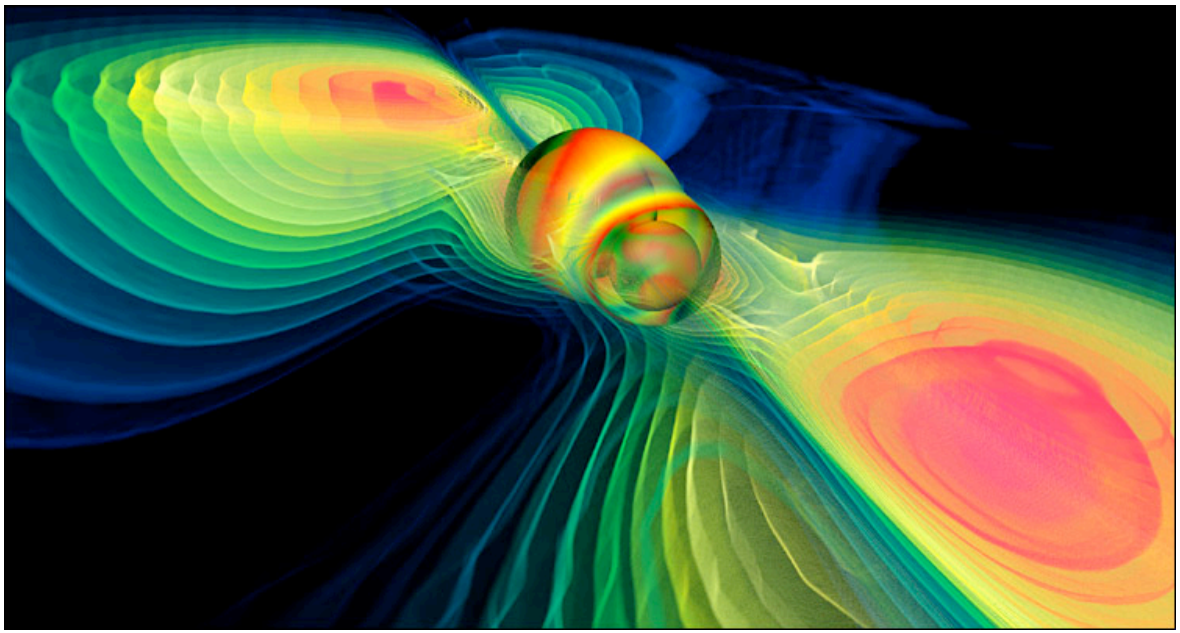
Extracting the Distribution of Black-hole Parameters from Gravitational-wave Observations



(Image: MPI for Gravitational Physics / W.Benger-ZIB)

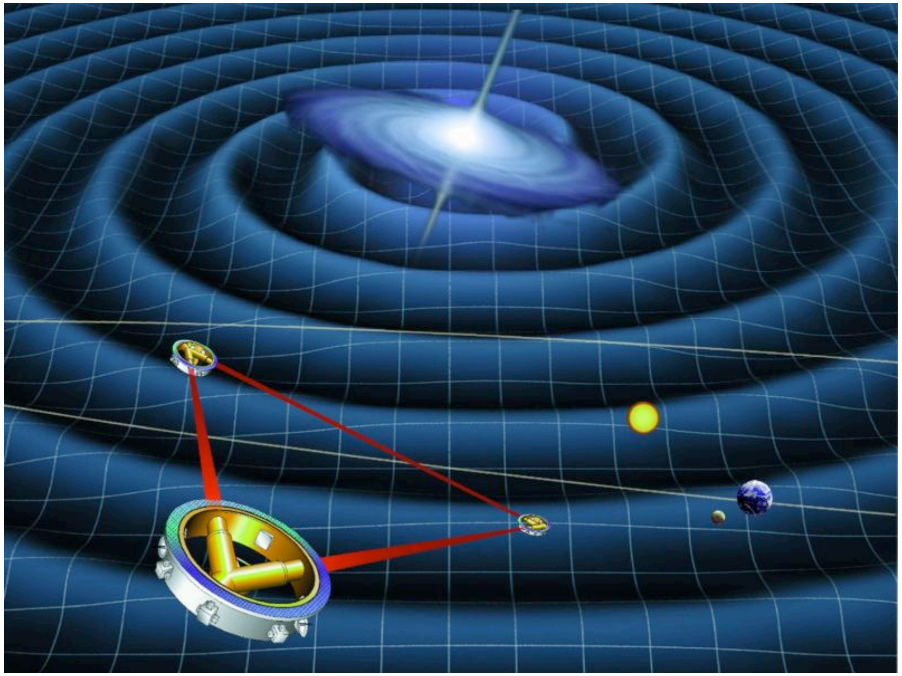
Ilya Mandel
(NSF AAPF, CIERA @Northwestern University)

February 19, 2010

Formation and Evolution of Black Holes, Aspen

Jantar Mantar, Delhi

Gravitational-wave observatories

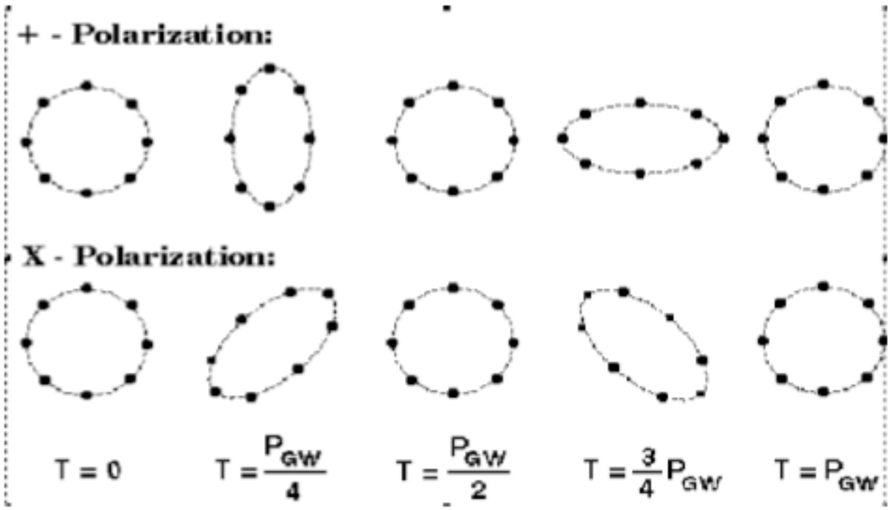


LIGO:
Laser
Interferometer
Gravitational-wave
Observatory

LISA:
Laser
Interferometer
Space
Antenna

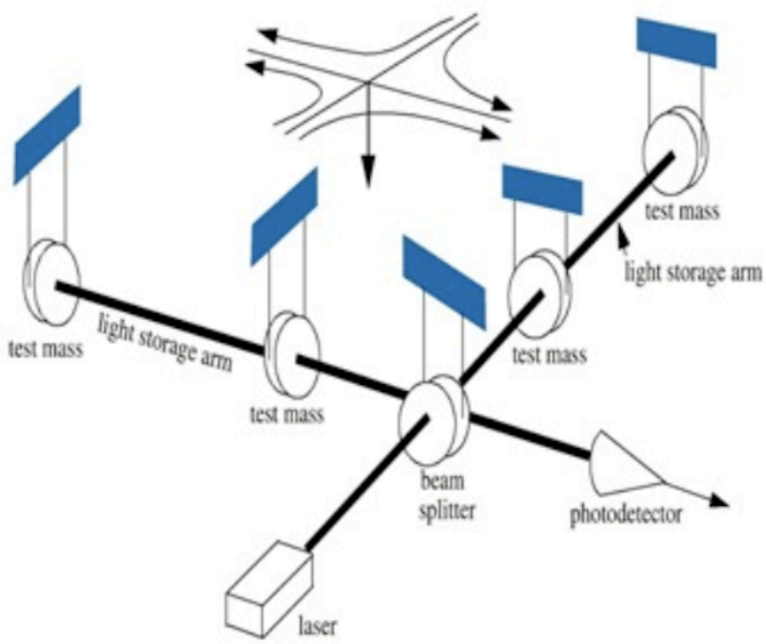
Gravitational Waves

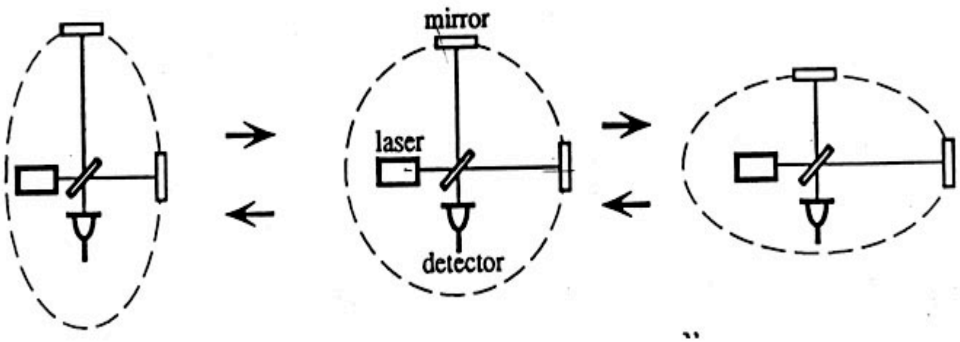
- Ripples in spacetime
- Caused by time-varying mass quadrupole moment; GW frequency is twice the orbital frequency for a circular, non-spinning binary



