Detection of EMRIs with LISA – algorithms, rates and template requirements

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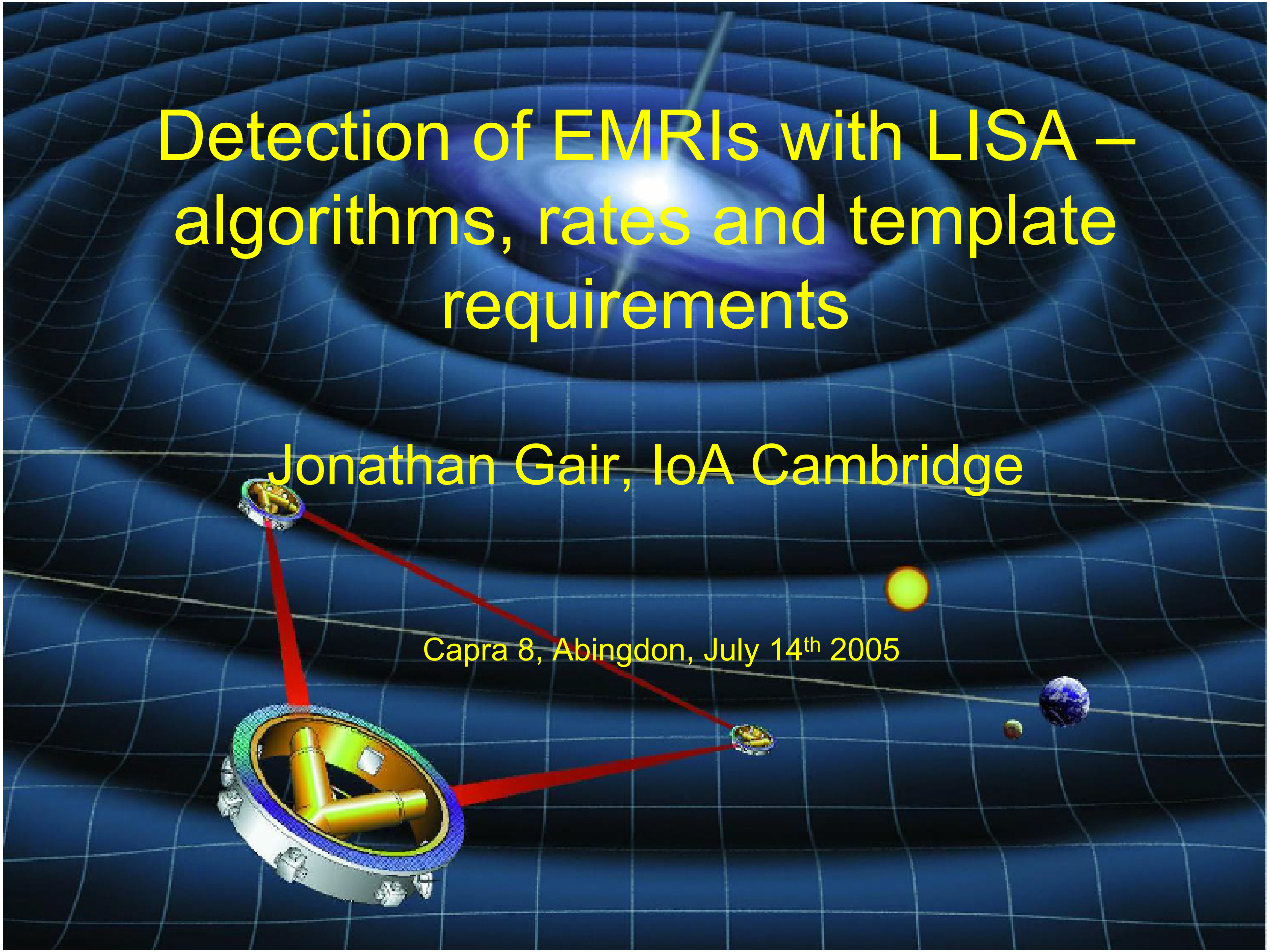

