esa

LISA

Unveiling a Hidden Universe

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for the

LISA International Science Team

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(Albert Einstein Institute: AEI)

(Animation: AEI/Milde Science Comm)

LISA: GW Observatory in Space

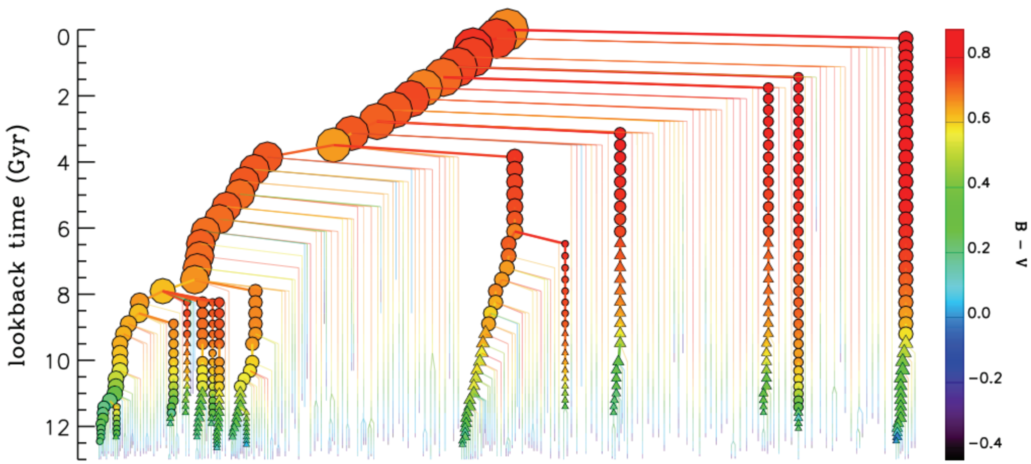
- **LISA in ESA program since 1995; NASA joined soon after.**
- **Originally a Fundamental Physics mission, doing astronomy**
- **Today: an Astronomical Observatory with important work in Fundamental Physics**
- **Reasons for this change:**

1. **Astronomy's focus is moving toward LISA's capabilities:**
   - Massive galactic black holes, key also to galaxy evolution
   - Transient astronomy: major ground-based facilities coming
   - The high-redshift universe: astronomy's next frontier
2. **Astrophysics and Fundamental Physics are converging: cosmology**
3. **Large community of astronomers around LISA have been exploring LISA's potential for many branches of astronomy.**

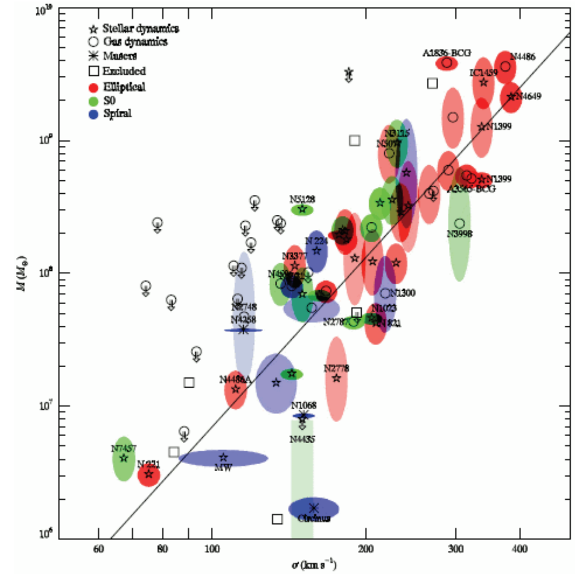
LISA offers revolutionary science

- Direct proof that massive central objects in galaxies really are BHs
- Measurement of mass, spin of 10^6 M_oBHs at z = 1 to ±0.1%
- Observation of universe before re-ionisation: BH mergers at z> 15
- Revealing how massive BHs formed and evolved z = 10-20
- Tests of BH no-hair theorem, cosmic censorship
- Unaided: Hubble constant at z = 0.5 with 0.4% precision or better
- Unaided: dark-energy *w*to z = 3 with 4% precision or better
- Mass function of central black holes of ordinary galaxies to z = 0.2
- Study of stellar black hole clusters around central black holes
- Catalogue > 10^4 new white-dwarf binary systems in the Galaxy
- Precise masses and distances for > 100 white dwarf binaries
- Determine the order of the electroweak phase transition