- Indirectly detected by Hulse & Taylor [binary pulsar]
- Huge amounts of energy released: 5% of mass-energy of a supermassive black hole binary is comparable to the electromagnetic radiation emitted from an entire galaxy over the age of the universe!
- GWs carry a lot of energy, but interact weakly: can pass through everything, including detectors!

Opportunity and Challenge



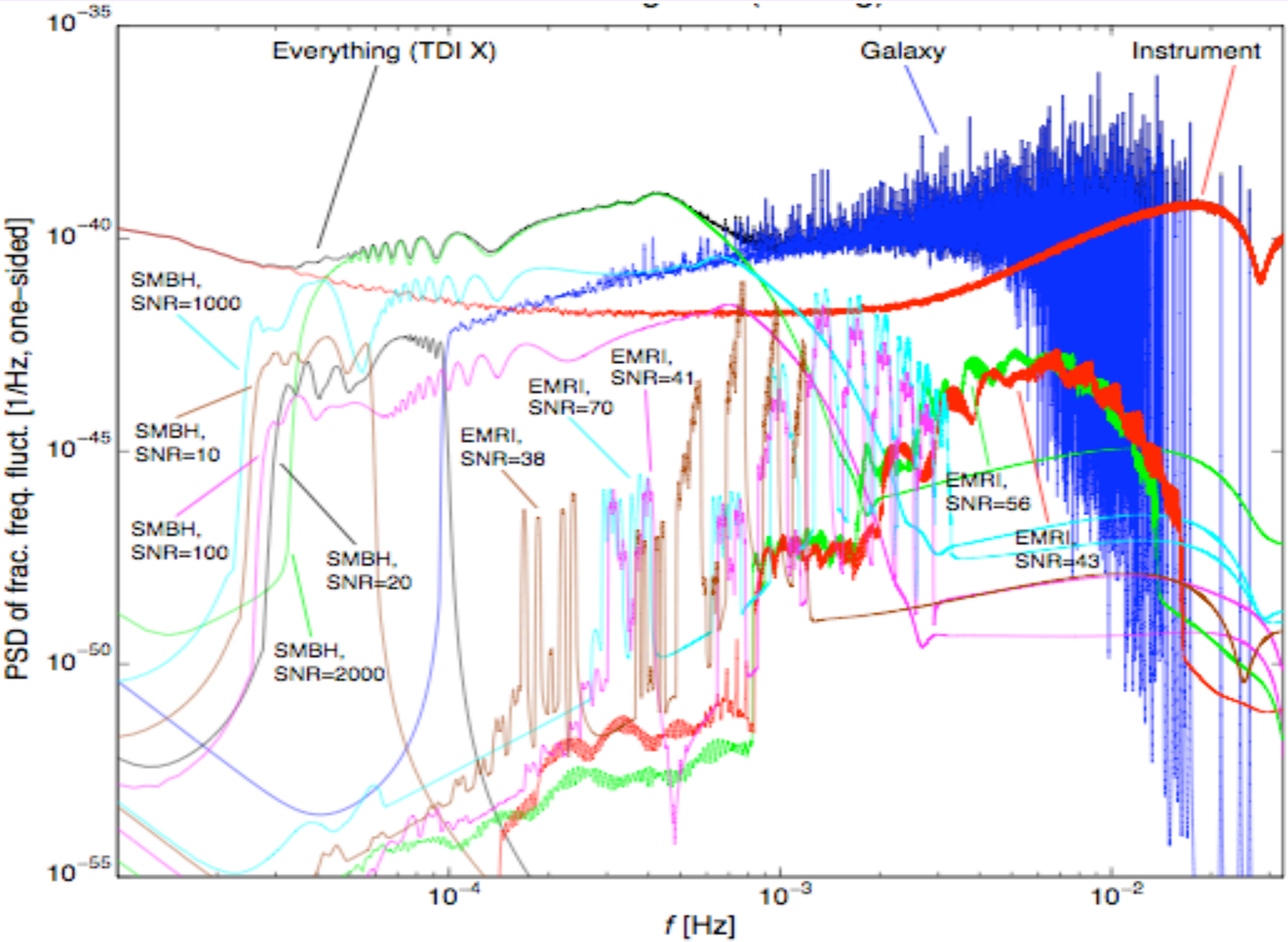


Michelson-type interferometers

LISA Binary Sources

- LIGO sensitive @ a few hundred Hz
  - NS-NS, NS-BH, BH-BH binaries
- LISA sensitive @ a few mHz
  - massive black-hole binaries
    - merger tree models to describe history of Galactic mergers
    - could be detected anywhere in Universe, SNR up to thousands
    - a few to tens of detections [e.g., Sesana et al., 2005]
  - extreme-mass-ratio inspirals of WDs/NSs/BHs into SMBHs
    - complicated modeling of dynamics in Galactic centers: loss cone problem, resonant scattering, etc.
    - could detect tens to hundreds to z~1 [e.g., Gair et al., 2004]
  - galactic white dwarf (and compact object) binaries
    - 30 million in Galaxy, create noise foreground [Farmer & Phinney, 2003]
    - 20,000 resolvable

Embarrassment of riches



[Arnaud et al., 2007, CQG 24 S551]

LISA Data Analysis

$$h(t) = h(M_1, M_2, \vec{S}_1, \vec{S}_2, \theta, \phi, D_L, e, ...; t)$$ 17 parameters

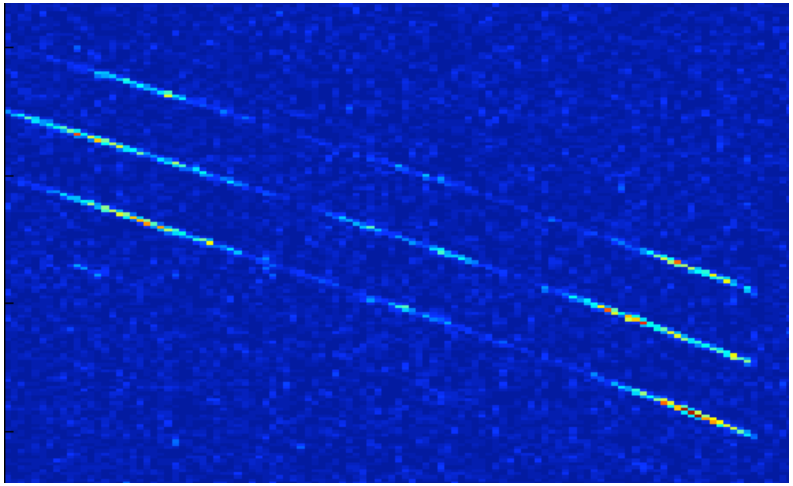
What has already been accomplished?

