Status of Gravitational-Wave Mission Concept Study

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Astrophysics Subcommittee Meeting

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Outline

- Mission Concept Study
- Context
- RFI Responses
- Assessment of the responses
- Science performance analysis
- Team-X Studies

Goals of the Study

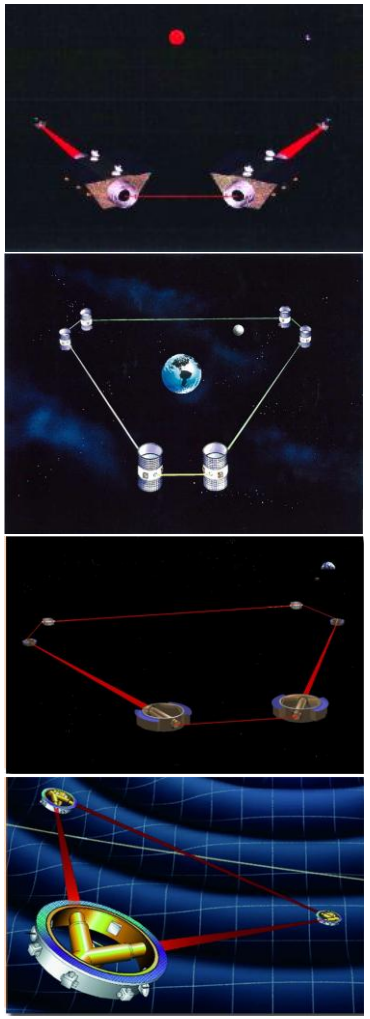
- Develop mission concepts that will accomplish some or all of the LISA science objectives at lower cost points.
- Explore alternative mission architectures and technical solutions (e.g., instrument concepts, enabling technologies).
- Assess the technical readiness and risk of the mission concepts, instruments and technologies.
- Report the options for science return at multiple cost points .

Elements of the Study

- Request for Information (RFI) – due Nov. 10th.
- Core Team – ~25 GSFC, JPL & university scientists and engineers critically reviewing RFI responses
- Science task force – ~15 volunteer scientists evaluating science performance of concepts
- Community Science Team (CST) – 10 scientists
- Public workshop – December 20-21st
- Concurrent engineering studies by JPL's Team-X in March and April
- Final Report to NASA Headquarters – June 6th
- Presentation to the Committee on Astronomy and Astrophysics (CAA) of the National Research Council (NRC)

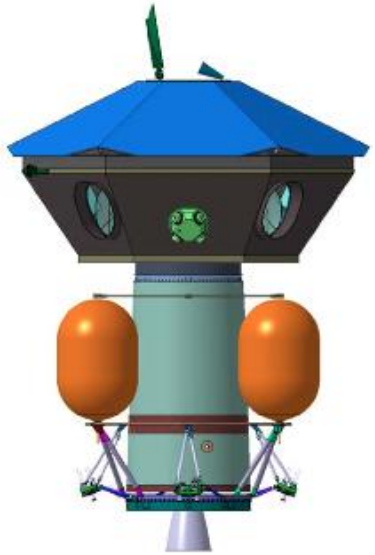
Context of the Study – A Brief History of LISA

- 1974 - A dinner conversation: Weiss, Bender, Misner and Pound
- 1985 – LAGOS Concept (Faller, Bender, Hall, Hils and Vincent)
- 1993 – LISAG - ESA M3 study: six S/C LISA & Sagittarius
- 1997 - JPL Team-X Study: 3 S/C LISA
- 2001-2015 - LISA Pathfinder and ST-7 DRS
- 2001 – NASA/ESA project began
- 2003 – TRIP Review
- 2005 – GSFC AETD Review
- 2007 – NRC BEPAC Review
- 2009 – Astro2010 Review
- 2011 – NASA/ESA partnership ended
- 2011 – Next Generation Gravitational-Wave Observatory (NGO) started



Context of the Study – Activities in Europe

- LISA Pathfinder
  - Demonstration of space-based GW technology, in late stages of I&T
  - 2014 launch
- Technology development
  - Inertial sensor electronics, charge control
  - Optical system
  - Laser system
  - Pointing and point-ahead mechanisms
- NGO
  - Candidate for ESA's Cosmic Visions L1, decision April 25th, before the end of the Study!