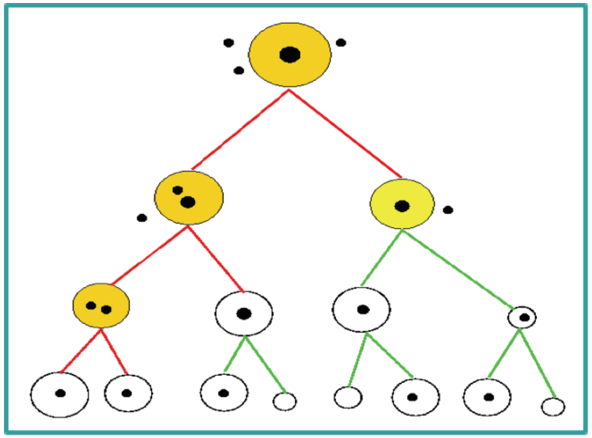
Why BHs? Co-evolution with galaxies



(De Lucia et al 2006)

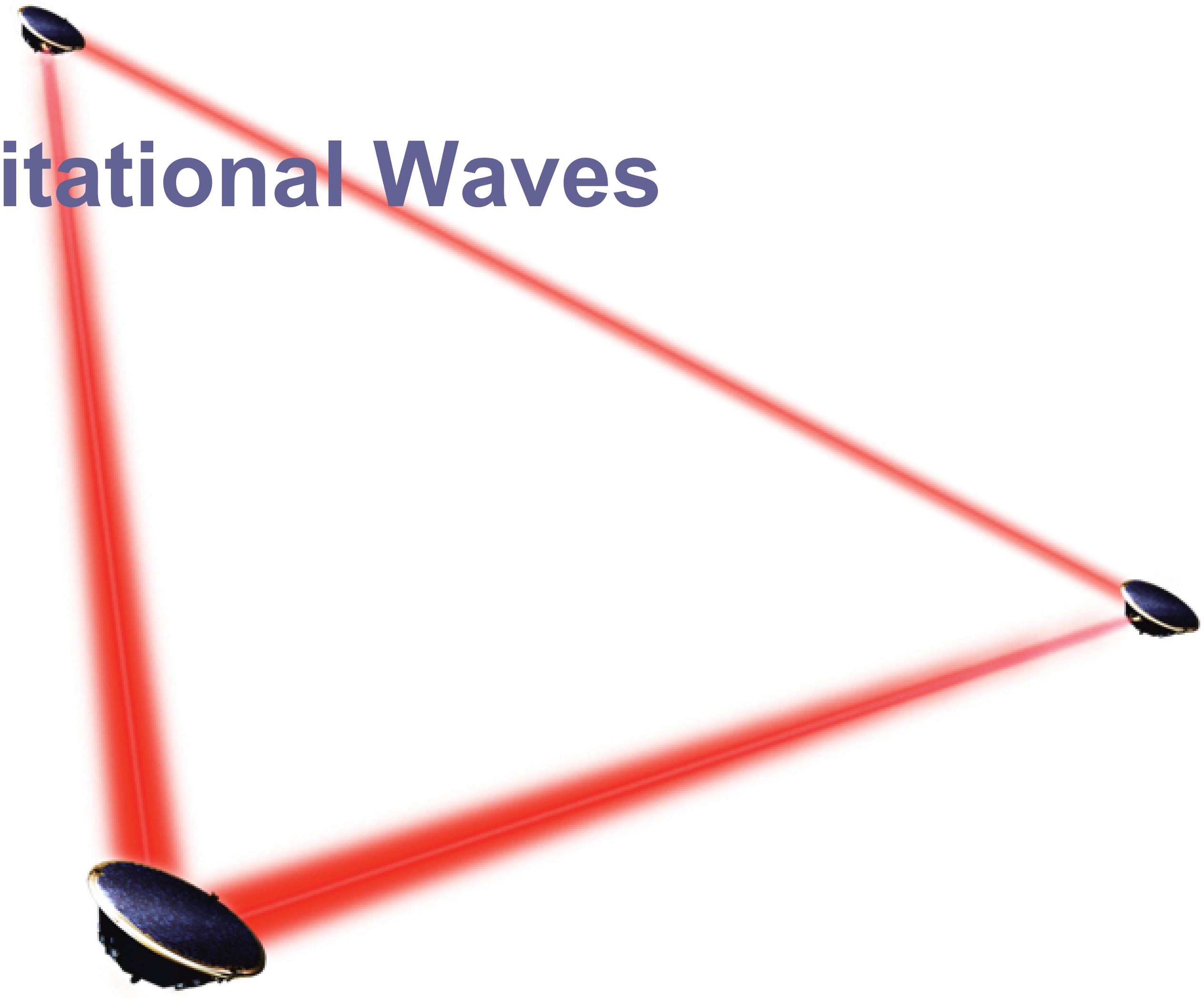


(Gulketin et al. 2009)