	MLDC 1	MLDC 2	MLCD 1B	MLDC 3
GB	• Verification ✓ • Unknown, isolated ✓ • Unknown, interfering ✓	• Galaxy of $3x10^6$ ✓	• Verification ✓ • Unknown, isolated ✓ • Unknown, confused ✓	• Galaxy of $6x10^7$ chirping ✓
MBH	• Isolated ✓	• 4–6x, over Galaxy and EMRIs ✓	• Isolated ✓	• Over Galaxy spinning, precessing ✓
EMRI		• Isolated ✓ • 4–6x, over Galaxy and SMBHs	• Isolated ✓	• 5 together, weaker ✓
New				• Cosmic string cusp bursts ✓ • Cosmological background ✓

Table by M. Vallisneri

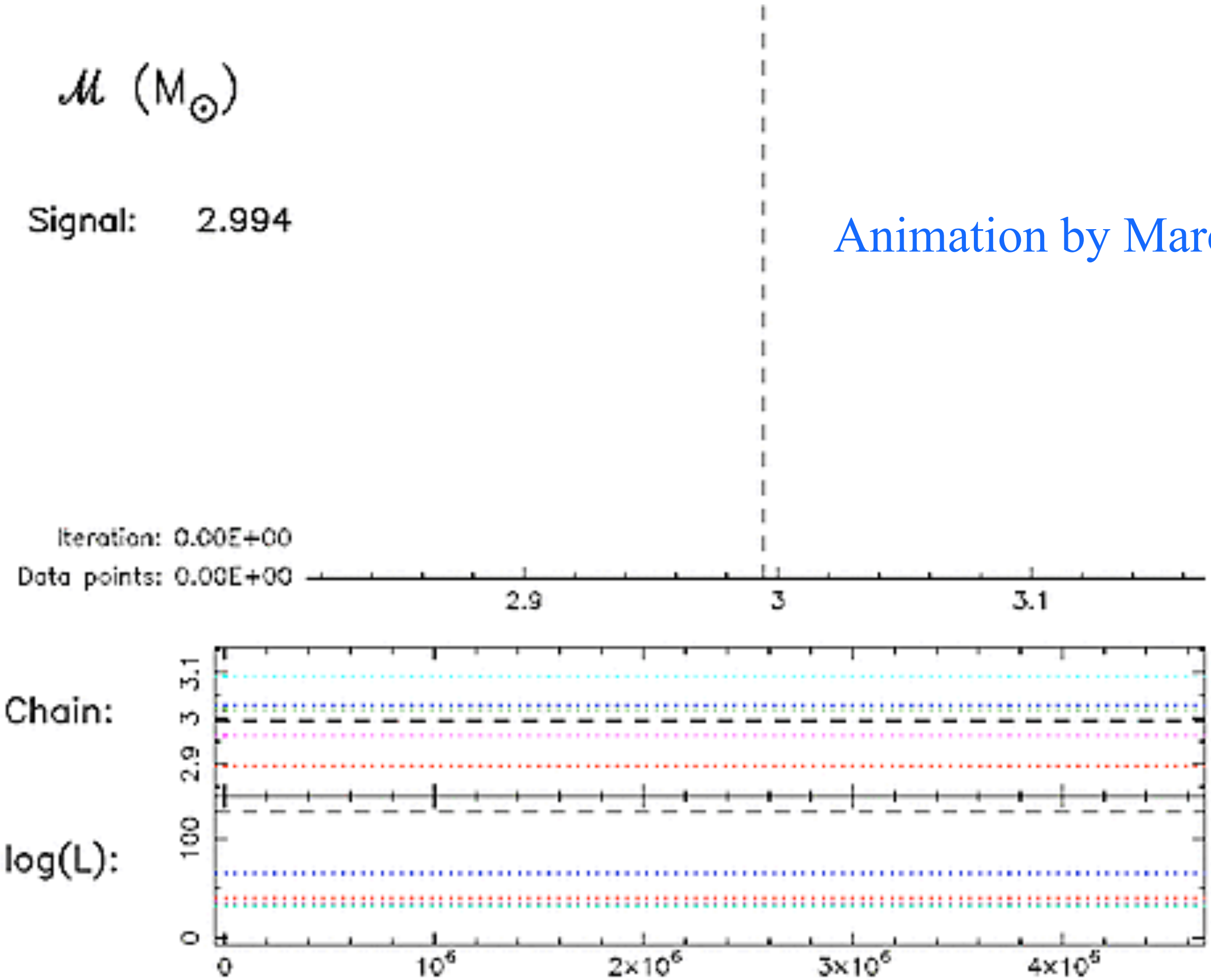
Mock LISA Data Challenges

Need innovative search techniques to separate many overlapping signals: Markov-Chain Monte Carlo, MultiNest, genetic algorithms



[Gair, IM, Wen, 2008, CQG 25 184031]

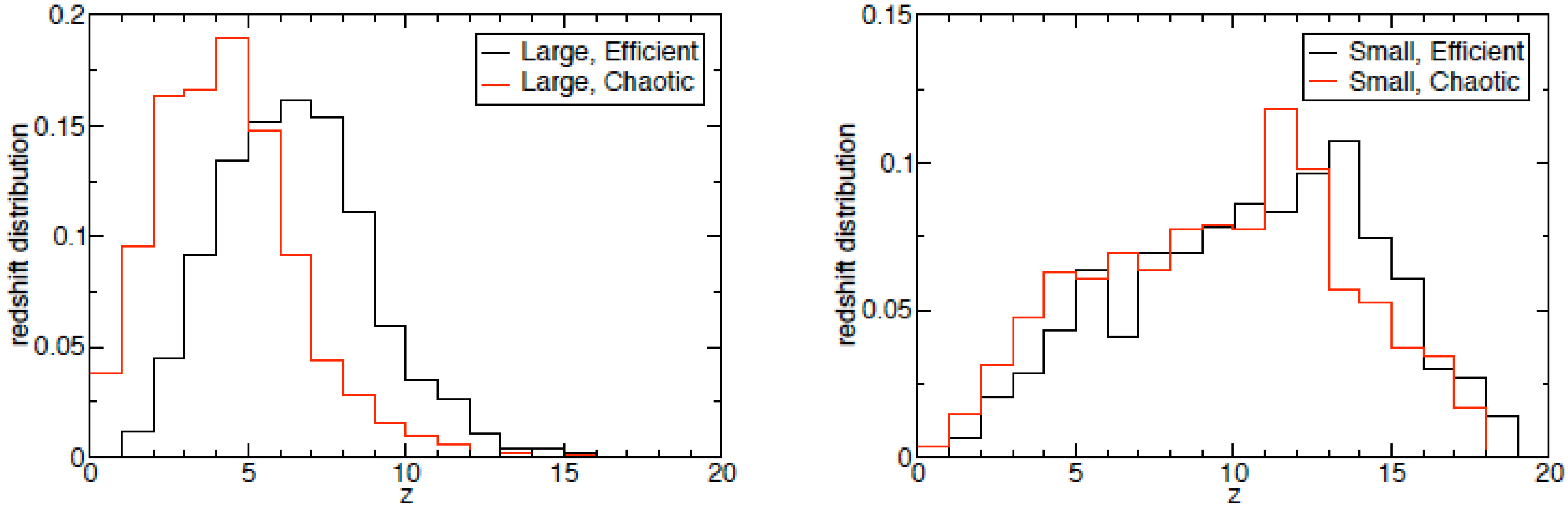
Markov Chain Monte Carlo



Animation by Marc van der Sluys

van der Sluys, IM, Raymond, et al., 0905.1323

SMBH binaries

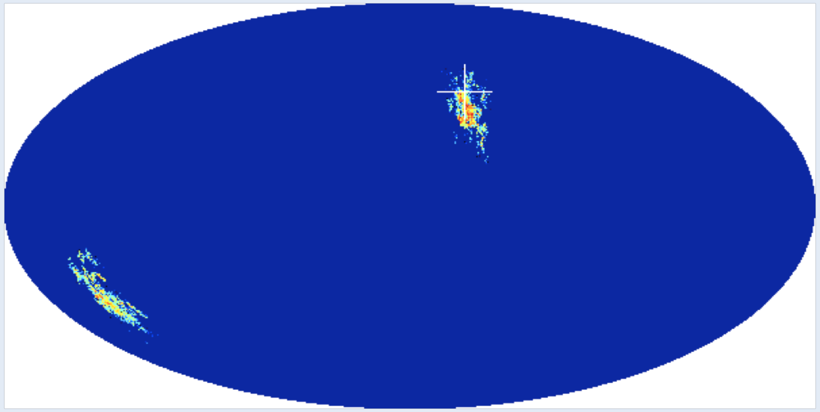


Model	N	$N_{\rm det}$	$N_{10\% D_L}$	$N_{10\,{\rm deg}^2}$	$N_{10\,{\rm deg}^2,\,10\% D_L}$	$N_{1\,{\rm deg}^2}$	$N_{1\,{\rm deg}^2,\,1\% D_L}$
SE	80	33 (25)	21 (8.0)	8.2 (1.5)	7.9 (1.1)	2.2 (0.6)	1.7 (0.1)
SC	75	34 (27)	17 (4.4)	6.1 (0.4)	5.5 (0.4)	1.3 (0.1)	1.3 (0.1)
LE	24	23 (22)	21 (7.7)	10 (0.8)	10 (0.7)	2.2 (0.1)	1.2 (0.05)
LC	22	21 (19)	14 (4.3)	6.5 (0.5)	5.4 (0.5)	1.8 (0.04)	1.0 (0.1)

from [Arun et al. (LISA Parameter Estimation Taskforce), 2008, CQG 26, 094027]