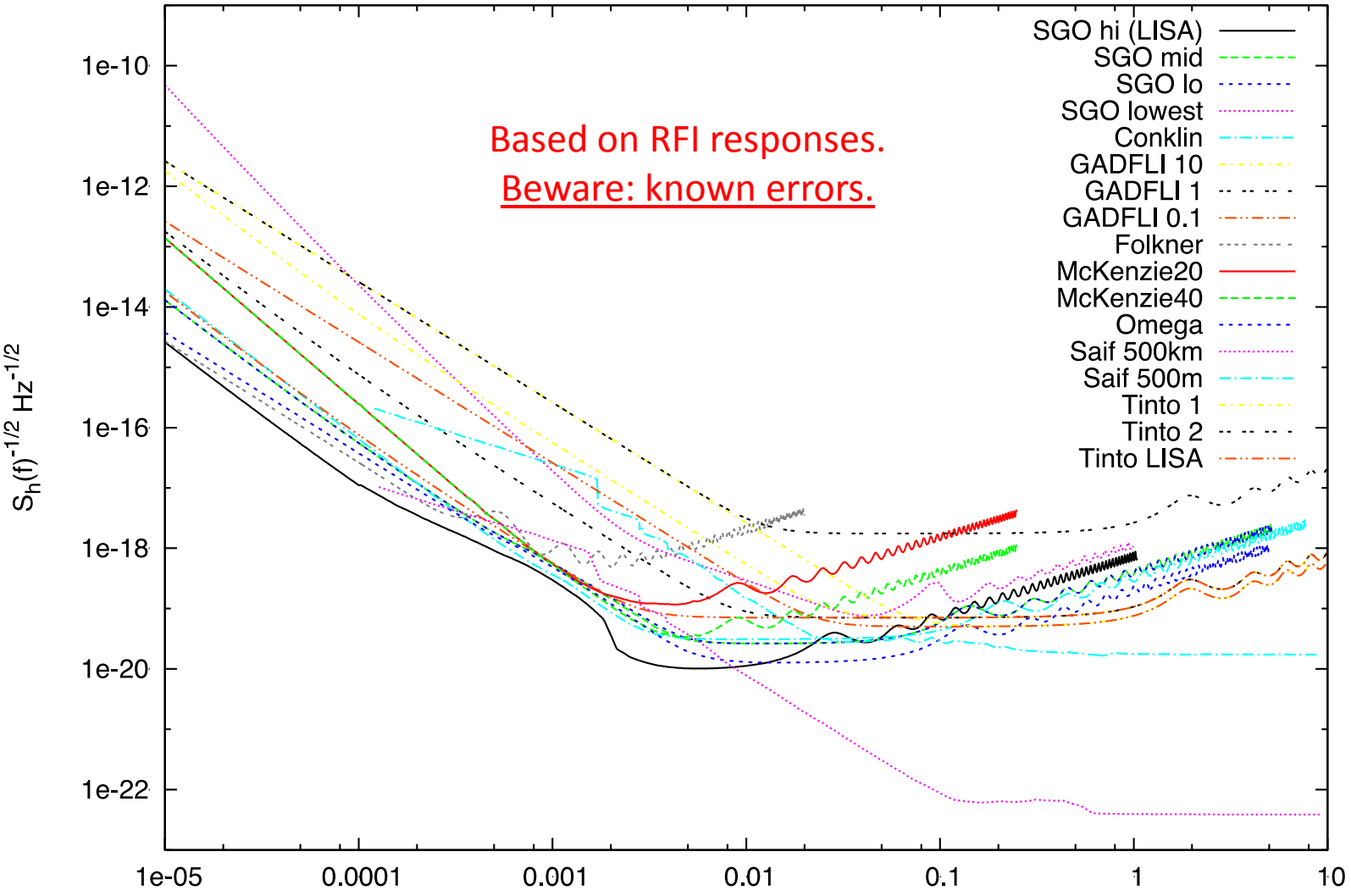
RFI Responses

- 17 responses total
  - 12 for mission concepts
  - 3 for instrument concepts
  - 2 for technologies
- Four natural groups
  - No drag-free concepts (2)
  - Geocentric orbits (4)
  - LISA-like (5)
  - Other (2)

What constitutes “LISA-like?”

- Drag-free control
  - Free-falling test mass
  - Precision stationkeeping
- Continuous laser ranging
- Heliocentric orbits
  - Constellation in stable equilateral triangle
  - No orbital maintenance
- Million-kilometer arms
- Laser frequency noise subtraction (TDI)
  - Michelson’s white-light fringe condition through post-processing

Science Performance



No-Drag-Free Concepts

Group	Group 1 (No drag-free)	
Proposal Number	**3**	**16**
Lead Author	**Folkner**	**McKenzie**
Acronym		**LAGRANGE**
Novel Idea	Long baseline, no drag-free	No drag-free, geometric reduction
Proposal Type	Concept	Concept
Number of Alternates	2	2
Arm length (km)	2.6×10^{8}	2.09×10^{7}
Spacecraft/Constellation	3/equilateral triangle //4/square	3/isosceles triangle
Orbit	Heliocentric	Heliocentric/ Earth-Sun L2
Trajectory	Not specified beyond HEO parking, double lunar assist. Solar electric propulsion mentioned.	Direct escape to L2, "drift" of SC1/3 to 8° leading/trailing
Inertial Reference	None	GOCE accelerometer
Displacement Measurement	3 arms, 6 links	2 arms, 4 links
Launch vehicle		Falcon 9 Block 3
Baseline/Extended Mission Duration	3 arms, 6 links	2
Telescope Diameter (cm)	30	20/40
Laser power out of telescope, EOL (W)	1	1.2
Sensitivity curve	Yes	Yes
Residual acceleration ($m/s^2/Hz^{1/2}$)	1.0×10^{-13}	4.4×10^{-14} (0.001/f)^0.75
Displacement sensitivity ($m/Hz^{1/2}$)	550×10^{-12}	150×10^{-12}

No-Drag-Free Concept Issues

- Misunderstanding about S/N ratio
- Inconsistent representation of noise sources
- Critical considerations
  - Rely on either very long arms (50X LISA) or geometry (100X reduction) to compensate for using the spacecraft as the test mass.
  - Disturbances are solar radiation pressure variability, solar wind, interplanetary magnetic field
  - Measure, model and remove spurious forces (10^2 - 10^4 X)
  - LISA test masses achieve $3x10^{-15}$ $m/s^2/\sqrt{Hz}$ residual acceleration 0.1-10 mHz
  - Displacement noise from motions of the spacecraft CG, owing to, say, thermoelastic effects

Geocentric Concepts

Group	Group 2 (Geocentric)			
Proposal Number	**4**	**17**	**7**	**10**
Lead Author	**Tinto**	**McWilliams**	**Hellings**	**Conklin**
Acronym	**GEOGRAWI**	**GADFLI**	**OMEGA**	**LAGRANGE**
Novel Idea	Geocentric orbit, single spherical TM	Smaller telescope and laser, smaller satellites	Novel trajectories, Explorer cost approach	Earth-Moon Lagrange points, spherical test mass, grating
Proposal Type	Concept	Concept	Concept	Concept
Number of Alternates	3	3	1	1
Arm length (km)	7.3×10^{4}	7.3×10^{4}	1.04×10^{6}	6.7×10^{5}
Spacecraft/Constellation	3/equilateral triangle	3/equilateral triangle	6/triangle	3/equilateral triangle
Orbit	Geostationary	Equatorial, geostationary	600,000 km geocentric, earth-moon plane (retrograde)	Earth-Moon L3, L4, L5
Trajectory	Not specified	Direct launch together to geostationary, re-phase 2 S/C	Butterfly trajectories to Weak Stability Boundary, 384 days total	Either: direct to WSB, return and lunar fly-by; direct to Trans Lunar Injection, return and lunar fly-by
Inertial Reference	Single, spherical	Two, rectangular	Single, rectangular	Single, spherical
Displacement Measurement	3 arms, 6 links	3 arms, 6 links		
Launch vehicle		Falcon 9 Block 2	Small Delta or Falcon 9	Falcon 9
Baseline/Extended Mission Duration		2	3	5
Telescope Diameter (cm)	Same as LISA	15	30	20
Laser power out of telescope, EOL (W)	Same as LISA	0.7	0.7	1
Sensitivity curve	Yes	Yes	Yes	Yes
Residual acceleration ($m/s^2/Hz^{1/2}$)	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}
Displacement sensitivity ($m/Hz^{1/2}$)	7×10^{-12}	8×10^{-12}	5×10^{-12}	5×10^{-12}

Geocentric Concept Issues

- Inconsistent treatment of noise
- Some technical issues
  - Less benign thermal environment
  - Sun in the telescope
- A big cost issue: can you do this for a factor of 4 less by employing nanosat technology, lower reliability standards, standard bus, a different way of doing business, …

