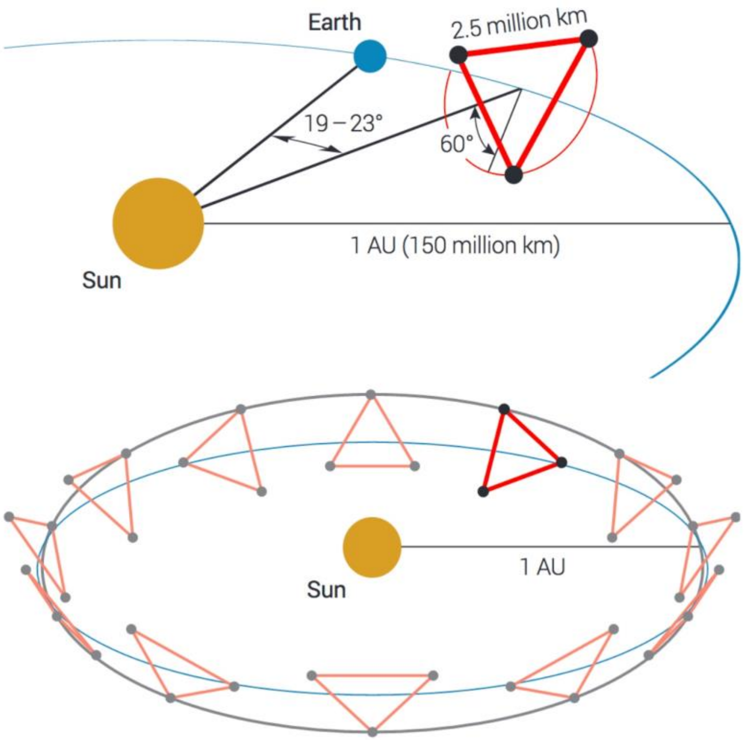
Overview of LISA Science

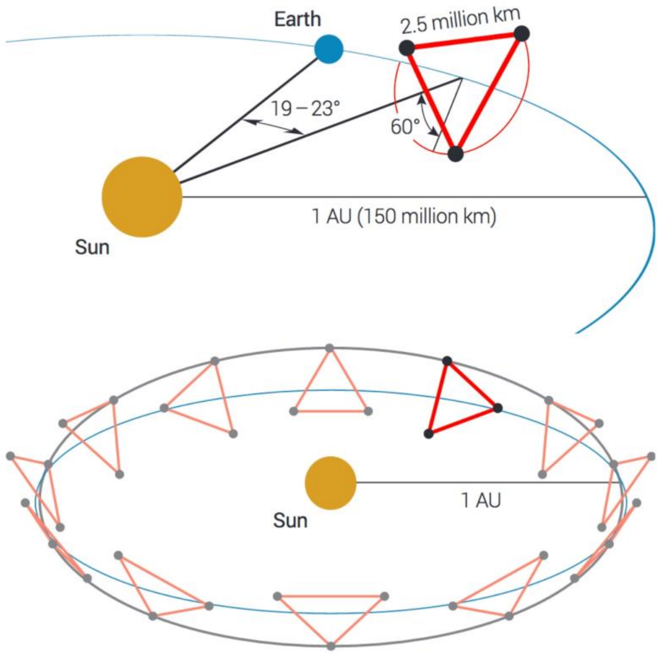
CURT CUTLER
Jet Propulsion Laboratory, California Institute of Technology



Overview of LISA Science

LISA:

- ➢is a joint ESA/NASA mission
- ➢is 3 drag-free satellites, separated by 5×10^6 km, and trailing the Earth by 20 deg
- ➢will detect GWs in $10^{-5} - 10^{-1} Hz$ band; main sources are:



✓Compact binaries in Milky Way, especially WD-WD binaries

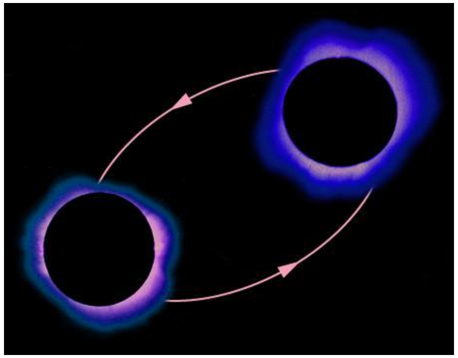
✓Mergers of $\sim 10^6 M_{sun}$ black holes in galactic nuclei at z > 1

✓Inspirals of compact stars (BHs, NSs, WDs) into massive BHs

? Bursts from cusps on cosmic (super-)strings

? Stochastic GWs generated by electro-weak phase transition

Binaries as standard GW sirens



(using quadrupole approximation for simplicity)

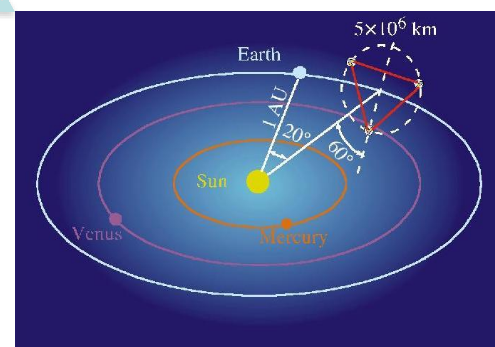
$$I^{ij} = \sum_A M_A r_A^i r_A^j$$

D

$$h_{ij} = \frac{1}{D} P_{TT} \frac{d^2}{dt^2} I_{ij}(t - D)$$

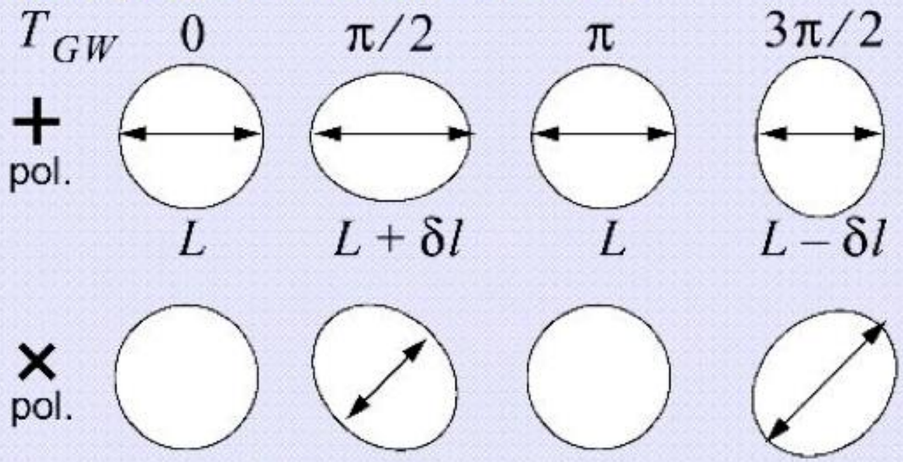
$$h(t) \sim D^{-1} \mu\, r^2 \Omega^2 \sim D^{-1} \frac{M_1 M_2}{M^{1/3}} f^{2/3}$$ x F(angles)

$$\frac{df}{dt} = \frac{96}{5} \pi^{8/3} \frac{M_1 M_2}{M^{1/3}} f^{11/3}$$ + higher order terms