Mock LISA Data Challenge Results

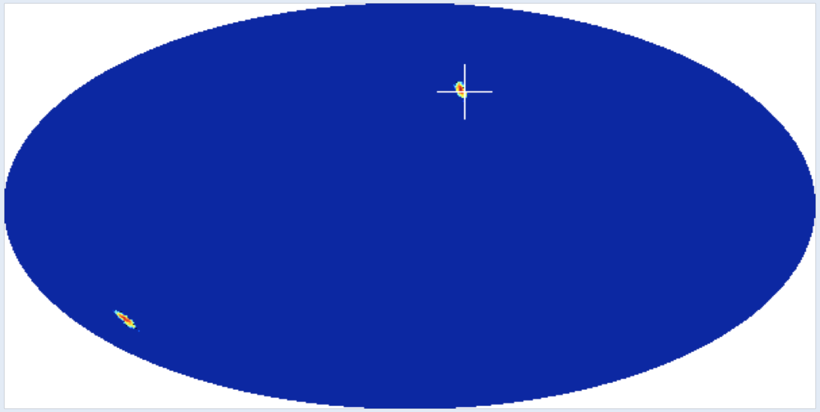
Challenge 3.2 : Massive Black Holes



30 days before merger

Monte Carlo by Neil Cornish

Challenge 3.2 : Massive Black Holes

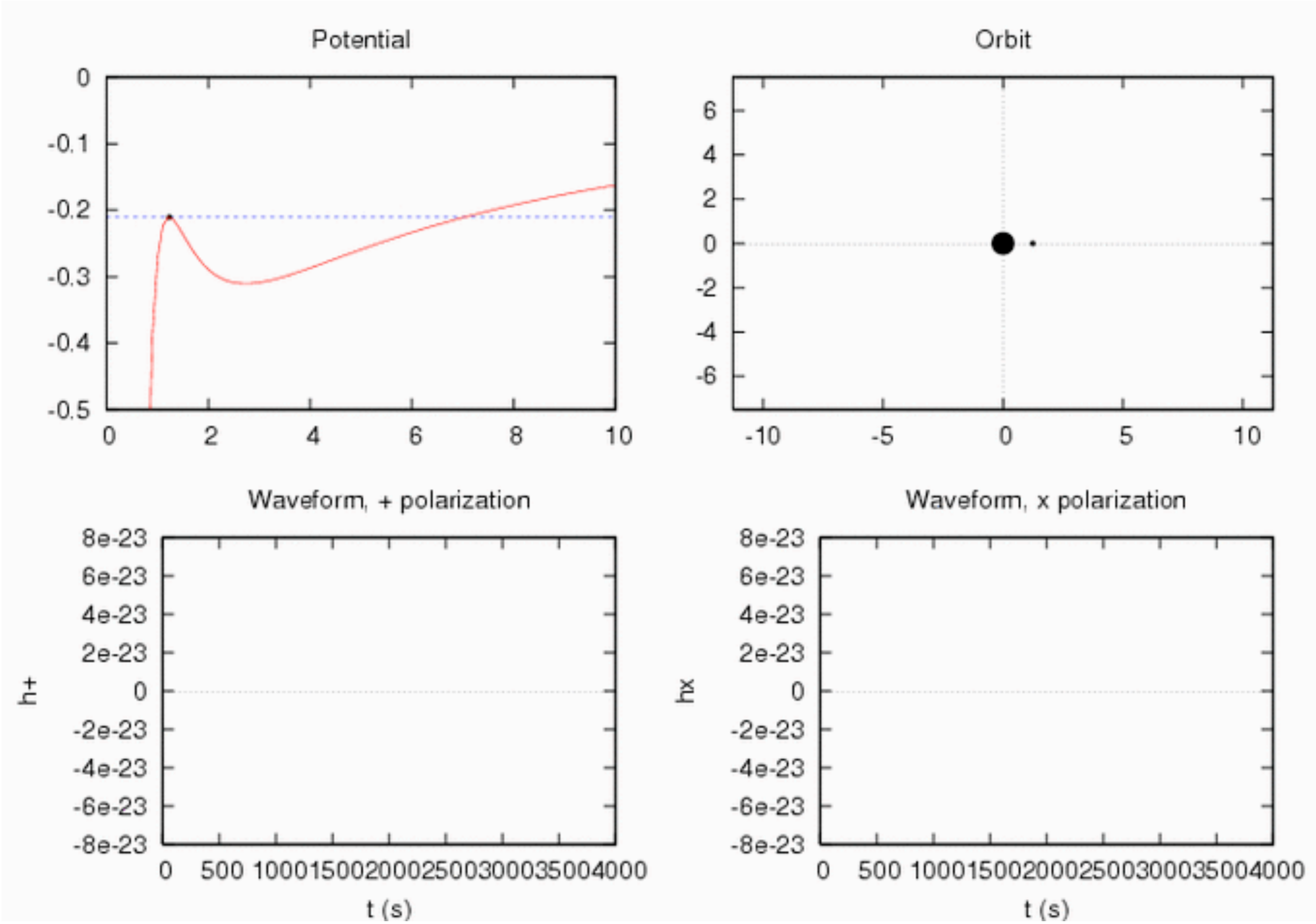


1 day before merger

Monte Carlo by Neil Cornish

source (SNR_{true})	group	$\Delta M_c/M_c$ $\times 10^{-5}$	$\Delta\eta/\eta$ $\times 10^{-4}$	Δt_c (sec)	Δsky (deg)	Δa_1 $\times 10^{-3}$	Δa_2 $\times 10^{-3}$	$\Delta D/D$ $\times 10^{-2}$	SNR	FF_A	FF_E
MBH-1 (1670.58)	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	1657.71	0.9936	0.9914
	CambAEI	3.4	40.7	24.8	2.0	8.5	79.6	0.7	1657.19	0.9925	0.9917
	MTAPC	24.8	41.2	619.2	171.0	13.3	28.7	4.0	1669.97	0.9996	0.9997
	JPL	40.5	186.6	23.0	26.9	39.4	66.1	6.9	1664.87	0.9972	0.9981
	GSFC	1904.0	593.2	183.9	82.5	5.7	124.3	94.9	267.04	0.1827	0.1426

