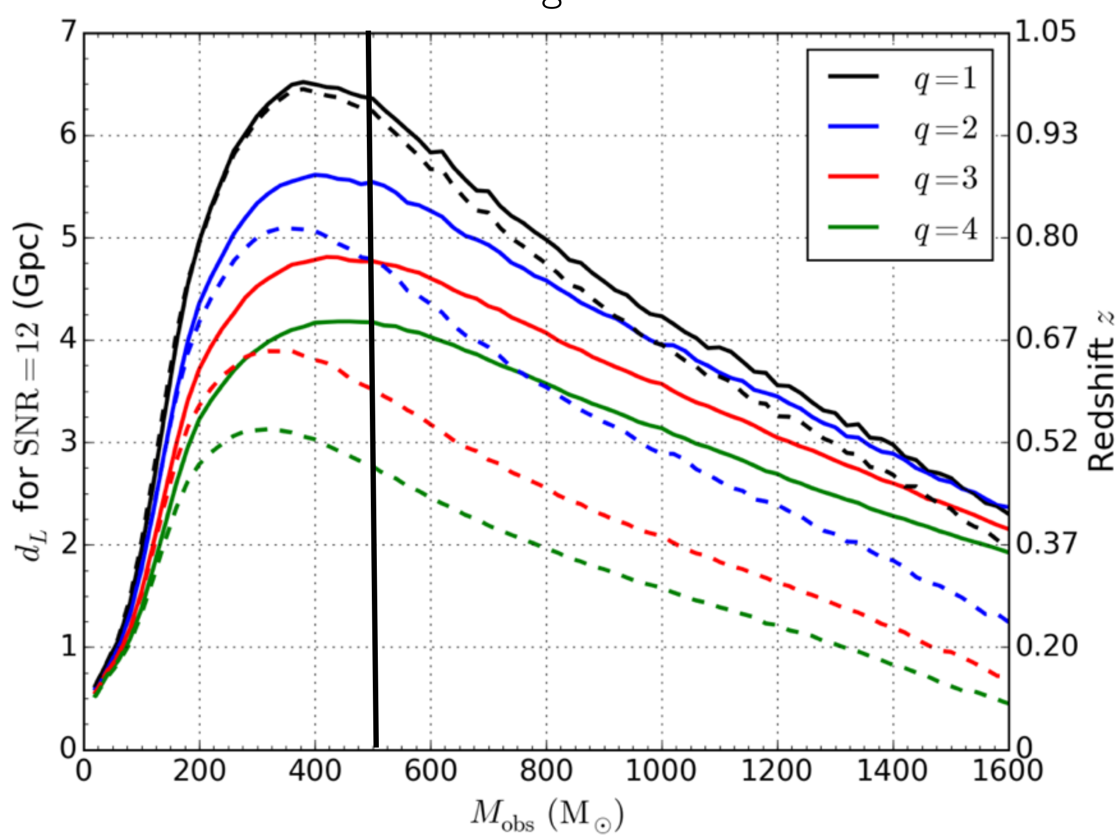
(Amaro-Seoane & Santamaria 2010)



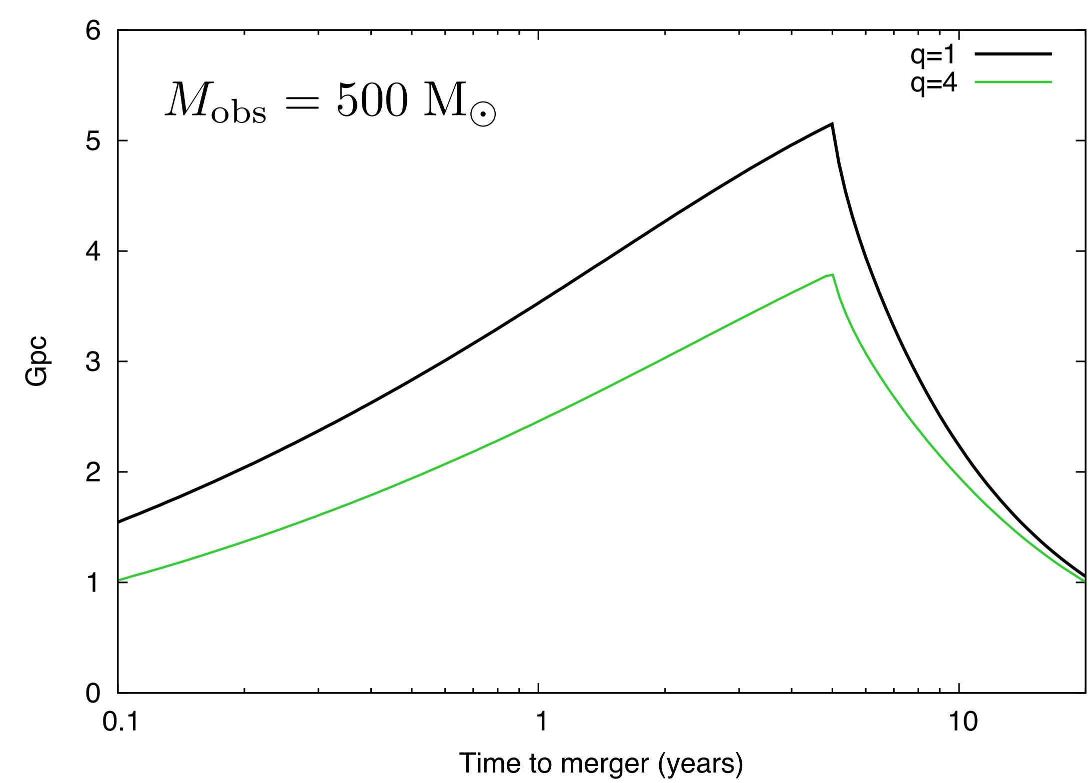
(Sesana 2016)