LISA-like Concepts

Group	Group 3 (LISA-like)				
Proposal Number	**11**	**14**	**15**	**12**	**13**
Lead Author	**Shao**	**Stebbins**	**Livas**	**Thorpe**	**Baker**
Acronym		**SGO High**	**SGO Mid**	**SGO Low**	**SGO Lowest**
Novel Idea	Formation-flying payload, torsion suspension for test mass	LISA with all known cost savings	Smallest LISA-like design with 6 links	Smallest LISA-like design with 4 links	Smallest in-line LISA-like design with 4 links
Proposal Type	Instrument	Concept	Concept	Concept	Concept
Number of Alternates	1	1	1	1	1
Arm length (km)	5.0×10^6	5.0×10^6	1.0×10^6	1.0×10^6	2.0×10^6
Spacecraft/Constellation	3+3/triangle	3/equilateral triangle	3/equilateral triangle	4/triangle (60-deg Vee)	3/In-line: Folded SyZyGy
Orbit	LISA-like	22° heliocentric, earth-trailing	9° heliocentric, earth drift-away	9° heliocentric, earth drift-away	≤9° heliocentric, earth drift-away
Trajectory		Direct injection to escape with recircularization and out-of-plane boost, 14 months	Direct injection to escape with out-of-plane boost, 21 months	Direct injection to drift away, with out-of-plane boosts, 21 months	Direct injection to escape, with small delta-v for S/C separation, 18 months
Inertial Reference	Single, torsion pendulum	Two, rectangular	Two, rectangular	Single, rectangular	Single, rectangular
Displacement Measurement		3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links
Launch vehicle	Falcon 9	Shared Falcon Heavy	Falcon 9 Block 3	Shared Falcon 9 Heavy	Falcon 9 Block 2
Baseline/Extended Mission Duration	5	5/3.5	2/2	2/2	2/0
Telescope Diameter (cm)		40	25	25	25
Laser power out of telescope, EOL (W)		1.2	0.7	0.7	0.7
Sensitivity curve	No	Yes	Yes	Yes	Yes
Residual acceleration ($m/s^2/Hz^{1/2}$)		3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}
Displacement sensitivity ($m/Hz^{1/2}$)		8×10^{-12}	8×10^{-12}	8×10^{-12}	8×10^{-12}

LISA-like Concept Issues

- How far can the LISA architecture be descoped?
- No technical or performance issues
- Science performance falls off much faster than cost
- Found the bottom!

Other Concepts

Group	Group 4 (Other)			Instrument Concepts/Technologies
Proposal Number	**5**	**8**	**9**	**6**
Lead Author	**Saif**	**Yu**	**Gulian**	**de Vine**
Acronym	**InSpRL**			
Novel Idea	Atom interferometry	Atom inteferometer for inertial sensor	Electrons in superconductor	Replace optical bench with photonic integrated circuit
Proposal Type	Concept	Instrument	Concept	Instrument
Number of Alternates	2			
Arm length (km)	0.5/500			
Spacecraft/Constellation	1//2/in-line		1	
Orbit	1200 km above geostationary	LISA-like	Not specified.	Comparable to LISA
Trajectory	Not specified	LISA-like	Not specified	
Inertial Reference	Atom interferometers			
Displacement Measurement				
Launch vehicle	Falcon			
Baseline/Extended Mission Duration				
Telescope Diameter (cm)				
Laser power out of telescope, EOL (W)	10-20			
Sensitivity curve	Yes			Comparable to LISA
Residual acceleration ($m/s^2/Hz^{1/2}$)				
Displacement sensitivity ($m/Hz^{1/2}$)				5×10^{-12}

Other Concept Issues

- The superconductor idea doesn't work.
- Atom Interferometry
  - Atoms clouds as test masses
  - Atom interferometer as a phasemeter
- InSpRL
  - Most aggressive proposal, overlooked laser frequency noise
  - Lacks enough definition to evaluate
  - Seems to require a few orders of magnitude improvement in several key performance parameters
- Yu proposal doesn't promise to be cheaper.
- Digital Interferometry is interesting.

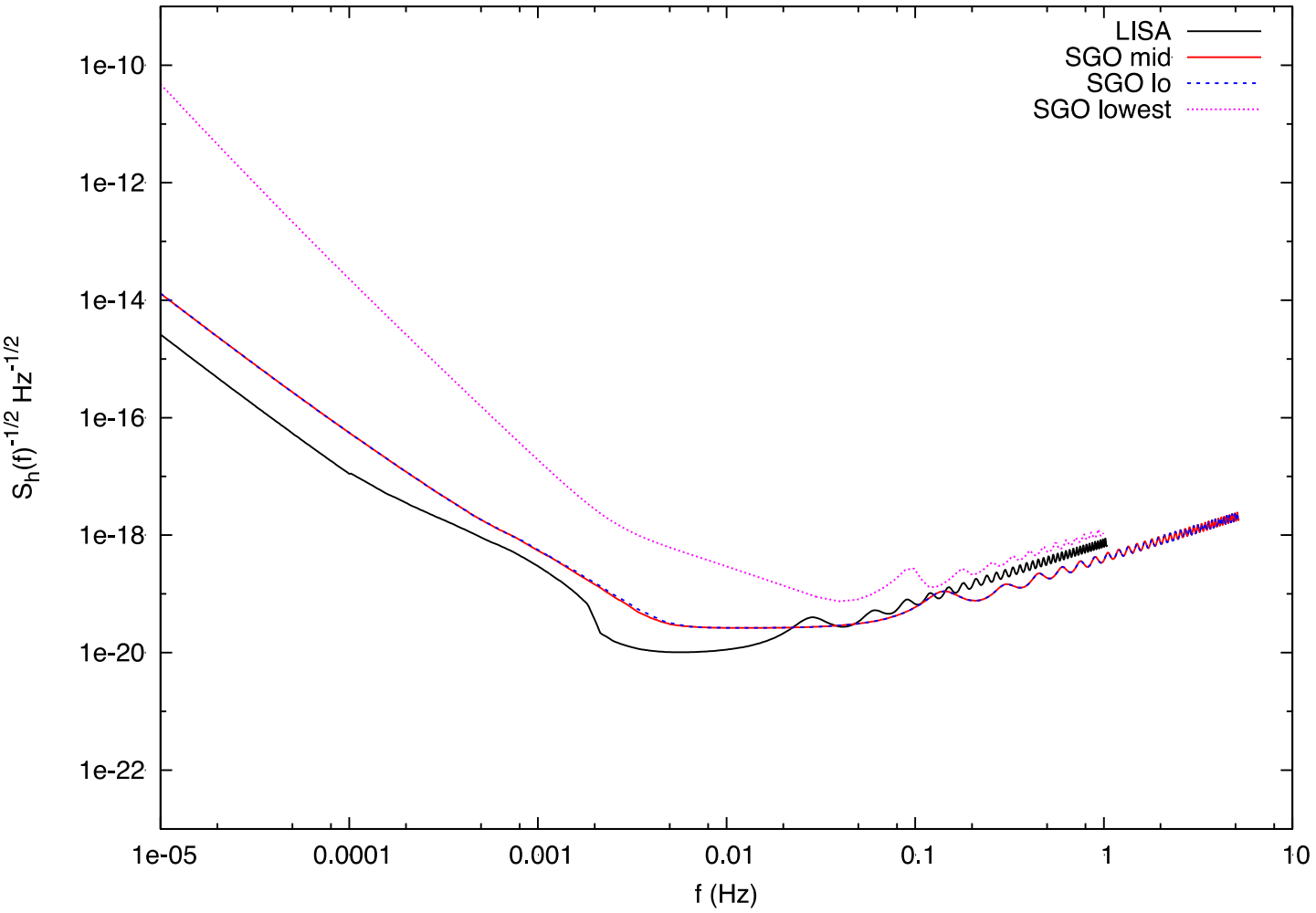
Astro2010 Endorsed LISA Science

- "Astro2010 endorsed LISA science" comes from NWNH and the Panel reports
- Origin and evolution of massive black hole binaries
- Galactic dynamics from extreme-mass-ratio inspirals (EMRIs) – stellar mass objects falling into central engines
- Galactic structure and stellar evolution from compact binaries
- Testing relativity with EMRIs
- Discovery of unanticipated sources, e.g., cosmological backgrounds, cosmic strings, etc.

