New Physics and Astrophysics with LISA (the Laser Interferometer Space Antenna)

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LBNL, 17 May 2007

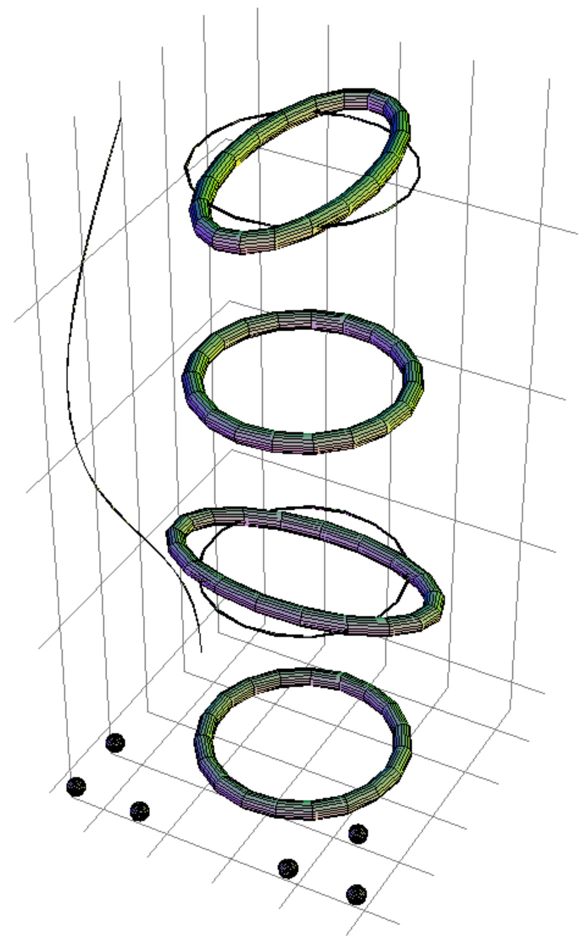
The New Science of Gravitational Waves

- Spacetime physics
  - Extreme dynamical spacetime in black hole mergers
  - High precision test of General Relativity under most extreme conditions
- Precision cosmology
  - Gravitationally calibrated, absolute & independent distances
- Opportunities for photon astronomy
  - Radio, optical, X-ray counterparts and host galaxies
- Astrophysics
  - Direct observations of massive black holes over the history of galaxy formation
- Galactic and stellar astronomy
  - Thousands of compact binaries throughout the Galaxy
- Unification physics, superstring physics, and the unknown
  - Terascale phase transitions at 100 GeV to 1000 TeV
  - Backgrounds and bursts from cosmic superstrings
  - Direct measurement of quantum gravity (Planck diffraction limit)?
  - ??????????

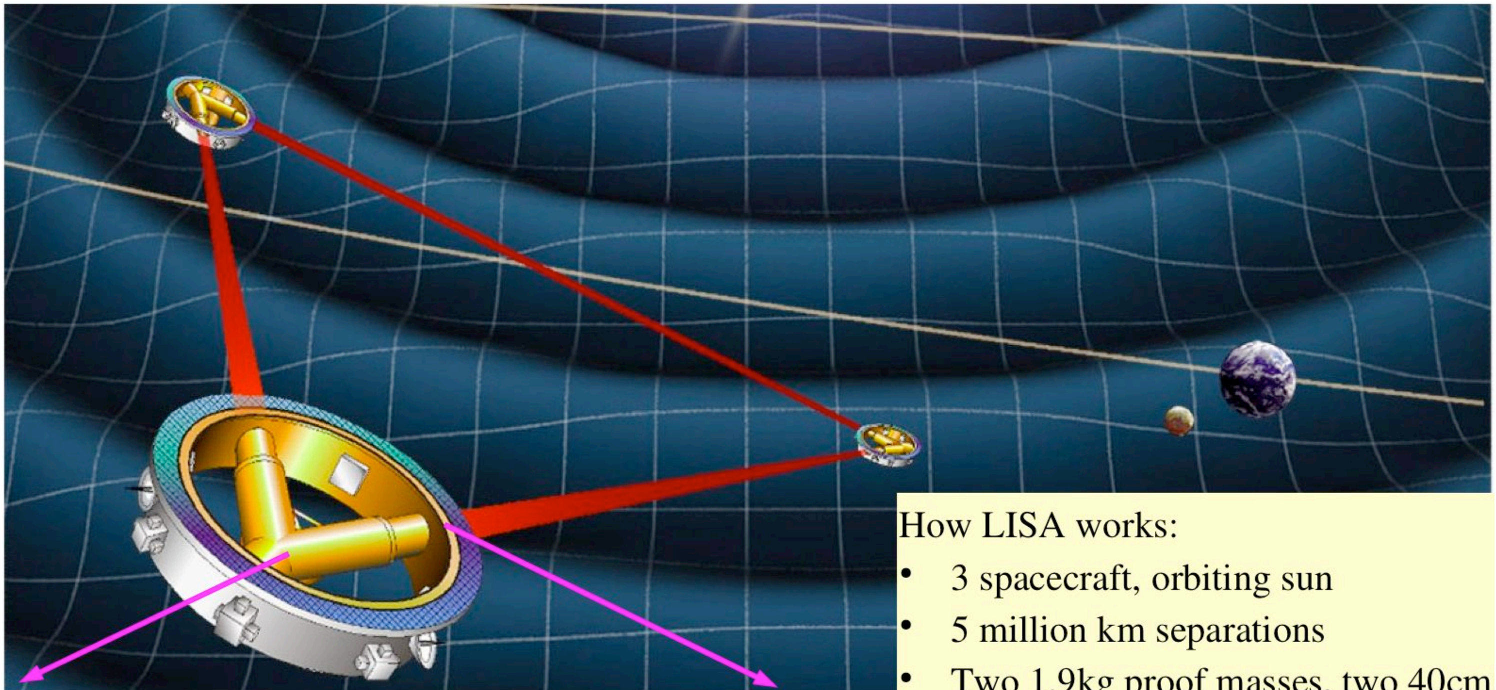
LISA: Sensing Spacetime Vibrations

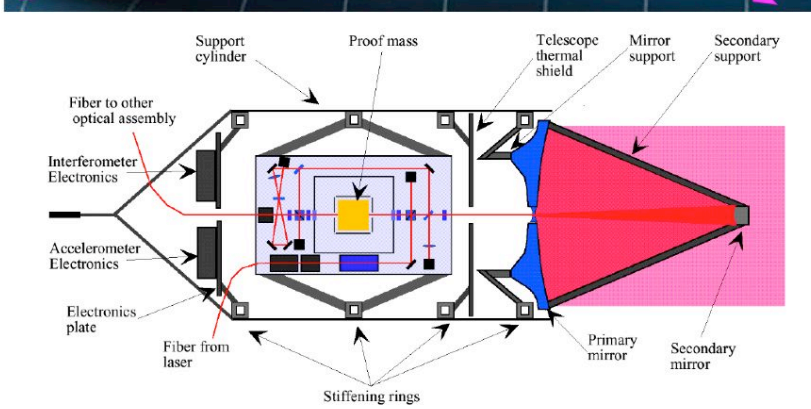
Gravitational Waves are an entirely new way to explore the Universe

- Caused by motions of mass and energy
- Waves penetrate:
  - any matter
  - black holes from the event horizon
  - early universe from singularity
- Waveforms record in precise detail the motion of distant matter
- Frequencies probed by LISA (~0.1 to 100 mHz) are rich in gravitational activity



LISA mission design: low frequencies from space

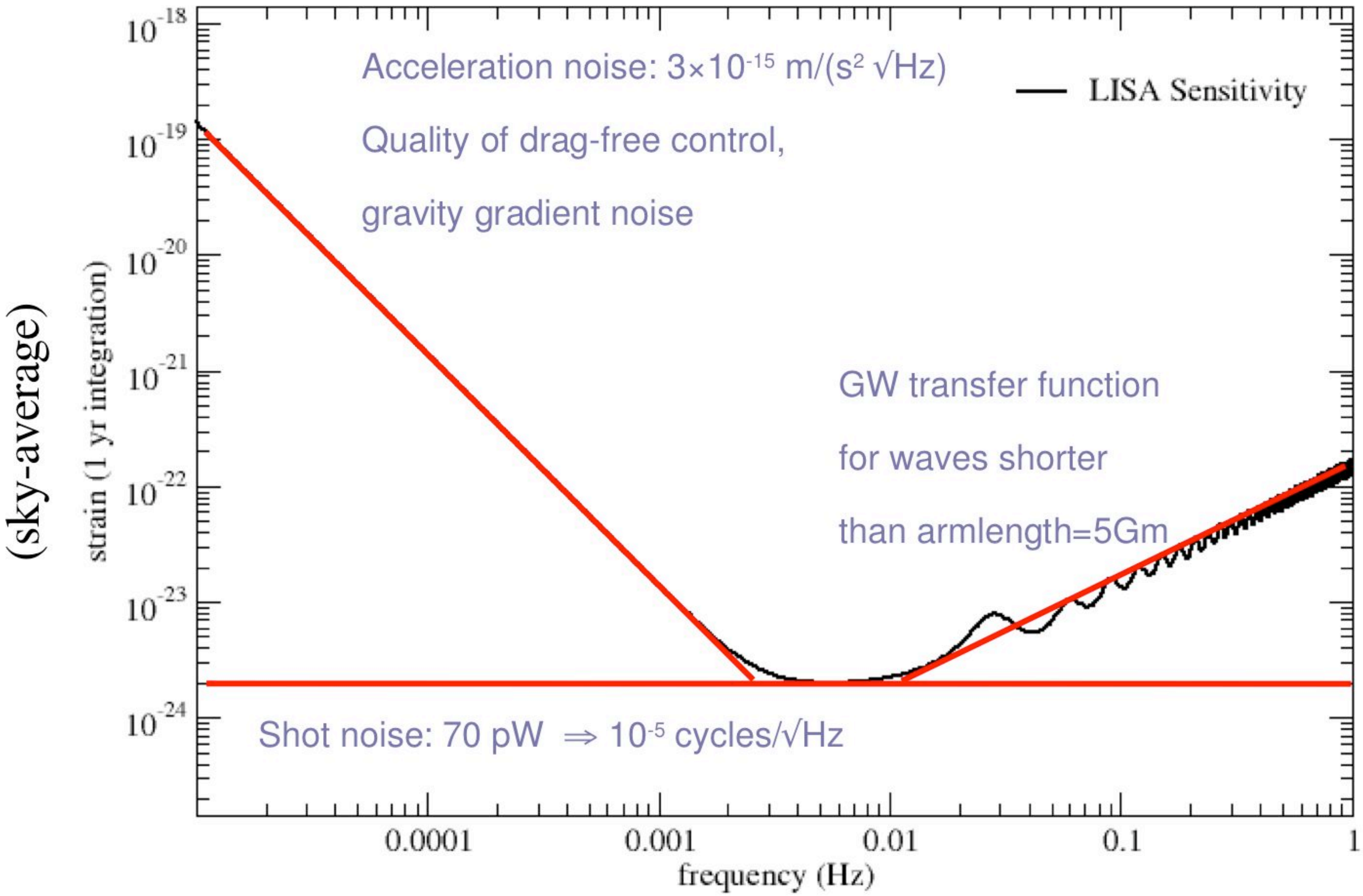




How LISA works:

- 3 spacecraft, orbiting sun
- 5 million km separations
- Two 1.9kg proof masses, two 40cm telescopes, and two phase-locked 1W lasers in each spacecraft.
- NO constellation control. Micronewton thrusters only to keep each s/c following its proof masses and all pointed at each other.
- 5 year mission (limited by component failure, not consumables)

Instrumental Noise and LISA *h* sensitivity

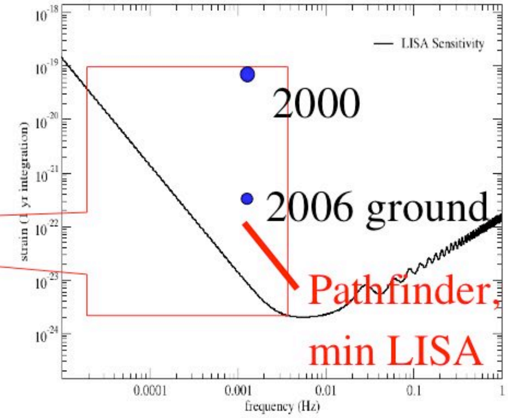


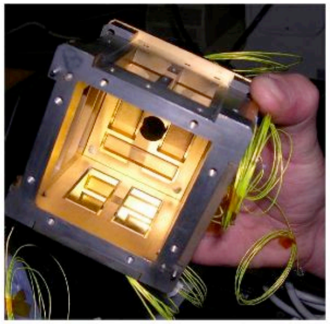
Can we actually attain this *h* sensitivity?

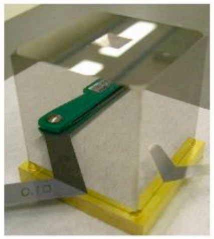
Yes!

Acceleration noise requirement on proof mass requires:

- •Micronewton thrusters for s/c control
- •low-noise Proof mass sensing
- •low-noise servo control loop

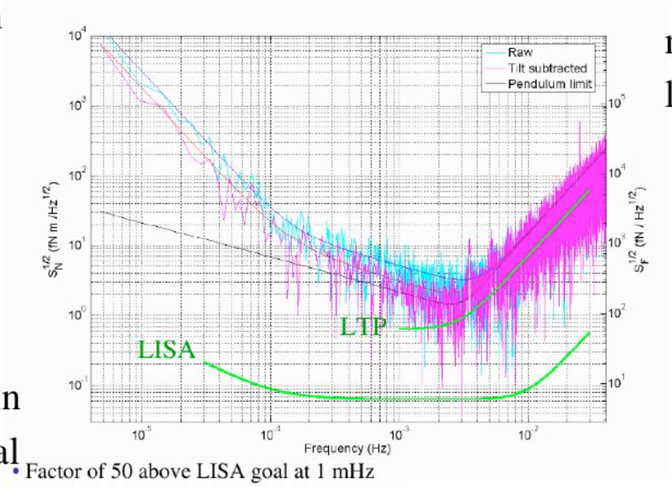






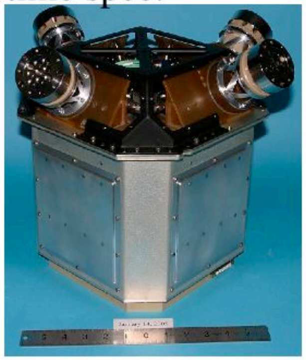
Torsion pendulum tests: limited by fiber and gravity gradient noise on earth. LISA Pathfinder will check noise 5x deeper (=LISA min mission; LISA goal 50 deeper at 1mHz.