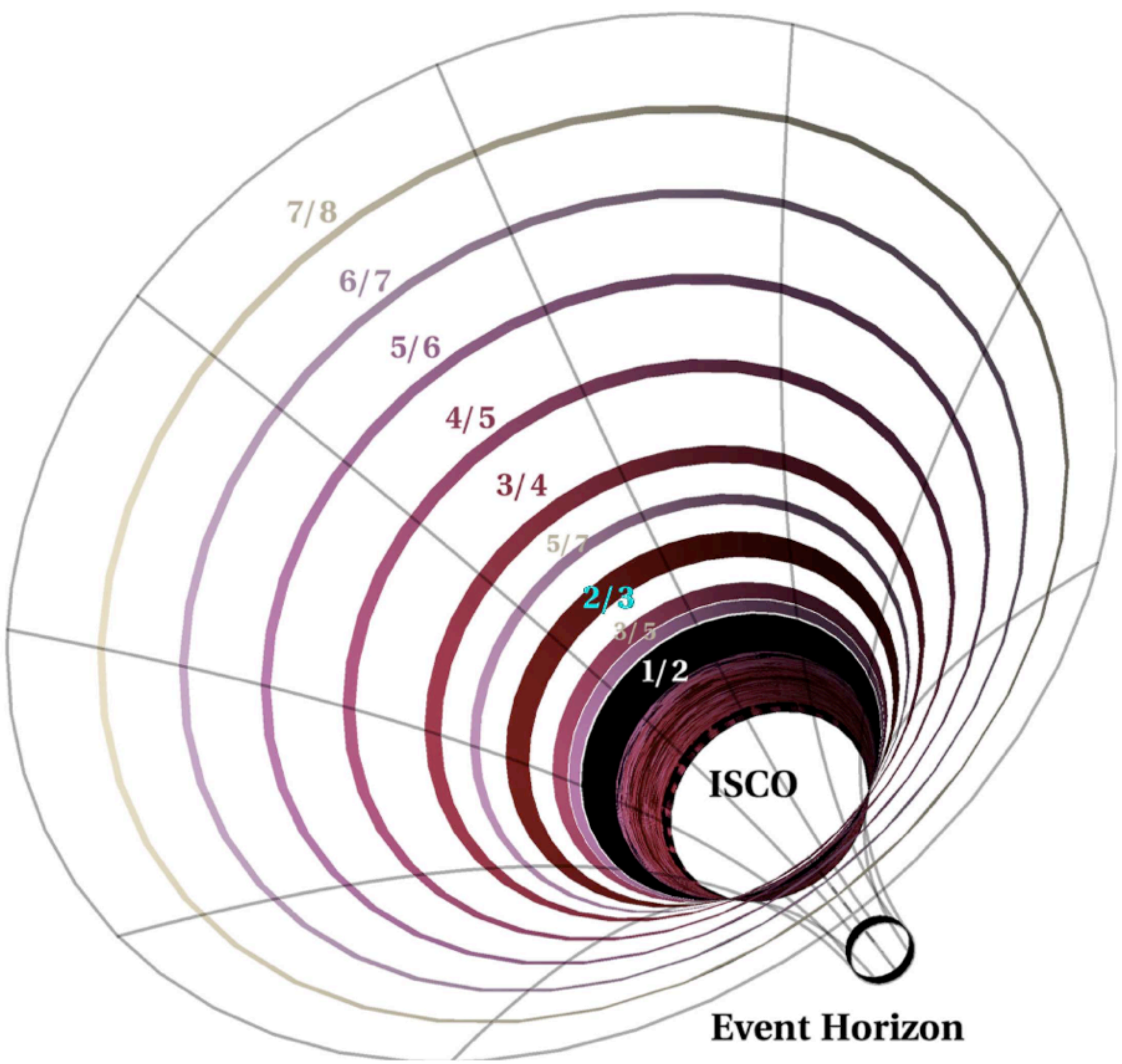
aLIGO/aVirgo Horizon



eLISA Horizon

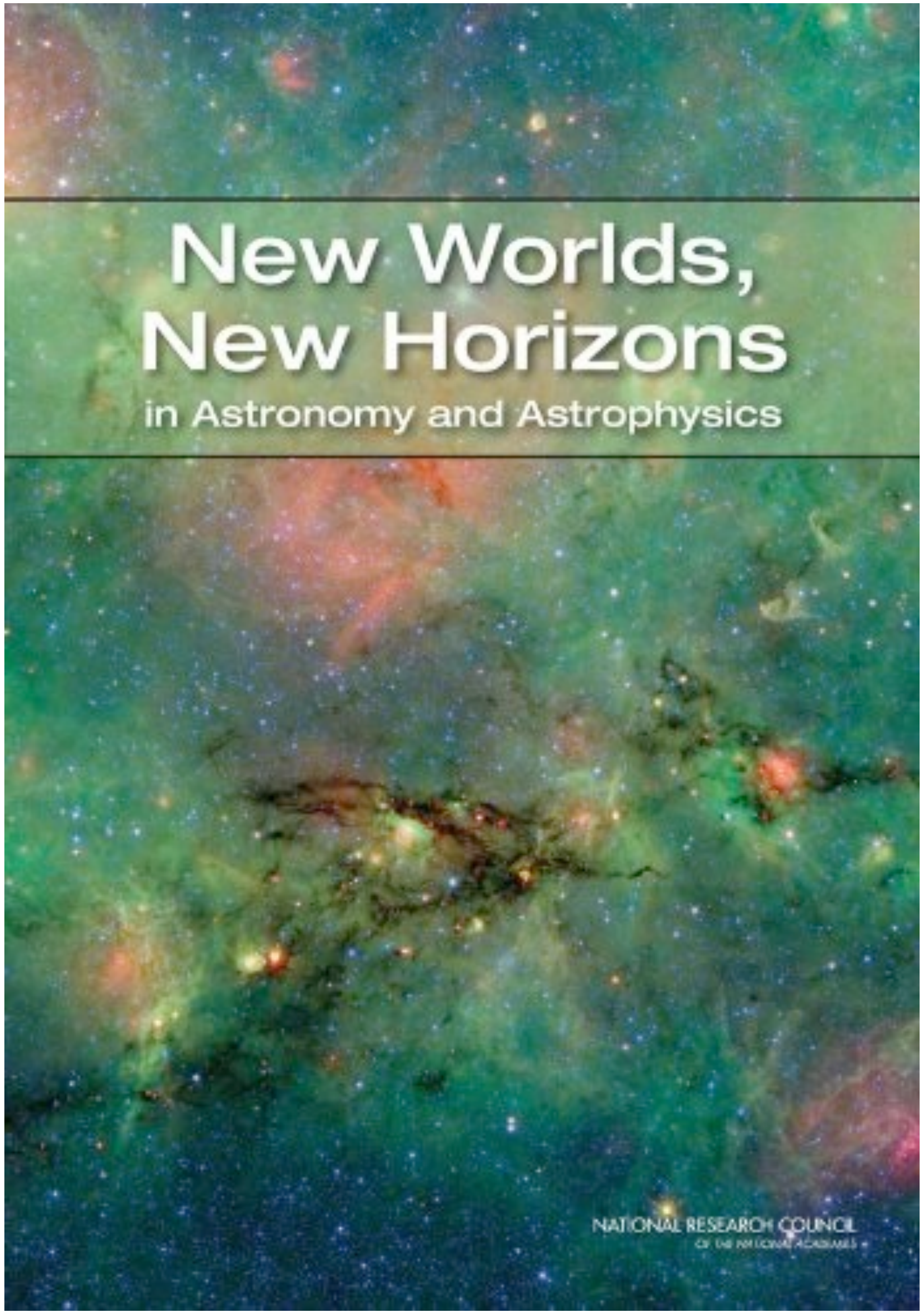


EMRI orbital resonances



- Each EMRI in LISA band passes through several resonances
- Jump in the frequency and phasing a challenge for detection algorithms
- Potential to improve parameter estimation and provide ultra-stringent GR tests

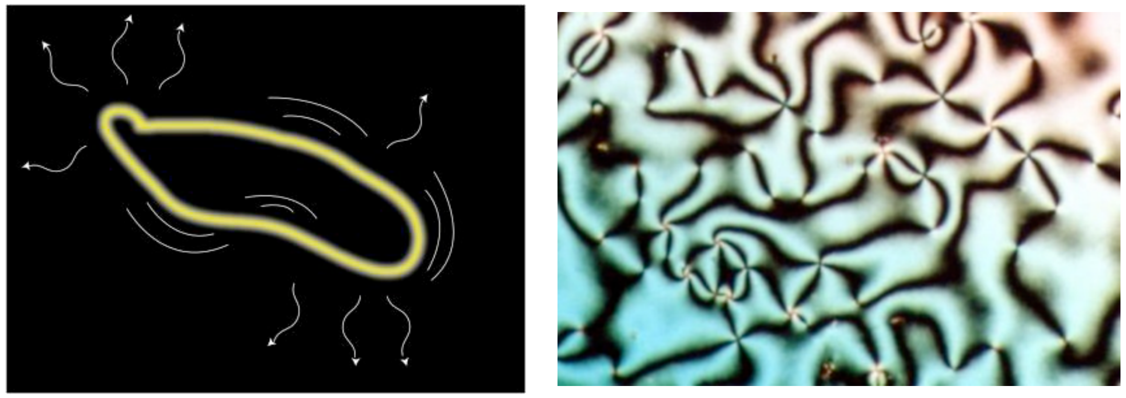
〔Brink, Geyer, Hinderer 13〕 〔Ruangsri, Hughes 13〕



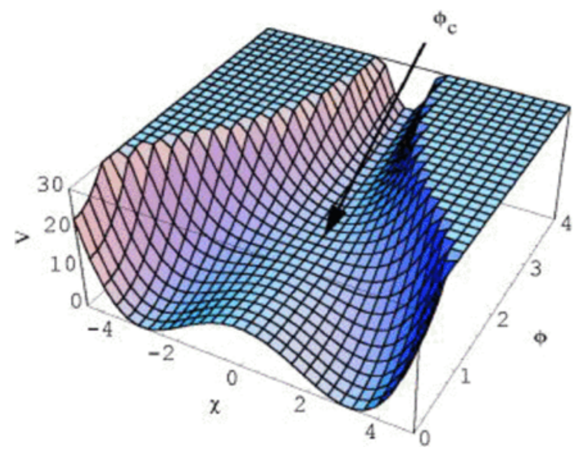
“It would be unprecedented in the history of astronomy if the gravitational radiation window being opened up by LISA does not reveal new, enigmatic sources”