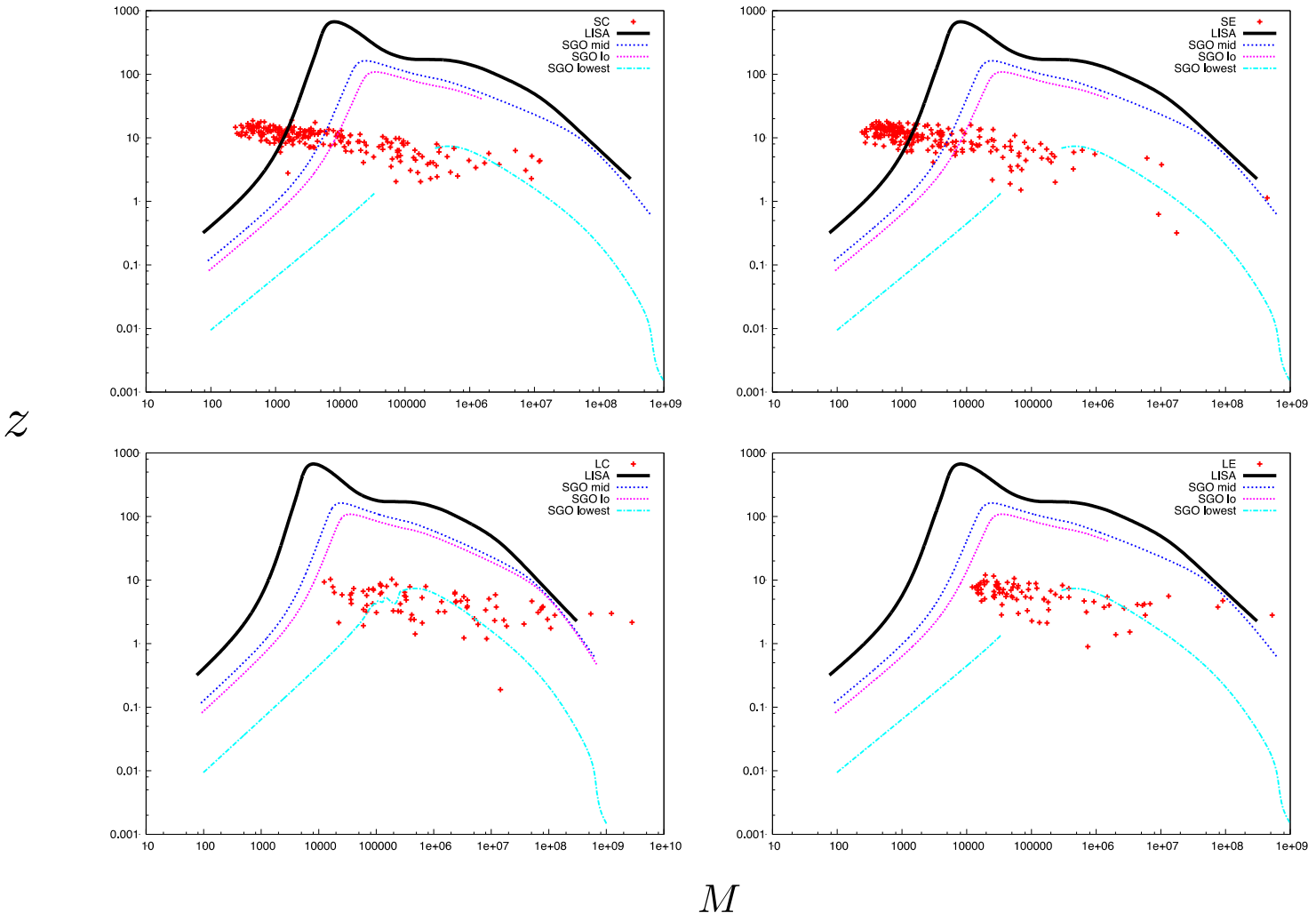
Science Performance

- The GW community can predict science performance from sensitivity curves.
- Plan
  - First use submitted sensitivity curves, then use corrected/complete sensitivity curves
  - Preliminary assessment of horizons with fiducial systems, rates/numbers
  - Estimate the accuracy of astrophysical parameters (masses, spins, luminosity distances, sky location, …) for representative populations
- Preliminary assessment
  - Horizons and rates with submitted sensitivity curves
  - Some parameter estimation on no-drag-free concepts
- Warning: The following 9 slides are preliminary results with known problems. They are only illustrative of the analysis in progress.