Sensor force noise upper limits from torsion pendulum noise data



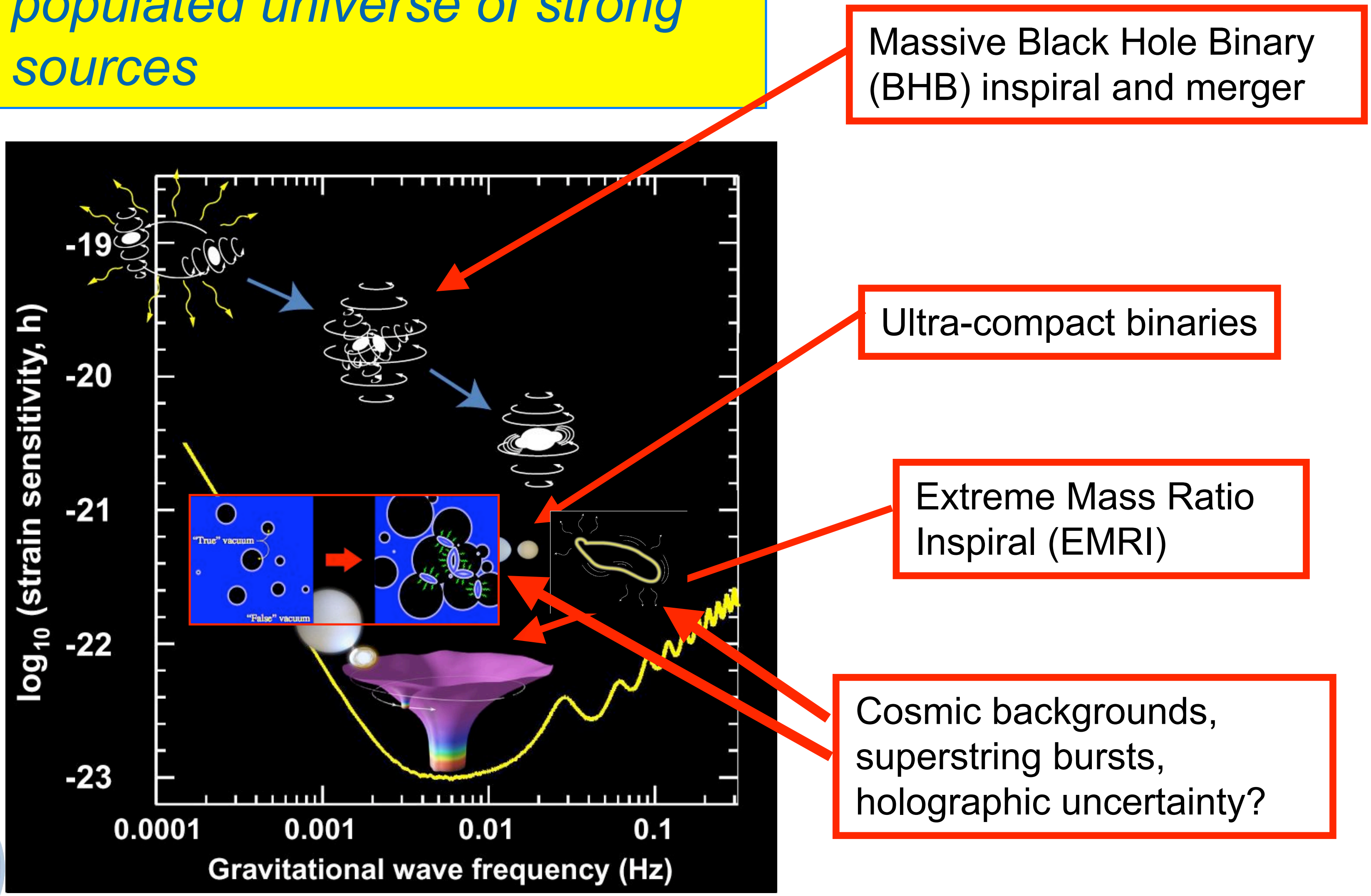
- Factor of 50 above LISA goal at 1 mHz
- Factor of 300 above LISA goal at 0.1 mHz

Busek colloid thrusters exceed LISA reqs on noise, linearity. LTP lifetime spec.



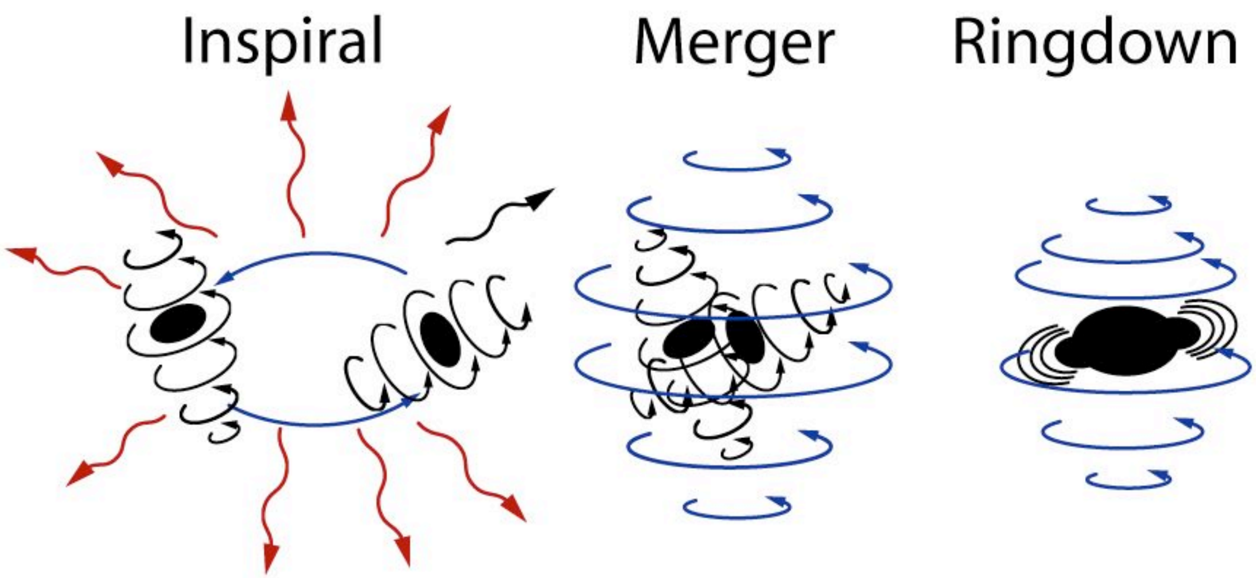
Strong Signals in the LISA frequency band

LISA signals record a richly populated universe of strong sources



Black Hole Binaries: cataclysms of pure vacuum spacetime

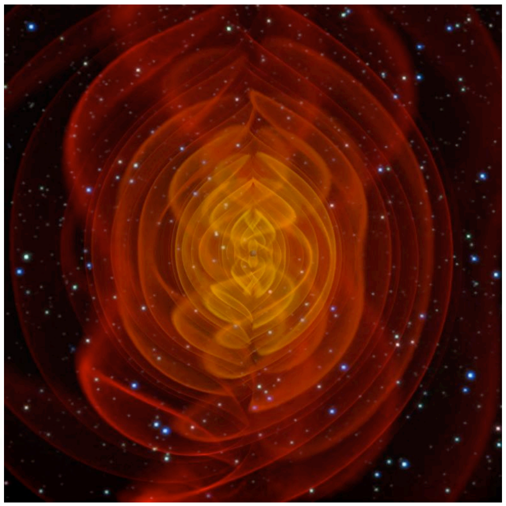
Signals from inspiral, merger and ringdown of massive binary black holes test General Relativity's most violent dynamical behavior



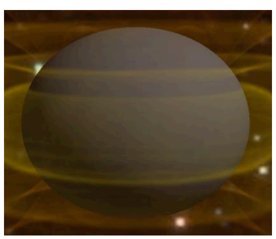
- Inspiral: precision better than 1% on black hole masses, spins, orbits, direction, distance
- Merger/Ringdown: dynamical behavior of spacetime interacting with itself

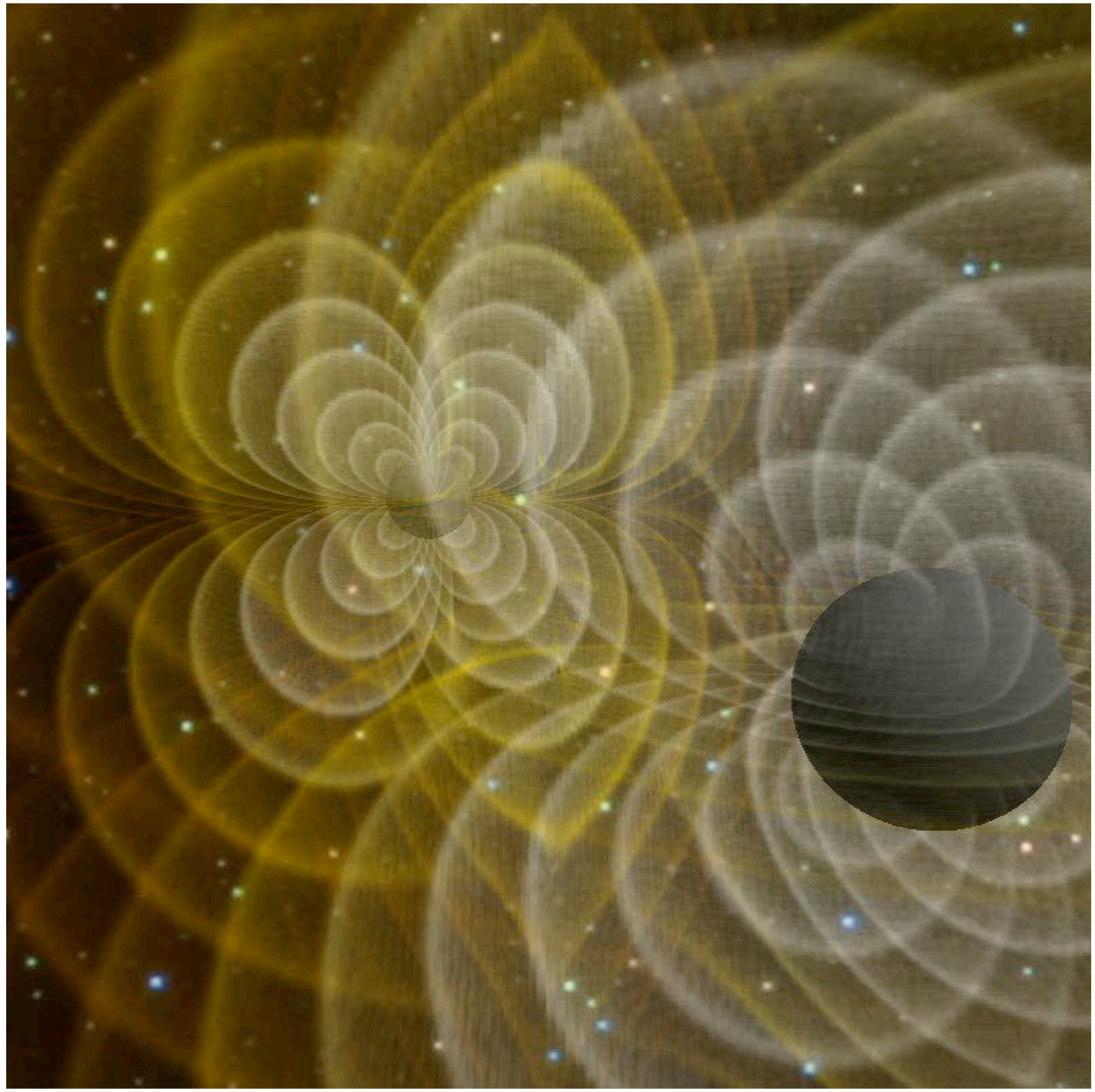
Dynamical Spacetime

Numerical tools are in hand to interpret LISA data using General Relativity in extreme spacetimes



Red shows gravitational radiation



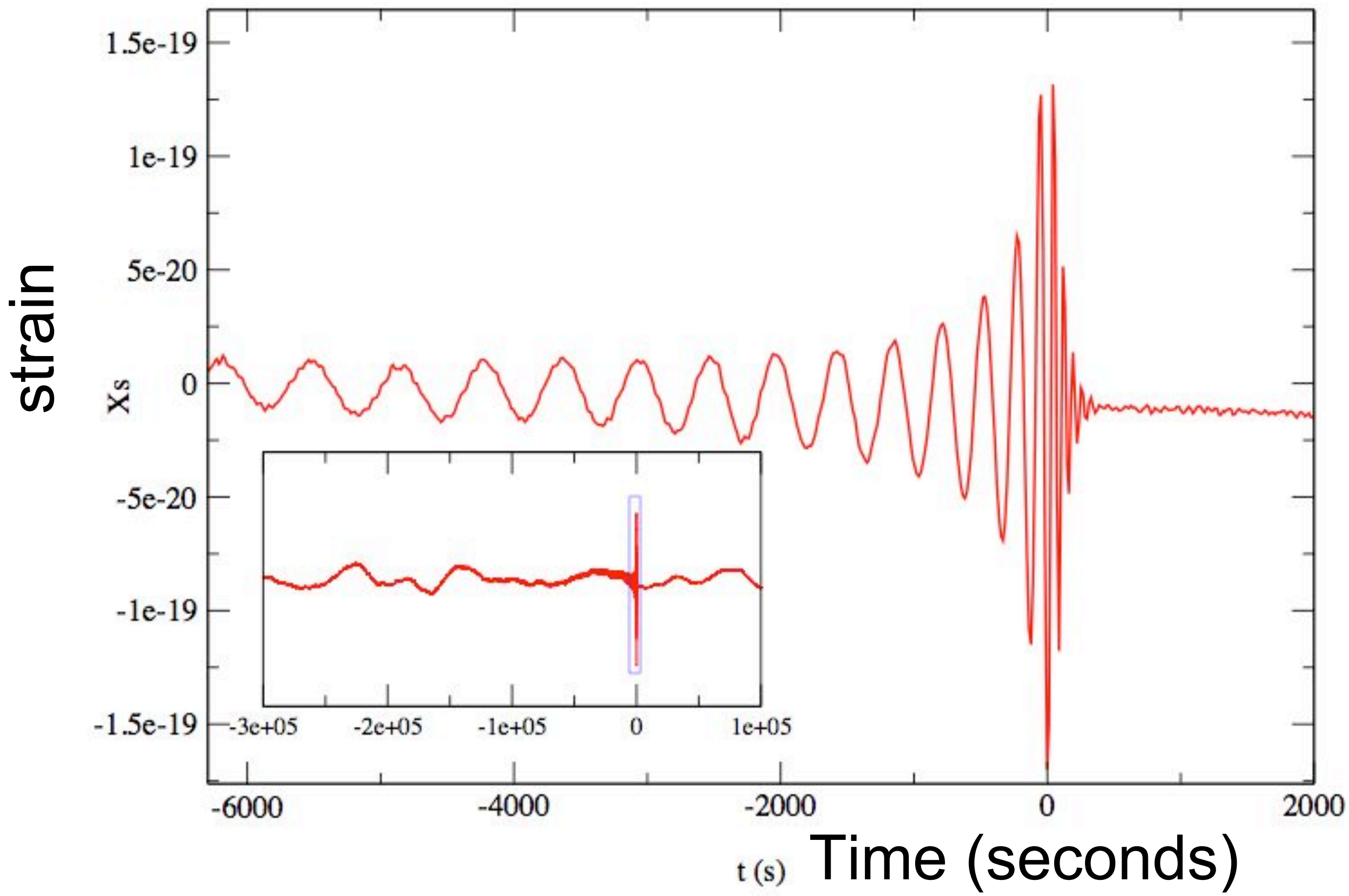


(computation NASA/GSFC,visualization NASA/Ames)

Signal from black hole merger event

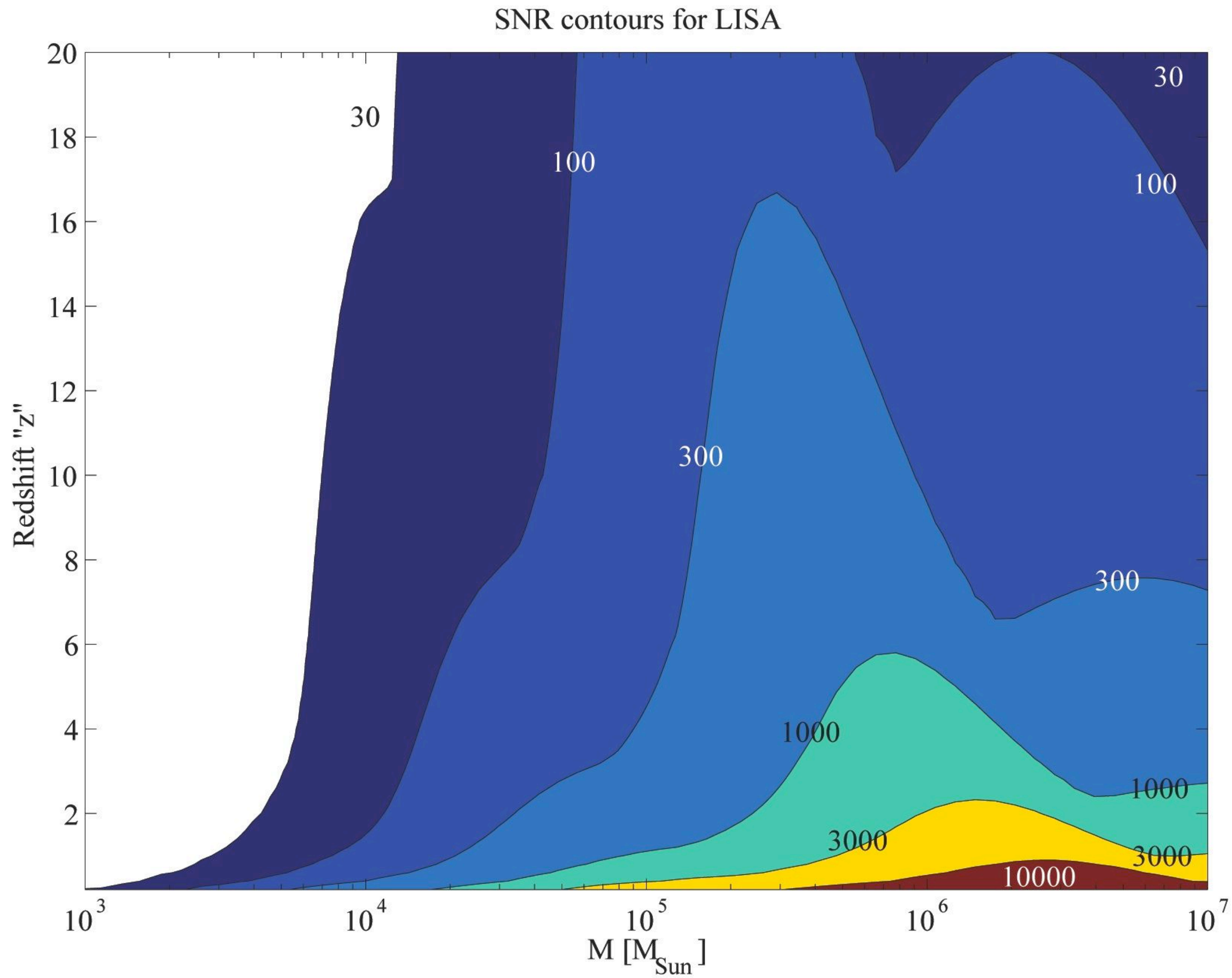
Merger signals have high SNR even in a single wave cycle