(VolonteriHaardt&Madau 2003)

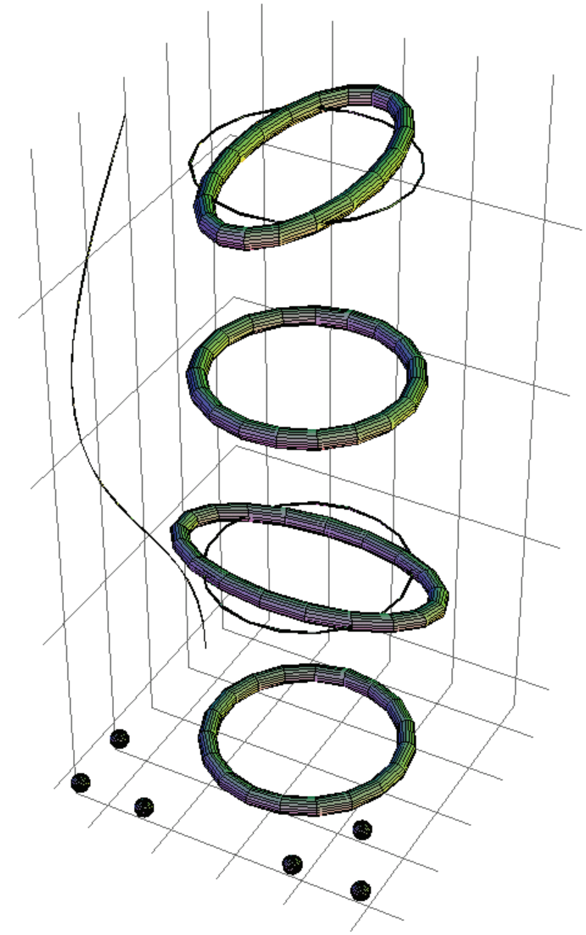
Gravitational Waves



LISA: Sensing Spacetime Vibrations

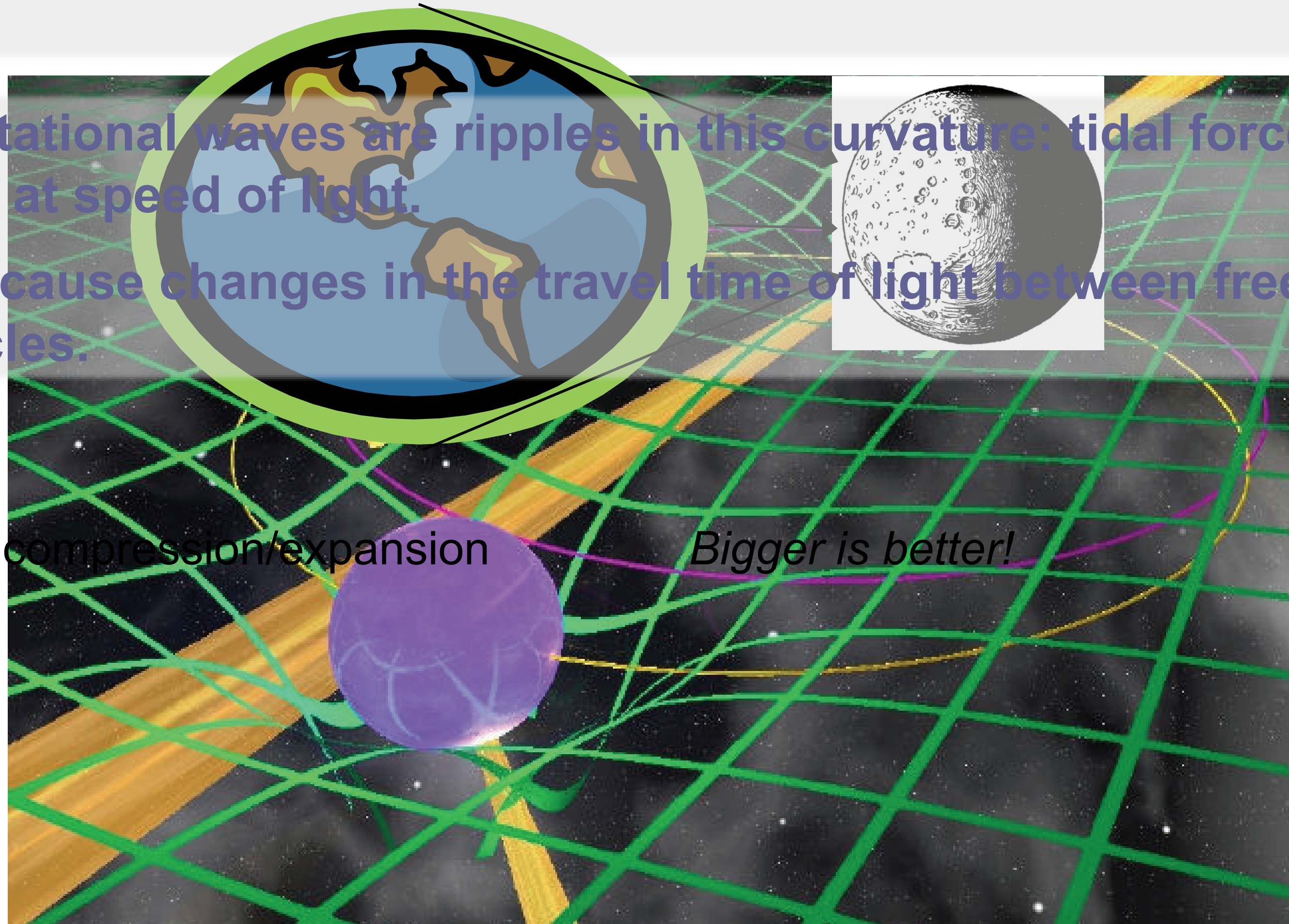
Gravitational Waves are an entirely new way to explore the Universe