Exotic Sources

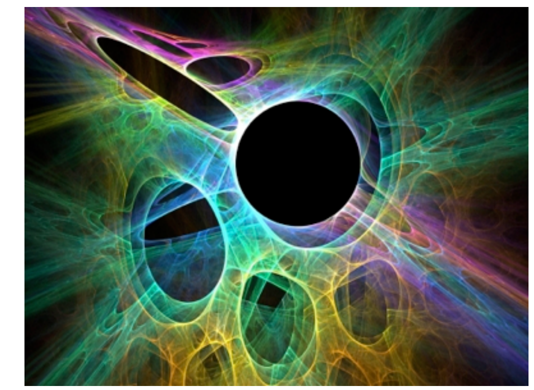
Imagined



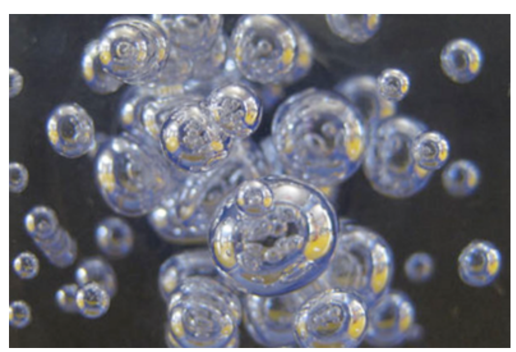
Topological defects



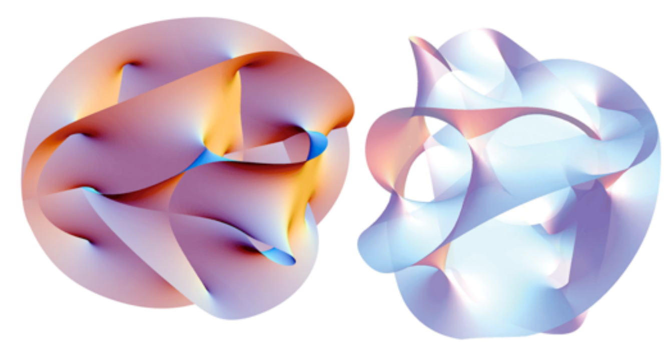
Pre-heating/Re-heating



Warped extra dimensions



Phase transitions- bubble nucleation, cavitation, collisions



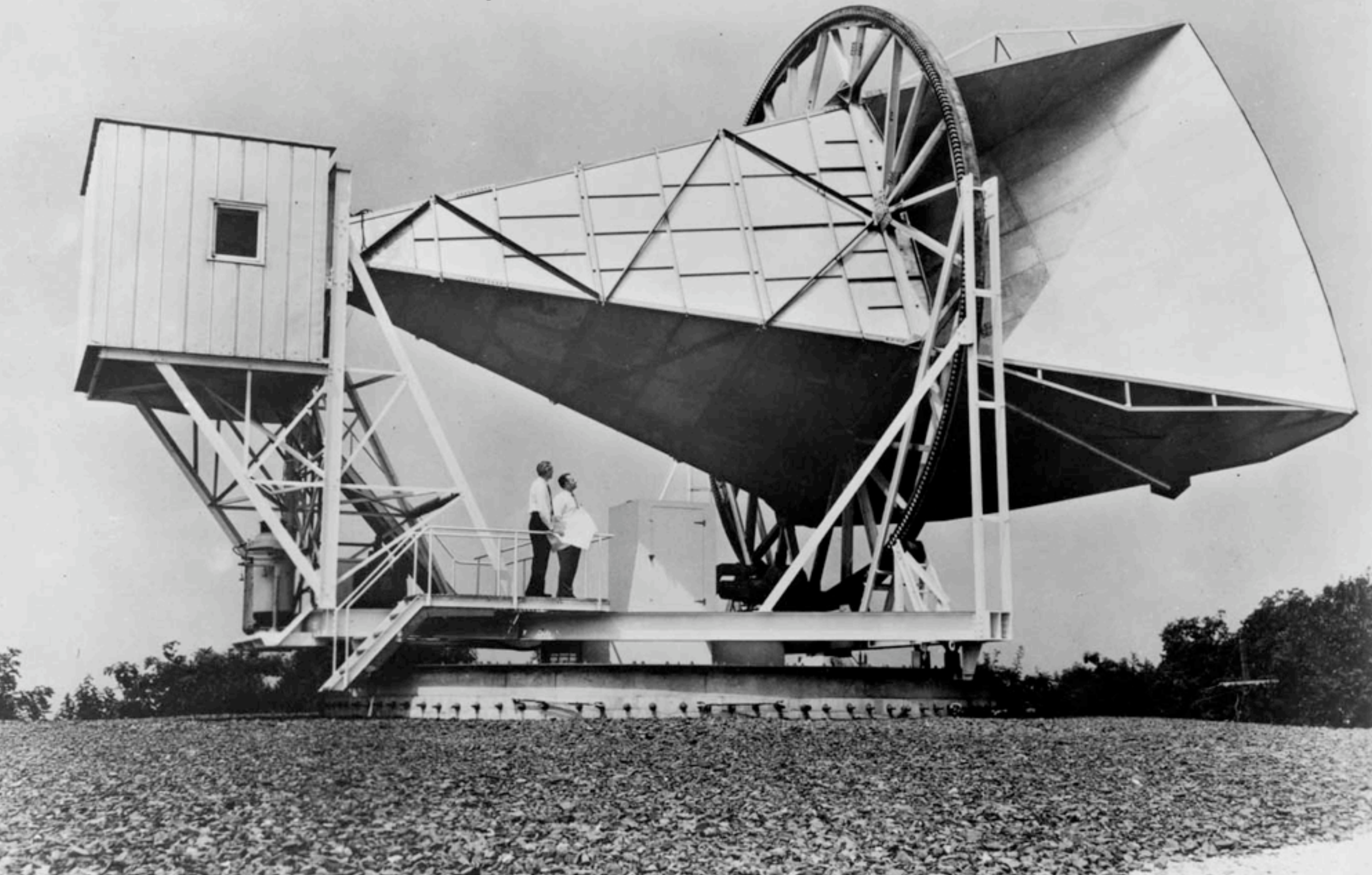
Braneworlds

Un-Imagined

Burst sources?

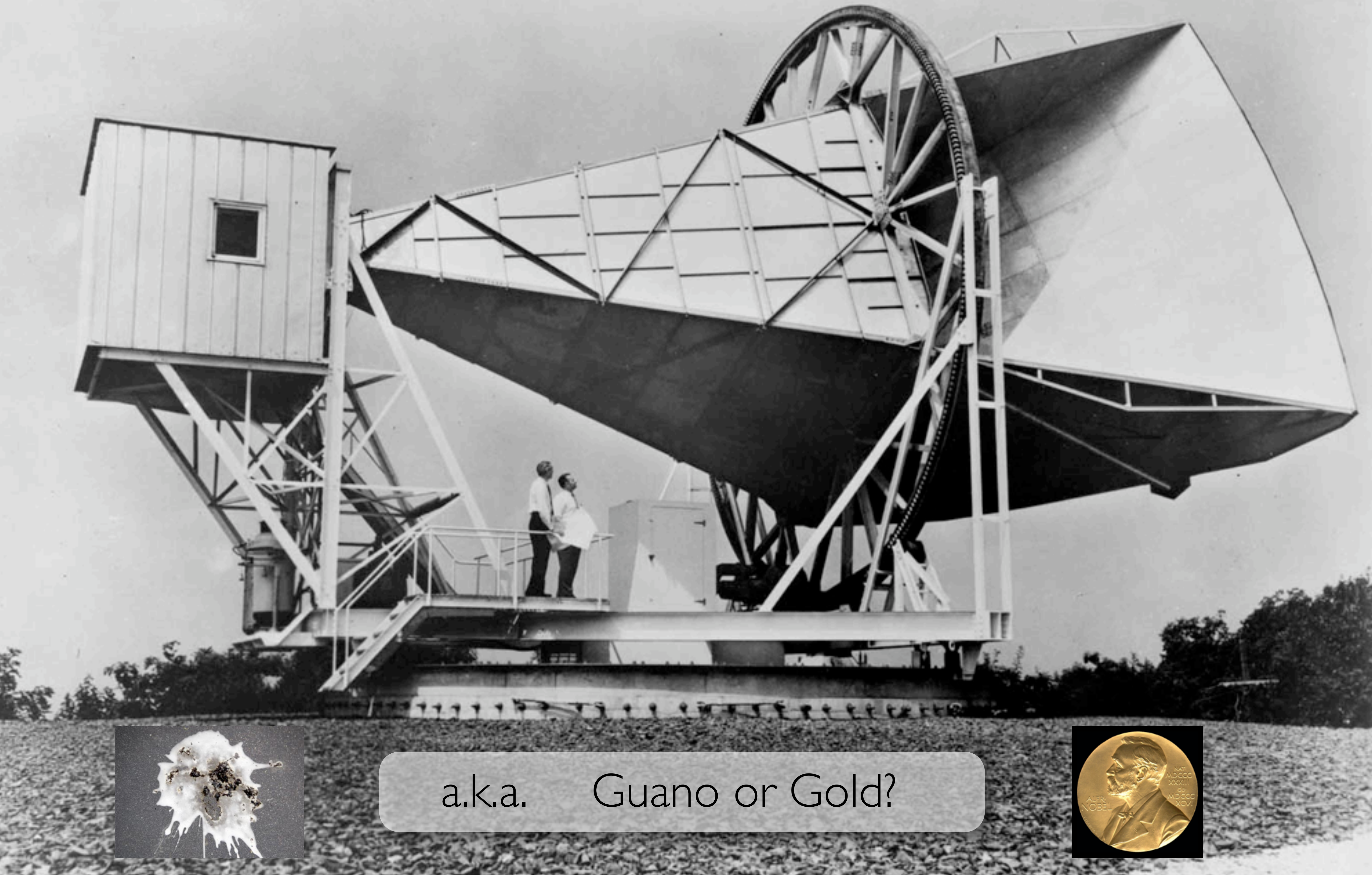
Detecting the Unmodeled and Unexpected

Is this a signal or an instrumental artifact?



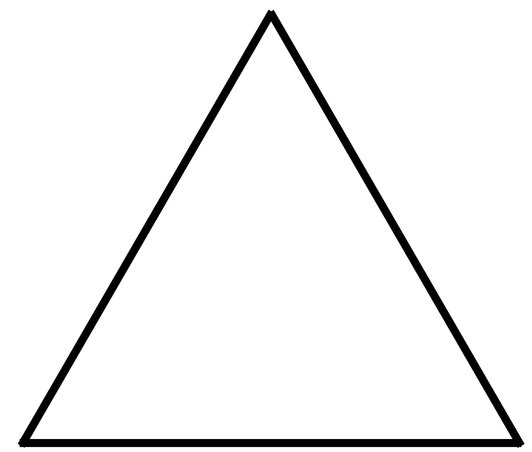
Detecting the Unmodeled and Unexpected

Is this a signal or an instrumental artifact?

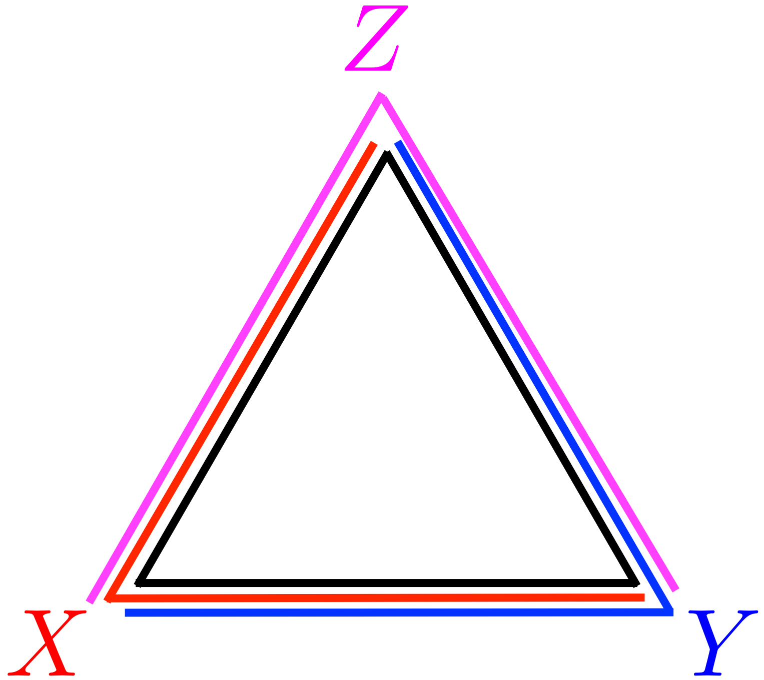


a.k.a. Guano or Gold?