Simulated LISA datastream:
two $10^5 M_\odot$ BH at z=5, simulated noise (S/N~500)



Massive Binary Black Holes: strong signals

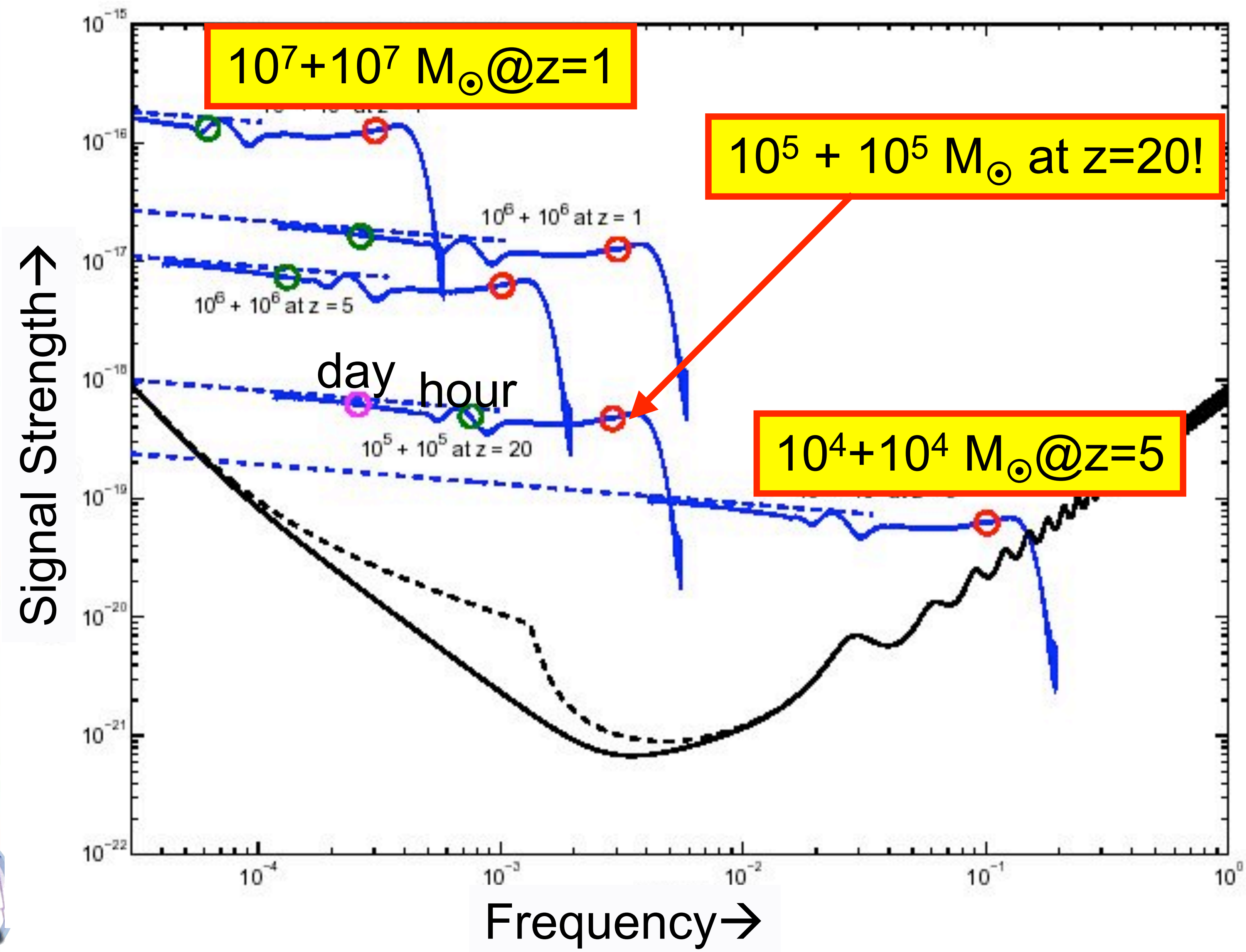
Contours of SNR, equal mass merger (optimal)



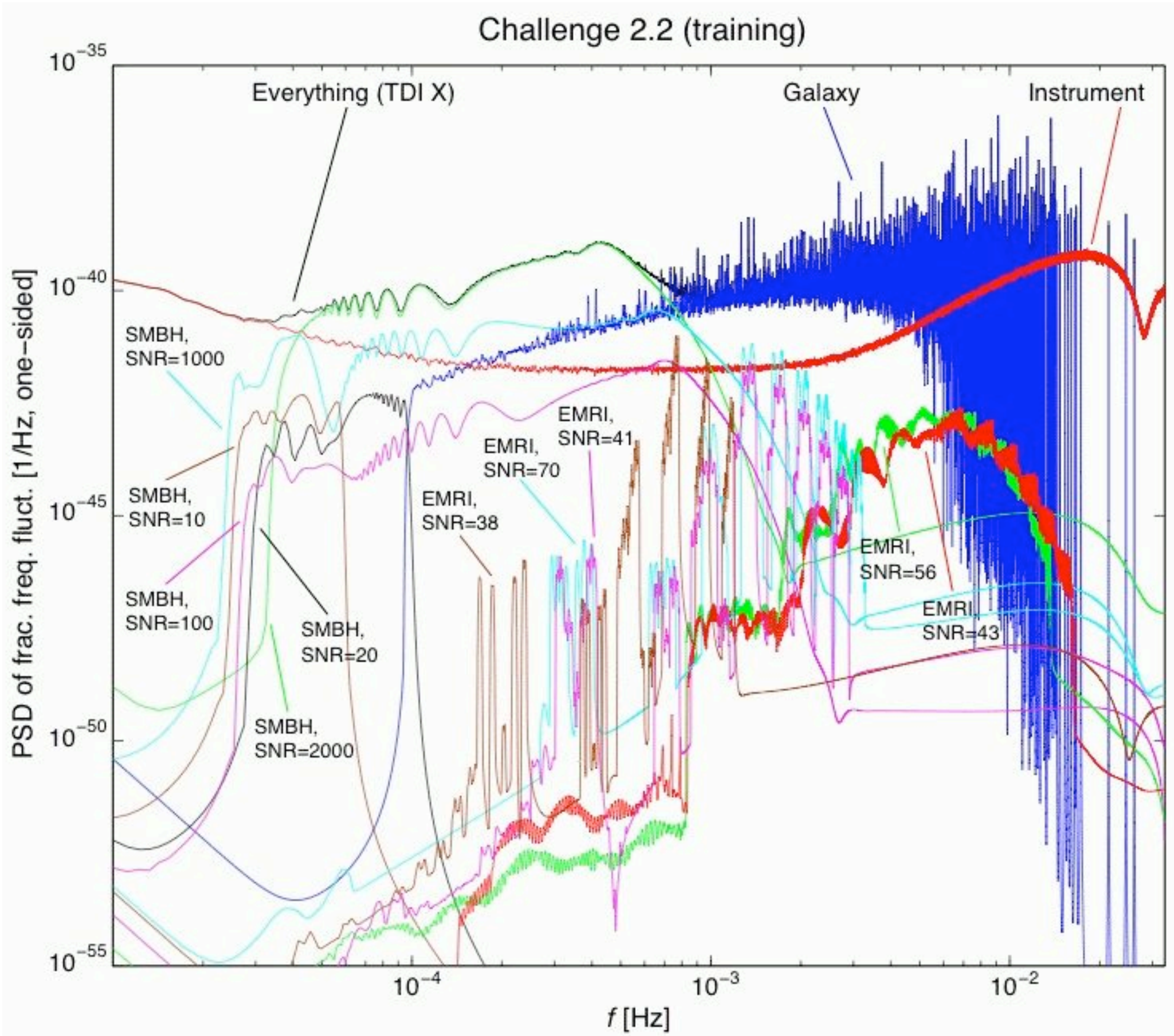
Redshift→

Mass→

Massive Binary Black Holes: signal evolution

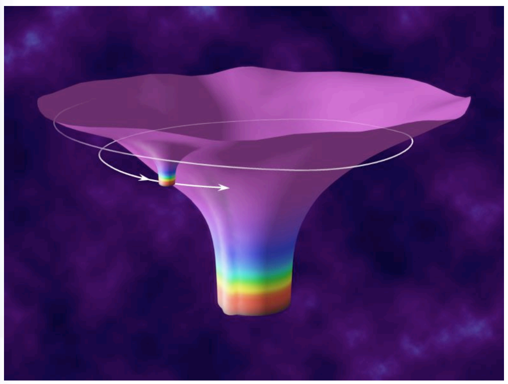


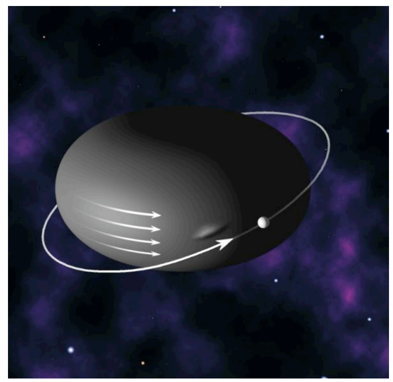
Signal extraction: Mock LISA Data Challenges



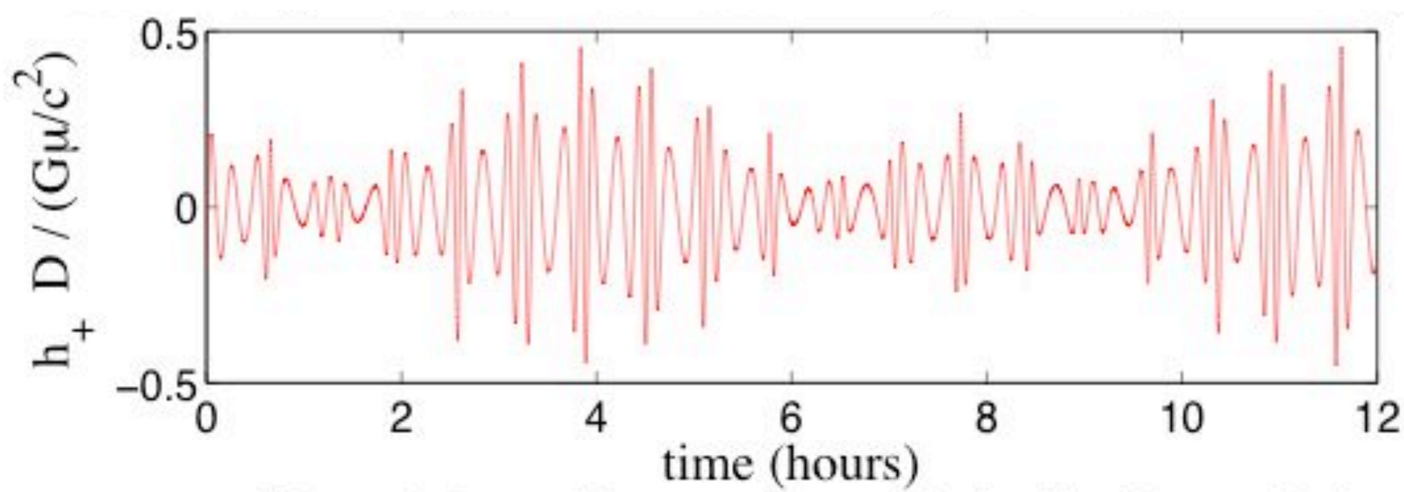
How well does General Relativity describe real black holes?

Waveforms of Extreme Mass Ratio Inspirals (EMRIs) test the unique Kerr black hole solutions of GR



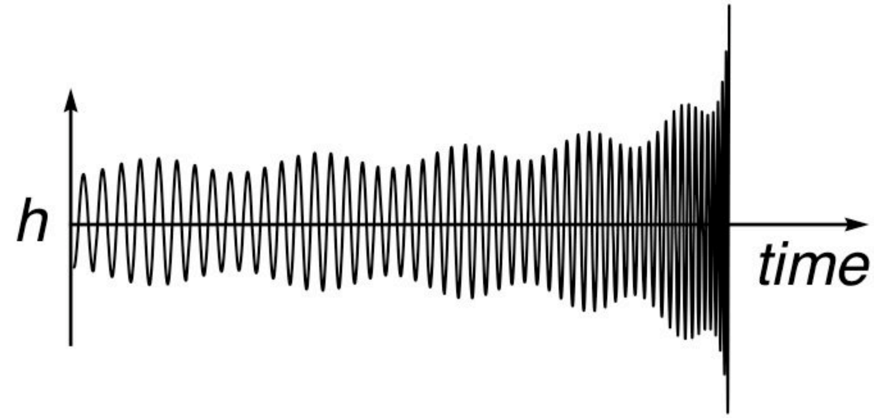


- ~10^5 orbits
- Rich waveforms test:
  - "No-hair Theorem" of General Relativity to ~0.01% accuracy
  - Response of dynamical tide on horizon to ~1%



Absolute Distances from Black Hole Binaries

Waveforms of black hole binaries give precise, gravitationally calibrated distances to high redshift



Absolute luminosity distances can be derived *directly* from

– amplitude

– orbital frequency

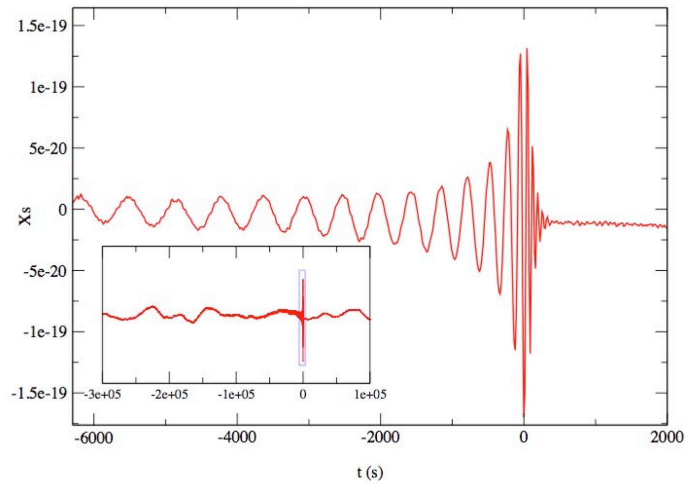
– chirp time

1. Distances accurate to 0.1% to 2% per event
2. Absolute, physical calibration using only gravitational physics

Principle of absolute distance measurement

- Orbital period ~ chirp time at the moment of merger
- Gives absolute Schwarzschild radius or size of final hole,

$$size \cong \frac{c}{\text{frequency}^2 \times t_{\text{chirp}}}$$

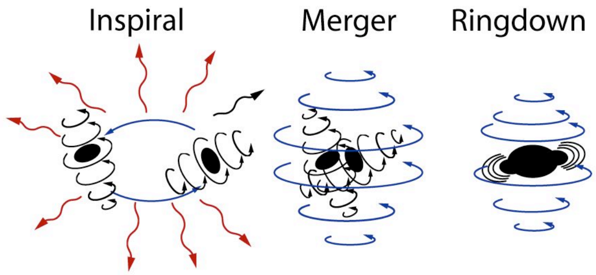


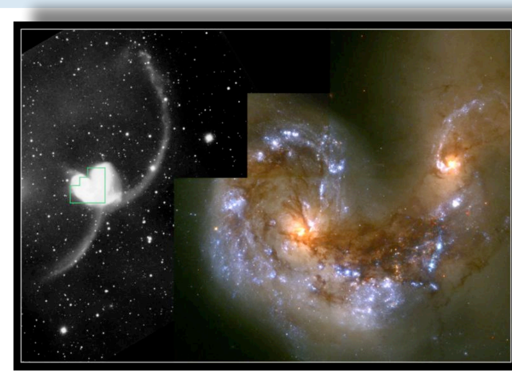
Amplitude gives ratio of BH size to distance, thus

$$\text{Distance} \cong c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}$$