Talk Outline

- Brief description of likely LISA extreme mass ratio inspiral (EMRIs) events
- Challenges of data analysis for EMRI detection
- Semi-coherent approach to data analysis
- Estimated EMRI detection rates using the semi-coherent scheme
- Alternative search algorithms
- Outstanding issues

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Extreme mass ratio inspirals

- Inspiral of a compact object (WD, NS, BH) into a supermassive black hole in the centre of a galaxy.
- Generate gravitational waves which can be detected by LISA for last several years of inspiral.
- Desire to detect many EMRI events has been driving part of LISA mission specification.
- Gravitational waveforms encode a map of the spacetime structure close to the SMBH.

EMRIs – event rates

- Using galaxy luminosity function and L-σ / M-σ relations,

$M_\bullet$ ($M_\odot$)	Space density ($10^{-3}\ h_{65}^{2} Mpc^{-3}$)	Merger rate ($Gpc^{-3}\ yr^{-1}$)			
		0.6 $M_\odot$ WD	1.4 $M_\odot$ NS	10 $M_\odot$ BH	100 $M_\odot$ IMBH
$10^{6.5\pm0.25}$	1.7	8.5	1.7	1.7	1.7×10^{-3}
$10^{6.0\pm0.25}$	1.7	6	1.1	1.1	10^{-3}
$10^{5.5\pm0.25}$	1.7	3.5	0.7	0.7	7×10^{-4}

Specifically, take Freitag's rates for the Milky Way and scale to other galaxies with a $M^{3/8}$ dependence.

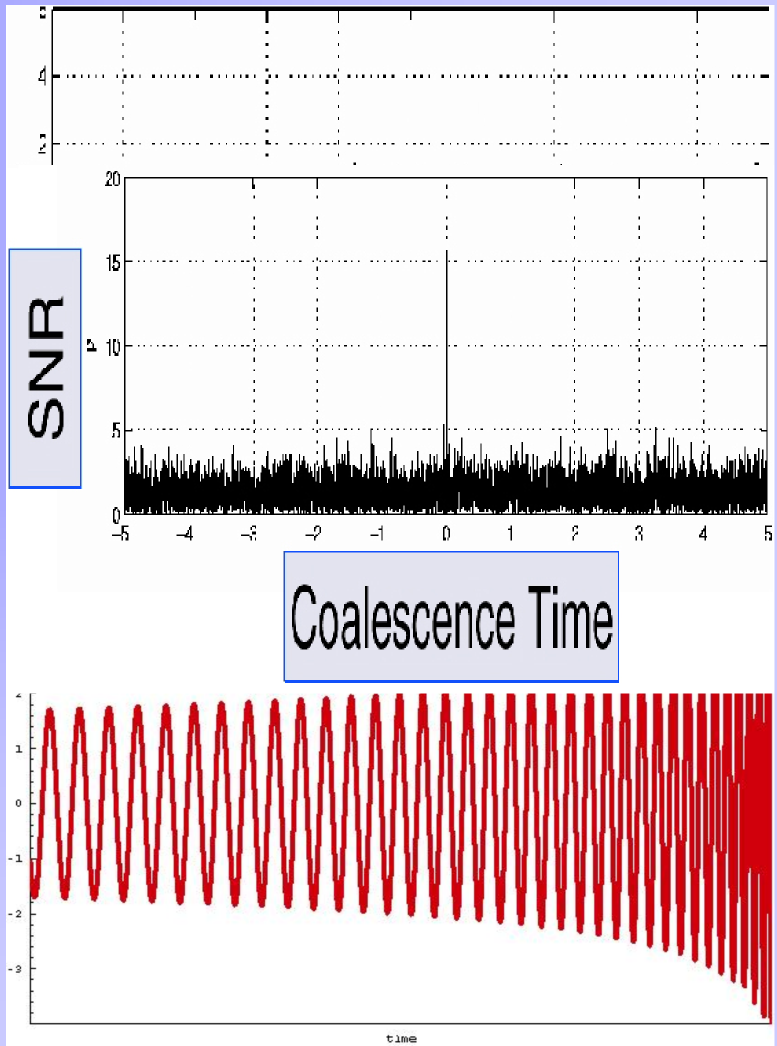
- Conservative rates could be a factor ~100 smaller for WDs, or a factor ~10 for BHs.