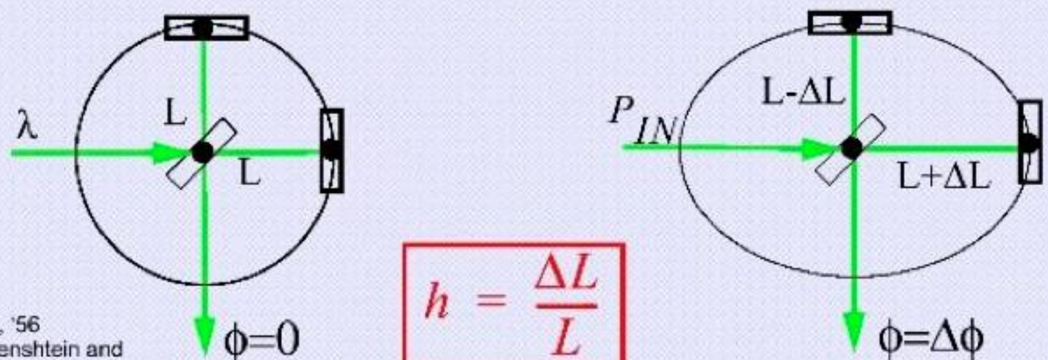


Gravitational Waves

❑ Two polarizations of GWs



❑ Laser interferometer

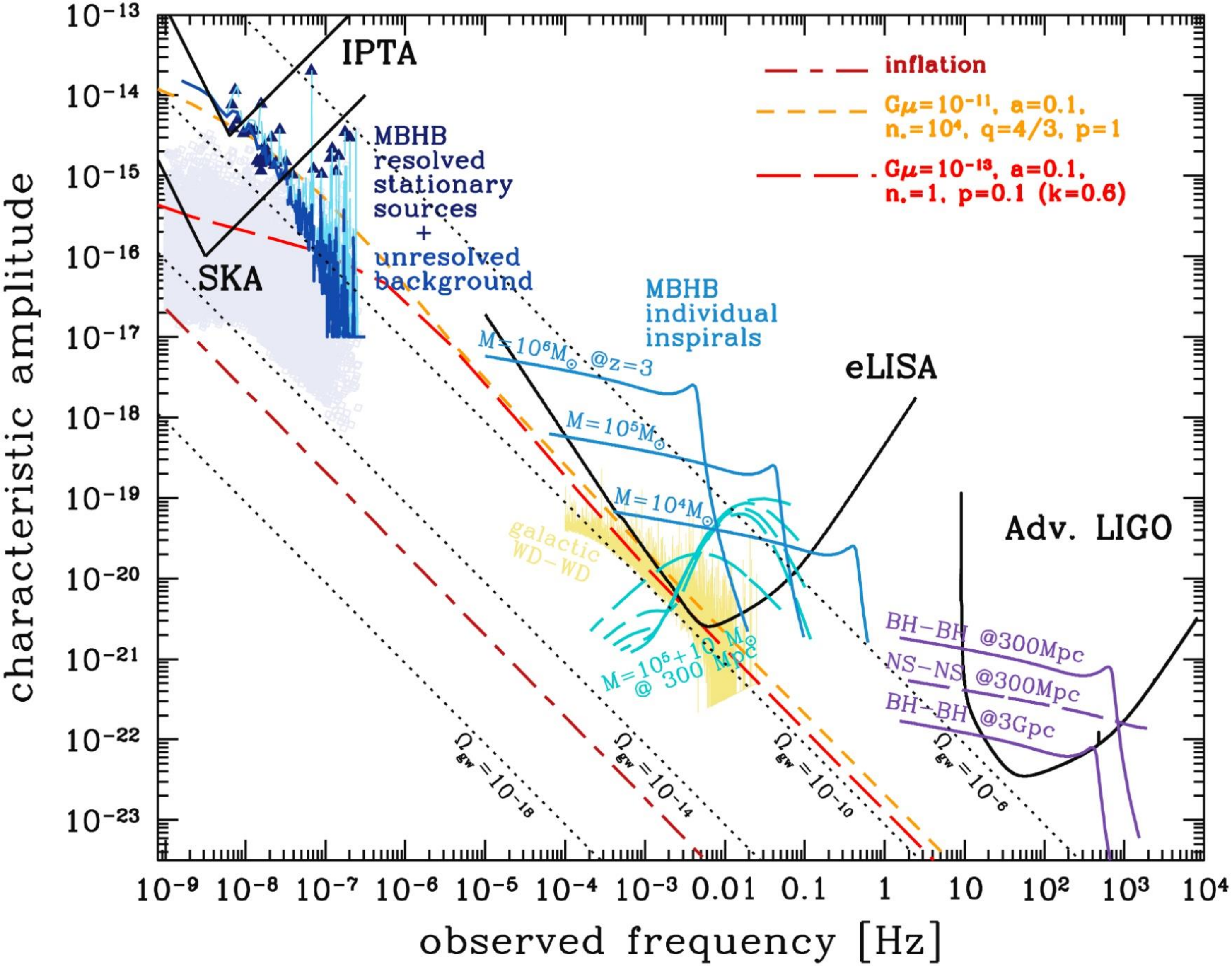


$$h = \frac{\Delta L}{L}$$

$$P_{OUT} = P_{IN} \cos^2(2k\Delta L)$$

Pirani, '56
Gertsenshtein and Pustovoit, '62
Weiss, '72
Forward, '72

GW sources/bands



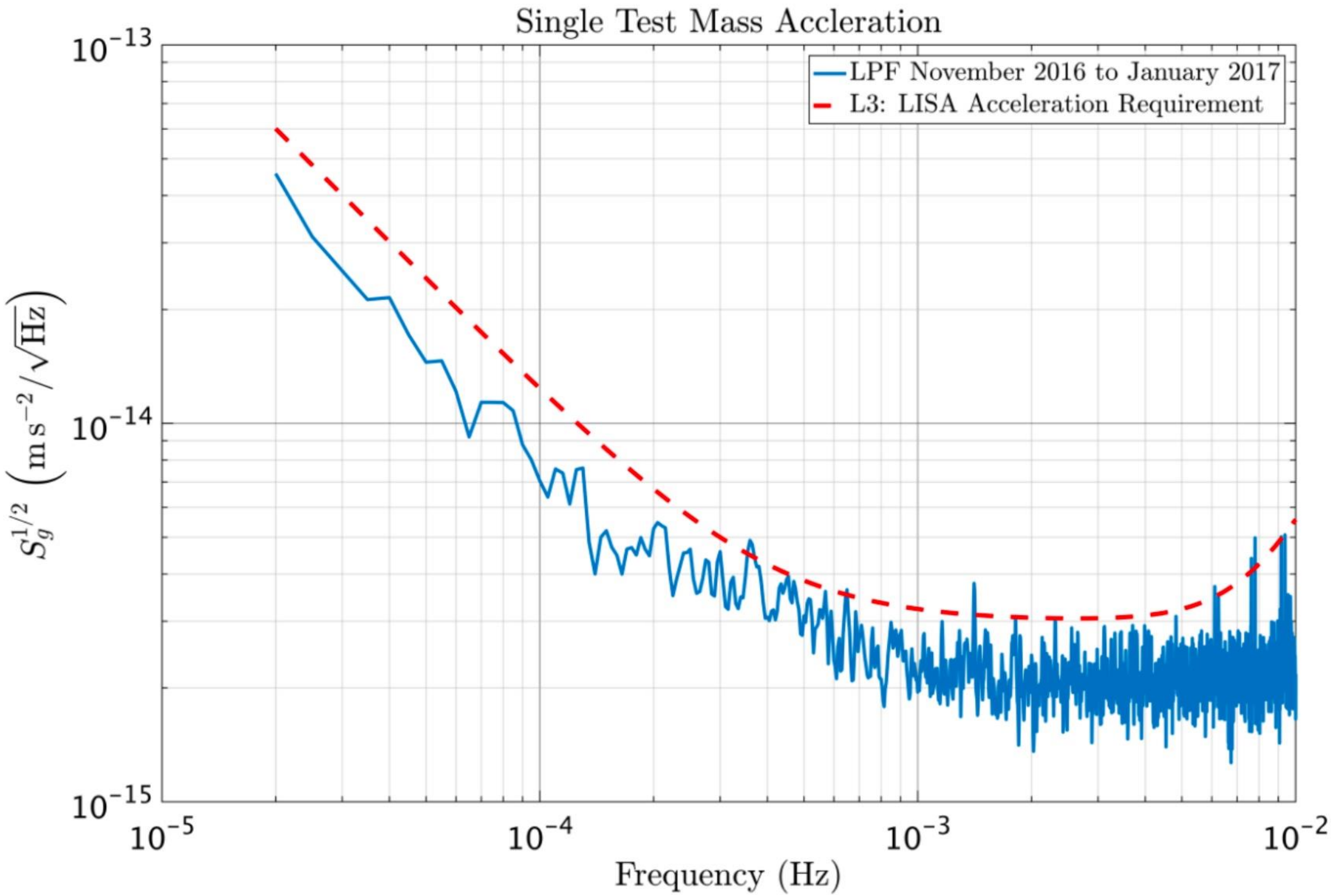
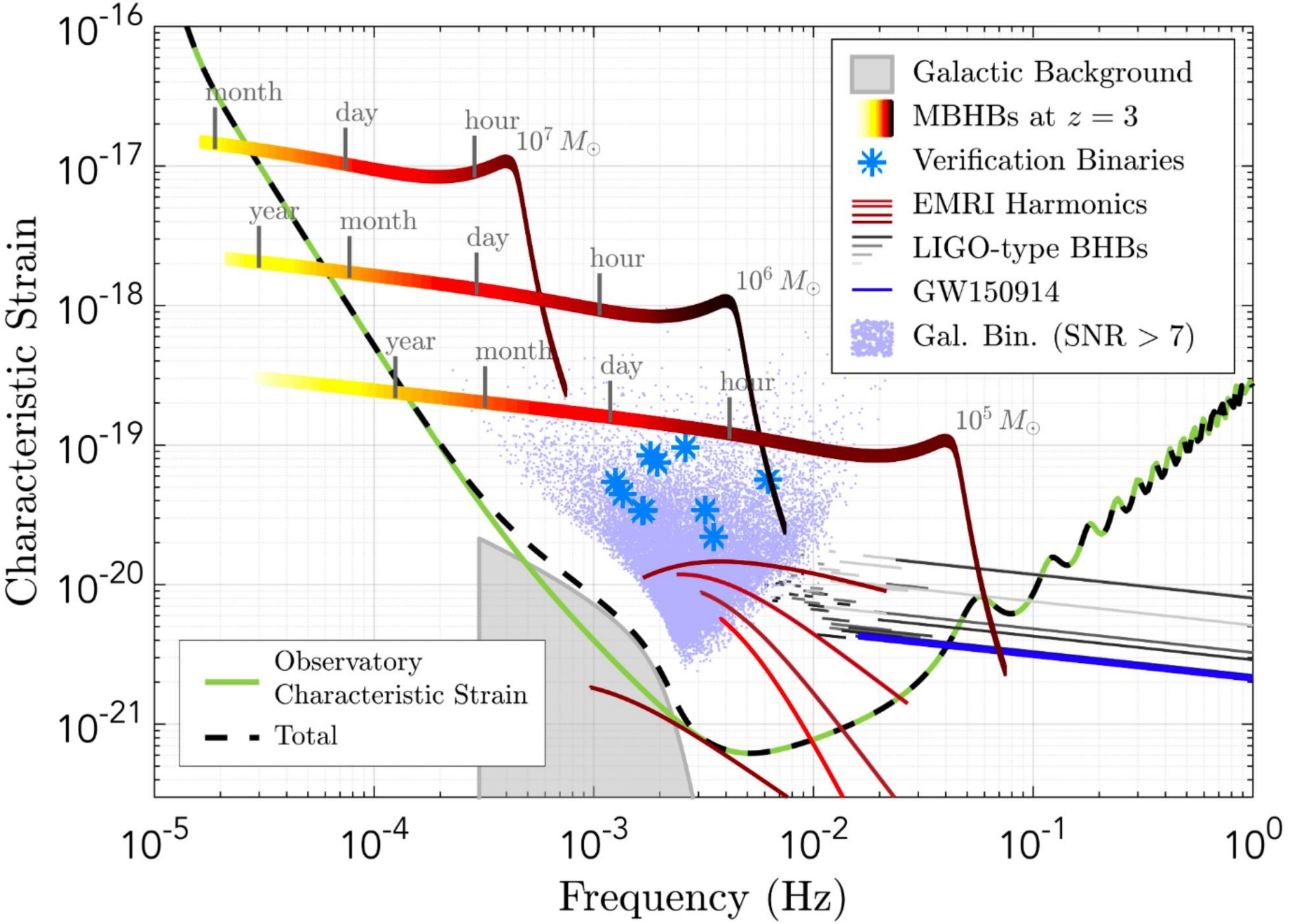


Figure 9: Average TM acceleration noise measured with LISA Pathfinder, compared against the LISA single TM acceleration requirement.