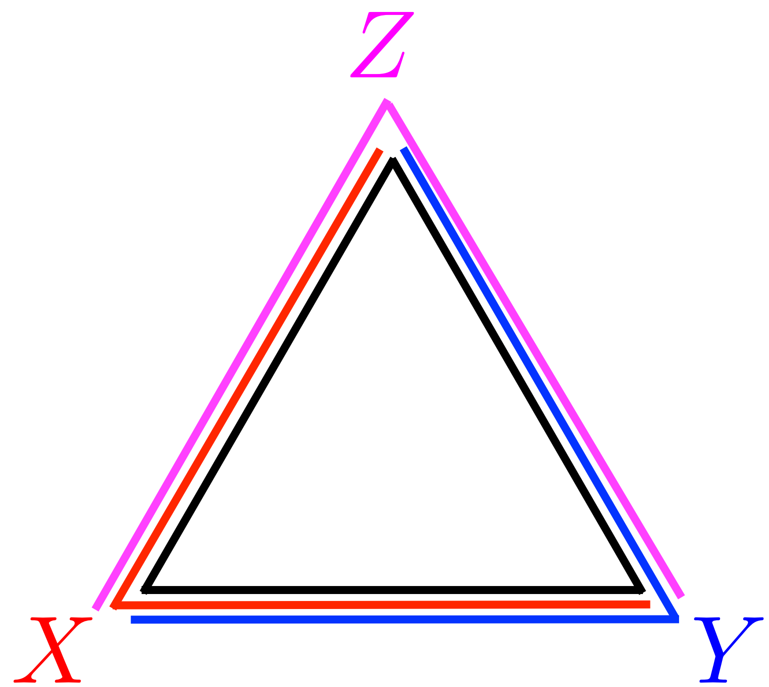
Three arms are better than two



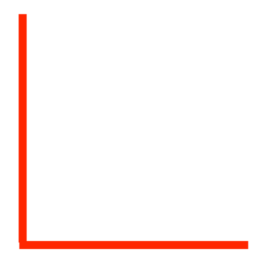
Three arms are better than two



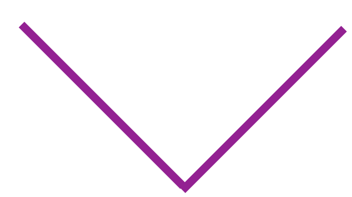
Three arms are better than two



$$S_{+} = \frac{\sqrt{3}}{2}\, X \quad \Rightarrow$$



$$S_{\times} = \frac{1}{2}\,(X + 2Y) \quad \Rightarrow$$

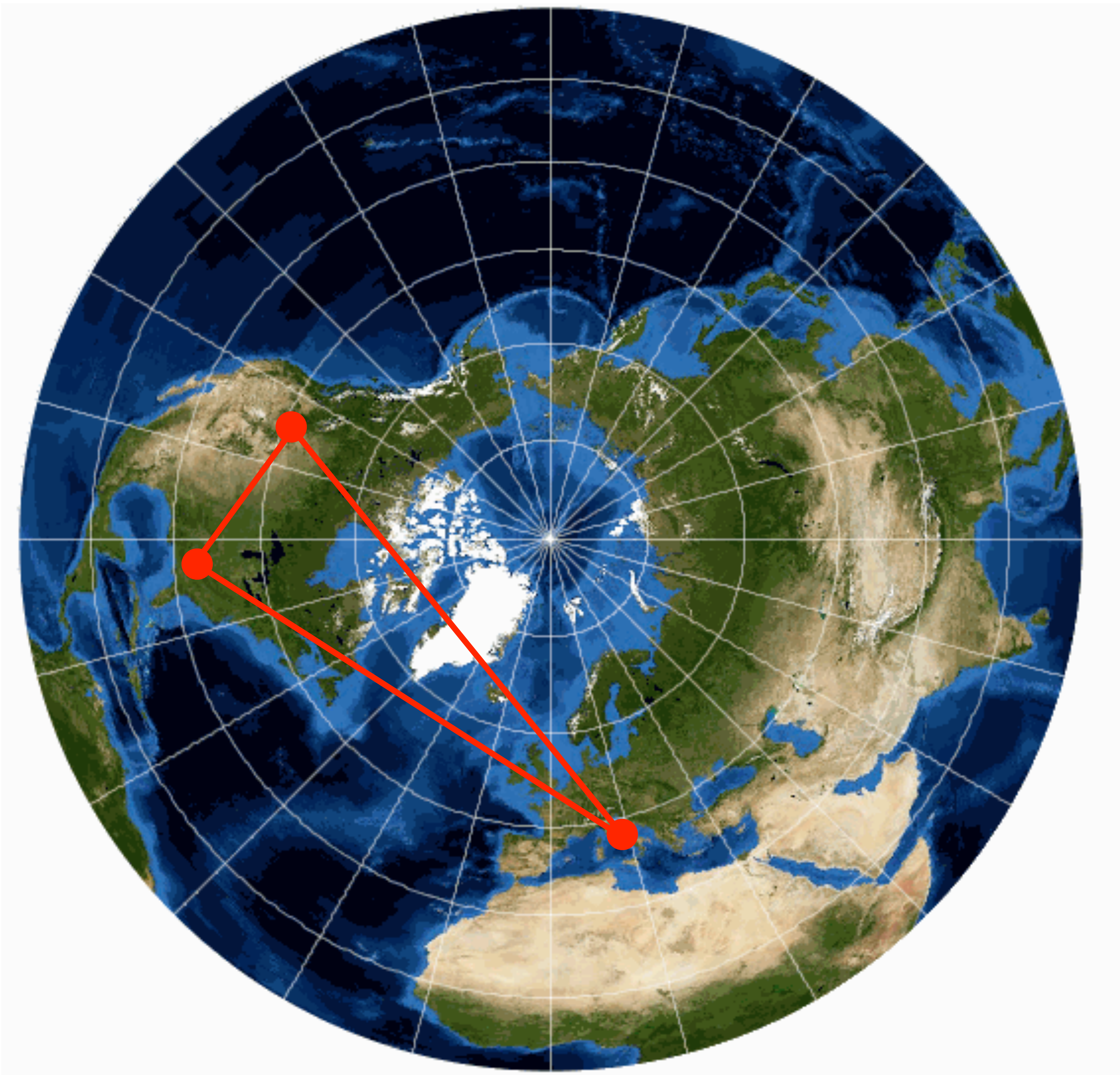


Instantaneous measurement of both polarization states and increased signal-to-noise

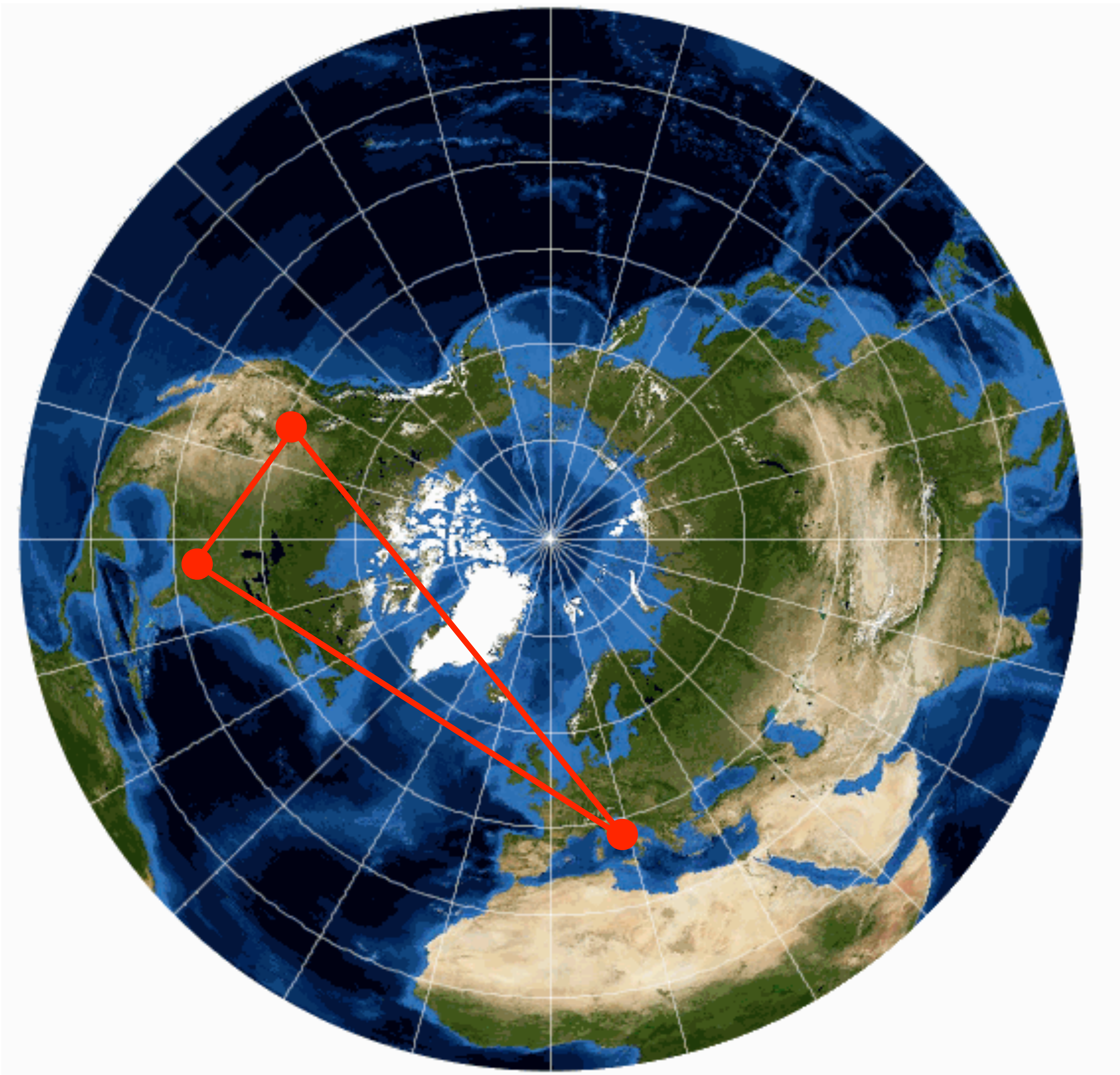
$$S_{\odot} = \frac{1}{3}\,(X + Y + Z) \quad \Rightarrow \quad \cdot$$