(absolute mass is degenerate with cosmic redshift)

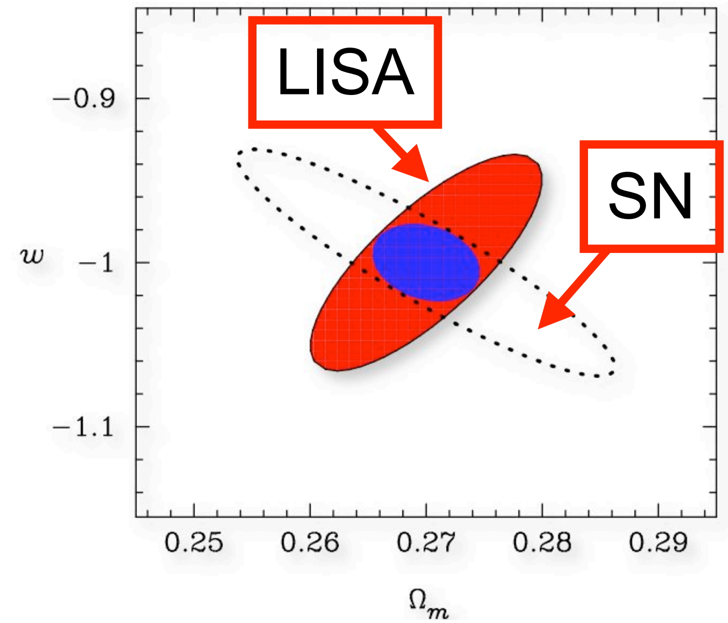
Absolute Distances: Hubble Constant and Dark Energy





H_0 and Dark Energy parameters potentially measured to <1%

- 100's of MBH expected to z~20
- ~100's of EMRIs to z~1
- Cosmological test requires (independent) redshift of host
- Noise from weak lensing at z>1
- Comparable precision to CMB, WL, BAO, CL, SN techniques
- *Absolute* & *Independent* measurement

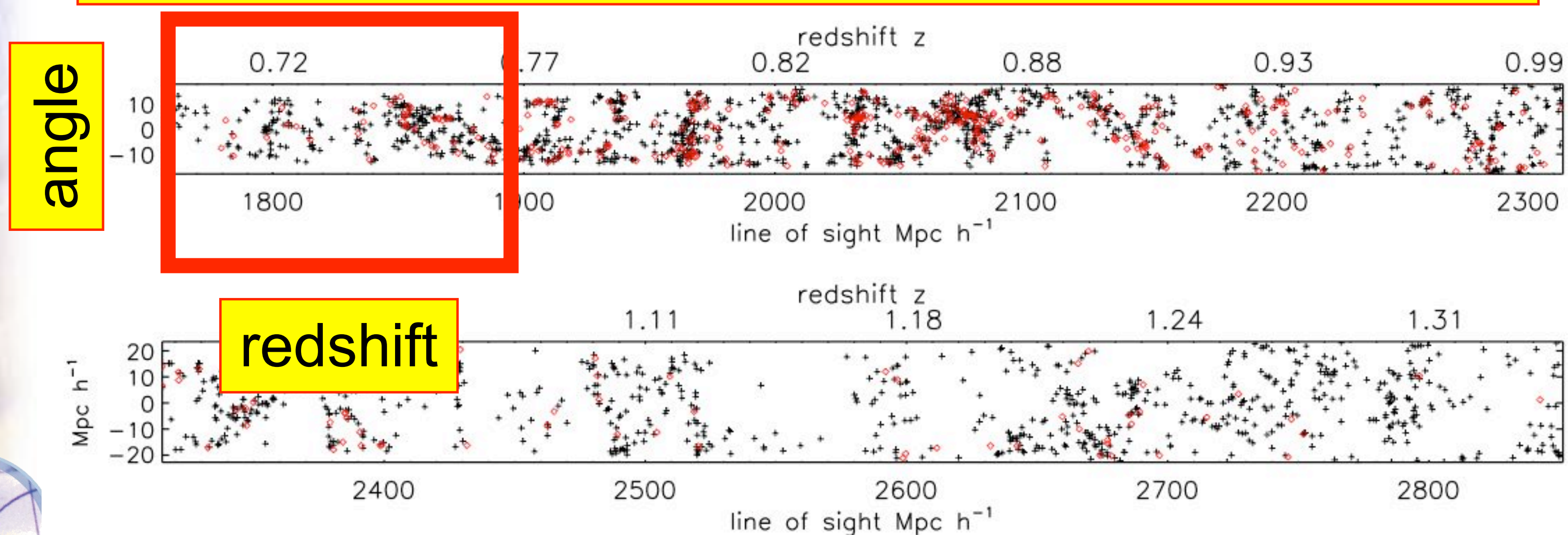


100 BHB, 3000 SNIa (Dalal et al 0601275), includes lensing noise

Statistical redshifts for precision cosmology

- Galaxies are highly clustered: "cosmic web"
- Redshift surveys in BHB error boxes at moderate redshifts (e.g. EMRIs at z<1) can yield some z information statistically without identification of individual hosts
- With high EMRI rates, H_0 to ~1% possible

LISA/EMRI angle+distance + "cosmic prior" error box



Statistical EMRI Redshift Information without IDs

- Mock EMRI fields in SDSS: galaxies "vote" on the Hubble constant
- Better than one percent absolute precision

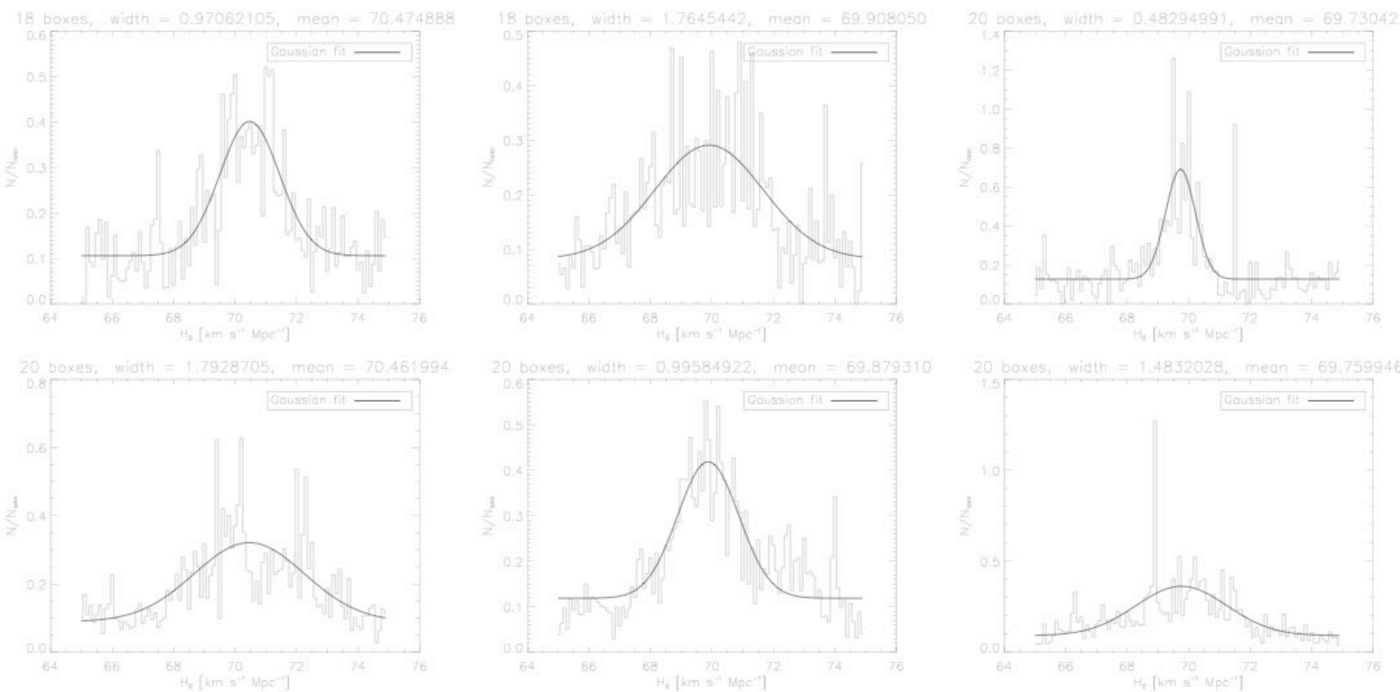
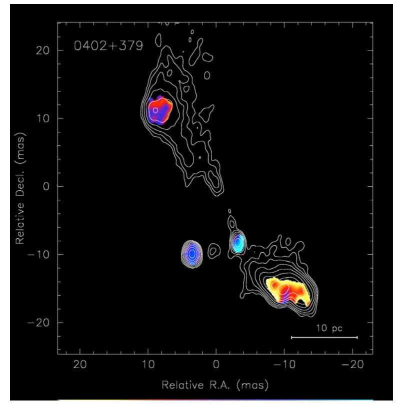


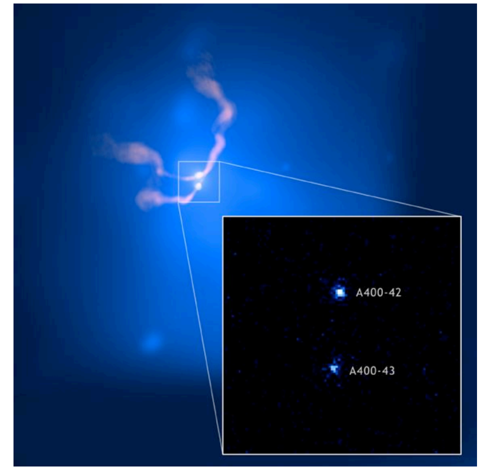
FIG. 2: Summed histograms for one synthetic interferometer, scaled to represent events at $z_{LISA} = 2z_{SDSS}$ (top row) and $z_{LISA} = 3z_{SDSS}$ (bottom row).

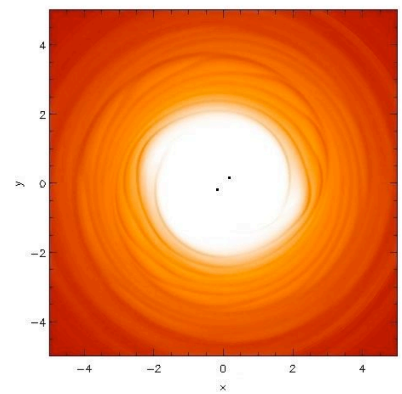
C. MacLeod, CJH

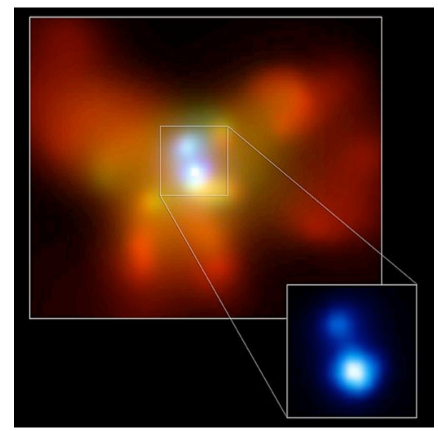
Visible signals from gravitational wave sources

LISA sources have possible electromagnetic counterparts over a wide variety of wavebands and timescales: an exploratory bonanza for wide field synoptic imaging and spectroscopy