GW Sources



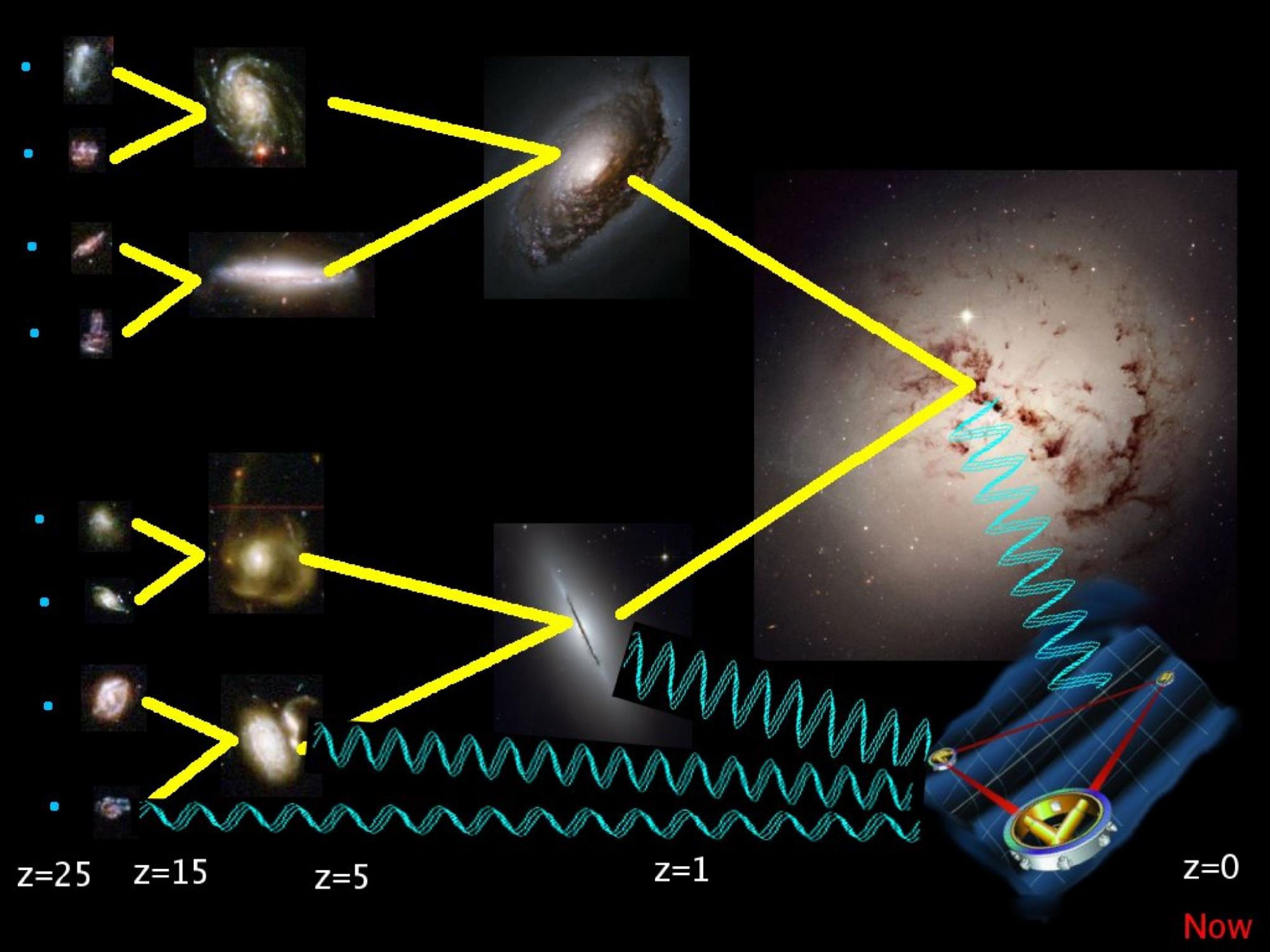
Characteristic Strain
Frequency (Hz)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
month
day
hour
$10^7 M_\odot$
year
month
day
hour
$10^6 M_\odot$
year
month
day
hour
$10^5 M_\odot$
Galactic Background
MBHBs at $z = 3$
Verification Binaries
EMRI Harmonics
LIGO-type BHBs
GW150914
Gal. Bin. (SNR > 7)
Observatory Characteristic Strain
Total

Massive BH mergers

- Basically all large galaxies contain massive BHs in their cores.

- When galaxies merge, dynamical friction brings their two BHs close together--presumably close enough that gravitational radiation will then cause them to merge in a Hubble time (though this is somewhat controversial for approximately equal mass holes).

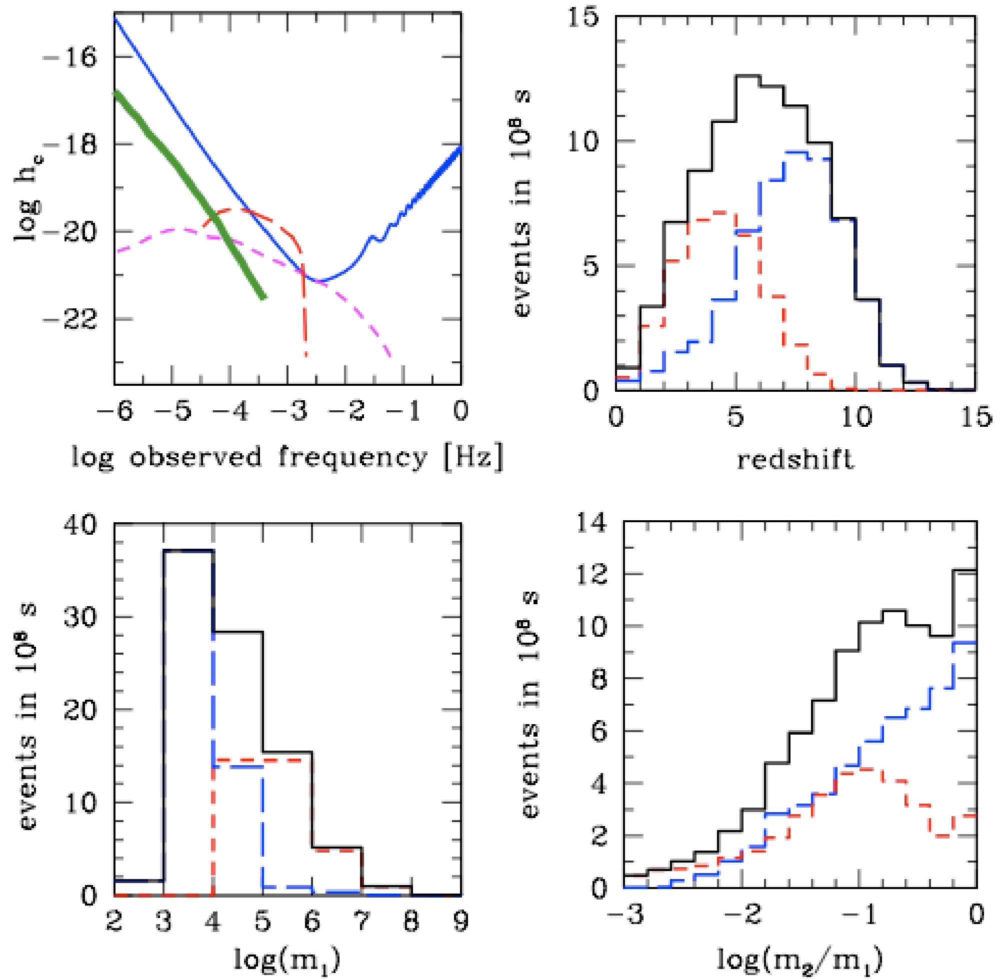
- Structure formation in the early universe is bottom-up: small galaxies merge to form larger galaxies, which merge to form even larger galaxies, etc. If the small proto-galaxies at high redshift contain central BHs, then LISA could detect hundreds of such mergers.


z=25
z=15
z=5
z=1
z=0
Now

Massive BH merger rates

- Most estimates give O(1) event/yr for 2 $\sim 10^6 M_{sun}$ BHs at z<2.

- If a large fraction of proto-galaxies have central BHs, then LISA's detection rate could be $\sim 10^2 - 10^3 / yr$ w/ typical source at z~6, and BH masses $\sim 10^4 M_{sun}$

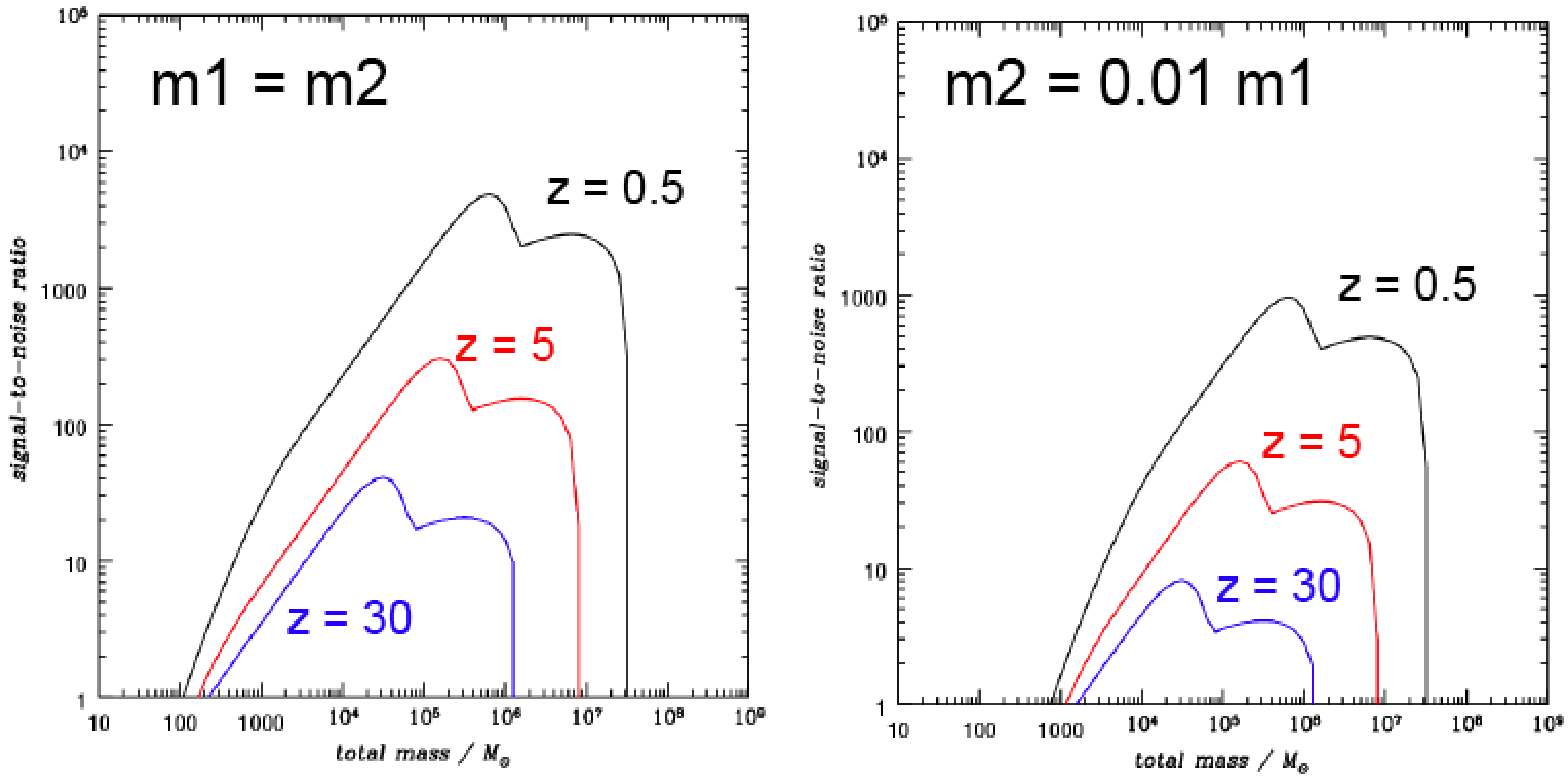


Distribution of ~90 LISA detections w/ SNR>5 in 3-yr integration

--from Sesana et al. (2005)

Science from MBH mergers

- "Brightest" merger events will have (matched-filter) SNR $\geq 10^3$
- For brightest events, inspiral will give us BH masses to fractional error $\sim 10^{-4}$, spins to $\sim 10^{-3}$, and D_L to $\sim 0.1-1\%$