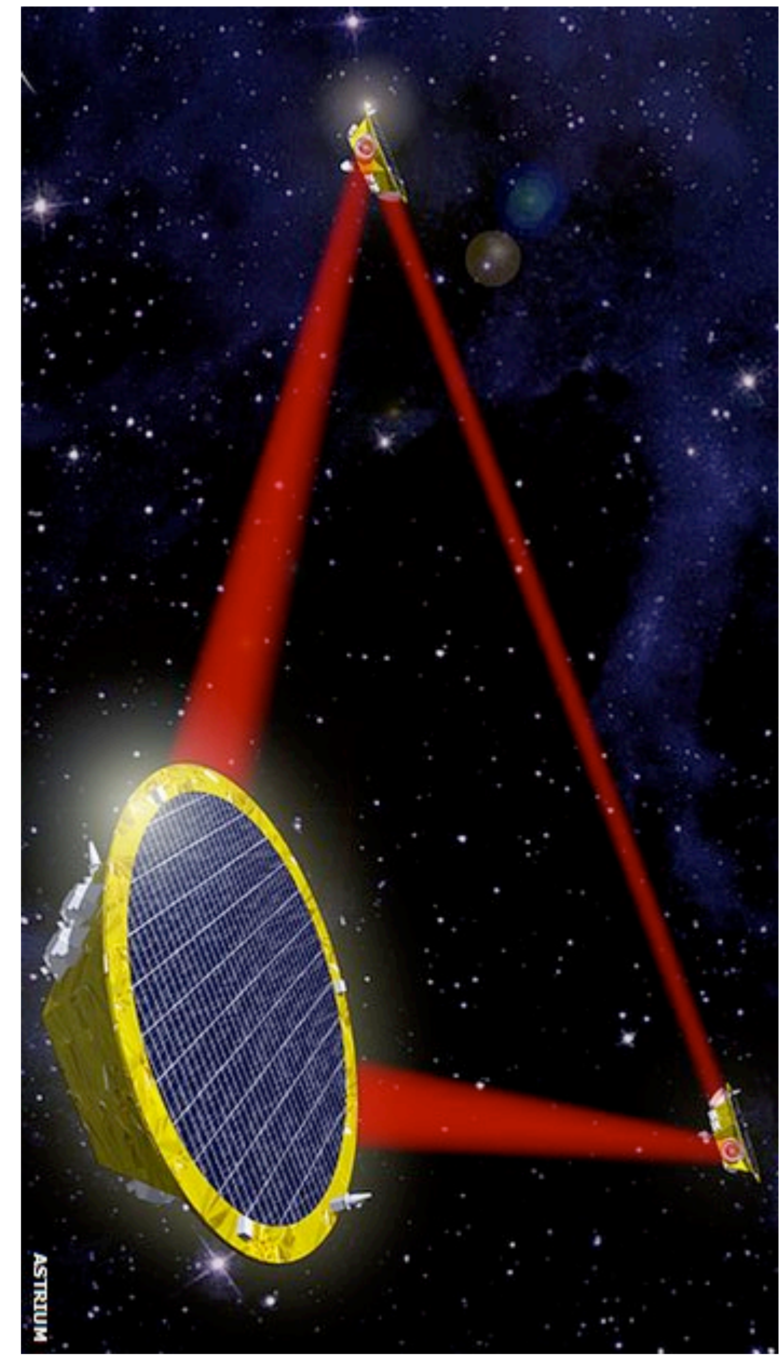
Null channel to monitor average low frequency instrument noise