EMRIs – typical parameters

- Central SMBH has mass M~few x $10^5 M_\odot$ – $10^7 M_\odot$. Set by location of floor of LISA noise curve.
- Central SMBH spin, $S/M^2 \sim 0 – 1$.
- Inspiralling object is captured on an orbit with e~1, random inclination and r_p ~ few x M – few x 10M.
- At plunge, eccentricity is still moderate, e ~ 0 – ~0.4, prograde orbits favoured observationally.
- Sky position, inclinations etc. randomly distributed.

EMRI detection

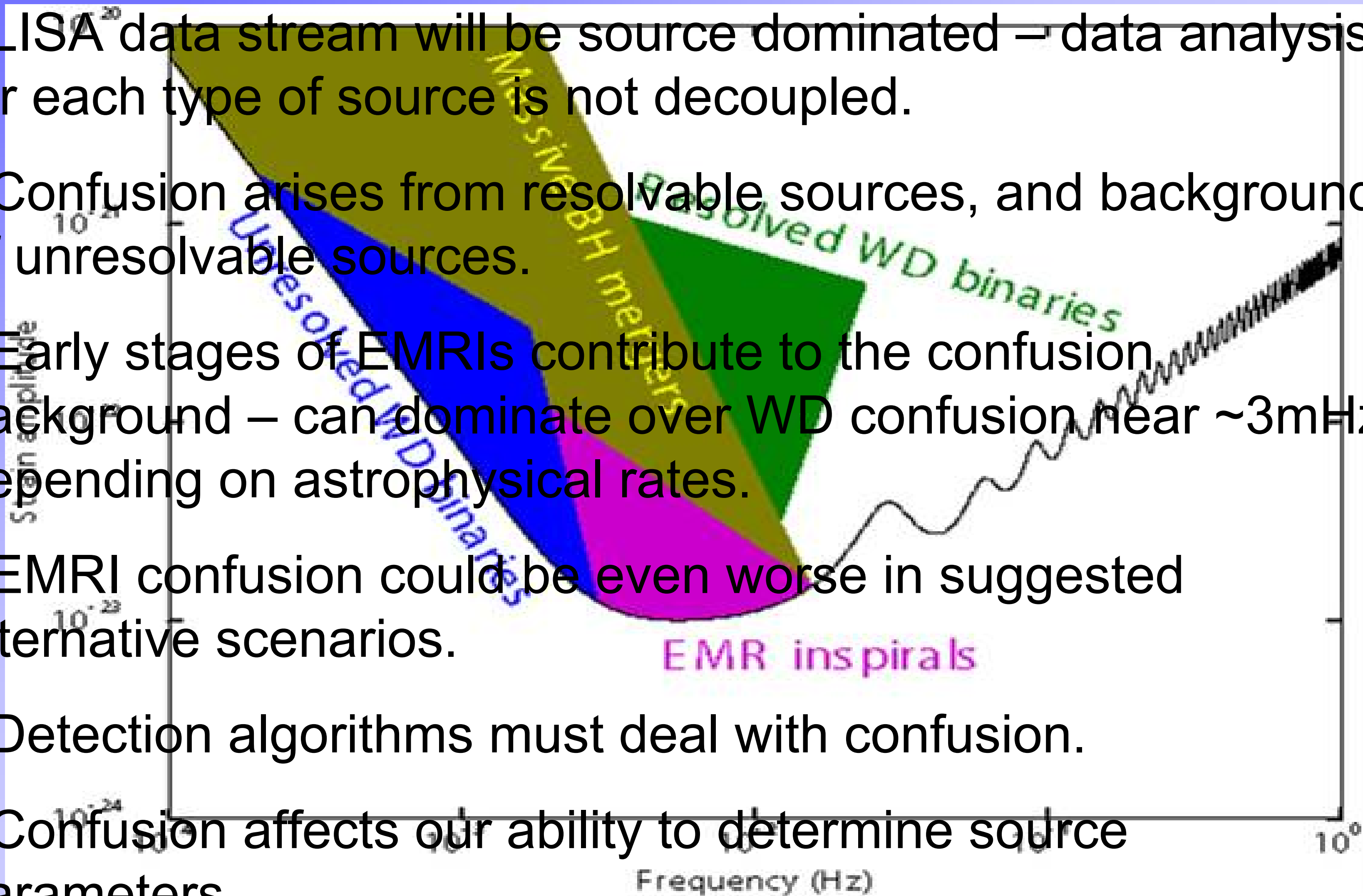
- EMRI events are faint, typically an order of magnitude below the noise.
- Detection will be by matched filtering using a bank of templates.
- Overlap of template with data pulls signal out of the noise.
- Has some parallels with radio astronomy, but cannot point LISA.