Extreme Mass Ratio Inspirals

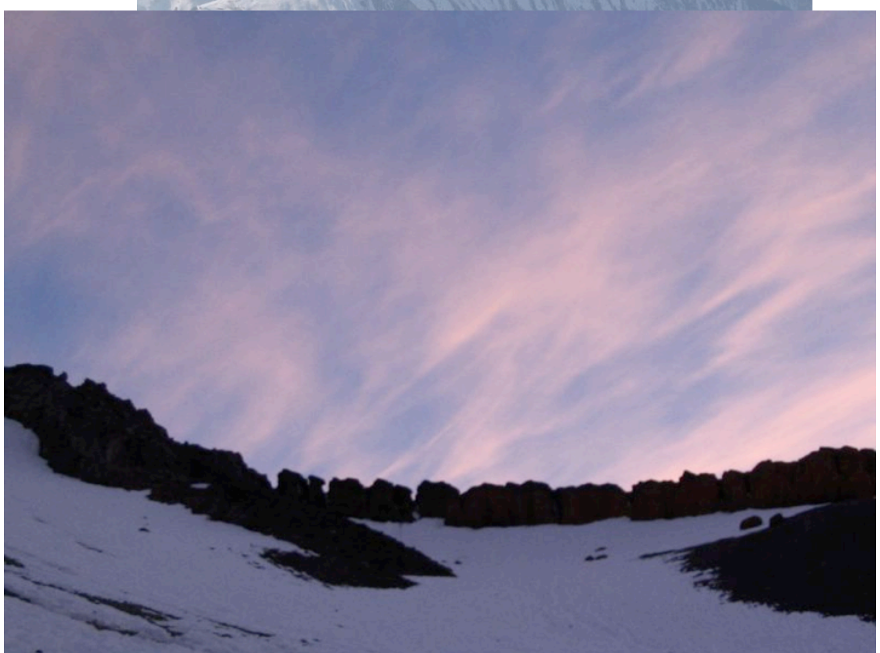


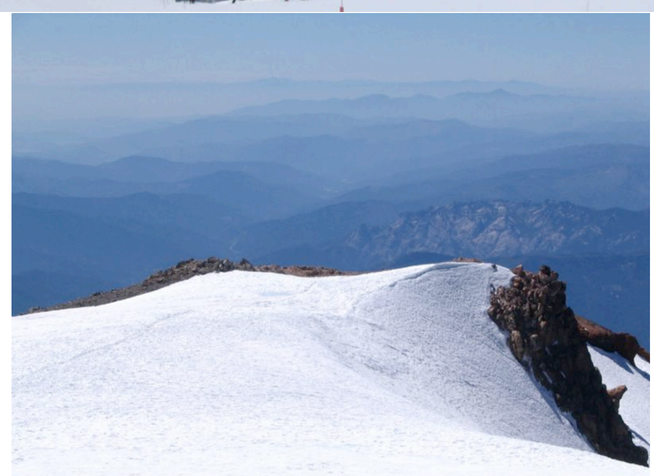
Sound from Scott Hughes

Animation from Jon Gair

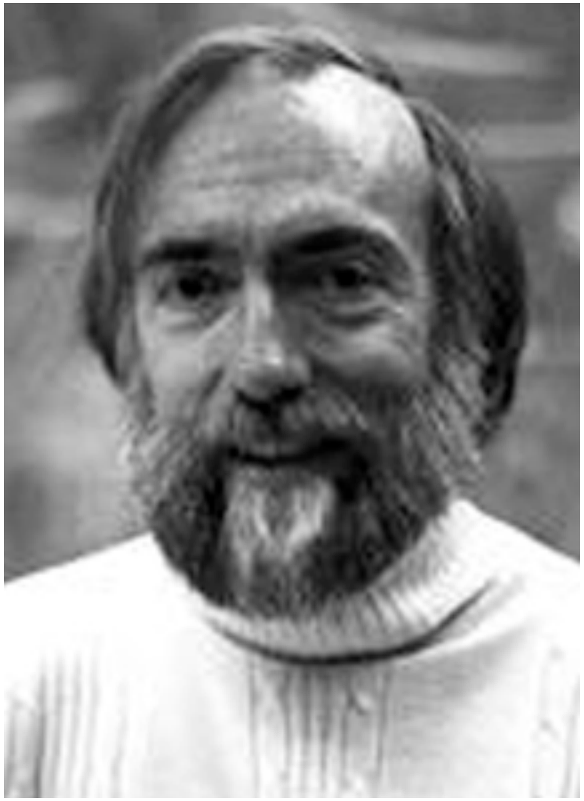
Exploring the spacetime...

... taking lots of pictures

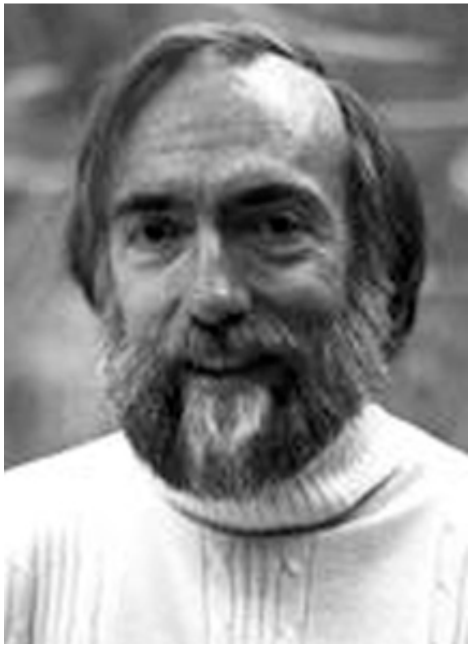




Testing the no-hair theorem

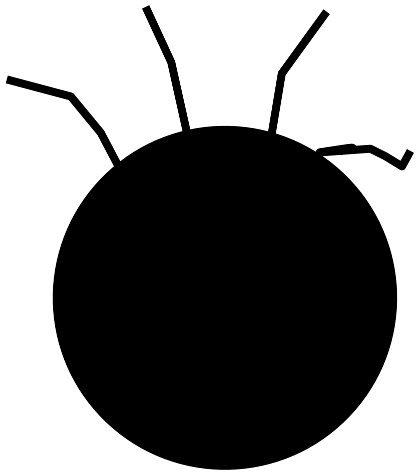


Testing the no-hair theorem?

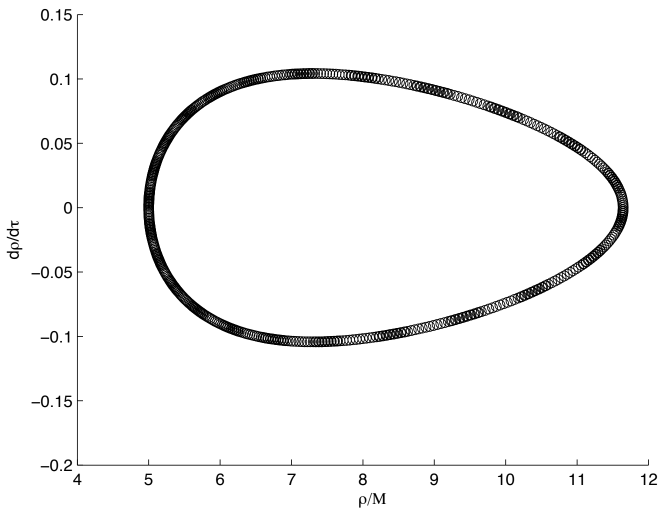


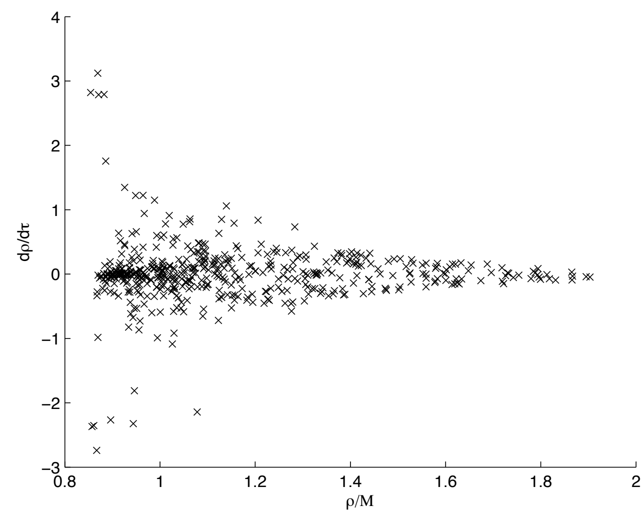
Stationary, vacuum, asymptotically flat spacetimes in which the singularity is fully enclosed by a horizon with no closed timelike curves outside the horizon are described by the Kerr metric

Do black holes have hair?