Triangulation- Source Localization

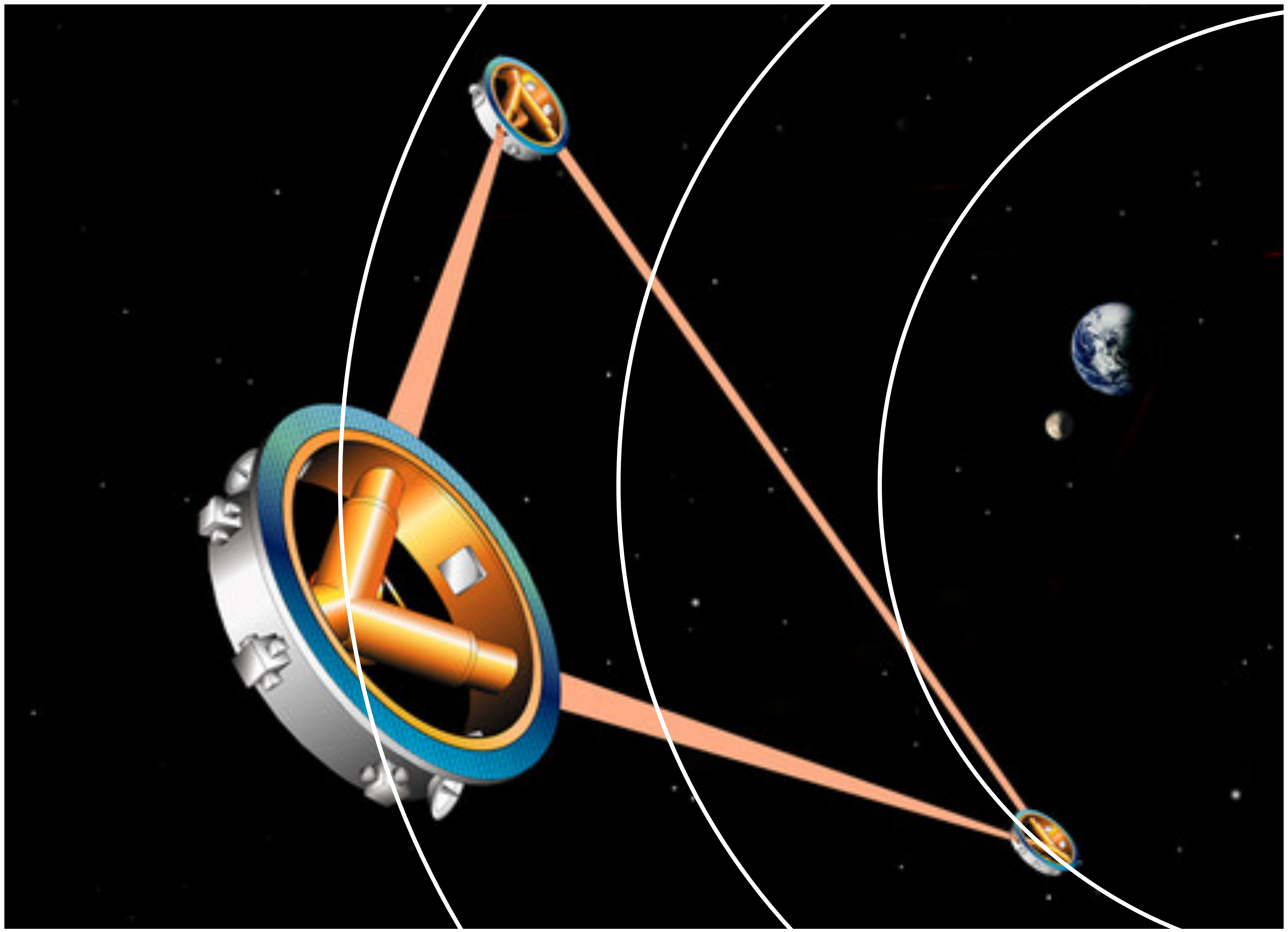


Triangulation- Source Localization





Separating Burst Signals from Noise



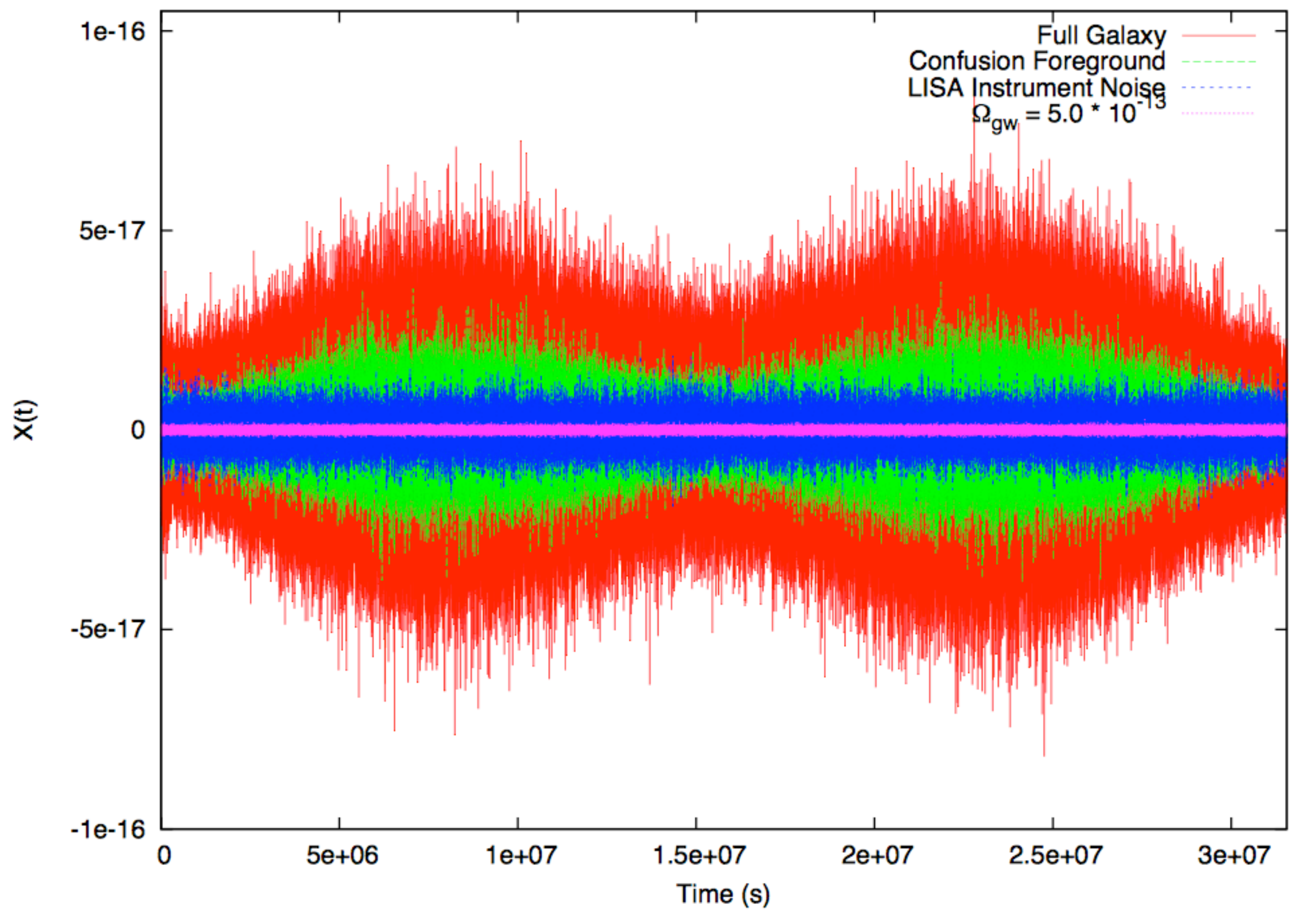
Noise delays

$$\Delta t = n\,\frac{L}{c}$$

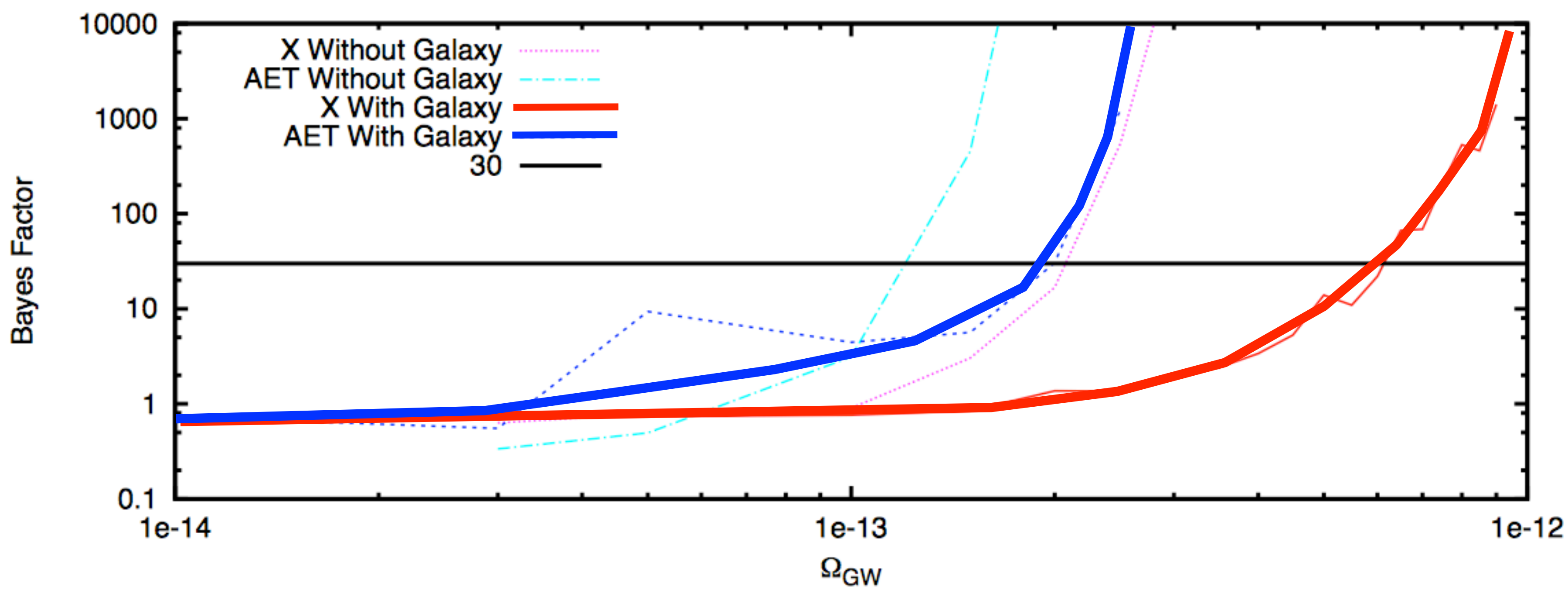
Signal delays

$$\Delta t = n\,\frac{L}{c} + \frac{\hat{k}\cdot\vec{L}}{c}$$

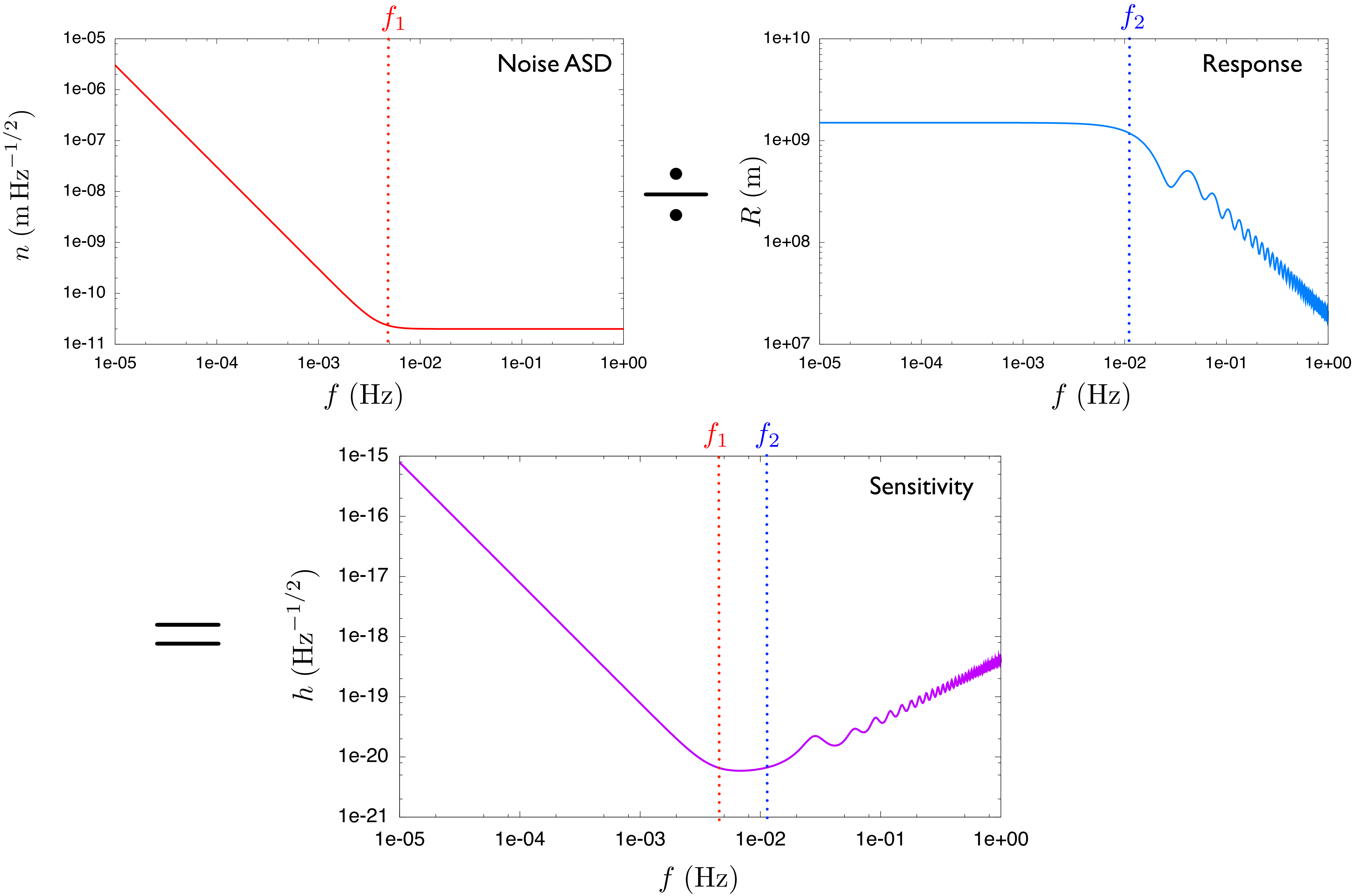
Detecting a Stochastic Background: (e)LISA