Sensitivity Curves – LISA-like Group

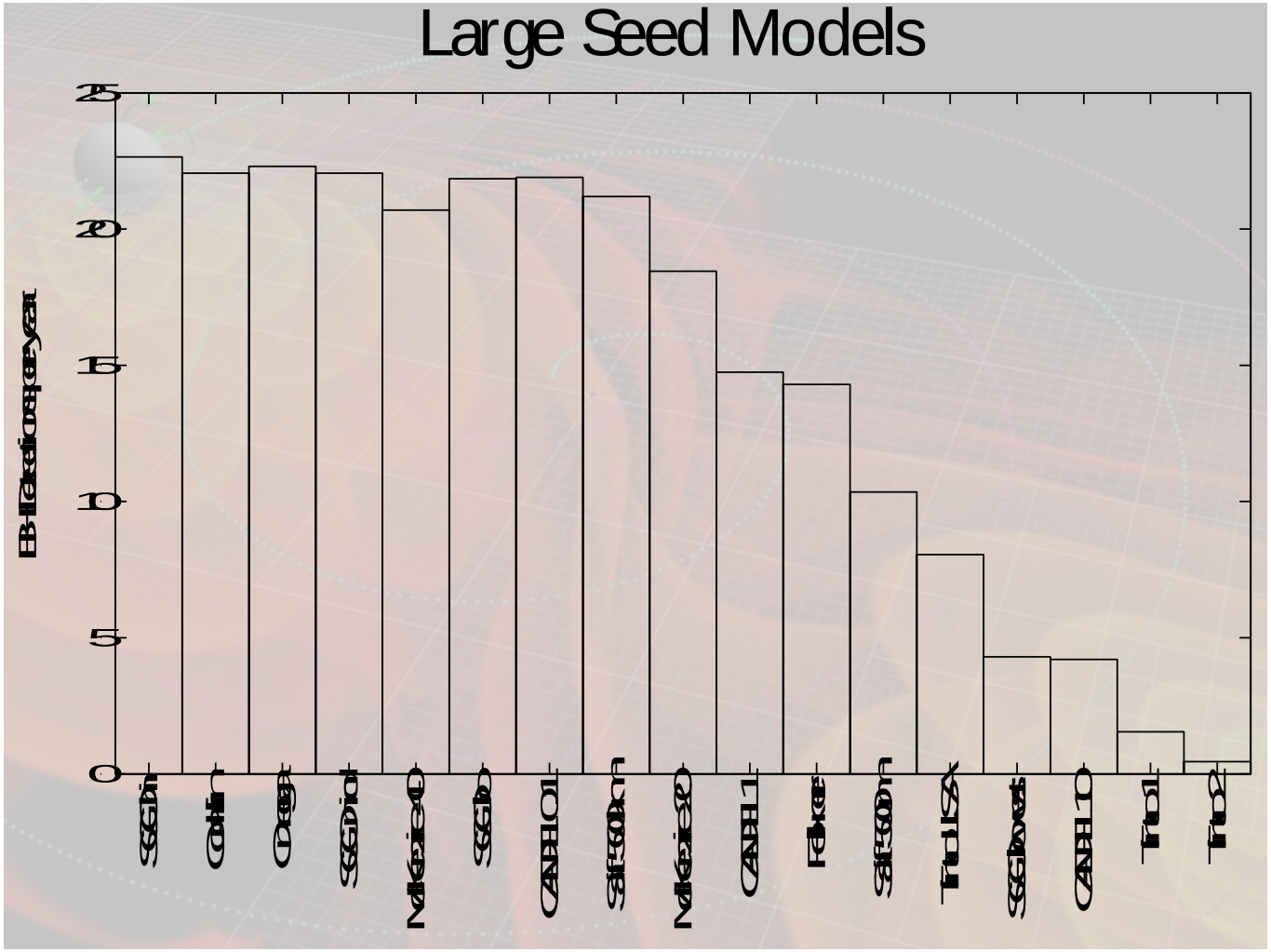


Massive Black Hole Horizons – Group 3

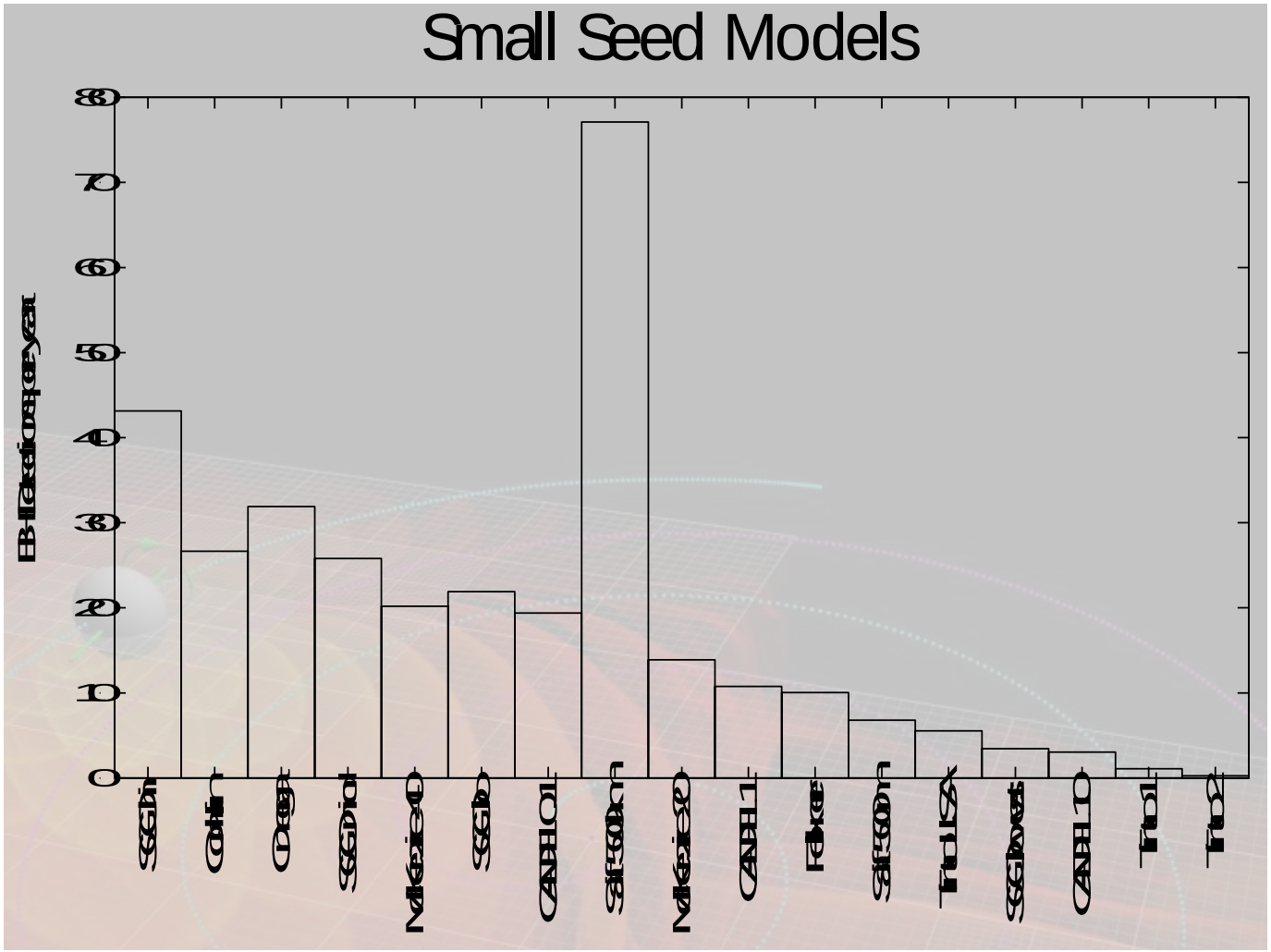


Fiducial system: mass ratio 3:1, spin 0.5/0.5, inspiral-merger-ringdown, SNR 10 threshold