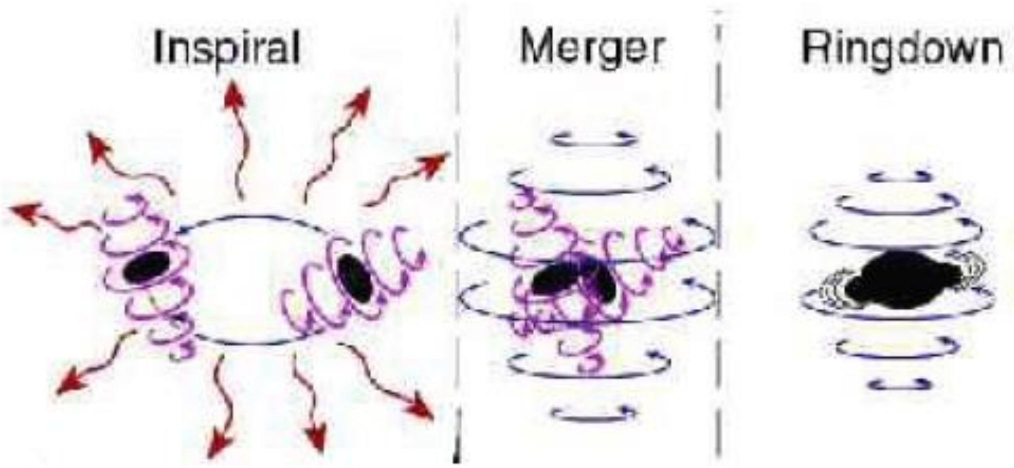


--from A. Vecchio

Science from MBH mergers

- Will learn about MBH demographics: the number and growth of BHs at z ~ 1-10.
- For nearest sources, from inspiral we learn binary params Extremely well: masses to $\sim 10^{-4}$ and spins to $\sim 10^{-3}$

Then can compare GW burst to predictions of numerical relativity--the ultimate strong-field test.



LISA-resolved Galactic binaries with f > 2 mHz

TABLE 1. Galactic merger rates and birth rates for binaries containing compact objects, with an (order of magnitude) estimate of the uncertainty and the number of systems that can be resolved by LISA (see Sect. 3 and 4).

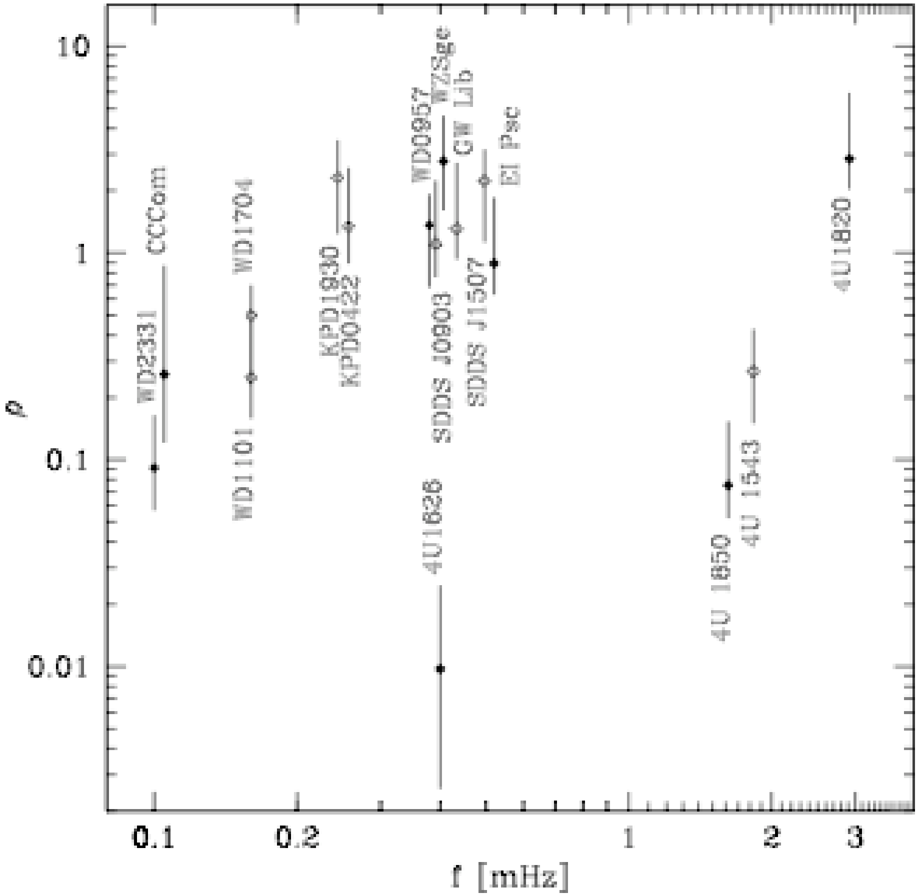
Type	birth rate (yr^{-1})	merger rate (yr^{-1})	uncertainty factor	resolved systems
(wd, wd)	2.0×10^{-2}	8.3×10^{-3}	5	10658
AM CVn	1.3×10^{-3}		50	9831
UCXB	1.1×10^{-5}		20	22
(ns, wd)	6.8×10^{-5}	3.8×10^{-5}	20	8
(ns, ns)	5.2×10^{-5}	2.5×10^{-5}	50	7
(bh, wd)	7.2×10^{-5}	2.6×10^{-6}	50	0
(bh, ns)	3.5×10^{-5}	1.0×10^{-5}	50	0
(bh, bh)	1.7×10^{-4}	5.1×10^{-6}	50	0

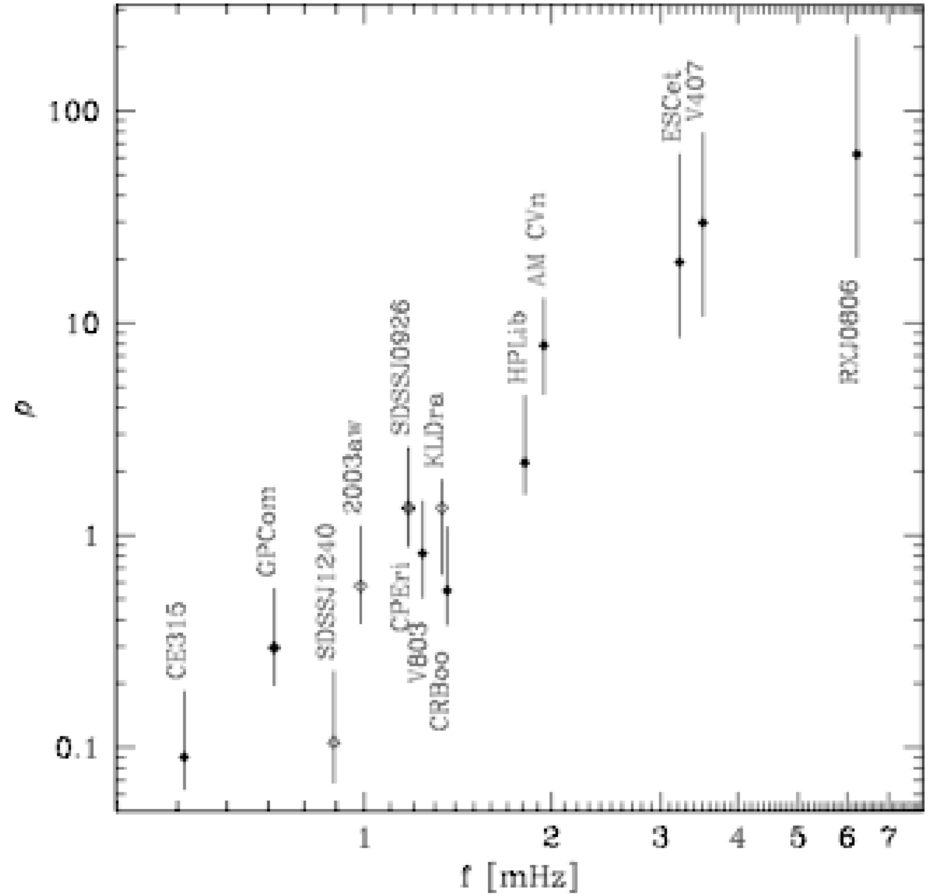
--G. Nelemans, astro-ph/0310800

LISA Verification Binaries

non-AM CVn's

AM CVn binaries





Plots show expected SNR of known Galactic binaries for 1-yr of LISA observation. At least 4 are clearly detectable.

--Stroeer & Vecchio

Science Payoff from Galactic Binaries

- Demographics: currently know ~100 WD-WD binaries, so LISA will increase known sample by large factor.

- Unless frequency is changing observably, GW signal alone does not give the masses or distance:

$$h(t) \propto f^{2/3} M_c^{5/3} D^{-1} \cos \int f\, dt \quad \text{where} \quad M_c \equiv M_1^{3/5} M_2^{3/5} \left(M_1 + M_2\right)^{-1/5}$$

- LISA can determine sky location to ~1 deg, so it should be possible to find optical counterparts for several hundred. sources with V-mag < 20. For these GAIA could determine D to 10%; this combined with LISA data determines M_c to ~10%.

Science Payoff from Galactic Binaries

- Coorary & Seto(2004) pointed out: ~40% of optically identified binaries will be eclipsing. Can then determine $R_1/a\cos\iota$, $R_2/a\cos\iota$, R_1/R_2

- Can then test that GWs travel at same speed of light: with single binary should be able to limit graviton mass to $m_g < 10^{-22}\, eV$
With ~100 binaries, should achieve $m_g < 10^{-23}\, eV$, which is almost 2 orders of magnitude better than Solar System bounds.

- For some high-frequency binaries, can also measure $\dot{f}$ (and for a few $\ddot{f}$). Many AM CVn's will have $\dot{f} < 0$
Then will learn about mass transfer.

Extreme-mass-ratio inspirals

- Captured main sequence stars are not LISA source, since they are tidally disrupted before they enter the LISA band.