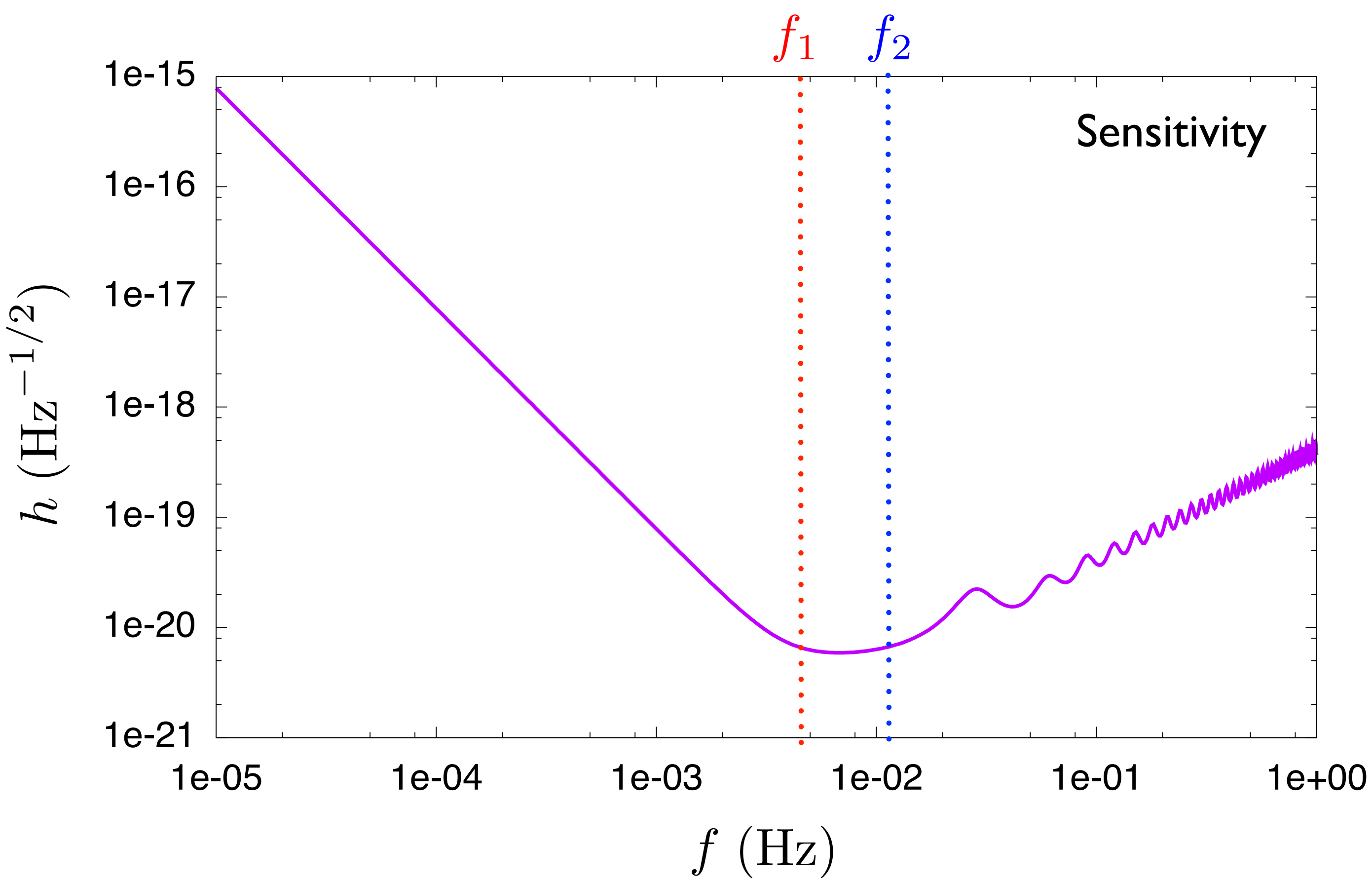
(Adams & Cornish 14)



LISA Sensitivity

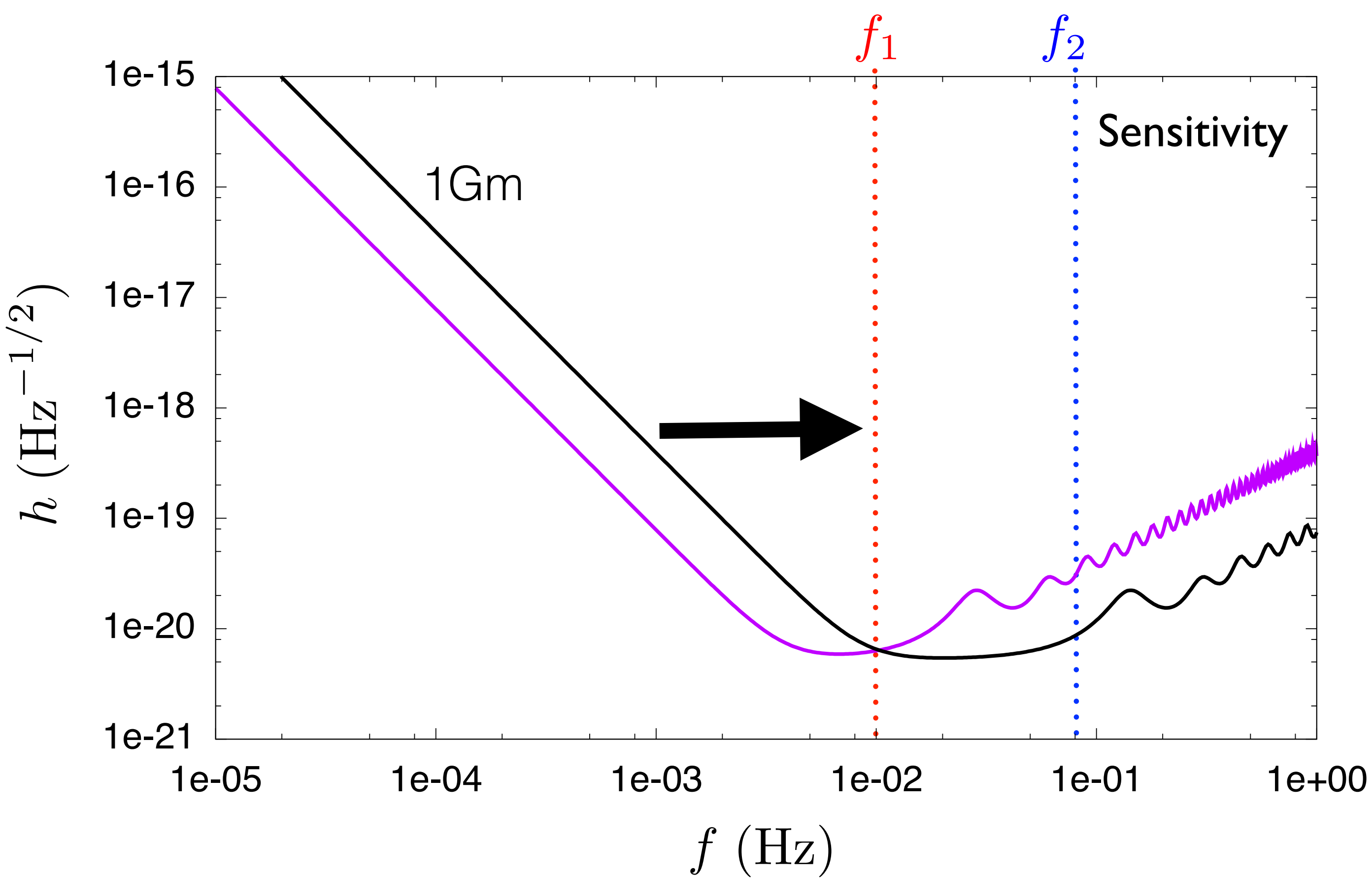


LISA Sensitivity



$$f_1 = \frac{1}{2\pi}\left(\frac{4S_a}{S_p}\right)^{1/4} \qquad f_2 = \frac{c}{2\pi L}$$