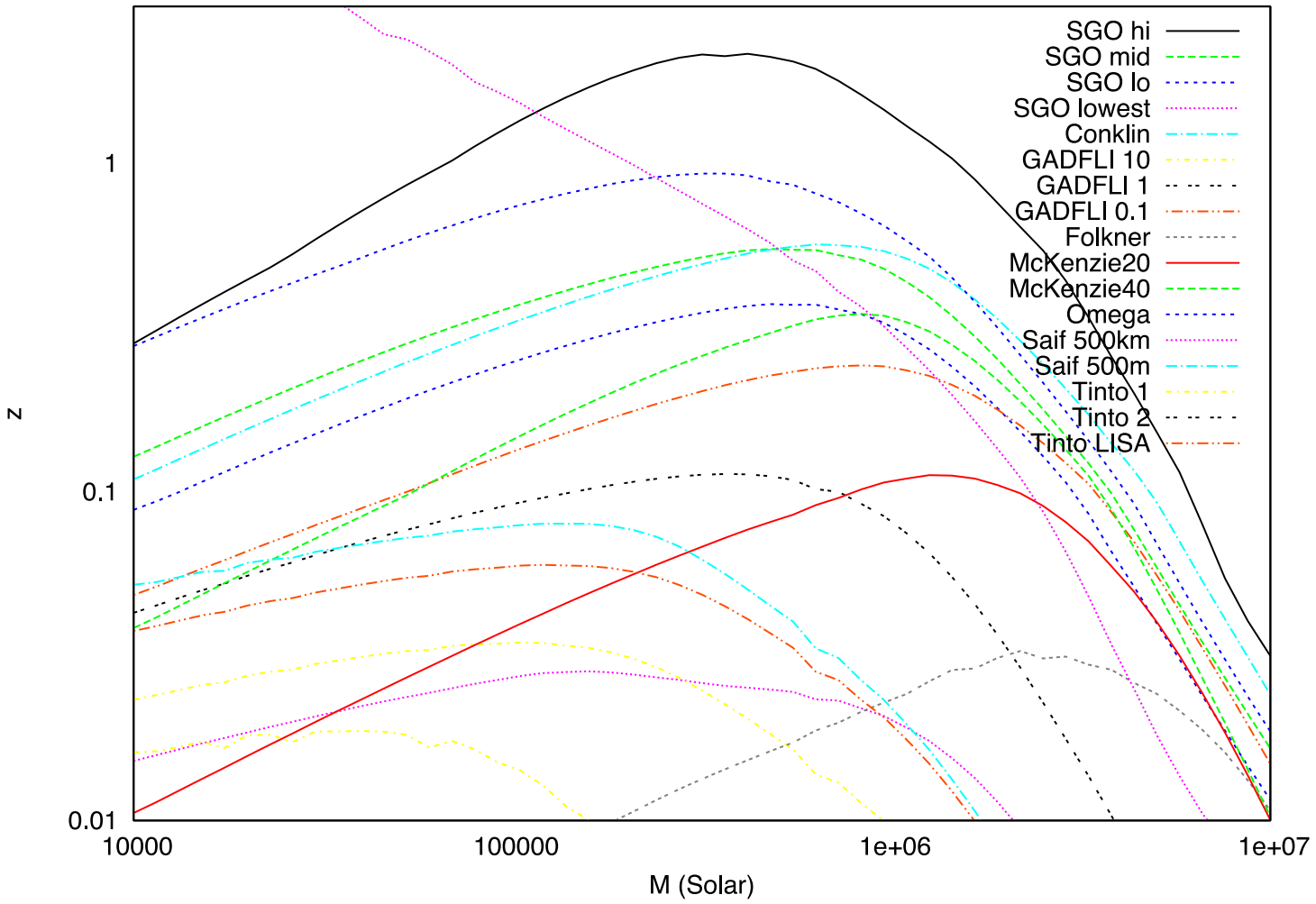
Detection Rates (/yr)



Detection Rates (/yr)