Data analysis challenges

- EMRI waveforms depend on 14 different parameters –
  M, S, m, e, r_p, ι, ψ_0, χ_0, φ_0, θ_K, φ_K, θ_S, φ_S, D.
- During last year of inspiral, the gravitational waveform has $\sim 10^5$ cycles. Might naïvely estimate $\sim(10^5)^8=10^{40}$ templates required.
- Computationally infeasible to do fully coherent matched filtering. Have been scoping out mixed coherent/incoherent methods using kludge waveforms.

DA challenges – confusion

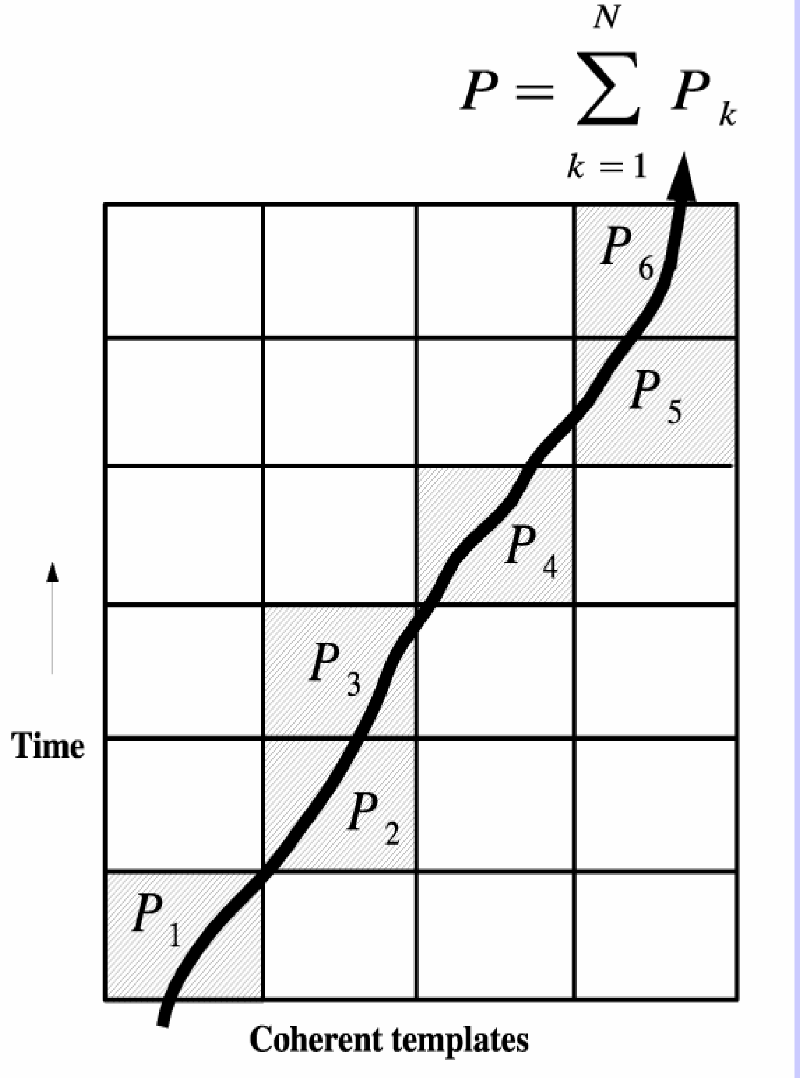


- LISA data stream will be source dominated – data analysis for each type of source is not decoupled.
- Confusion arises from resolvable sources, and background of unresolvable sources.
- Early stages of EMRIs contribute to the confusion background – can dominate over WD confusion near ~3mHz, depending on astrophysical rates.
- EMRI confusion could be even worse in suggested alternative scenarios.
- Detection algorithms must deal with confusion.
- Confusion affects our ability to determine source parameters.

Semi-coherent search algorithm