- WDs, NSs, and BHs all captured whole. Captures of $\sim 10\, M_{sun}$ probably dominate the detection rate, due to mass segregation in the inner few parsecs, and because they can be seen to greater distance: to $z \geq 1$

- BH capture rate in Milky Way $\sim 10^{-8} - 10^{-6} / yr$ Implies LISA detection rate of $\sim 10 - 1000 / yr$

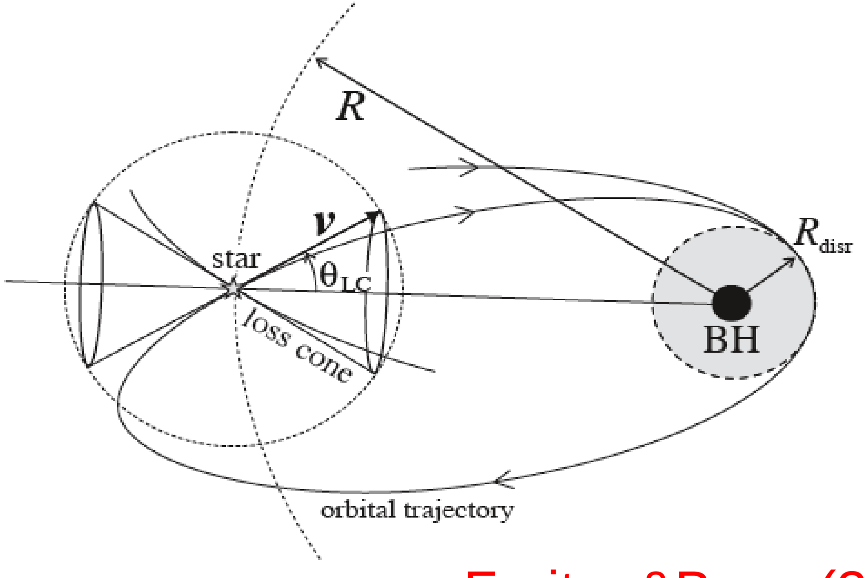
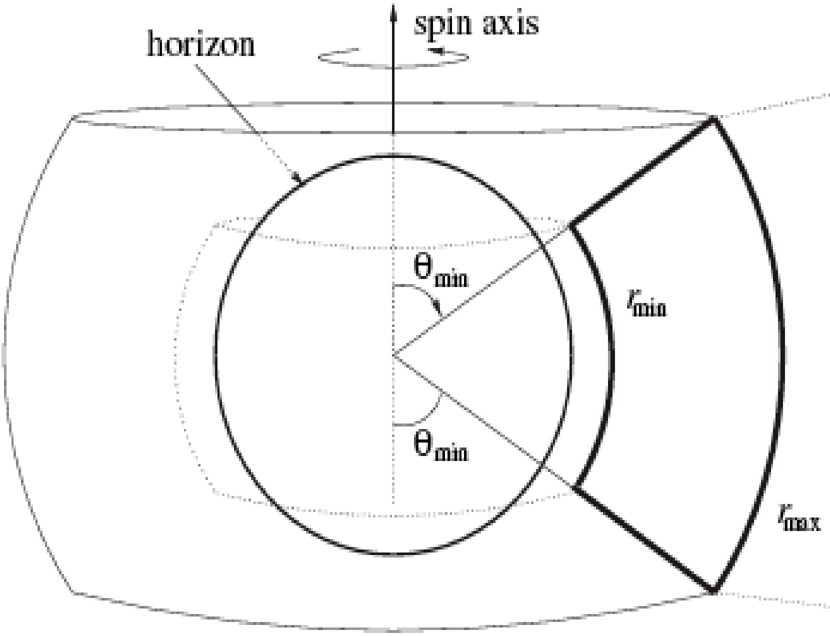
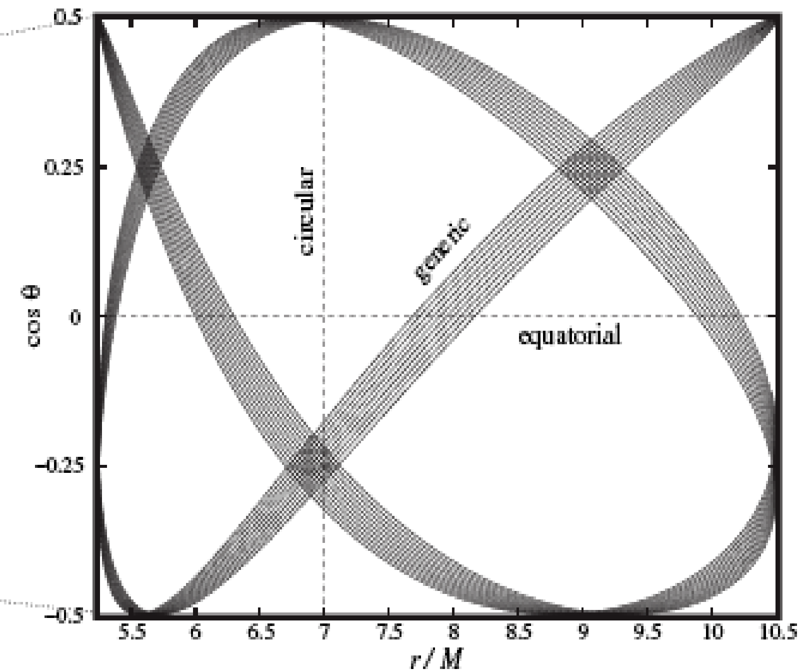


Fig. 3. Diagram of the loss cone. --Freitag&Benz (2002)

geodesic orbits in Kerr





--from Drasco&Hughes ('06)

There are 3 basic frequencies: $f_\phi\ ,\ \ f_\theta\ ,\ \ f_r$

Gravitational waves measured at infinity have a discrete spectrum made up of harmonics of just these 3 frequencies:

$$f_{mkn} = m f_\phi + k f_\theta + n f_r$$

with m,k,n integers.

Snapshot waveforms

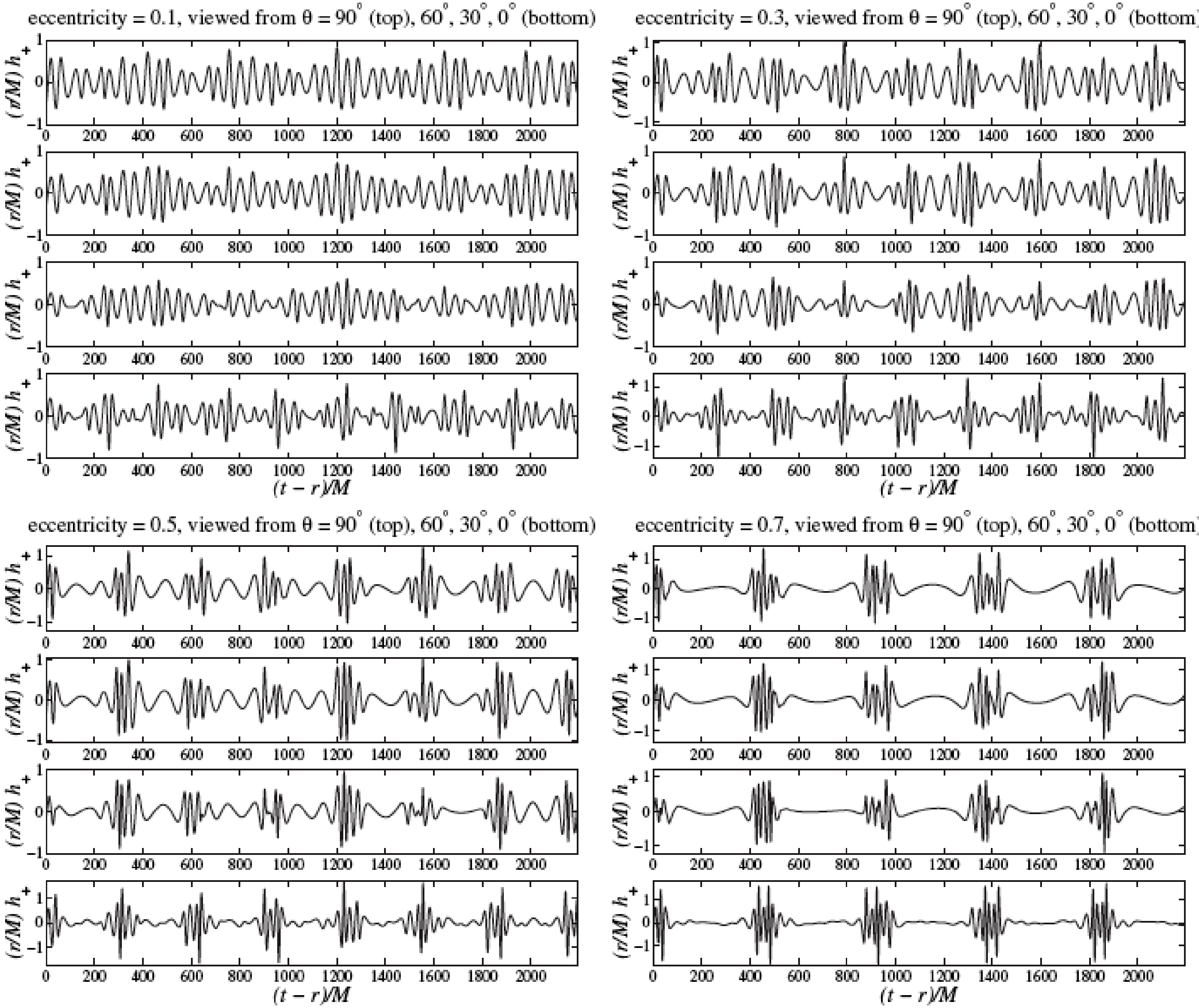


FIG. 6. Snapshot waveforms for orbits with inclination $\theta_{\rm inc} = 80°$, semilatus rectum $p = 6$, and eccentricities $e = 0.1, 0.3, 0.5, 0.7$. The magnitude of the black hole's spin angular momentum is $aM = 0.9M^2$.

--from Drasco&Hughes ('06)

Matched filtering: basic idea

measured signal = inst. noise + GW

$$s(t) = n(t) + h(t)$$

$$\int_0^T dt\, s(t)h(t) = \int_0^T dt\, n(t)h(t) + \int_0^T dt\, h^2(t)$$

$$\int_0^T dt\, n(t)h(t) \sim T^{1/2} \qquad \int_0^T dt\, h^2(t) \sim T$$

$$SNR \sim \frac{rms\{h\}}{rms\{n\}} N_{cyc}^{1/2}$$

with N_cyc ~ 10^5 for EMRIs

Moral: Knowledge is Power

Precision of EMRI parameter determination

$$\frac{\Delta m}{m} \sim \frac{\Delta M}{M} \sim \Delta\left(\frac{S}{M^2}\right) \sim 10^{-4} \qquad \Delta\theta \sim 2^o \qquad \frac{\Delta D}{D} \sim 0.05$$

S/M^2	0.1	0.1	0.1	0.5	0.5	0.5	1	1	1
e_{LSO}	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
$\Delta(\ln M)$	2.6e−4	5.6e−4	5.3e−5	2.7e−4	9.2e−4	7.7e−5	2.8e−4	2.5e−4	1.5e−4
$\Delta(S/M^2)$	3.6e−5	7.9e−5	4.5e−5	1.3e−4	6.3e−4	5.1e−5	2.6e−4	3.7e−4	2.6e−4
$\Delta(\ln \mu)$	6.8e−5	1.5e−4	7.4e−5	6.8e−5	9.2e−5	1.0e−4	6.1e−5	9.1e−5	1.0e−3
$\Delta(e_0)$	6.3e−5	1.3e−4	2.9e−5	8.5e−5	2.8e−4	3.2e−5	1.2e−4	1.1e−4	1.6e−4
$\Delta(\cos \lambda)$	6.0e−3	1.7e−2	1.3e−3	1.3e−3 $\Delta\theta \sim 2$	5.8e−3	2.4e−4	6.5e−4	8.4e−4	4.7e−4
$\Delta(\Omega_s)$	1.4e−3	1.6e−3	6.3e−4	1.4e−3	2.1e−3	6.3e−4	1.4e−3	8.3e−4	6.2e−4
$\Delta(\Omega_K)$	5.6e−2	5.5e−2	4.7e−2	5.5e−2	5.2e−2	4.7e−2	5.5e−2	5.1e−2	4.8e−2
$\Delta(\tilde{\gamma}_0)$	4.0e−1	6.3e−1	3.8e−1	1.0e+0	6.1e−1	3.9e−1	9.3e−1	3.4e−1	3.9e−1
$\Delta(\Phi_0)$	2.6e−1	6.7e−1	2.2e−1	1.4e+0	7.5e−1	2.7e−1	1.5e+0	1.7e−1	3.3e−1
$\Delta(\alpha_0)$	6.2e−1	5.8e−1	5.5e−1	6.3e−1	5.9e−1	5.6e−1	6.4e−1	5.9e−1	5.9e−1
$\Delta[\ln(\mu/D)]$	8.7e−2	3.8e−2	3.7e−2	3.8e−2	3.7e−2	3.7e−2	3.8e−2	7.0e−2	3.7e−2
$\Delta(t_0)\nu_0$	4.5e−2	1.1e−1	3.3e−2	2.3e−1	1.3e−1	4.4e−2	2.5e−1	3.2e−2	5.5 − 2