$$M_n + iS_n \neq M(ia)^n$$

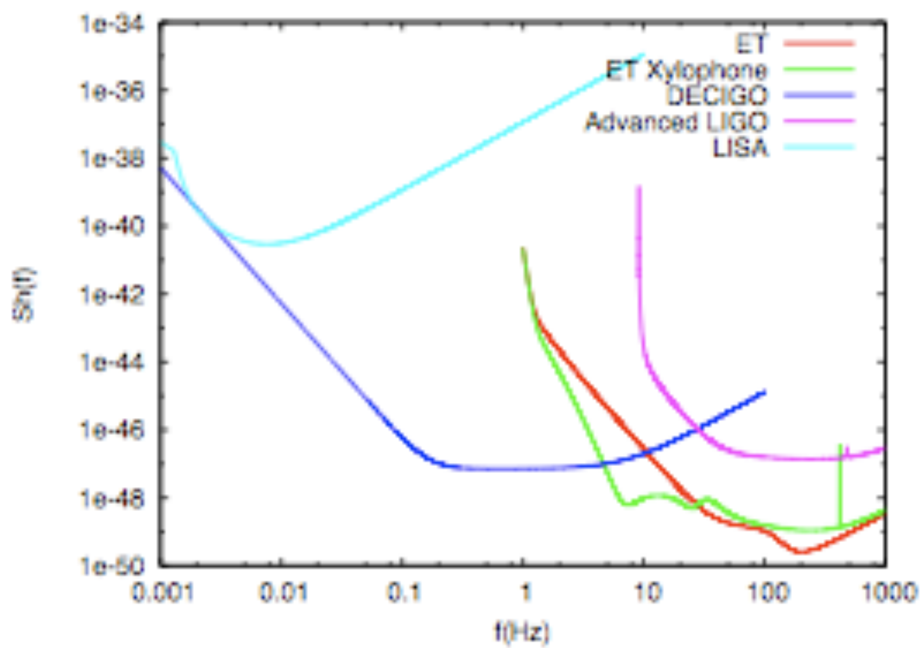




[Gair, Li, IM, 2009, PRD 77:024035]

Third-generation detectors

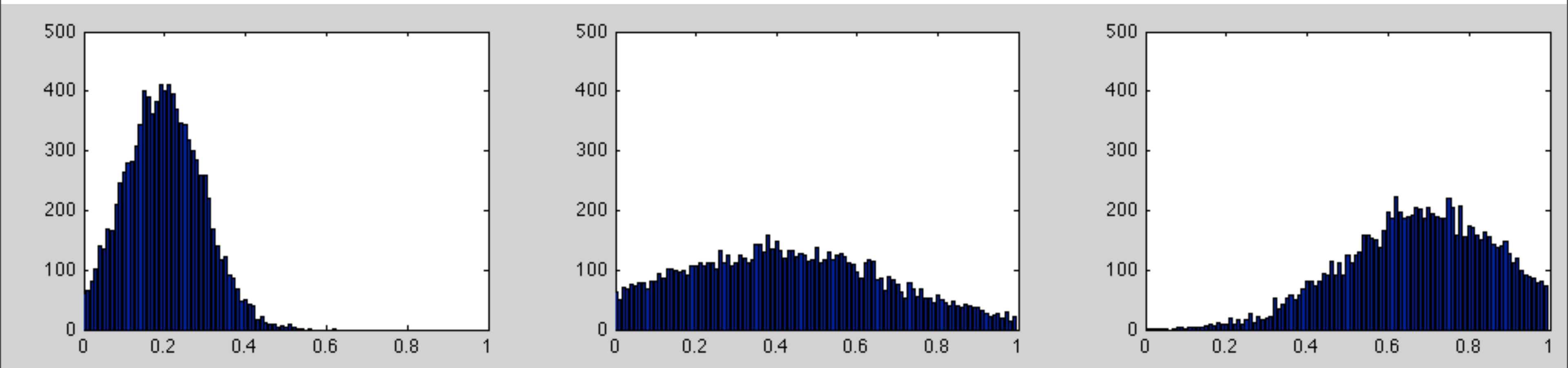
- The Einstein Telescope:
  - Underground, sensitive to 1 Hz
  - Exciting science example: mergers of light seeds of massive black holes at high redshifts [Sesana, Gair, IM, Vecchio, 2009]
- ALIA/DECIGO/BBO
  - Space-based LISAs on steroids
  - Exciting science example: using 300,000 merging binaries as standard candles for precision cosmology: Hubble constant to 0.1%, w to 0.01 [Cutler & Holz, 2009]
- Pulsar timing [see next talk!]
  - Sensitive to SMBHBs @ 10^{-8} Hz



from [Gair, IM, Sesana, Vecchio, 2009]

Parameter estimation on multiple GW detections:

yield a set of individual marginalized posterior probability density functions



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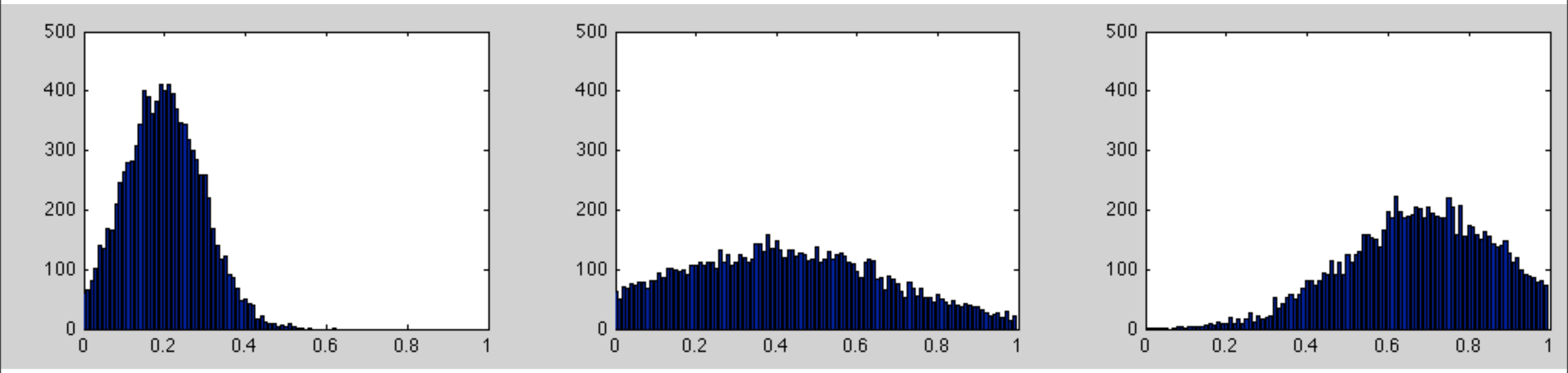

How do we combine these to make a statement about parameter distribution of the population being sampled?

Parameter estimation on multiple GW detections:

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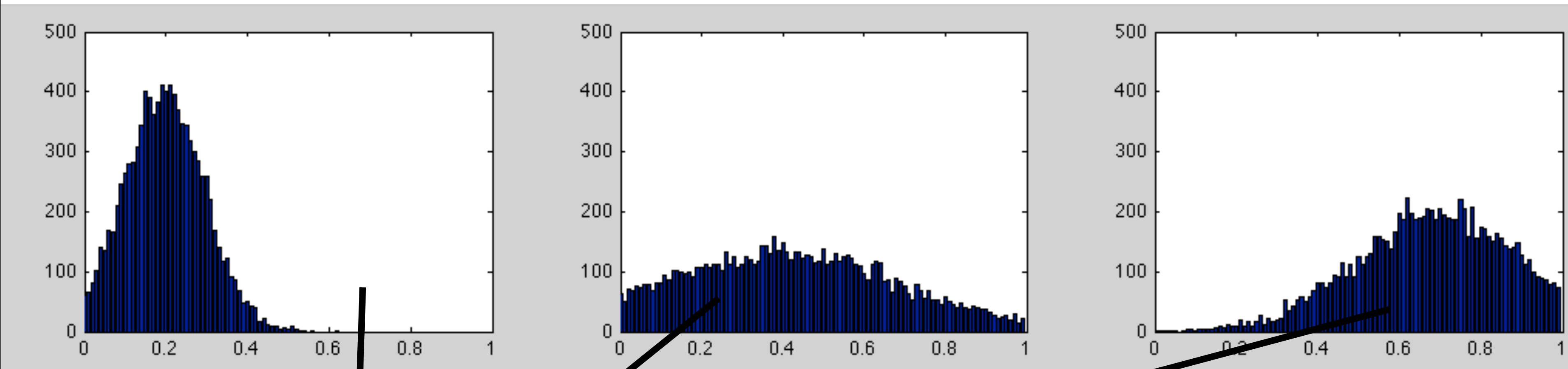
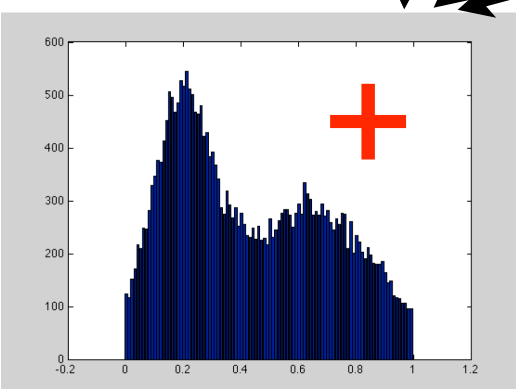


POLL: How do we combine these to make a statement about parameter distribution of the population being sampled?