- Search is hierarchical. First stage is a fully coherent search for short waveform segments.
- Five parameters are extrinsic. Can maximize over these automatically.
- Use Fast Fourier Transforms to maximize over one further parameter (a time offset) cheaply.
- First stage dominates computational cost of search. Assuming 50 Teraflops computing power, can search $\sim 10^{10}$ templates. Monte Carlo simulations indicate this limits the coherent segments to a length ~2-3 weeks.

- SNR is built up during second stage by combining power incoherently.
- Maximize over two remaining phase angles (using templates) before stacking.
- The resulting search statistic is the sum of the maximized power along trajectories through the coherent segments.
- For a false alarm rate of 1%, find SNR threshold for detection is ~35.



Expected detection rate

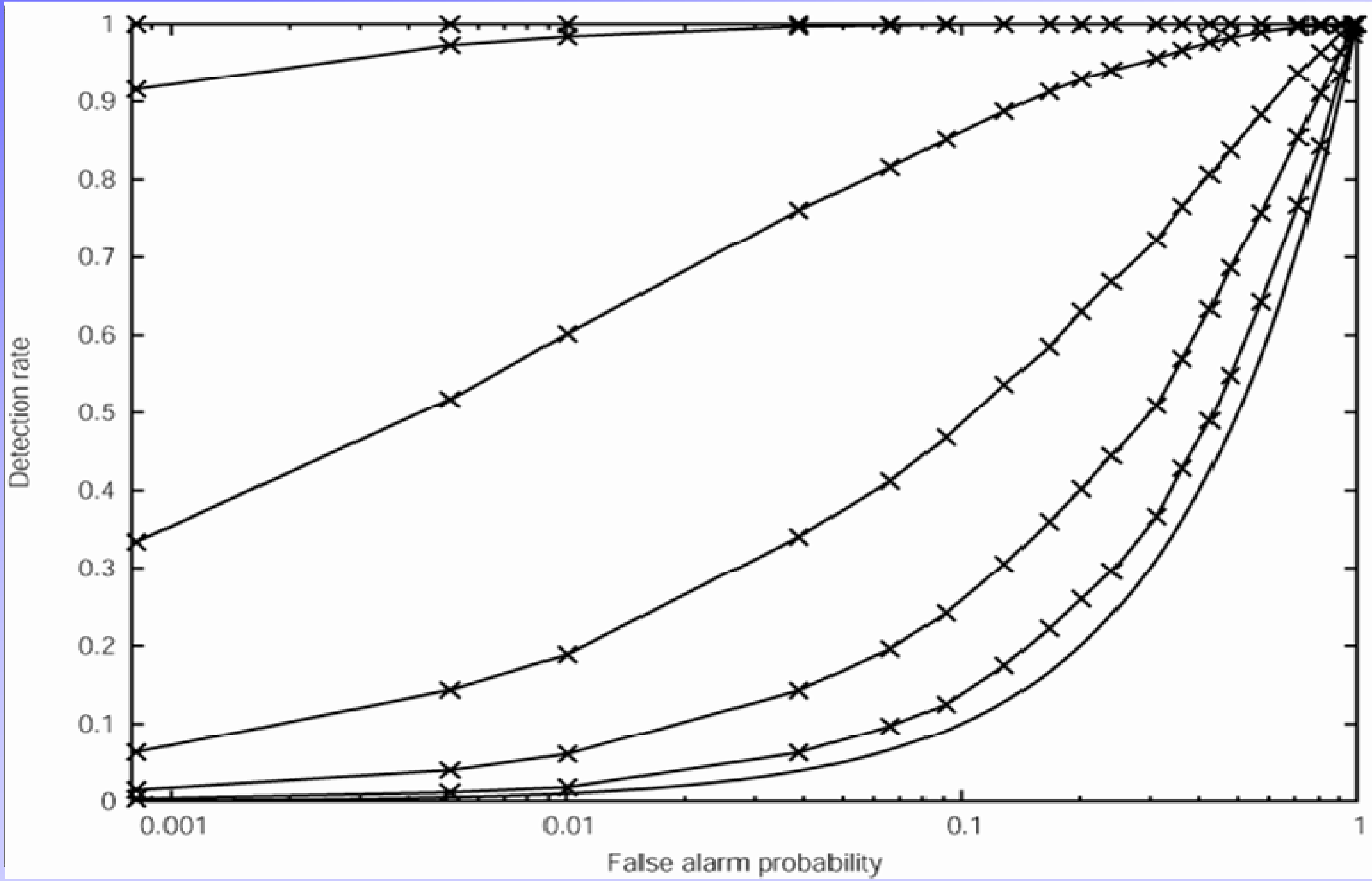
$M_\bullet$	m	Optimistic	Very pessimistic
300000	0.6	10	0
	10	700*	10
	100	1*	1*
1000000	0.6	100	<1
	10	1100*	70*
	100	1*	1*
3000000	0.6	70	0
	10	1700*	15
	100	2*	1*