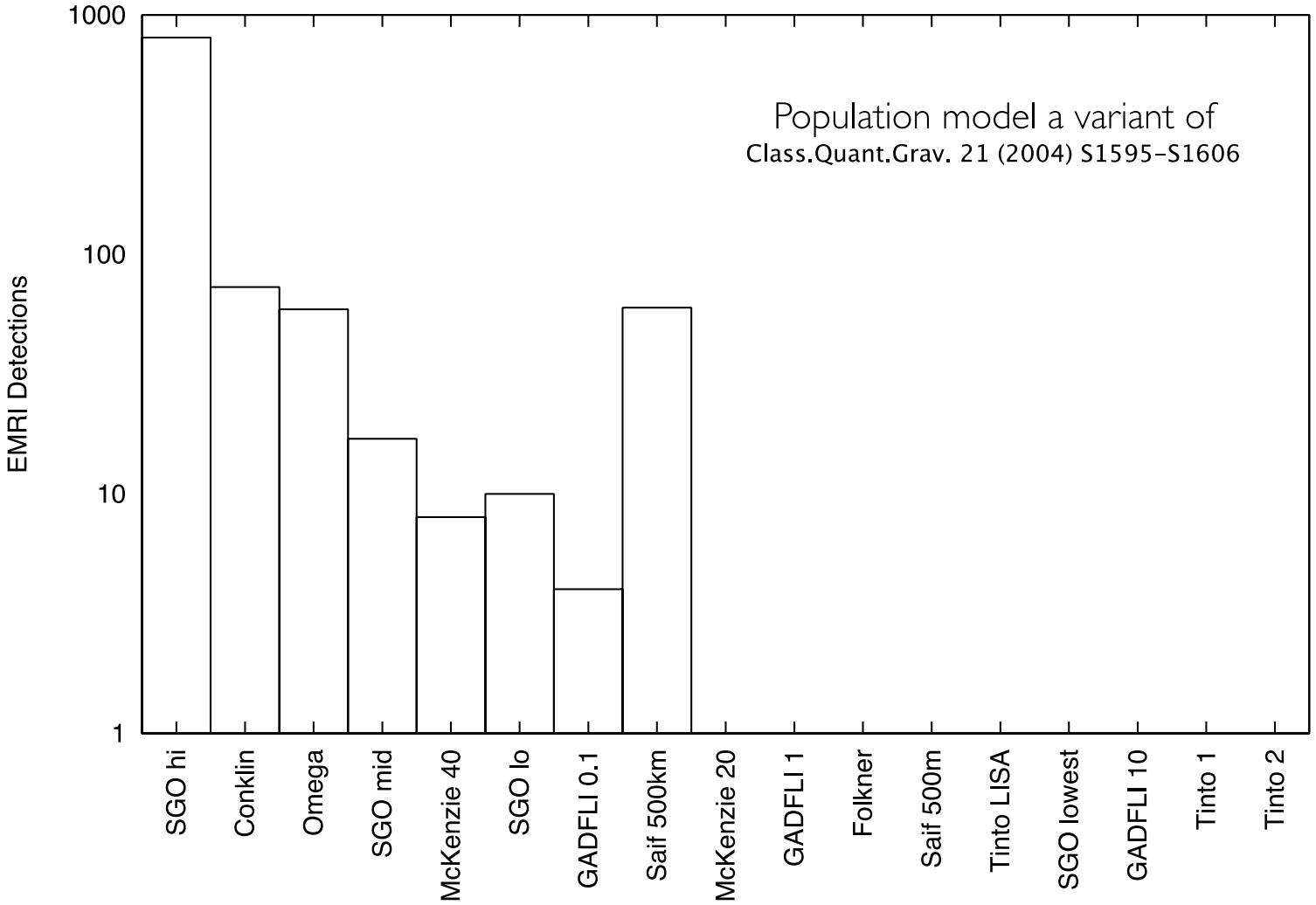


EMRI Horizons

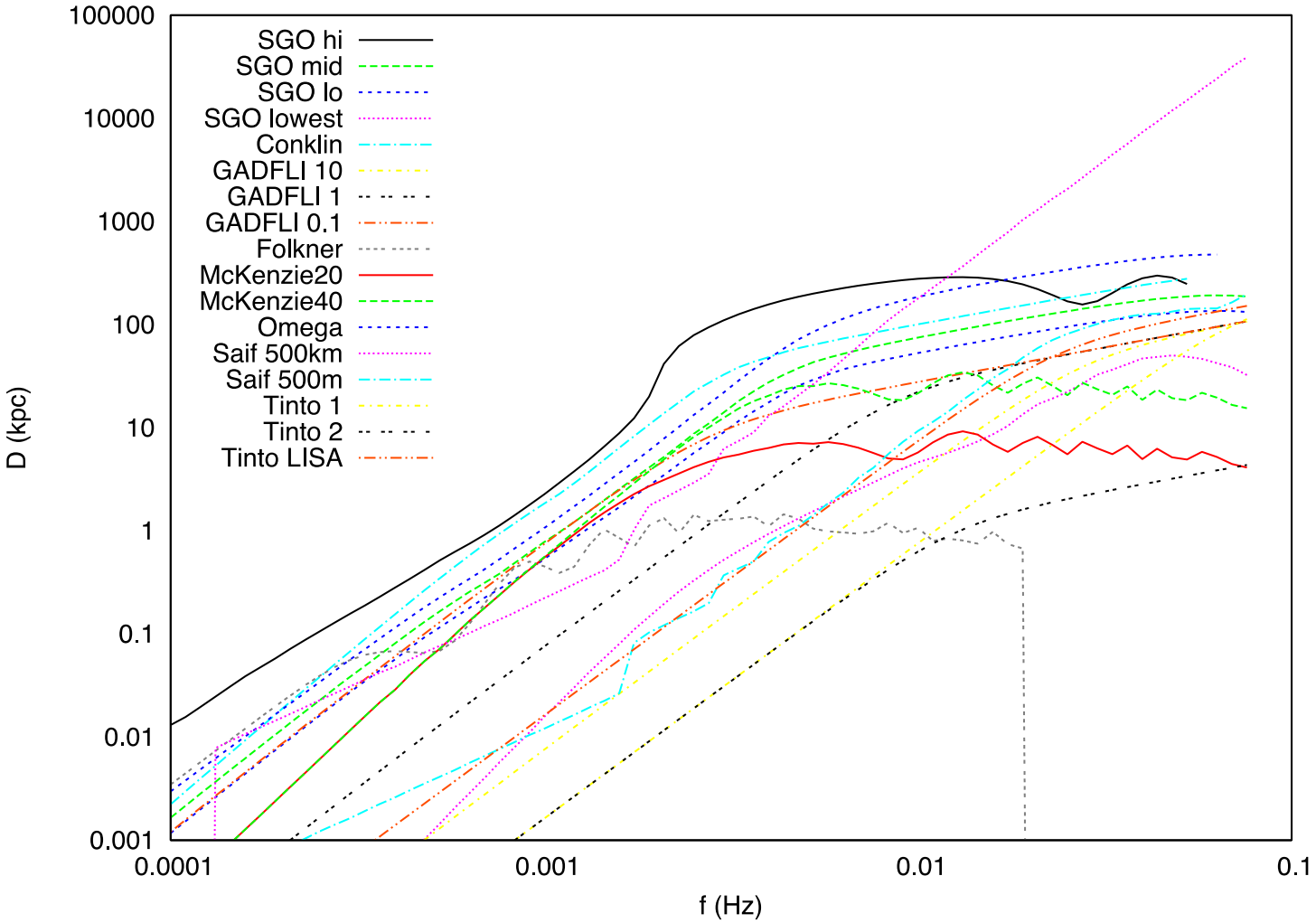


10 $M_{\odot}$ compact object, eccentricity 0.5 at 2 yrs to plunge, spin 0.5 central BH, SNR=15