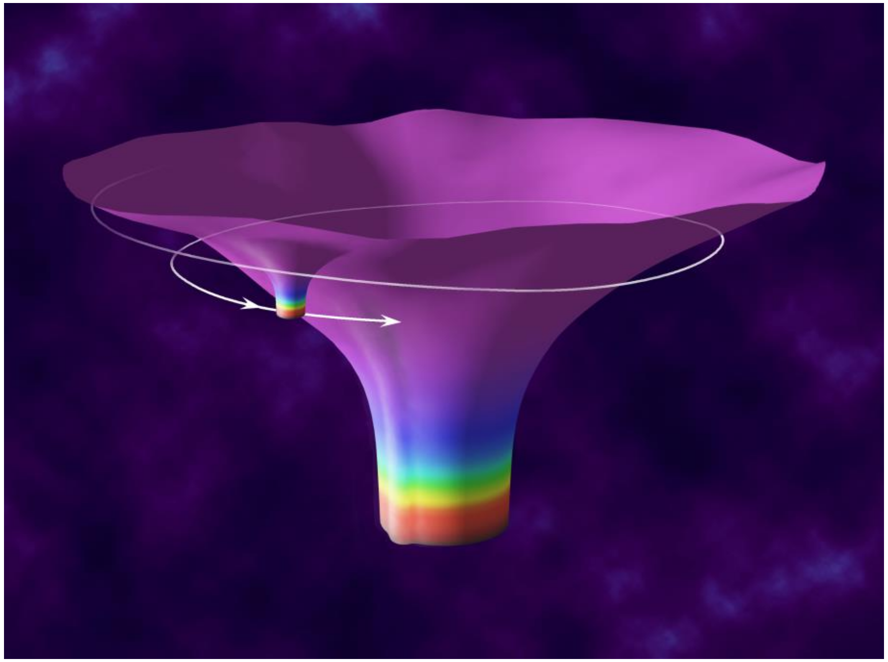
TABLE III. Parameter accuracy estimates for inspiral of a $10M_\odot$ CO onto a $10^6 M_\odot$ MBH at SNR=30 (based on data collected during the last year of inspiral). Shown are estimates for the accuracy in determining the various physical parameters, for various values of the MBH's spin magnitude S and the final eccentricity e_{LSO}. The rest of the parameters are set as follows: $t_0 = (1/2)$yr (middle of integration); $\tilde{\gamma}_0 = 0$; $\Phi_0 = 0$; $\theta_S = \pi/4$; $\phi_S = 0$; $\lambda = \pi/6$; $\alpha_0 = 0$; $\theta_K = \pi/8$; $\phi_K = 0$.

--Barack&Cutler (2004)

Extreme-mass-ratio inspirals

- Matched filtering required to dig EMRIs out of the noisy data, but full numerical relativity NOT required to produce the waveforms: one can do perturbation theory in the mass ratio $m/M \sim 10^{-5}$, with small body treated as point particle.

- The radiation reaction force diverges at the point particle, and so must be regularized. A prescription for doing The regularization was given by Wald&Quinn ('97) and Mino, Sasaki, &Tanaka ('97), but developing a practical numerical implementation remains an active area of research, with a yearly meeting devoted to it.



Current technology is likely adequate for detecting EMRI signals, but not for extracting maximal information content.

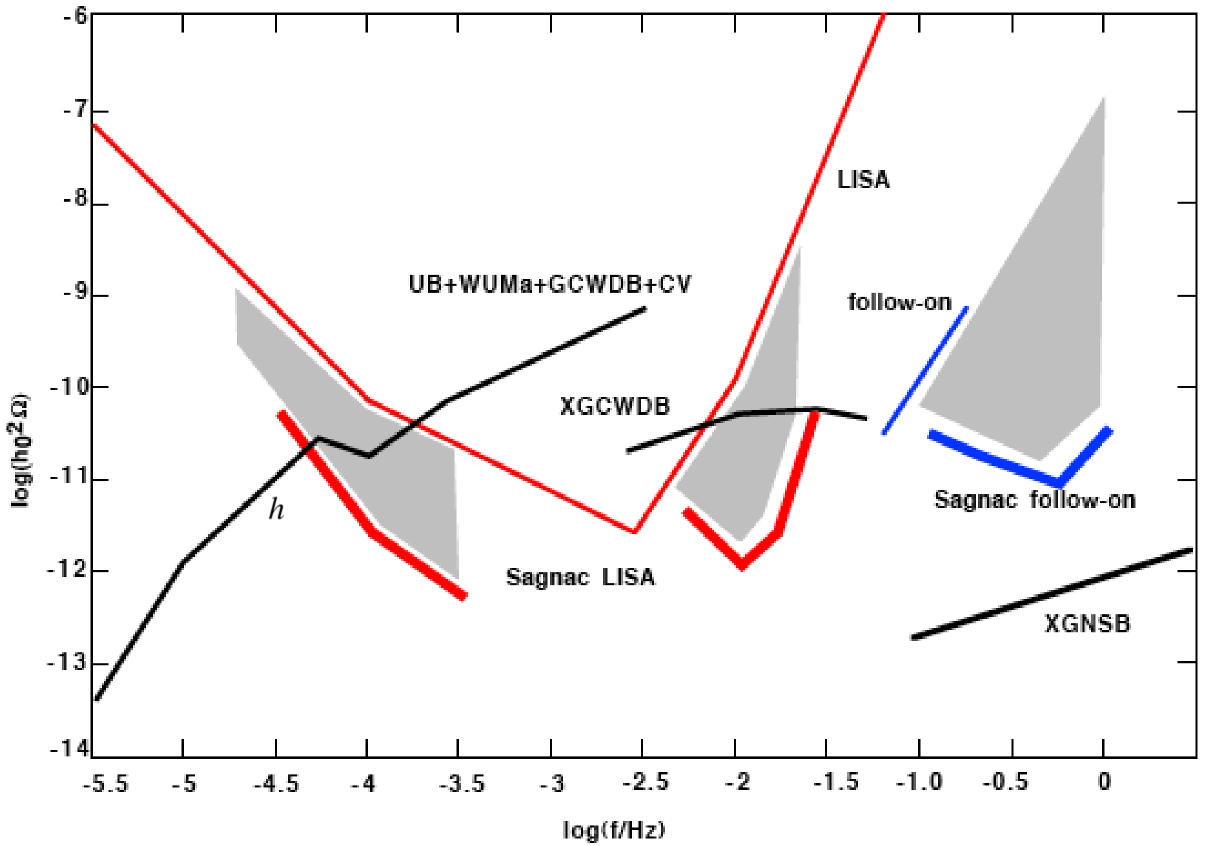
Stochastic GW backgd

LISA can measure a GW stochastic backgd down to

$$h_{100}^2 \Omega_{gw} \sim 10^{-11}$$

However, any Early Universe backgd is ‘covered up’ by our galactic binary foreground, with

$$h_{100}^2 \Omega_{gw} \sim 10^{-10}$$



--from Hogan&Bender, PRD 64 (2001) 062002

GWs from strongly 1st-order electro-weak phase transition

Colliding bubbles produce GWs with $\lambda \sim H^{-1}$, which then get redshifted. GWs produced by an electro-weak phase transition at $kT_* \sim 100\, Gev$ would be in the LISA band today.

The E-W transition is not strongly 1st order in the standard model, but is in some supersymmetric extensions, with $\Omega_{gw} \leq 4 \times 10^{-11}$
(Apreda et al., hep-ph/0102140)

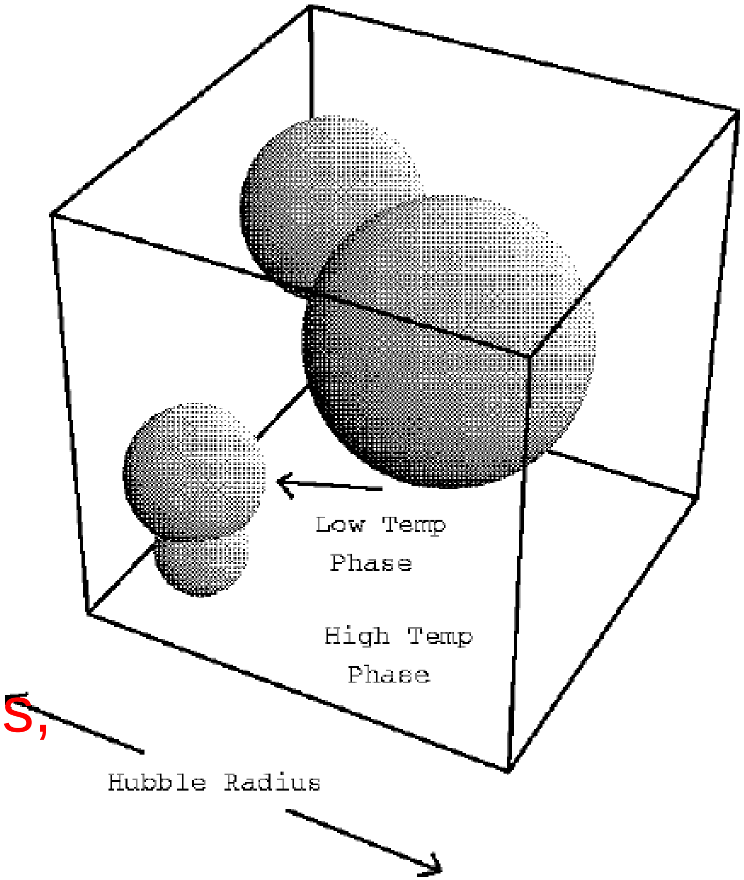
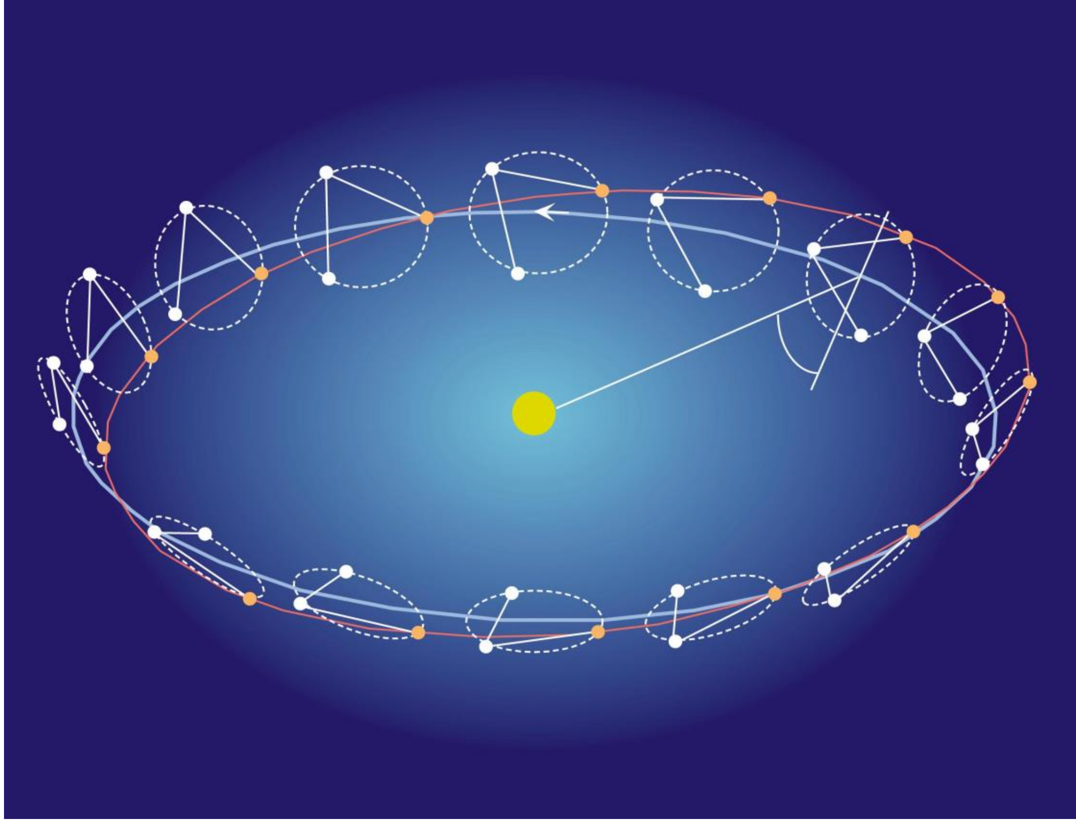