- Events with a ‘*’ are z<1 lower limits.
- Astrophysical rate uncertainties are not included.

Template accuracy requirements

- Requirements are much less stringent for detection
  - Phase needs to match for ~2 weeks only.
  - Typical waveform has ~1000 cycles →require 0.1% accuracy.
  - Dephasing can be partially explained by errors in the other parameters.
  - Adiabatic templates (with conservative corrections) may suffice.
  - Non-template searches have no phase requirements!
- Parameter estimation requires phase tracking for up to several years → 0.001% accuracy requirement.
- Must understand parameter dependence of phasing in order to assess parameter determination accuracy and quantify tests of black hole geometry.

Time-frequency analysis techniques



Alternative algorithms

- Alternative time-frequency algorithms should be examined – alternative generation of the spectrogram, Hough transform, clustering, hierarchical schemes.
- Markov Chain Monte Carlo techniques – provides a more intelligent way to explore large parameter spaces. But – no guarantee of convergence.
- Hierarchical refitting of parameters – extract sources sequentially, resolving for the parameters at each step.
- Final data analysis will employ a combination of techniques – maximize science output for given computing resources, ensures greater confidence in the results.

Outstanding issues

- Effects of source interference need to be understood – have considered search for single sources only.
- Optimization of search algorithms – e.g., search for higher multipoles, division into coherent segments, threshold choice etc.
- Better estimates of intrinsic event rates to allow tuning of the search.
- Interface with data analysis for other sources – how does WD or BBH subtraction affect EMRI detection and parameter estimation?
- Efficiency of alternative search algorithms.
- Geometry mapping – astrophysics, templates, null hypothesis test

Summary

- EMRI detection is difficult, but algorithms are under development.
- LISA could see as many as several thousand events during the mission lifetime.
- Best search presently known is semi-coherent and requires templates that are phase accurate for ~2 weeks.
- Alternative algorithms may detect the brightest sources at a small fraction of the computational cost.
- Final parameter determination will involve a matched filtering search and imposes much stricter requirements on template phase accuracy – self-force!