A: Add them?



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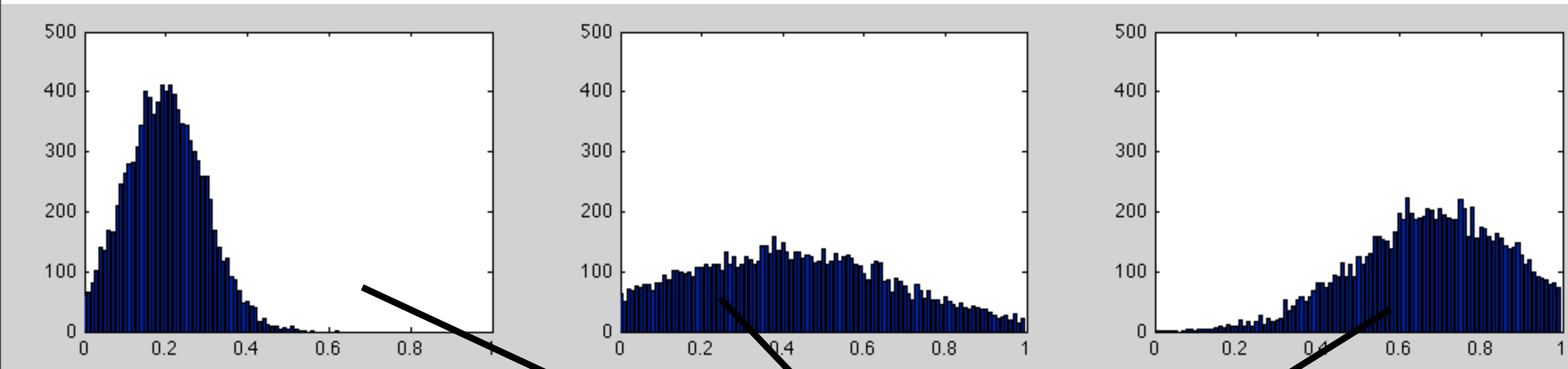

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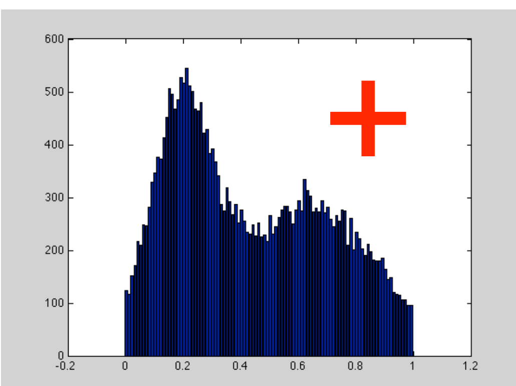
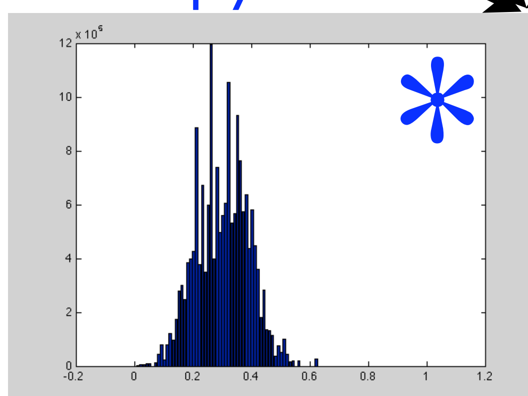


B: Multiply them?



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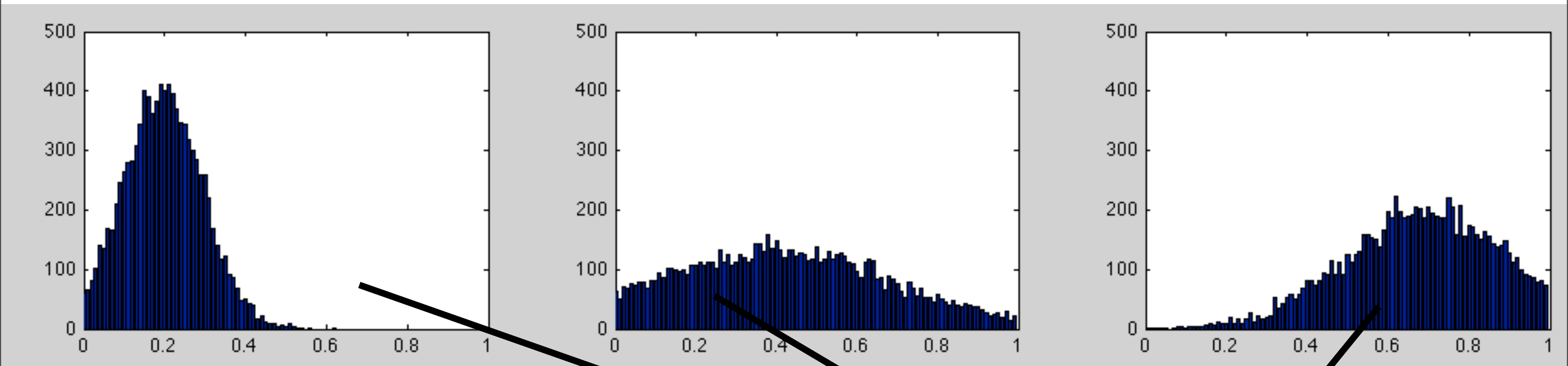

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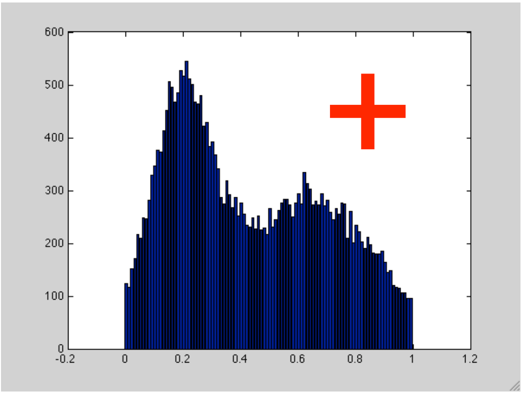

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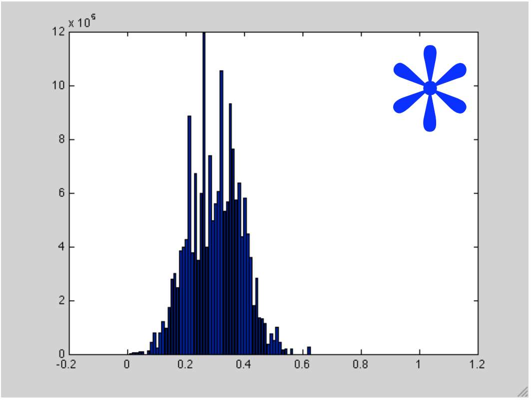
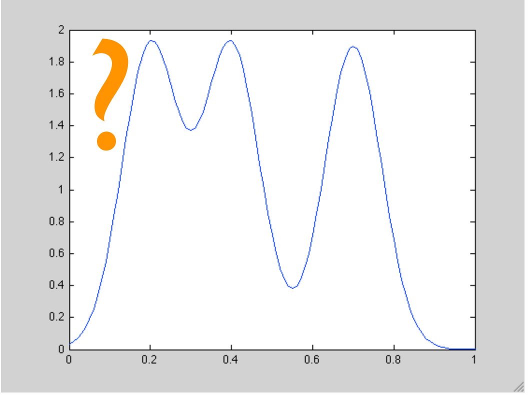


C: Something else?