LISA Sensitivity



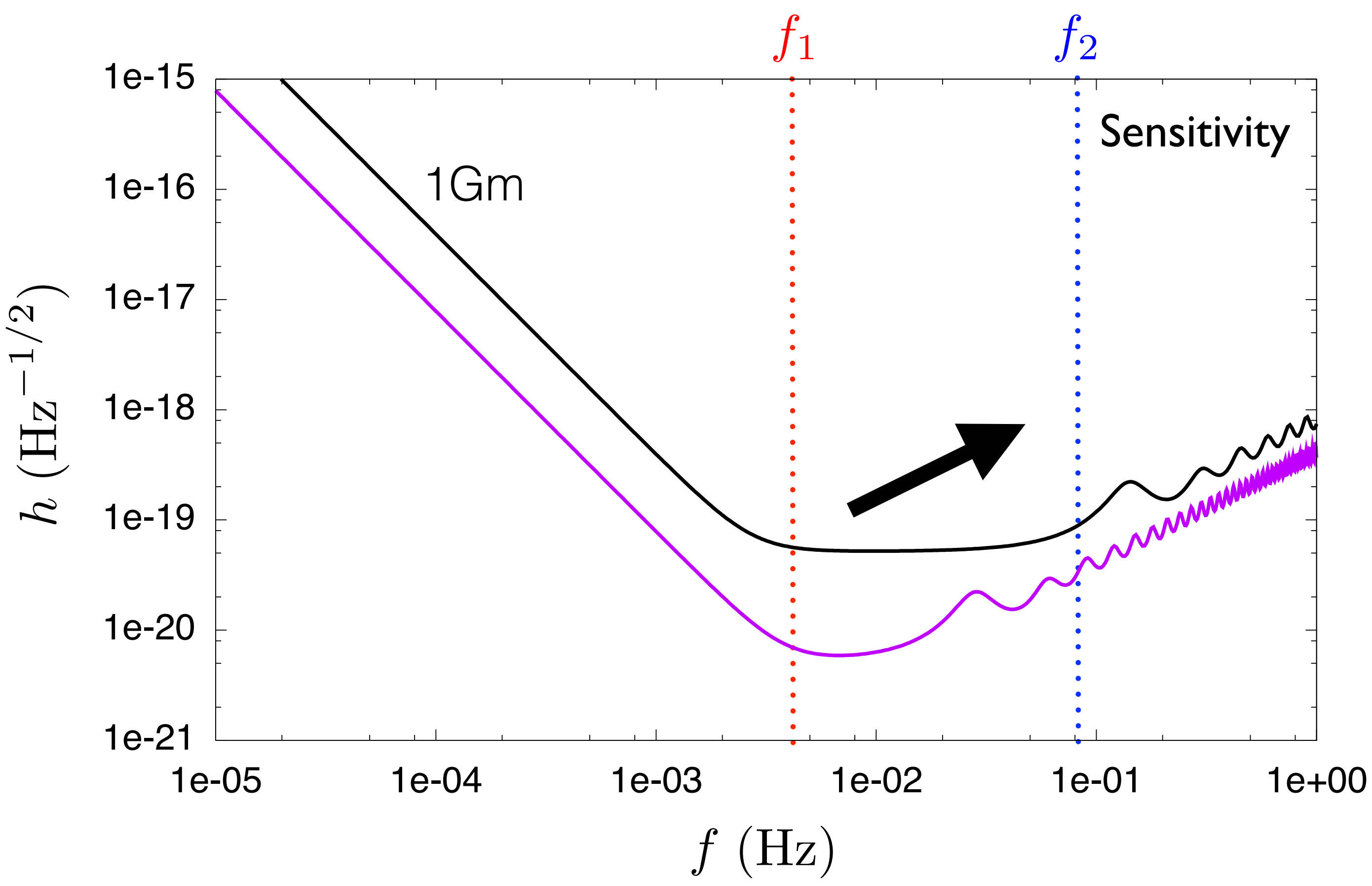
If just shot noise

$$S_p \sim \frac{L^2}{\epsilon\, P_{\mathrm{laser}}\, D^4}$$

$$f_1 \sim \frac{1}{L^{1/2}}$$

$$f_2 \sim \frac{1}{L}$$

LISA Sensitivity

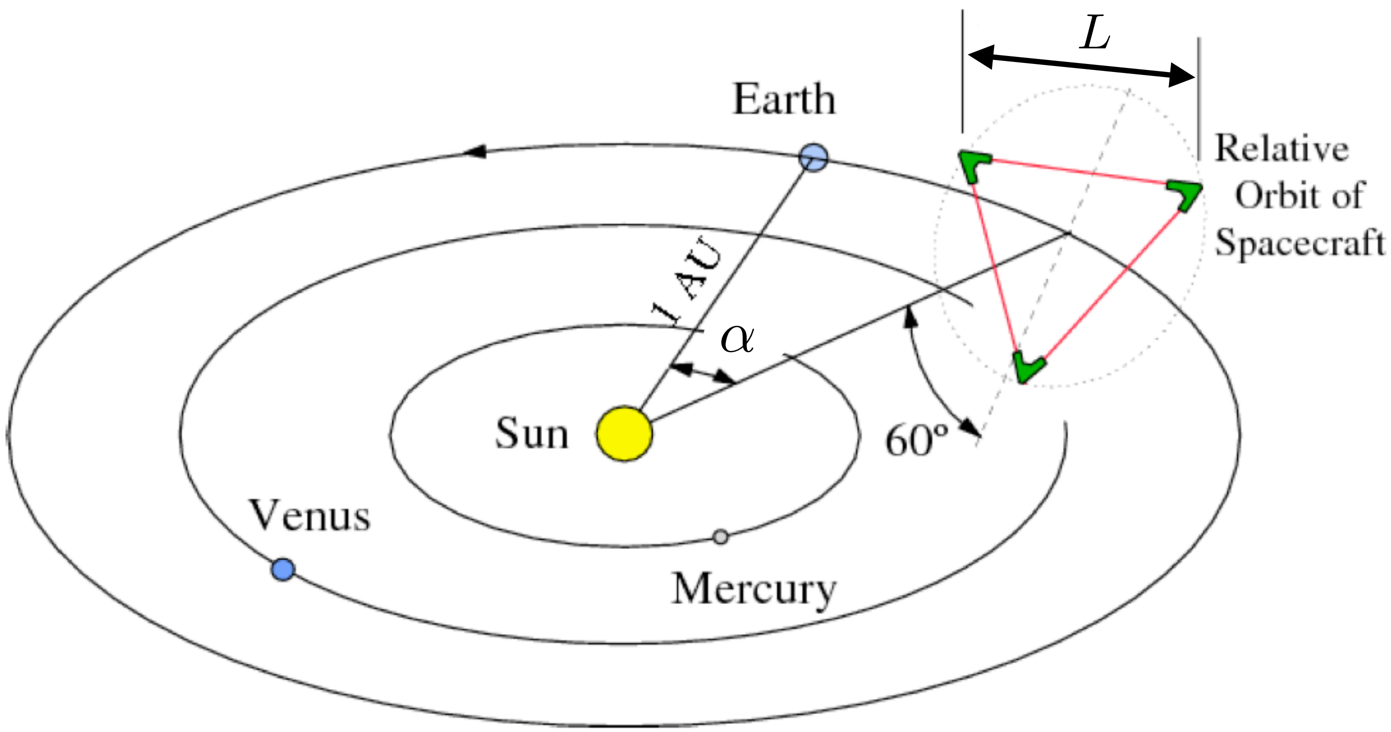


Fixed position noise

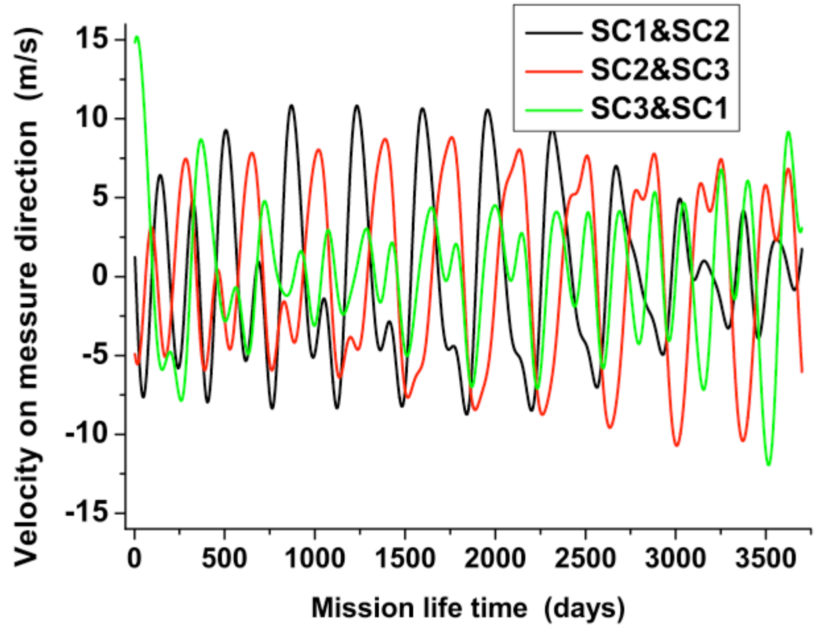
$f_1 \sim L^0$

$f_2 \sim \frac{1}{L}$

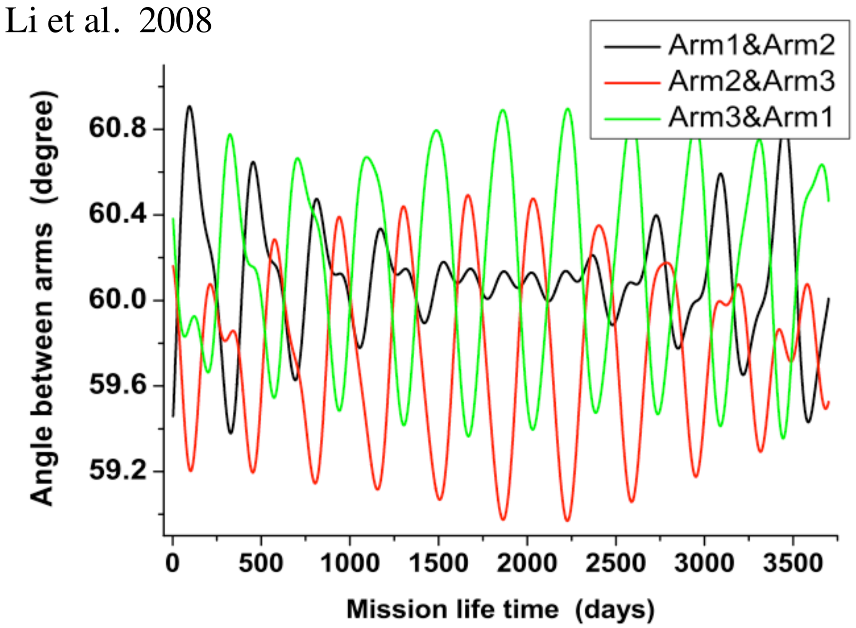
Orbit Selection



$$a_{\oplus} = \frac{2GM_{\oplus}\,L}{(\alpha\ \mathrm{AU})^3}$$



Li et al. 2008



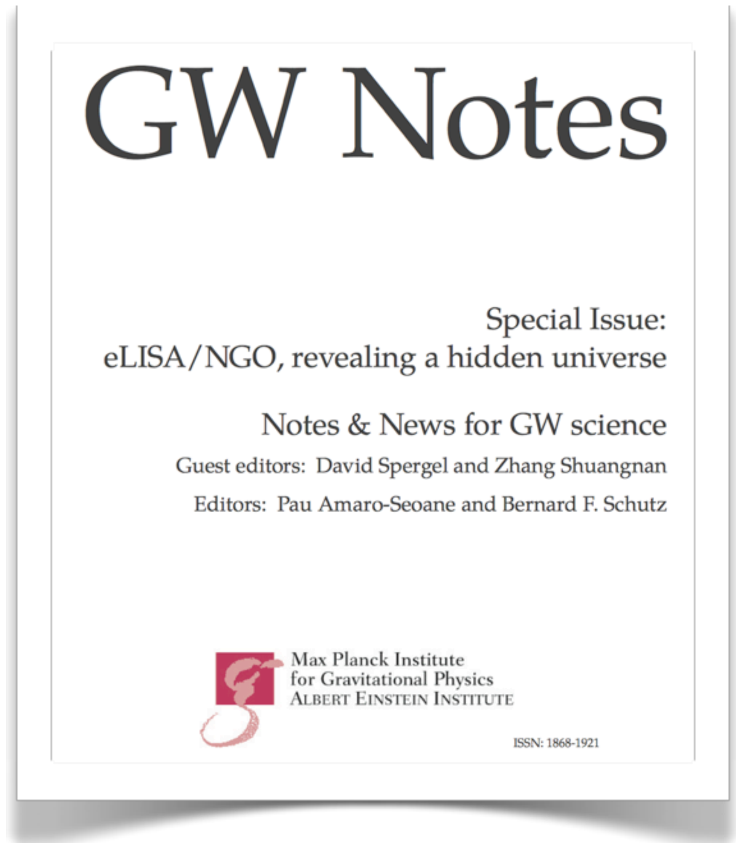
LISA Design Trades

- Low frequency sensitivity - Bigger better
- High frequency sensitivity - Shorter not always better
- Lifetime - Shorter arms = longer life
- Orbit - Further away better
- Articulation vs Infield Guiding - Shorter better
- Number of links should never be on the table

See talks by G. Mueller and J. Livas in this session

To learn more....

http://brownbag.lisascience.org/



https://www.elisascience.org/whitepaper/

http://www.cosmos.esa.int/web/GOAT