Fig. from B. Allen, gr-qc/9604033

Government sponsorship acknowledged.

extras

➢Like ground-based GW detectors, LISA is an all-sky monitor; all sources appear together in 3 time series X(t), Y(t), Z(t)



➢Unlike ground-based GW detectors, LISA has thousands of guaranteed sources:

- most sources are long-lived; visible for weeks to years
- hence thousands of sources are all ‘on’ at same time
- source positions and polarization are encoded in the signal modulation pattern, due to the motion of the detector

Testing General Relativity w/ EMRIs

BH Uniqueness: all multipole moments of the stationary background spacetime are determined by mass & spin of hole:

$$M_l + iS_l = M\left(i\frac{S}{M}\right)^l$$

- Ryan('95) showed how for a slightly eccentric and slightly non-equatorial orbit, all the multipole moments of the spacetime in principle can be "read off" redundantly from the sweep of the two precession frequencies thru the inspiral.

- Extending this result to orbits with significantly eccentric, non-equatorial orbits is subject of current research.

GW bursts from cusps on cosmic (super-)strings

Gw's beamed along $\dot{x}_0$

$$h(t) \propto |t - t_c|^{1/3}$$

$$\tilde{h}(f) \propto |f|^{-4/3}\,\Theta(f_h - f)\Theta(f - f_l)$$

with $$f_h \approx \frac{2}{L\delta^3}$$

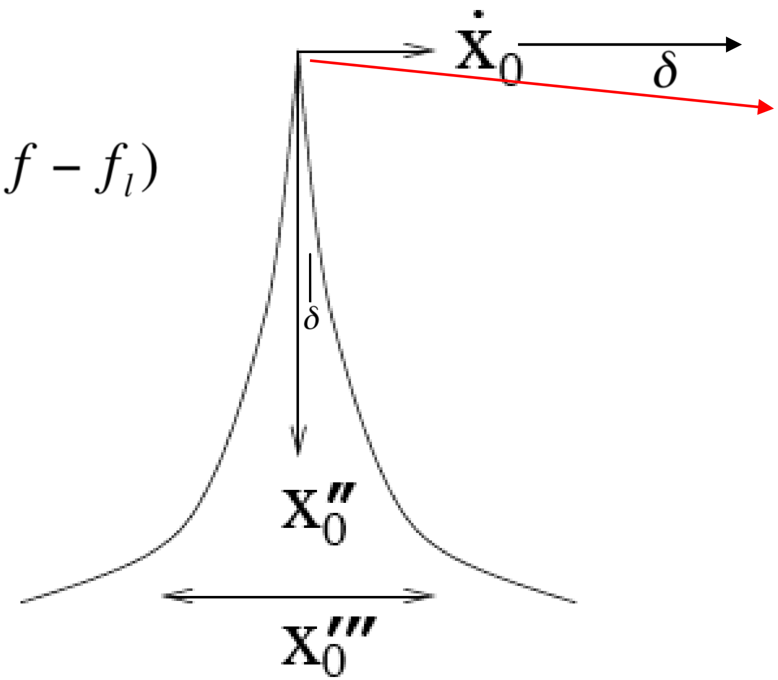
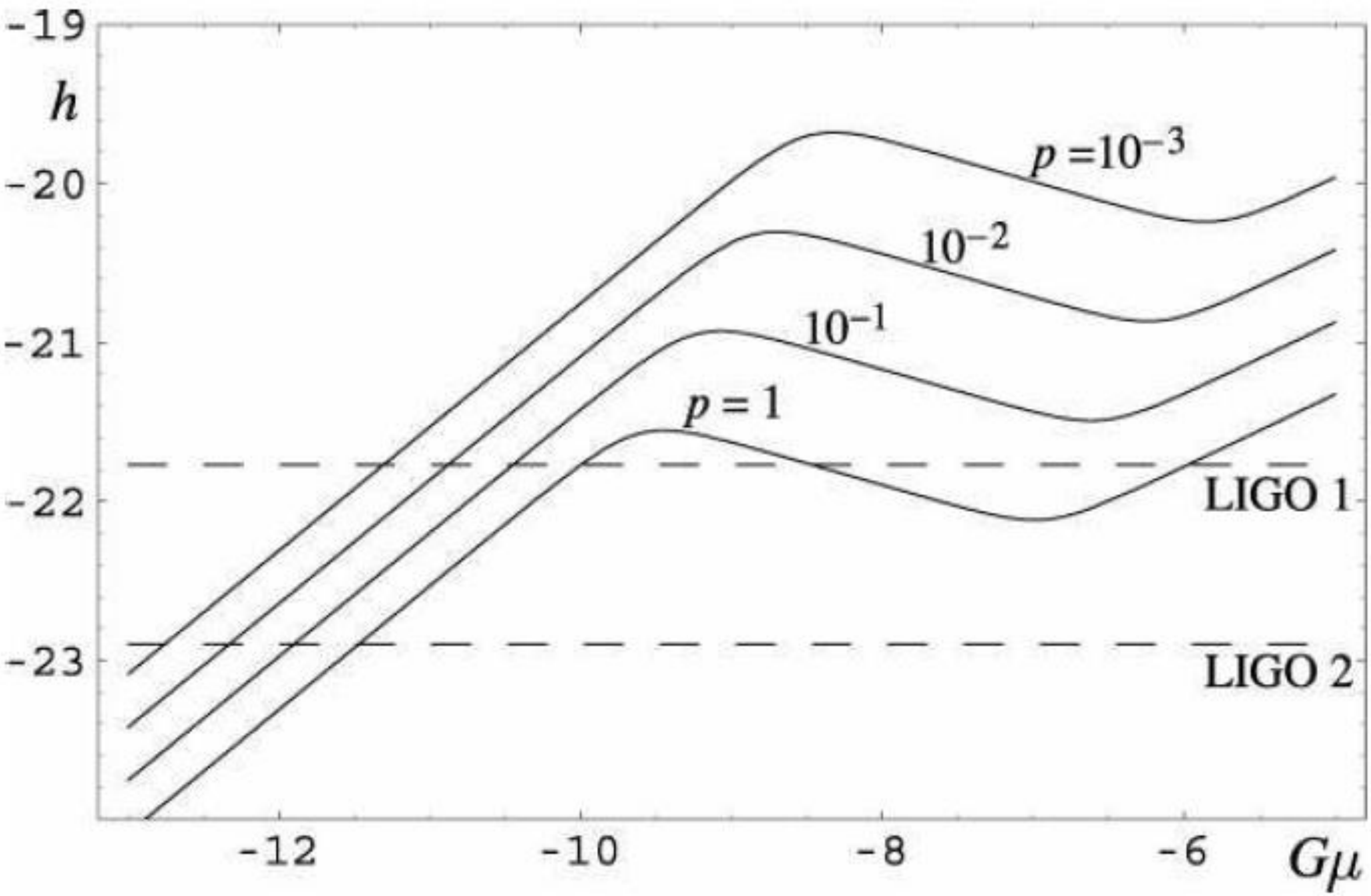


FIG. 1. The parameters of a cusp. The tip moves at the speed of light in the direction $\dot{x}_0$, the direction of the string near the cusp is given by x_0'', and the spreading of the strings is in the direction x_0'''.