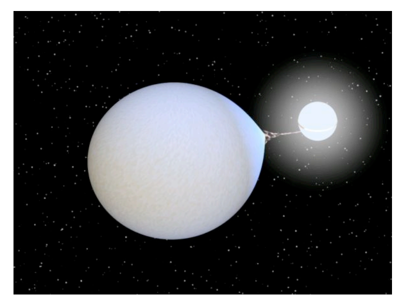




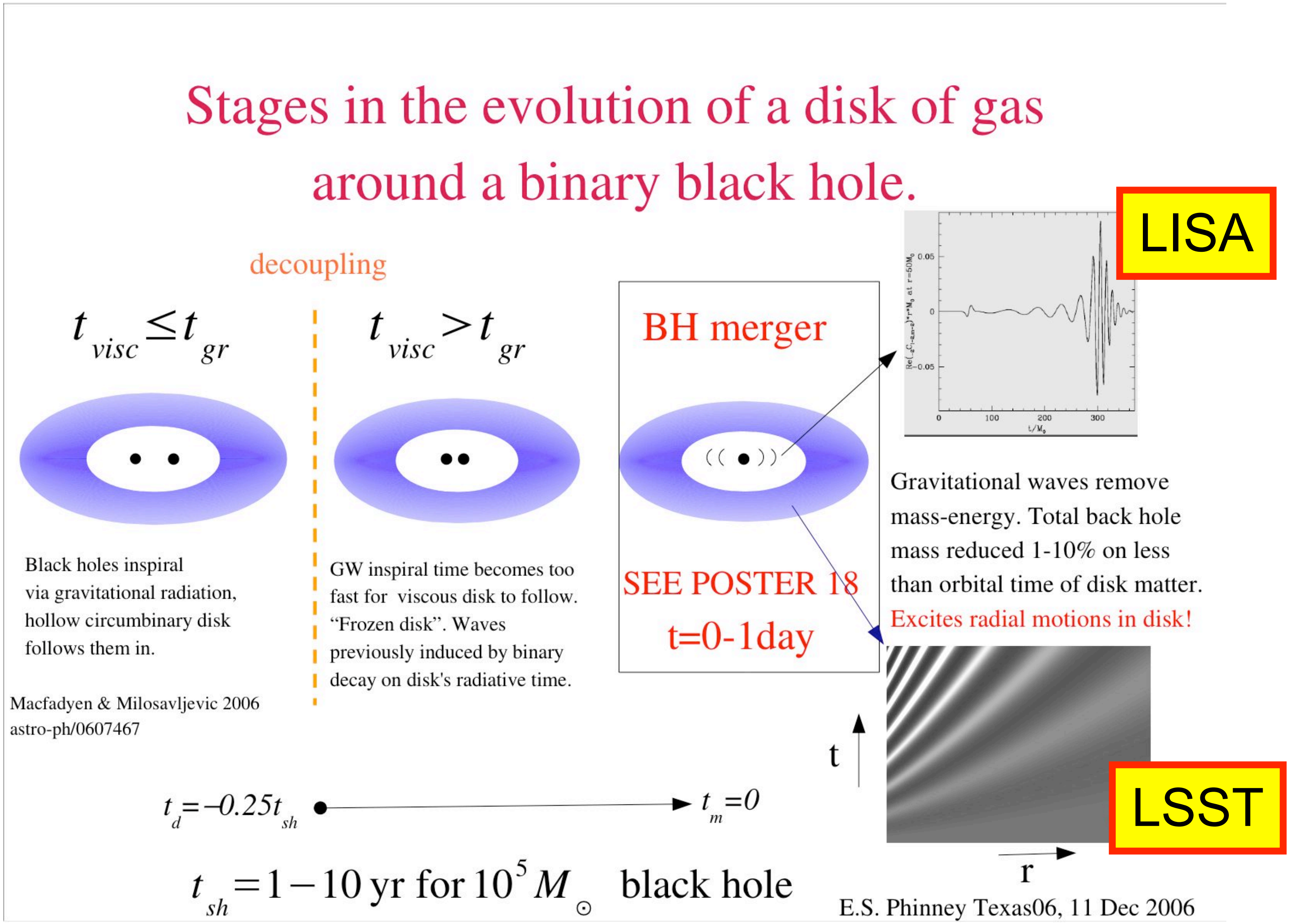




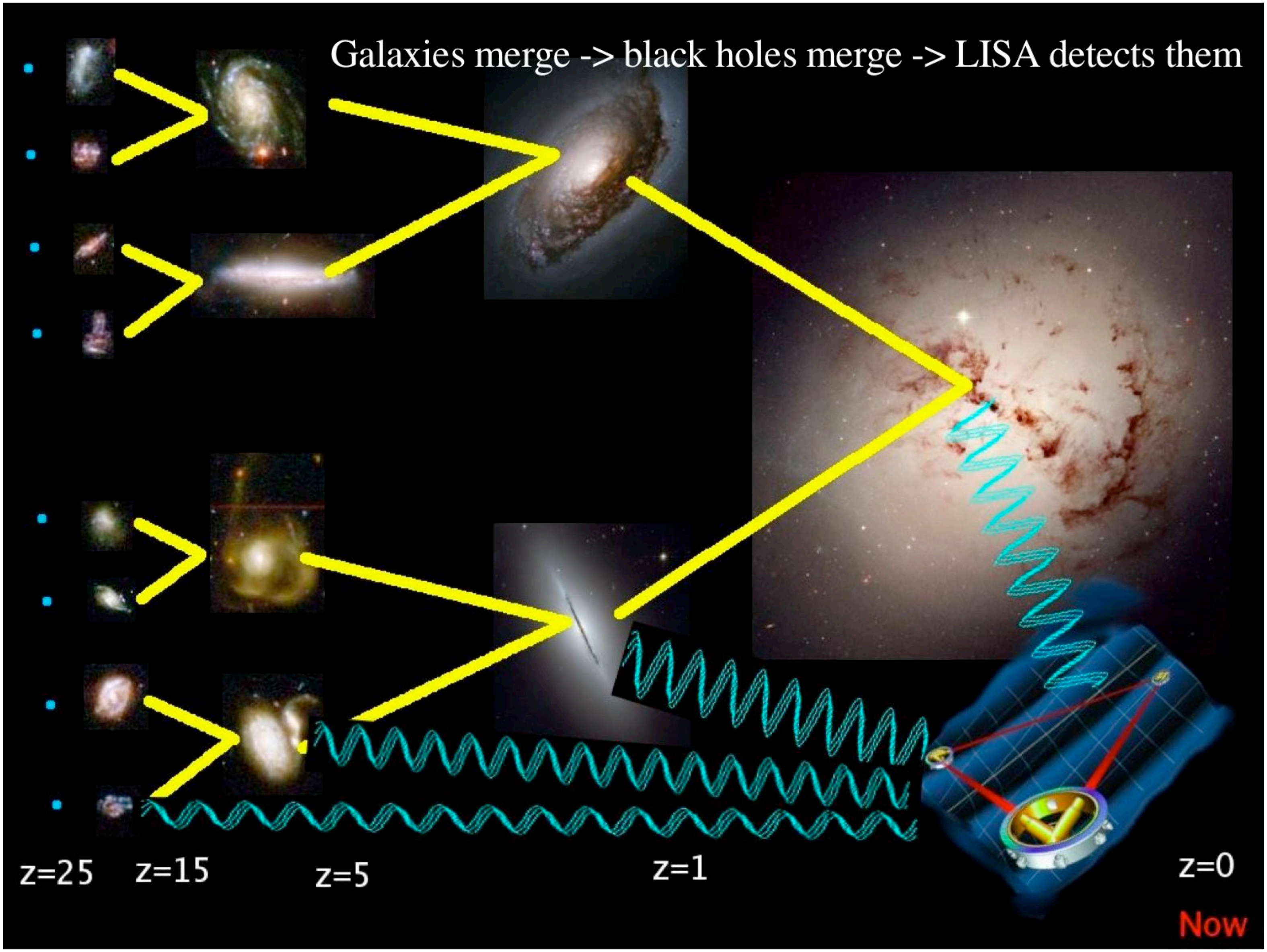
- Black-hole mergers in real time
  - hours to weeks notice within 1°
- Precursor, prompt and afterglow emission from gas around black hole mergers: radio to X-rays
- Host galaxies: infrared nuclear starbursts to z~10 (JWST)
- Tidally heated, eclipsing and accreting white dwarf binaries (several known already)



Optical counterparts: accretion disk variability

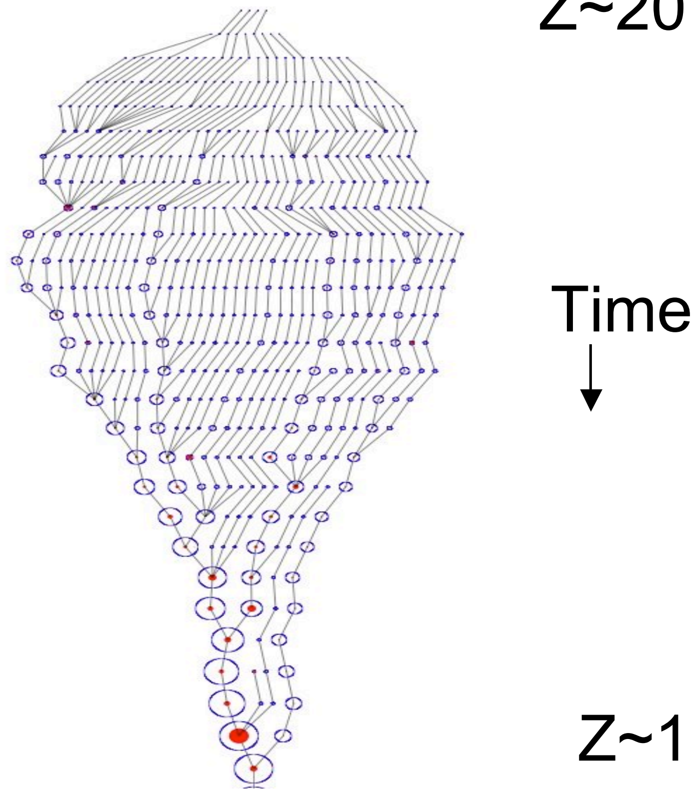


History of massive black hole mergers



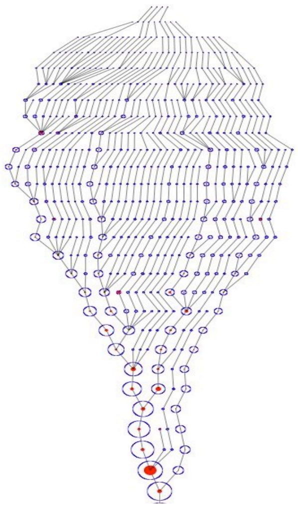
LISA directly observes growth of massive black holes

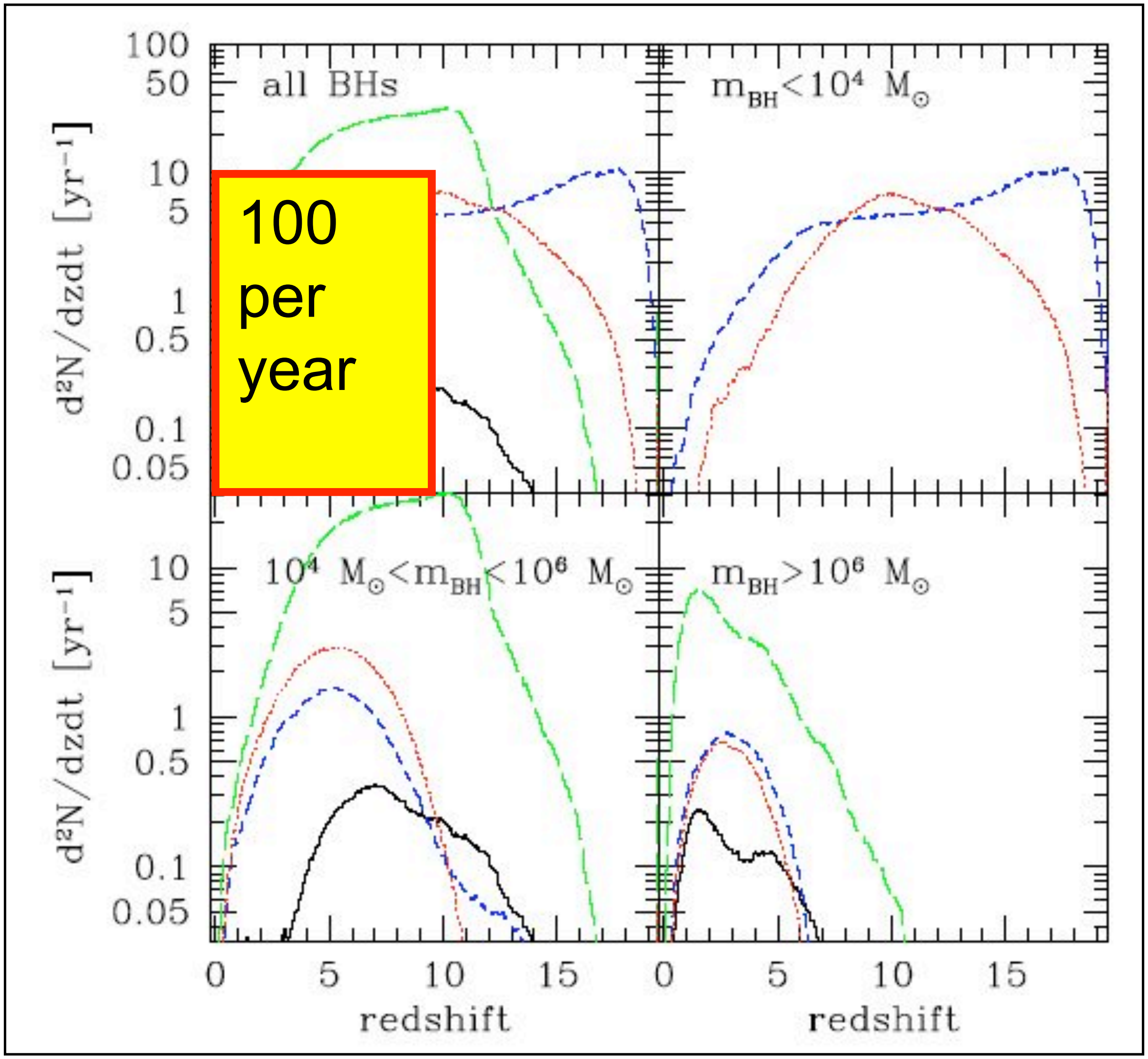
BH mergers at high redshift record in detail the history of galaxy formation and nuclear evolution



- ΛCDM cosmology predicts 100’s to 1000’s of LISA black hole merger events
- Merger events record seed masses, growth/merger history, mass and spin since z=20

MBH merger rate estimates in ΛCDM scenarios





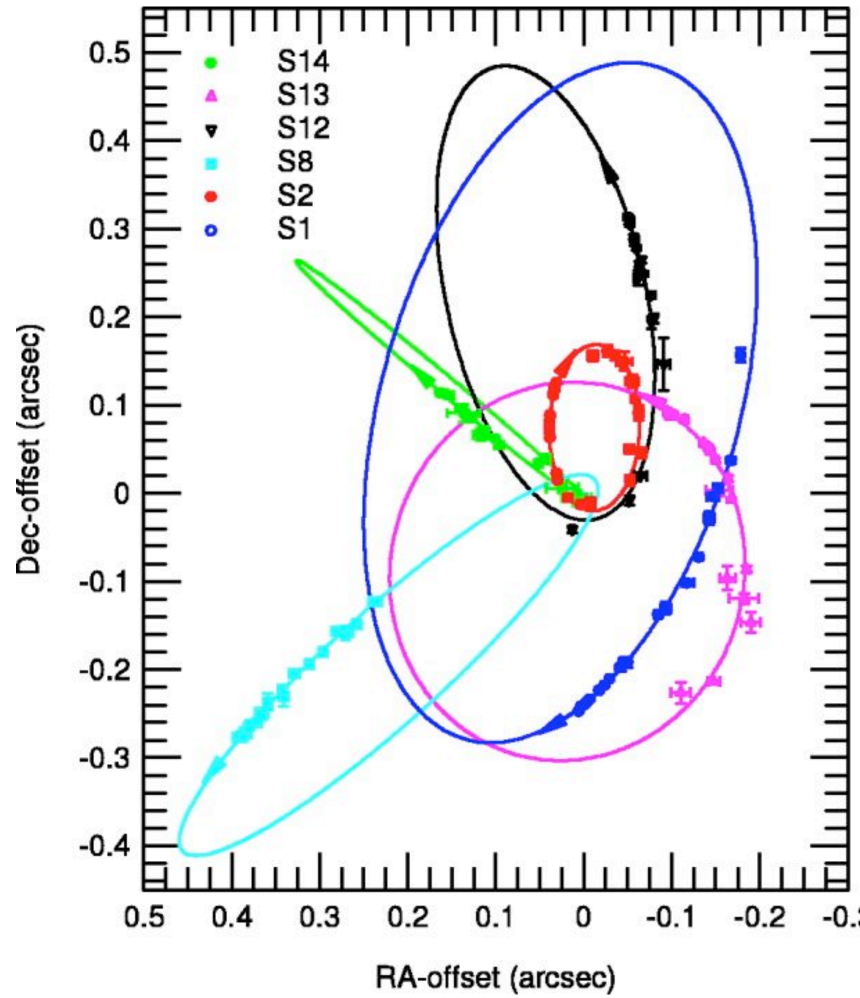
Predicted rates of massive binary black hole coalescences. Red, blue curves: scenarios with $150M_{sun}$ black hole seeds resulting from the collapse of the first stars formed at z > 20. Black, green curves: scenarios with heavy seed black holes, 10^{4-5} M.

Sesana, Volonteri et al.

Galaxy nuclei: Massive Black Holes and What Else?