EMRI Detections

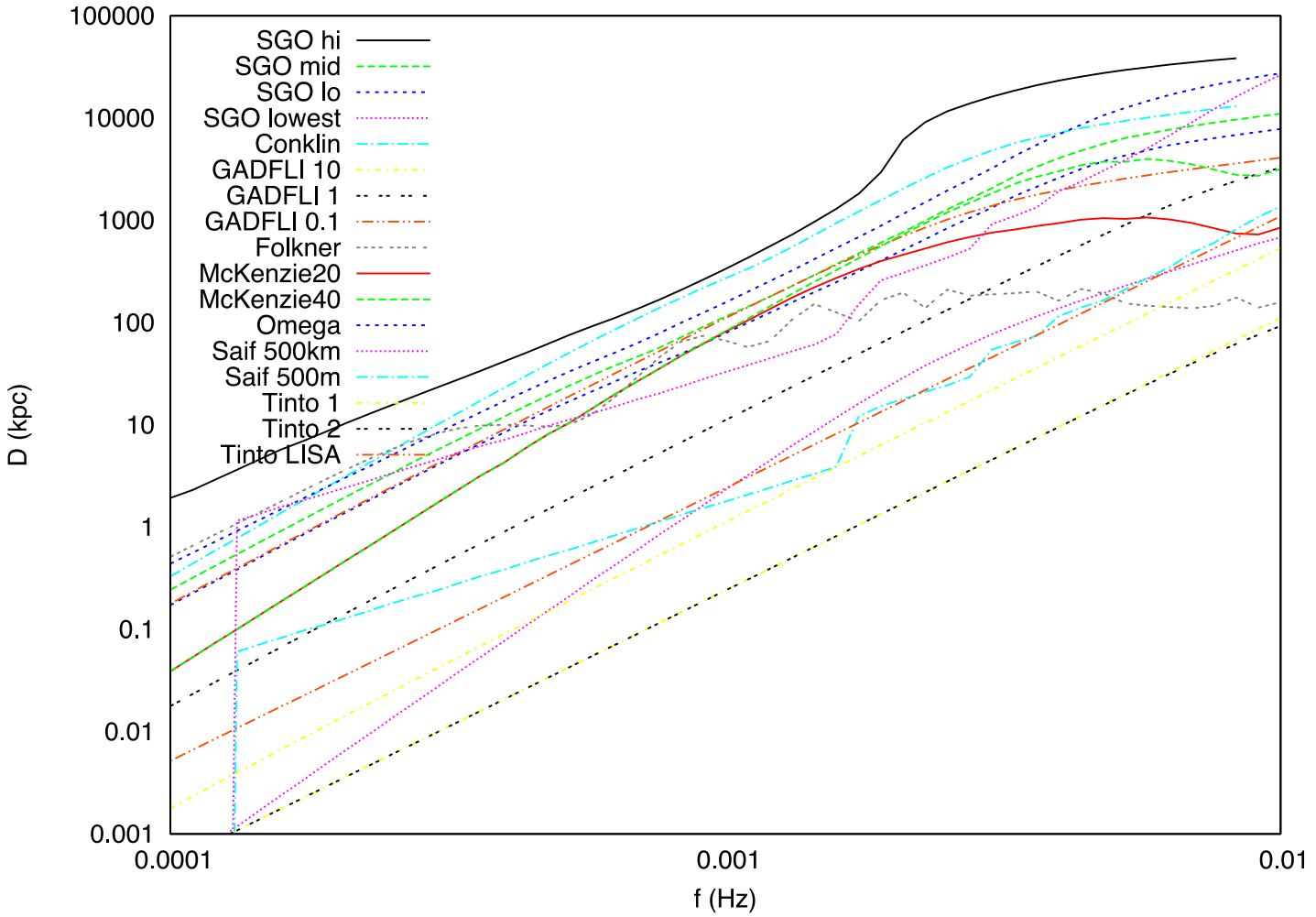


WD-WD Horizons



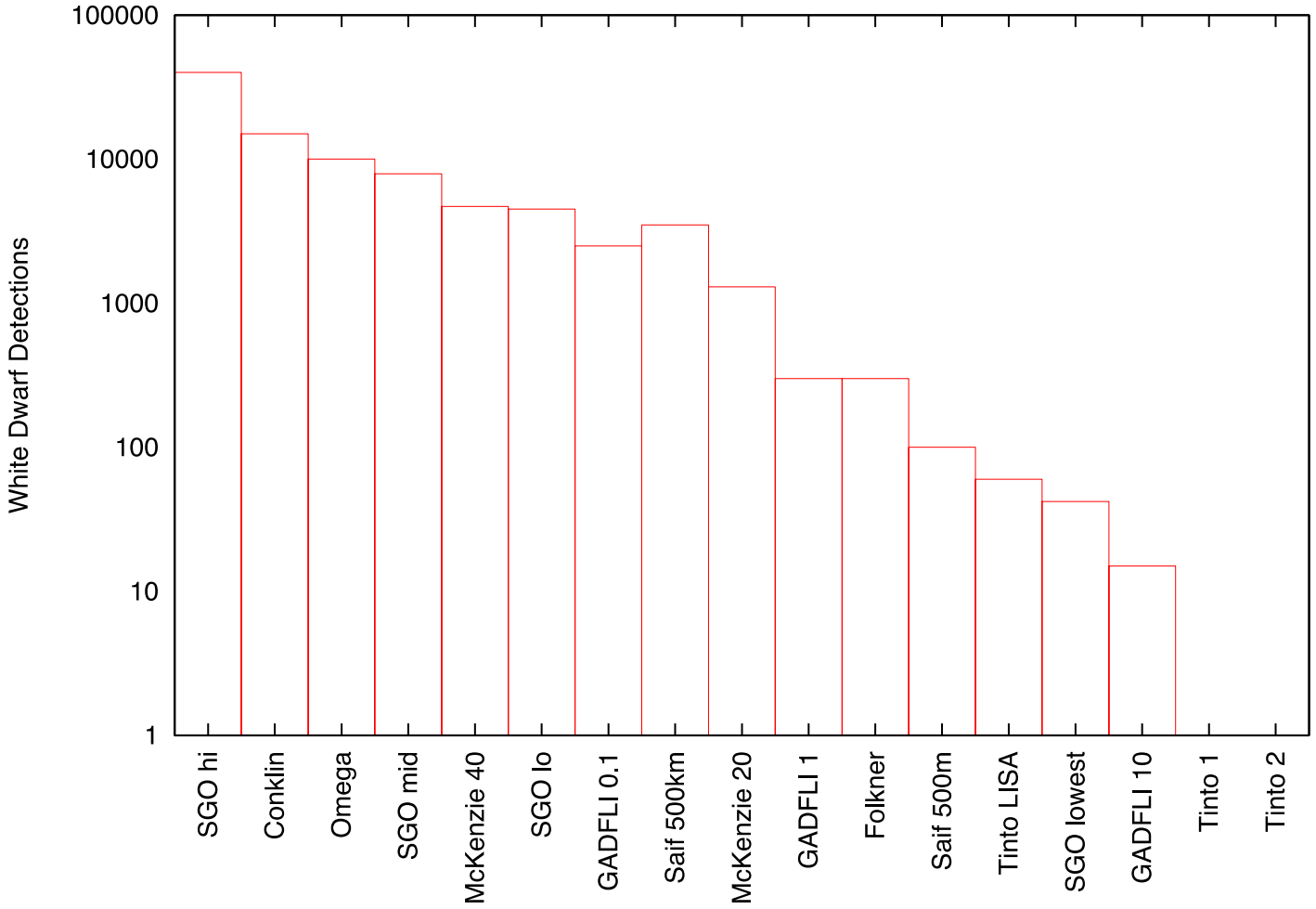
0.5/0.5 $M_{\odot}$ white dwarf binary, SNR=7 threshold

BH-BH Horizons



10/10 $M_{\odot}$ stellar black hole binary, SNR=7 threshold

WD-WD Detections



Planned Team-X Studies

- LISA-like: SGO Mid (March 5-8)
  - Cost basis for common subsystems
  - Single agency costing, low cost launch vehicles
- No-drag free: LAGRANGE (March 20-22)
  - Eliminates the most science equipment possible
  - Significant uncertainties about showstoppers!
- Low-cost instrument: OMEGA (March 27-29)
  - Could grow by factor of 2-3, and still be interesting
- Low-cost mission concept: OMEGA (April 3-5)
  - Tests a different cost basis

Summary

- The community has been canvassed for alternative mission concepts through an RFI and a workshop.
- RFI responses include:
  - Previously offered concepts (scaled down LISA, vee instead of a triangle, geocentric rather than heliocentric, atom interferometry, six spacecraft, etc.)
  - Two novel no-drag-free concepts
- Responses have been examined and technical issues are being studied.
- A preliminary science analysis has been conducted to identify what science each concept might produce
- Three concepts have been selected for Team-X study