-from Blanco-Pillado & Olum, PRD 59 (1999) 063508

STRONGEST BURST IN 1 YR

p = re-connection probability



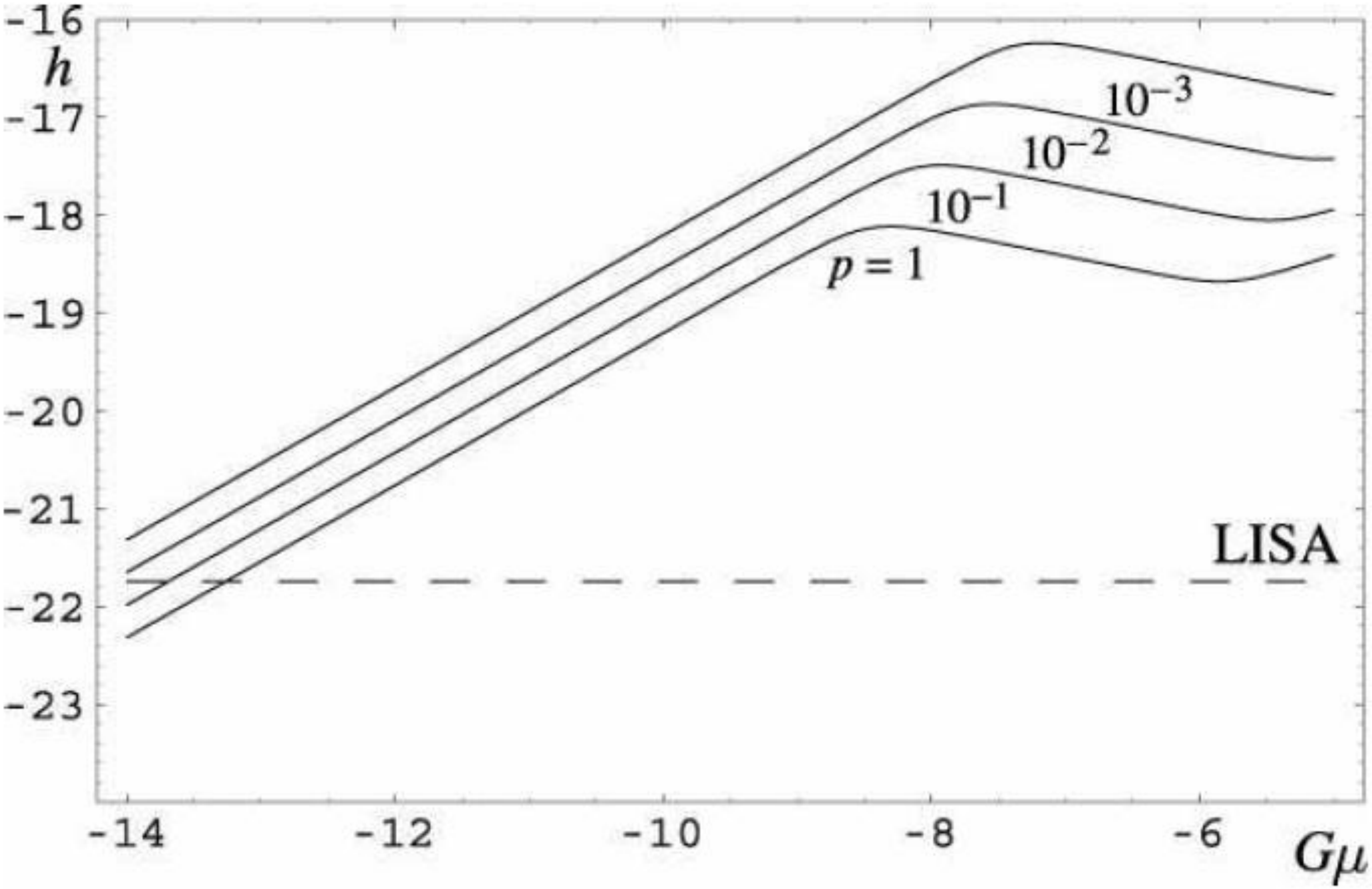
SNR=1

SNR=1

-from Damour &Vilenkin, PRD 71 (2005) 063510

STRONGEST BURST IN 1 YR

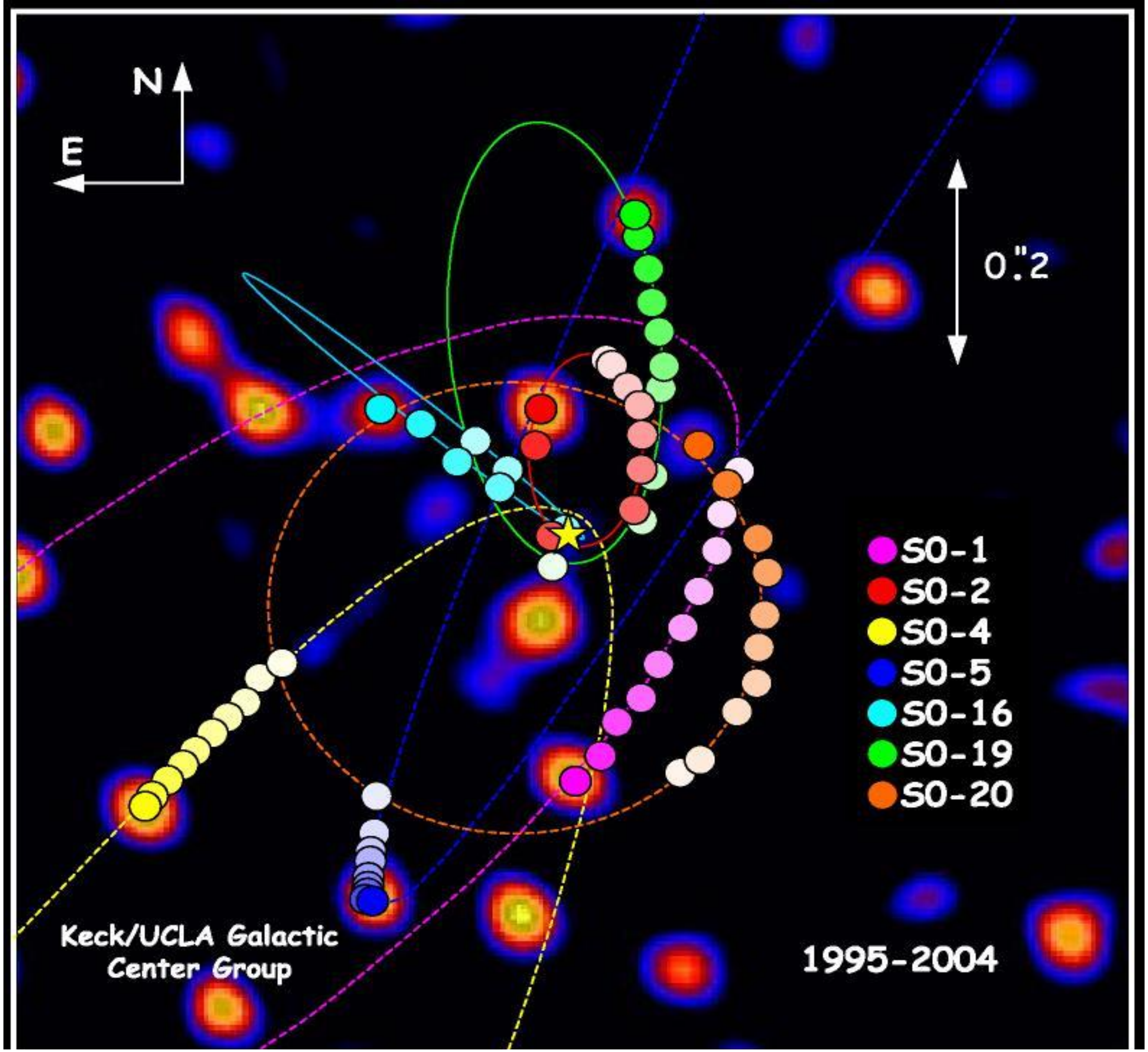
p = re-connection probability



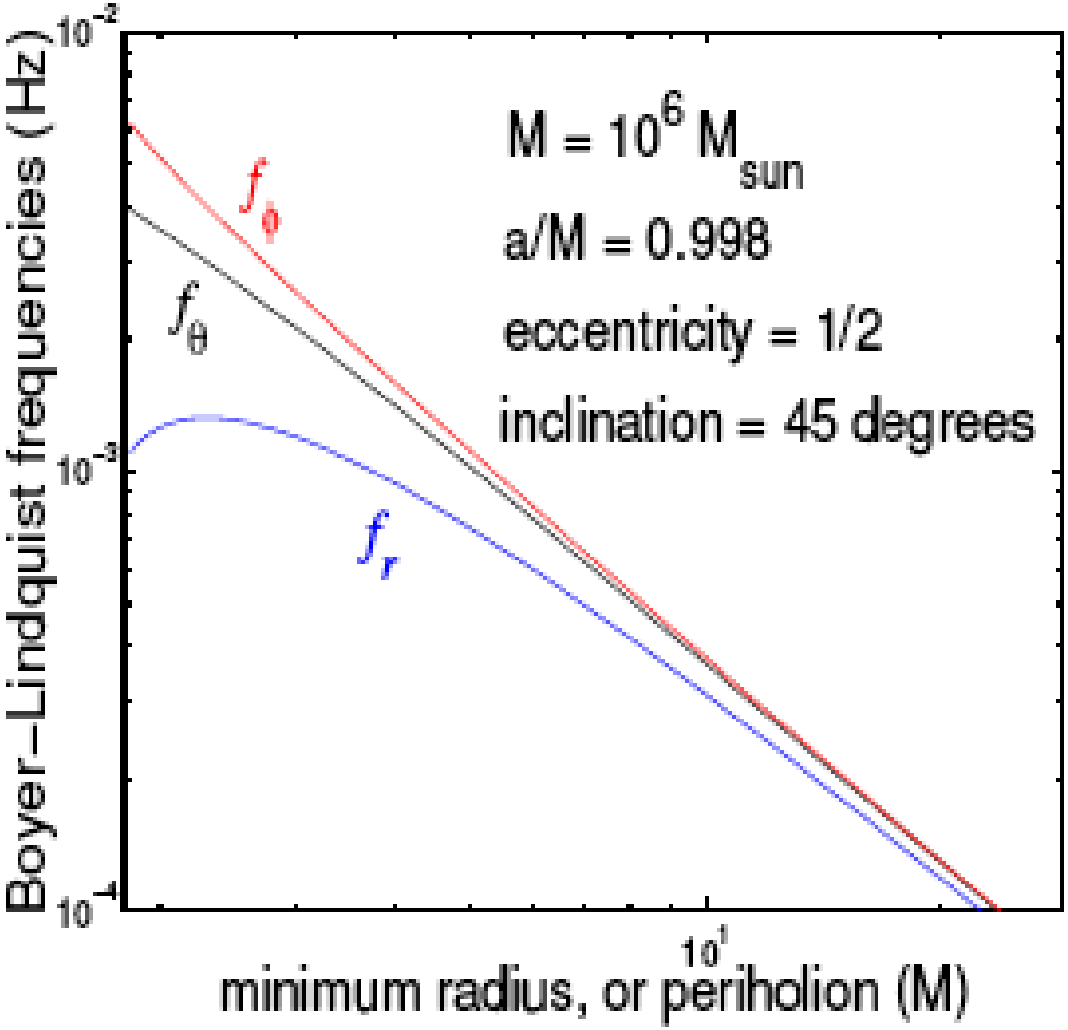
SNR=1

-from Damour &Vilenkin, PRD 71 (2005) 063510

3.7 million solar mass BH at center of Milky Way



Caption:
The orbits of stars within the central 1.0 X 1.0 arcseconds of our Galaxy. In the background, the central portion of a diffract
has been seen to move over the past 9 years, estimates of orbital parameters are only possible for the seven stars that ha
these seven stars are plotted as colored dots, which have increasing color saturation with time. Also plotted are the best fit
yet for a supermassive black hole, which has a mass of 3.7 million times the mass of the Sun.


Boyer–Lindquist frequencies (Hz)
10^-2
10^-3
10^-4
M = 10^6 M_sun
a/M = 0.998
eccentricity = 1/2
inclination = 45 degrees
f_φ
f_θ
f_r
10^1
minimum radius, or periholion (M)