LISA will help reveal the rich astrophysics of stellar populations interacting with central black holes

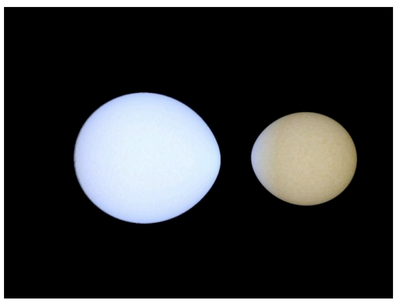
- ordinary stars, black holes, neutron stars, white dwarfs, brown dwarfs captured and swallowed
- Waves emitted during MBH banquet
- Spins of BHs measure angular momentum history

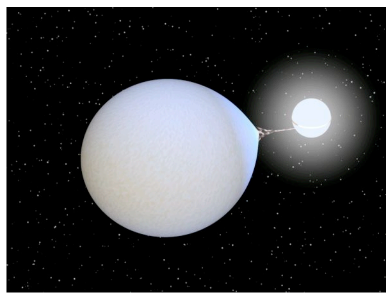


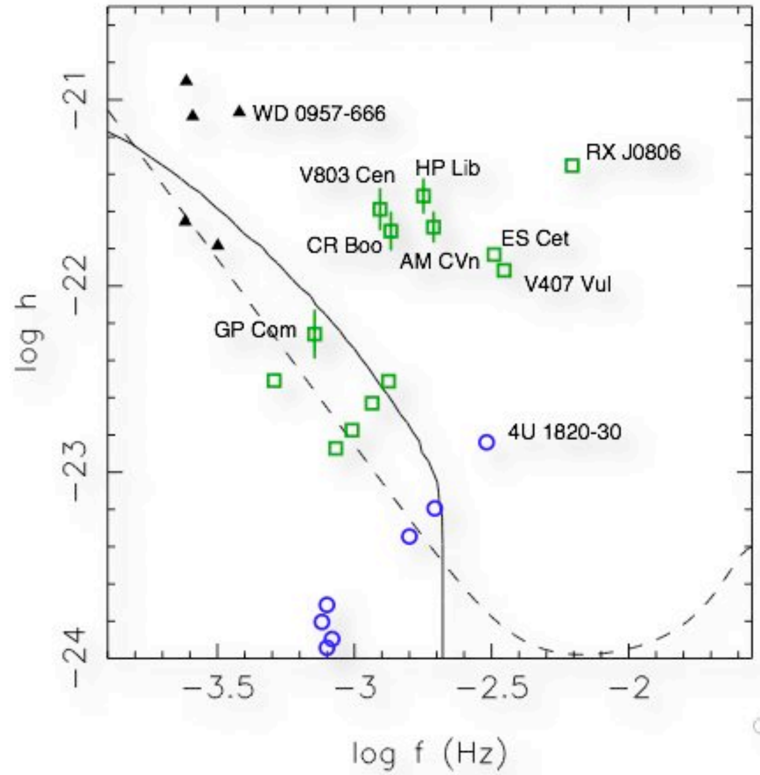
MBH in Milky Way

Exploring a new Galaxy of compact binary stars

LISA will measure orbital motions and 3D positions throughout our Galaxy of binary stars at the extreme endpoints of their evolution



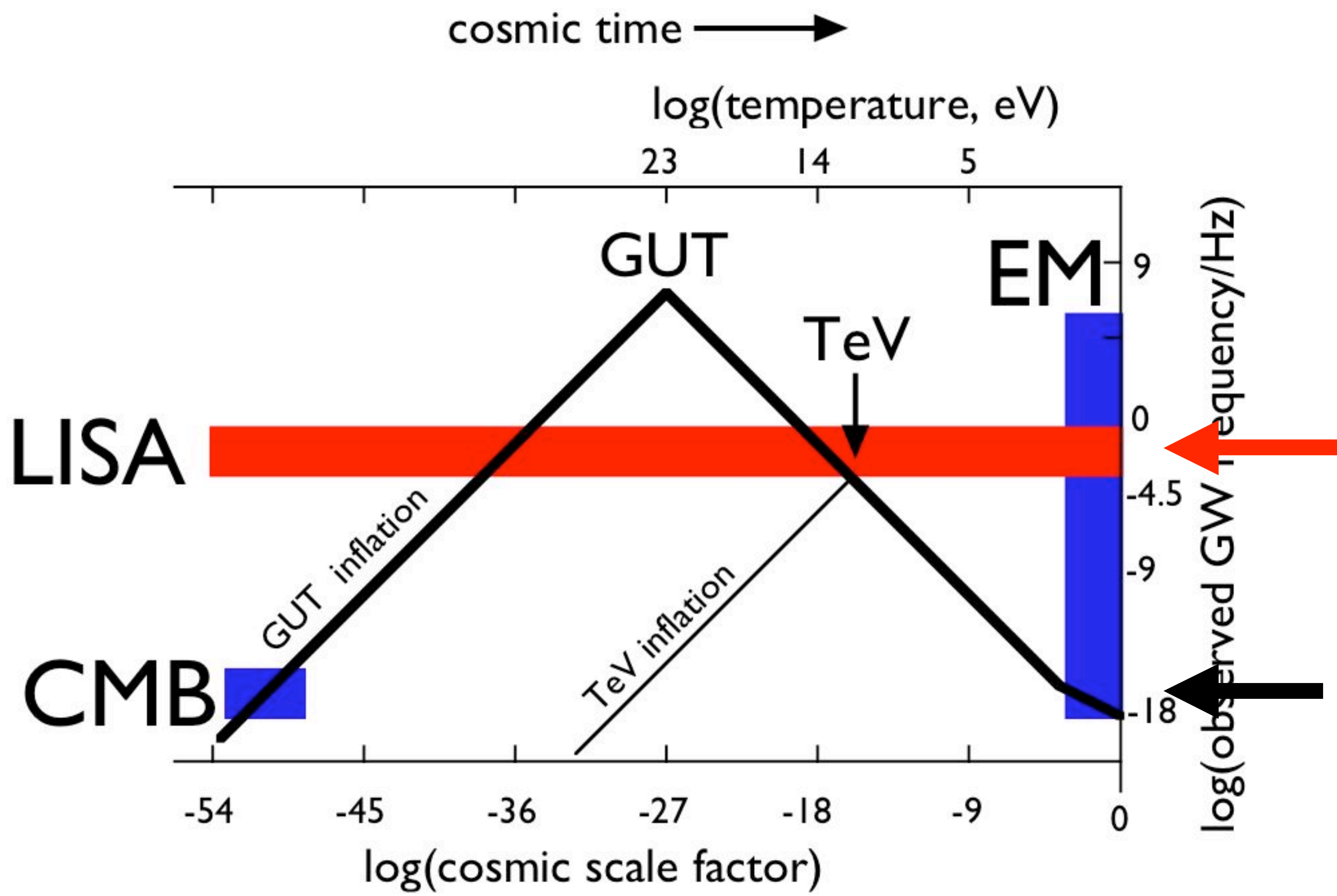


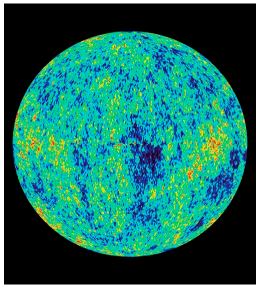


- ~10 known binaries are guaranteed “verification sources”
- ~10,000 more will be individually detected
- Millions contribute to low frequency confusion background
- Extreme degenerate stars (mainly white dwarfs, some NS, BH)
- Precursors of Type Ia SNe, millisecond pulsars, exotic novae

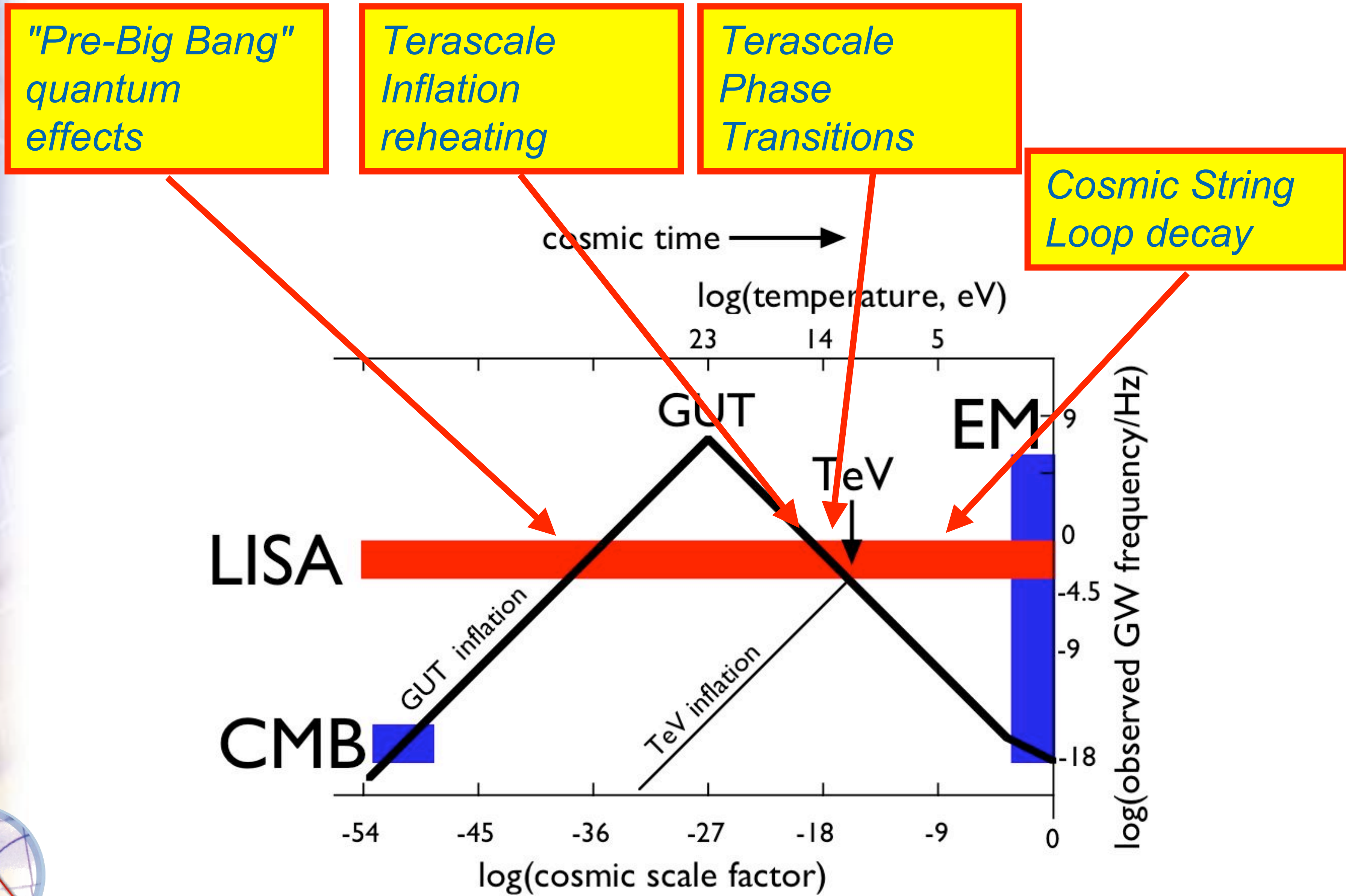
LISA and photons see different slices of cosmic history

With a new way of observing motions of all forms of mass-energy back to the beginning of the universe, LISA may discover entirely new phenomena



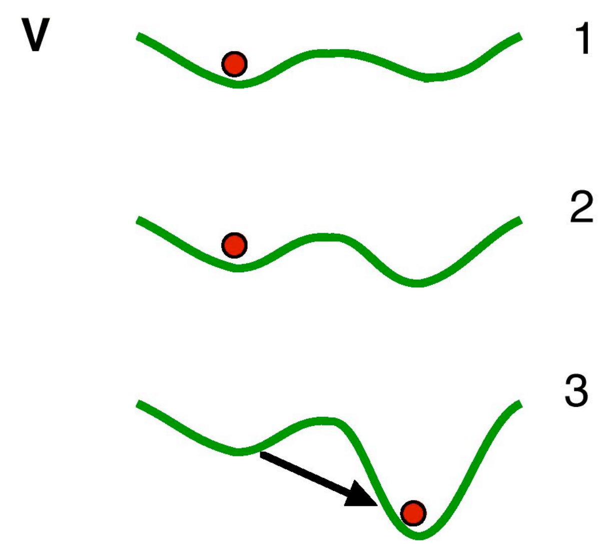


Sources of Primordial Noise Associated with New Physics



Decay of vacuum: free energy into bulk relativistic flows

- Free energy associated with Higgs mechanism (standard model, grand unification, inflation,….)
- Decay by phase transition: intermediate stage of mesoscopic flows before eventual thermalization
- Flows of mass-energy lead to gravitational waves that survive to the present

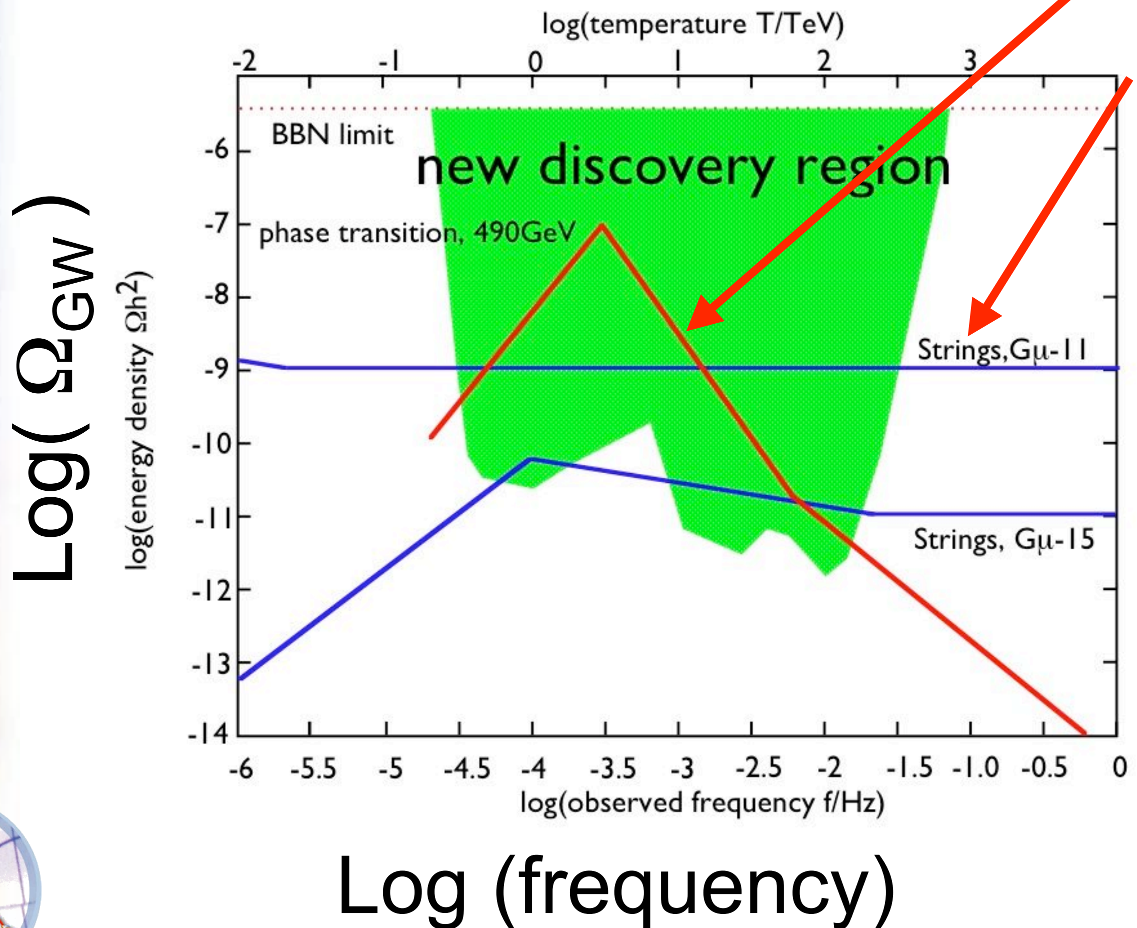


Gravitational Wave Backgrounds

LISA could show evidence of new physics from the early universe: phase transitions or strings

Background spectra from:

- Terascale first-order phase transitions
- Cosmic superstring loops



Energy density of background

A "Roaring Big Bang": loud end to inflation?

•"Preheating", second order transition: inflationary reheating thermalizes via turbulent cascade

•Free energy converts into horizon-scale bulk flows

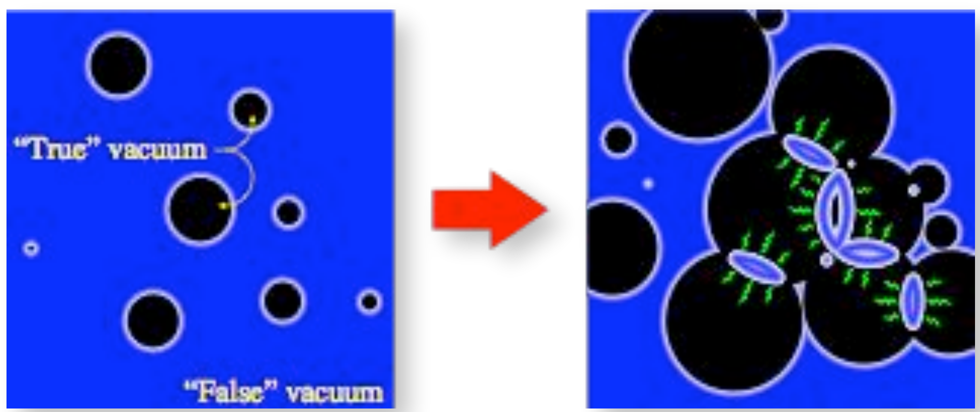
• gravitational waves survive

•In LISA band for ~Terascale reheat temperature

Khlebnikov & Tkachev, Felder & Kofman, Easther & Lim

First-order phase transitions at the Terascale

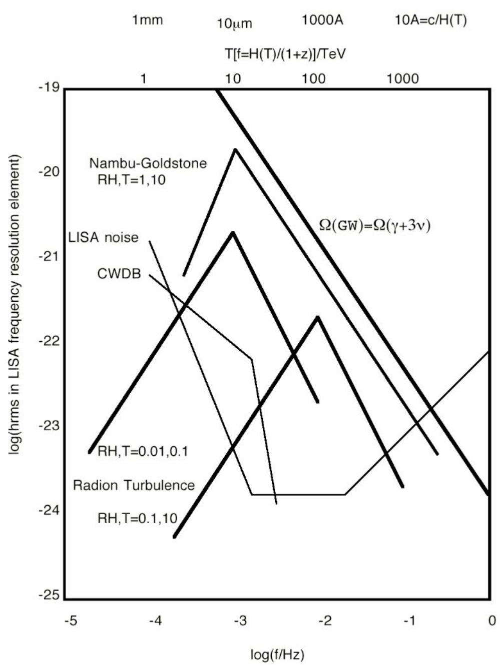
- Nucleation, Cavitation, Explosive Bubbles
- Collisions, Turbulence give GW
- Scale up to 1% of horizon
- Efficiency up to few %
- Frequency in LISA range for ~0.1 to 1000 TeV
- Electroweak? Baryogenesis? Extra dimensions?