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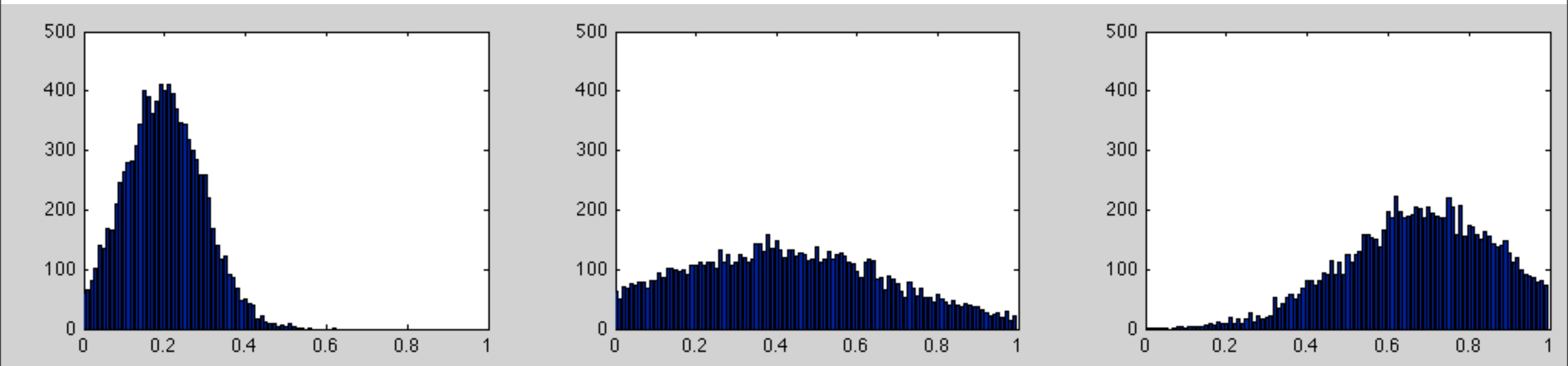

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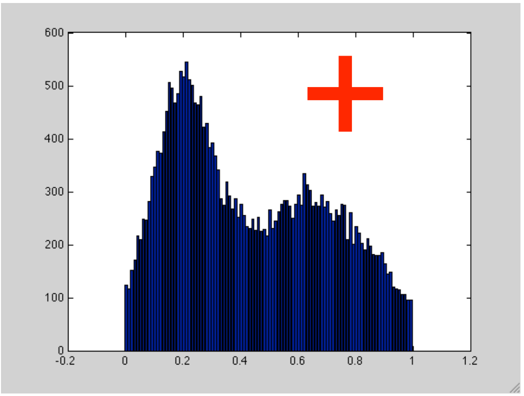

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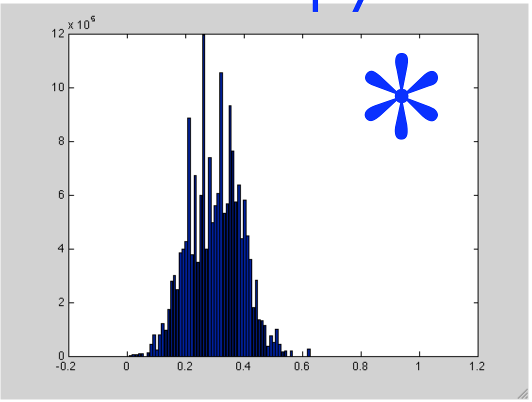

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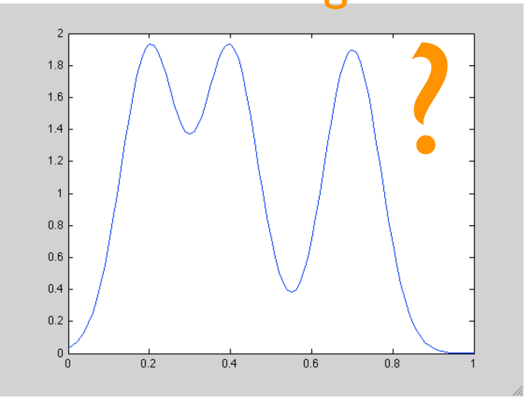

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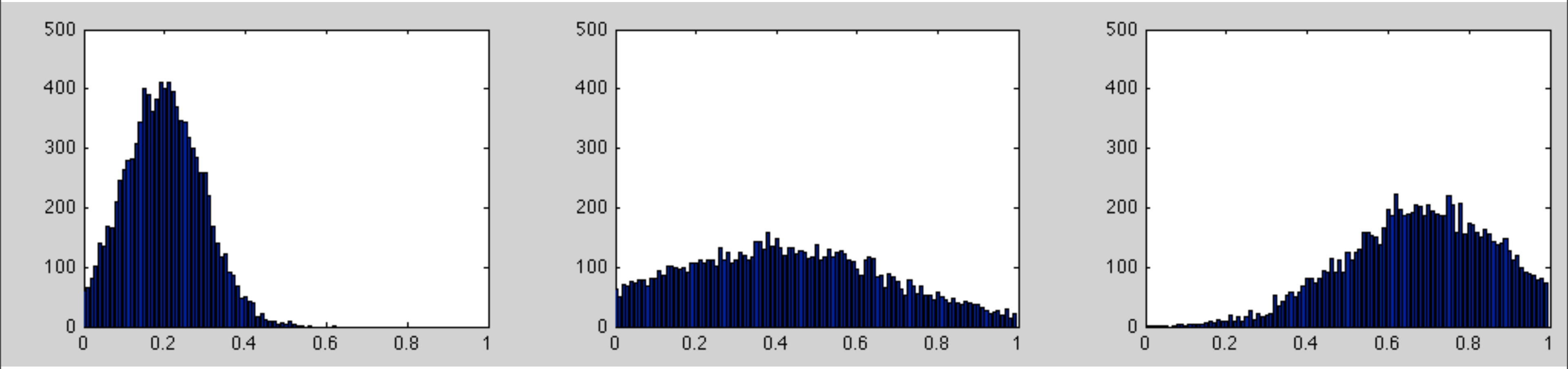

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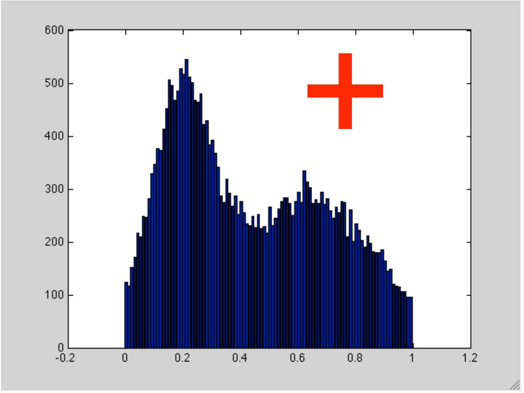

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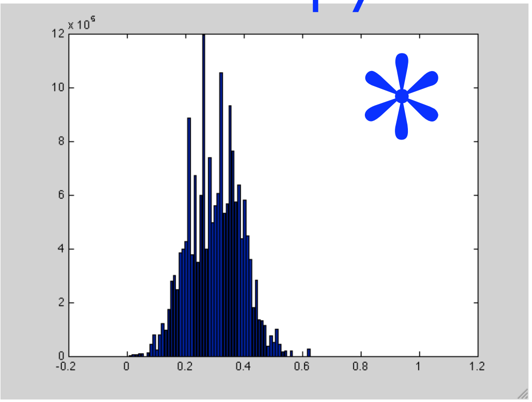

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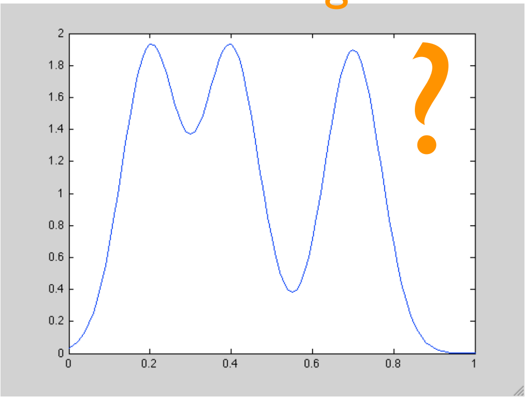

See IM, 2010, arXiv:0912.5531 for the answer. :-)