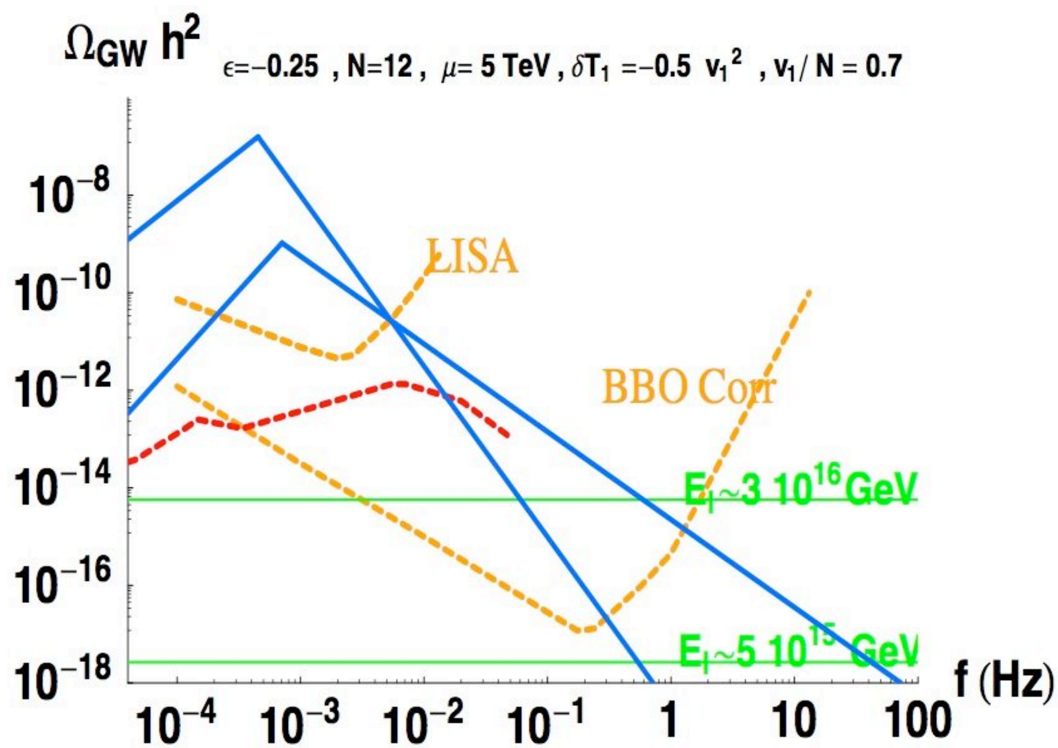


Witten 1984, CJH 1986, 2000, Kosowsky & Turner 1992, Kamionkowski et al. 1994, Kosowsky et al. 2002, Dolgov *et al.* 2002, Randall &Servant 2006

Background from formation of extra dimensions

- Free energy from brane stabilization
- Background from transition from AdS-Schwarzschild phase to RS1

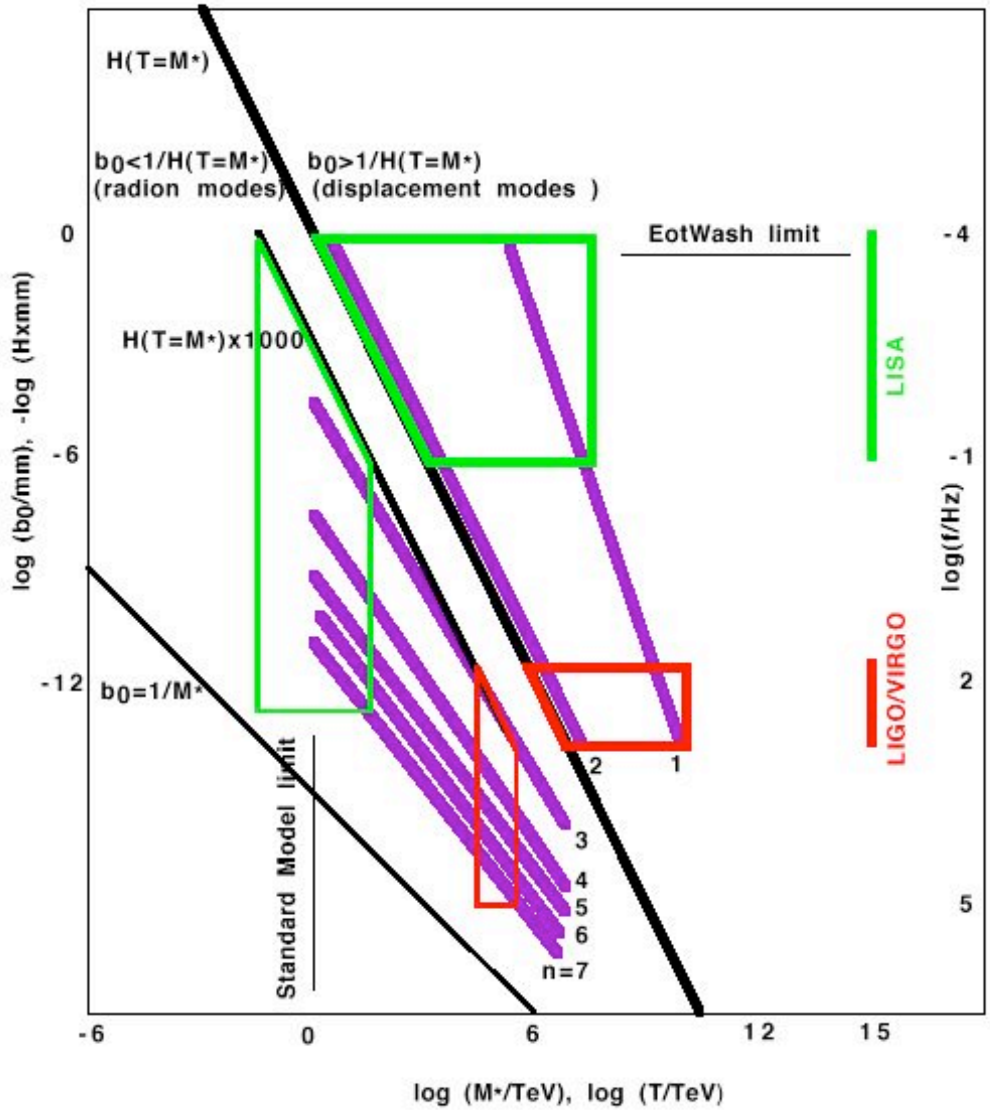




CJH, Randall & Servant

Extra dimensions probed by LISA, LIGO, VIRGO

Size of n largest extra dimensions, Hubble length

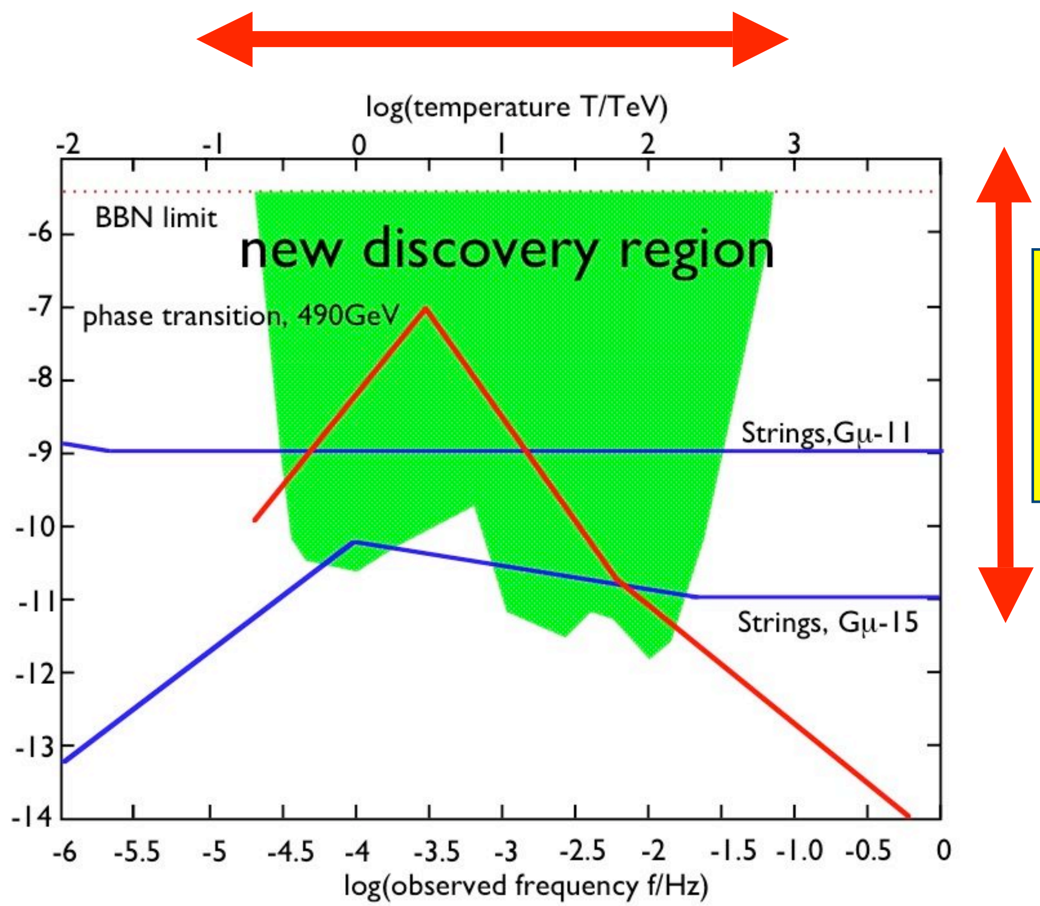


CJH 2000

Unification scale, temperature

Sensitivity of LISA to new physics of vacuum energy

LISA frequencies span critical temperatures from 0.1 to 1000 TeV



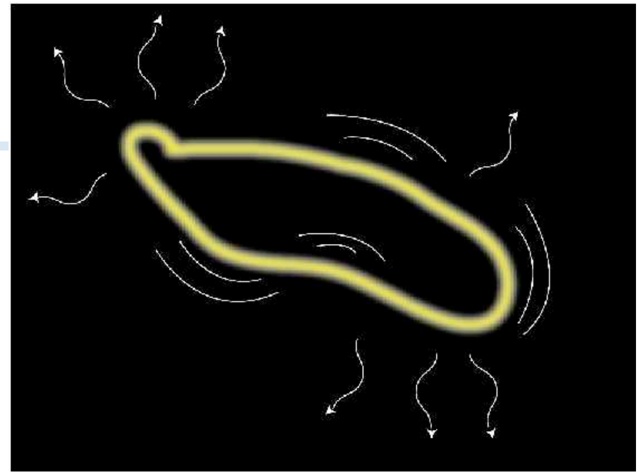
Log(Ω_{GW})

Log (frequency)

GW production efficiency as small as 10^{-7}

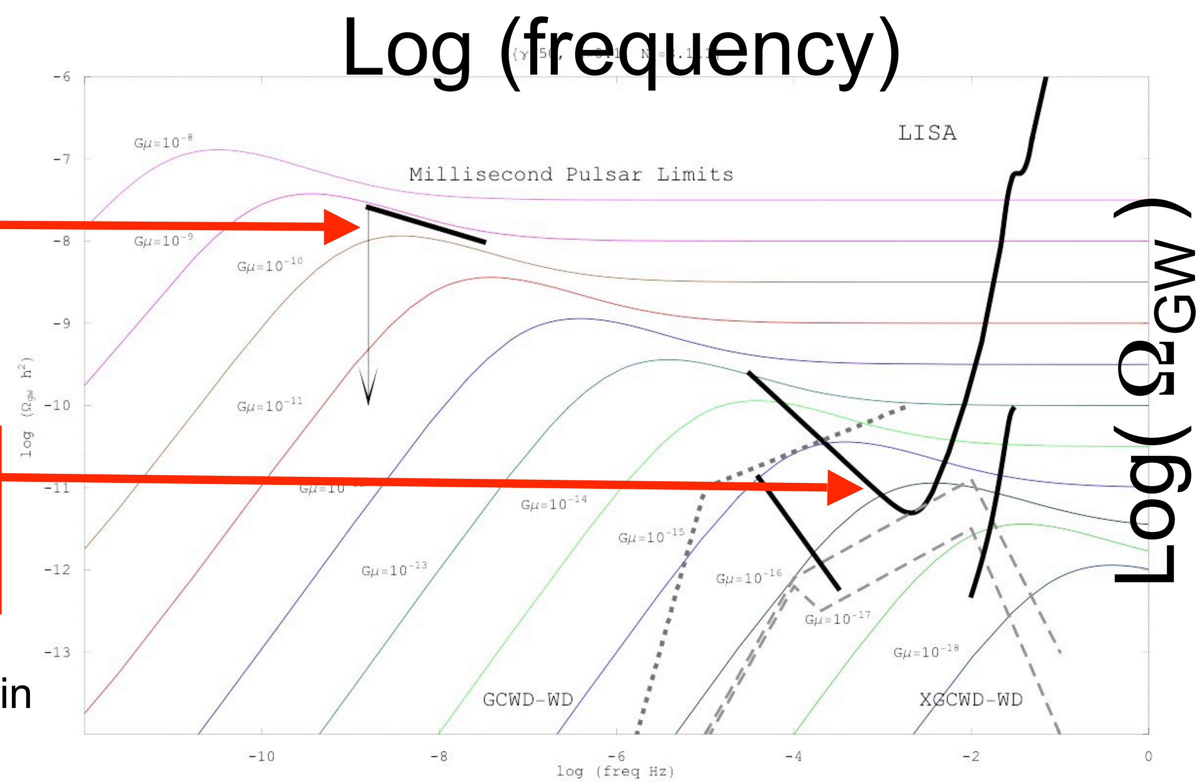
Cosmic superstring backgrounds

- New form of energy: flux tubes (fields), 1-branes (strings)
- Mass per length $G\mu$
- Formed after inflation, stretched by cosmic expansion
- Main observable effect is gravitational wave backgrounds from decaying loops



Current limit (Jenet et al): $G\mu=10^{-9}$

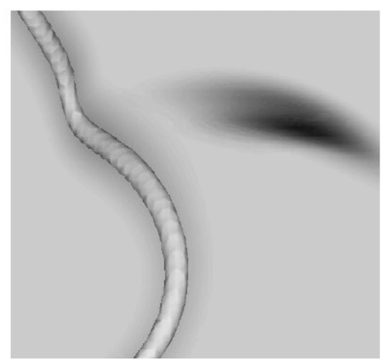
LISA limit: $G\mu=10^{-16}$



DePies & CJH; Vanchurin & Vilenkin

Measuring superstrings with gravitational waves

- Millisecond pulsar timing already constrains "brane inflation" predictions for string mass (Tye, KKLT, et al.)
- They are close to their limit
- LISA will probe ~6 orders of magnitude further, well beyond current expectations ($G\mu=10^{-16}$)
- Occasional rare bursts may beam in our direction, producing distinctive waveform (Damour & Vilenkin, Olum & Vilenkin, Siemens et al.)



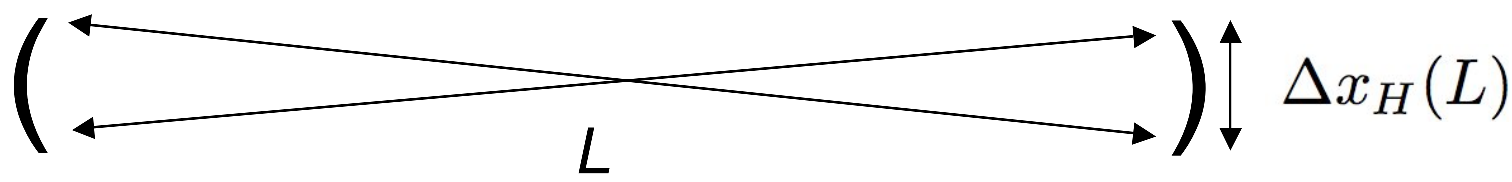
Holographic Uncertainty: macroscopic quantum gravity

- Can interferometers detect quantum indeterminacy of the spacetime metric?
- LISA will reach for the first time to the "Planck Diffraction limit"

Angular orientation of any trajectory is indeterminate:

limit on precision for wavelength l_P over length L:

$$\Delta\theta(L) = (l_P/L)^{1/2}$$



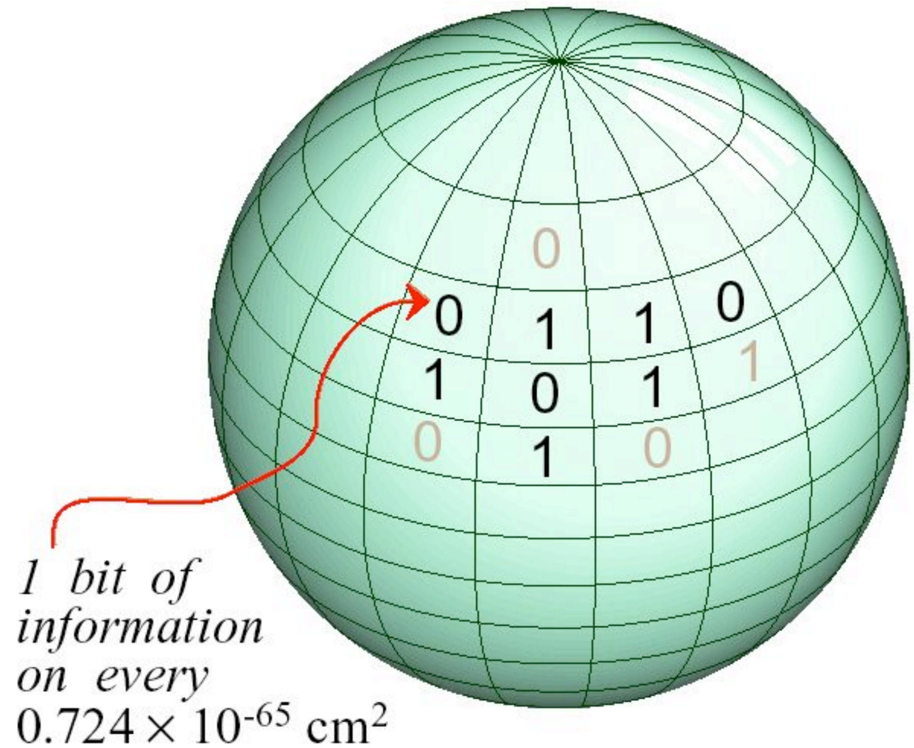
$$\Delta x_H(L) = C(L l_P)^{1/2}$$

CJH,astro-ph/0703775

Holographic Bound on Degrees of Freedom

- Black hole thermodynamics $S = A/l_P^2 4\ln 2$
- Exact state counts of extremal holes in large D
- AdS/CFT type dualities: N-1 dimensional duals
- Covariant entropy bounds: universal feature of quantum gravity

Everything about the 3D world can be encoded on a 2D surface at Planck resolution



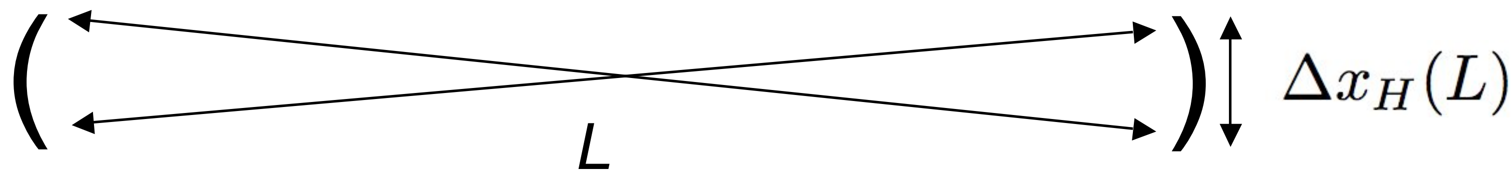
Beckenstein, Hawking,
Bardeen et al.,
'tHooft, Susskind, Bousso

Information limits blur the "virtual" 3D holographic world

3D world has limited number of independent pixels (degrees of freedom)

Holography limits the Hilbert space dimension of everything

Quantum mechanical unitarity can only be preserved in a 3D world with Hilbert space much smaller than predicted in a standard field theory



$$\Delta x_H(L) = C(Ll_P)^{1/2}$$

leads to blurring at the "Planck Diffraction Limit"

Holographic Uncertainty Principle (conjectured)

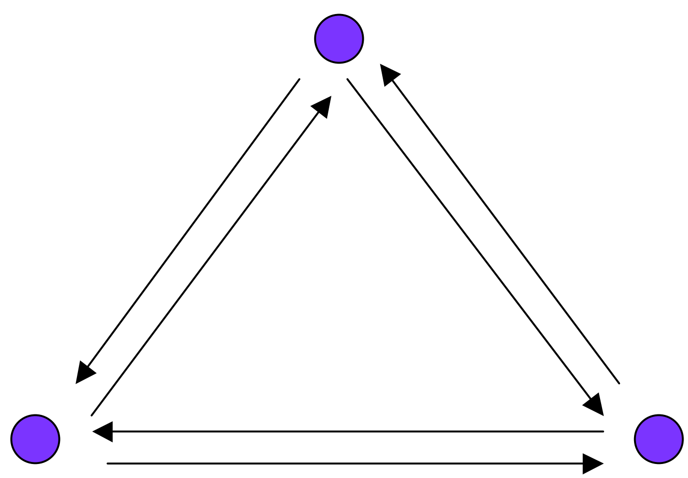
The spatial wavefunction of a body at rest at distance L from any observer has a width in transverse directions greater than

$$\Delta x_H(L) = C(L l_P)^{1/2}$$

This effect can be detected interferometrically

Direct measurement of holographic uncertainty

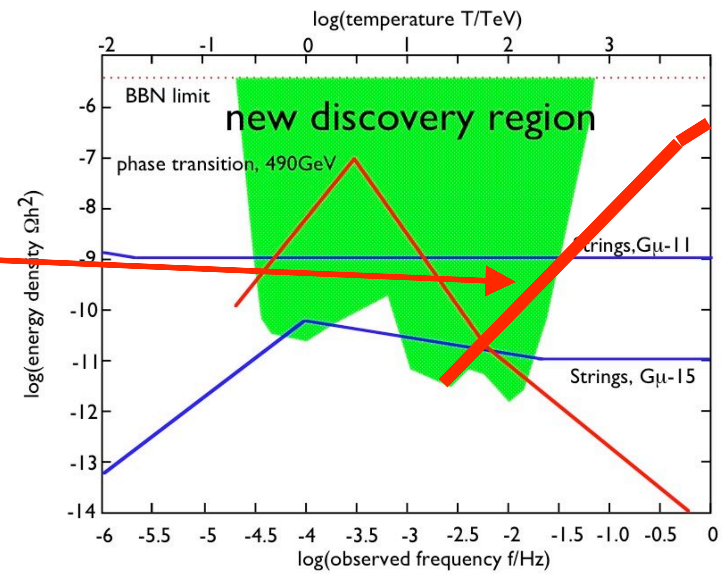
- Requires precise measurement of tiny transverse position or angle, ~10^{-22} at LISA separation
- Interferometers reach "halfway to the Planck scale"
- Not possible with pure Michelson-type, pure radial measurement
- Sagnac type configuration needed



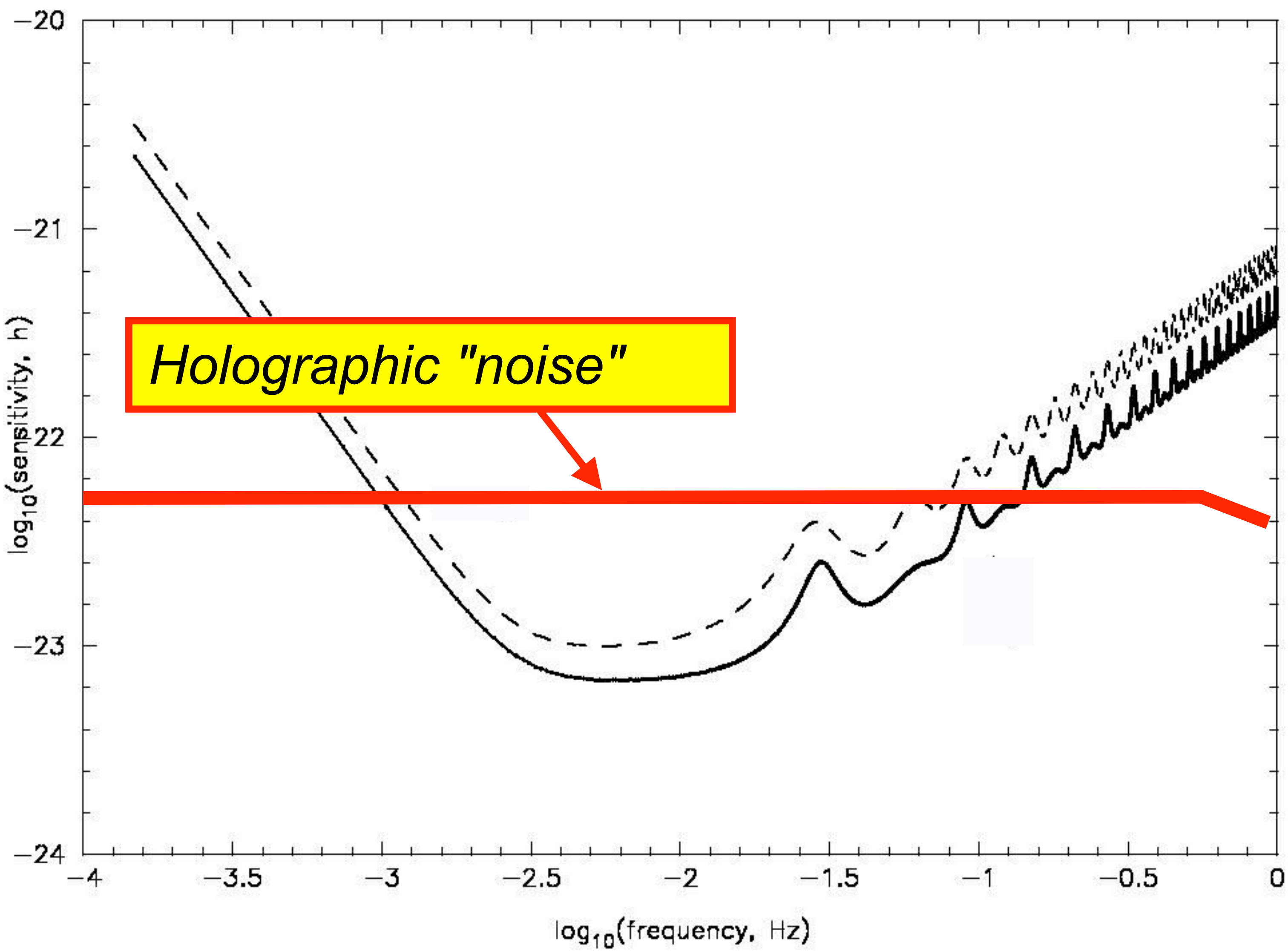
LISA reaches into "holographic" regime for the first time

- Proof mass positions subject to holographic uncertainty
- Quantum-gravitational indeterminacy leads to random "noise"
- Signatures: nonlocality, spectrum, signal phases (symmetric Sagnac)

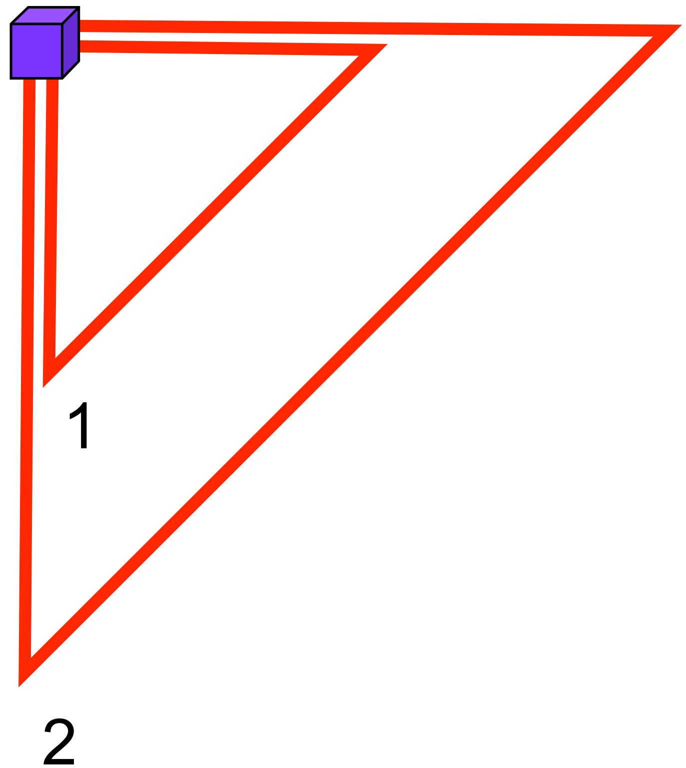
Holographic "noise"? (predicted, with no parameters)



LISA sensitivity and Holographic "Noise"



Test with new ground-based interferometers?



Requires LIGO-like metrology, plus a design sensitive to transverse position

New (quantum) physics with LISA

- Roaring big bang: Terascale inflationary reheating
- Terascale motions: first order phase transitions
- Superstrings: beyond brane inflation limit, down to 10^{-8} of Planck scale
- Direct measurement of holographic uncertainty?
- (even more) unknown unknowns?

LISA will explore new phenomena of energy and spacetime that can be explored in no other way

The New Science of Gravitational Waves

- Spacetime physics
  - Extreme dynamical spacetime in black hole mergers
  - High precision test of General Relativity under most extreme conditions
- Precision cosmology
  - Gravitationally calibrated, absolute & independent distances
- Opportunities for photon astronomy
  - Radio, optical, X-ray counterparts and host galaxies
- Astrophysics
  - Direct observations of massive black holes over the history of galaxy formation
- Galactic and stellar astronomy
  - Thousands of compact binaries throughout the Galaxy
- Unification physics, superstring physics, and the unknown
  - Terascale phase transitions at 100 GeV to 1000 TeV
  - Backgrounds and bursts from cosmic superstrings
  - Direct measurement of quantum gravity (Planck diffraction limit)?
  - ??????????

LISA International Science Team

- **European Members**

  Karsten Danzmann, MPI for Gravitationsphysik (Albert-Einstein-Institut) and U. Hannover, Co-Chair, ESA Mission Scientist

  Oliver Jennrich, ESTEC, ESA Project Scientist

  Pierre Binetruy, APC - College de France

  Massimo Cerdonio, U. of Padova

  Michael Cruise, U. of Birmingham

- US Members

  Tom Prince, Caltech/JPL, Co-Chair, NASA Mission Scientist

  Robin Stebbins, GSFC, NASA Project Scientist

  Peter Bender, U. of Colorado

  Sasha Buchman, Stanford U.

  Joan Centrella, GSFC

  Kip Thorne, Caltech

Science Case document (v 1.0, 117 pages):

"LISA: Probing the Universe With Gravitational Waves"

http://www.lisa-science.org/resources/talks-articles/science

In addition, the *LISA International Science Community* has a membership of 240 scientists from 104 international institutions

LISA will sense the remote Universe in an entirely new way, and will explore new things that can be explored in no other way