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



Gravitational waves

- Newton: tidal forces are the observable action of gravity in free fall.
- Einstein: tidal forces of gravity are the curvature of space-time.
- Gravitational waves are ripples in this curvature: tidal forces that move at speed of light.
- They cause changes in the travel time of light between free particles.



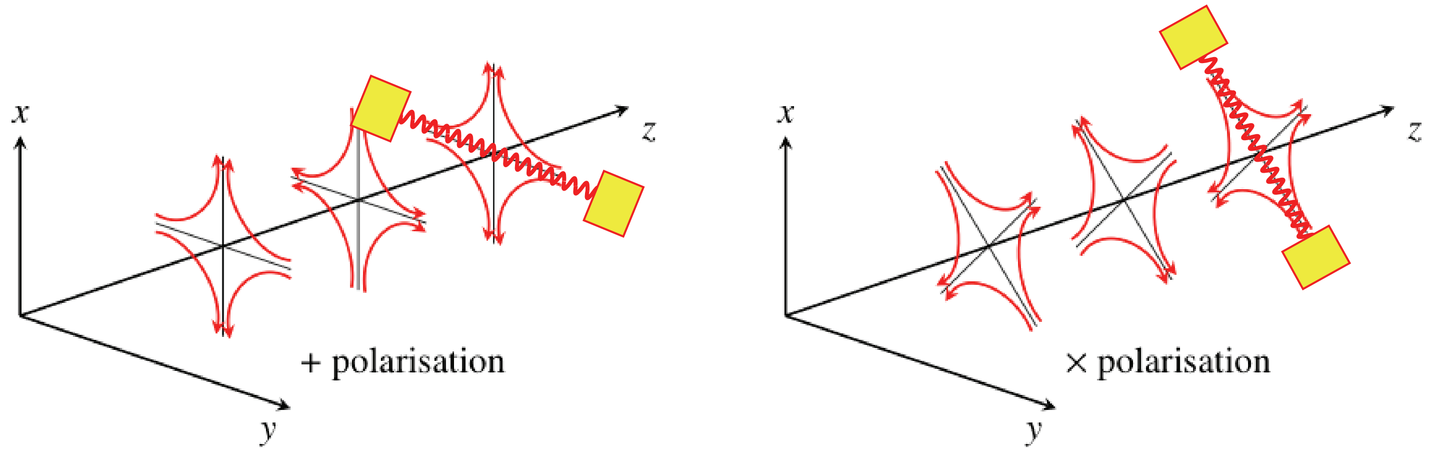
Anisotropic compression/expansion *Bigger is better!*

(Kramer)

Understanding gravitational waves

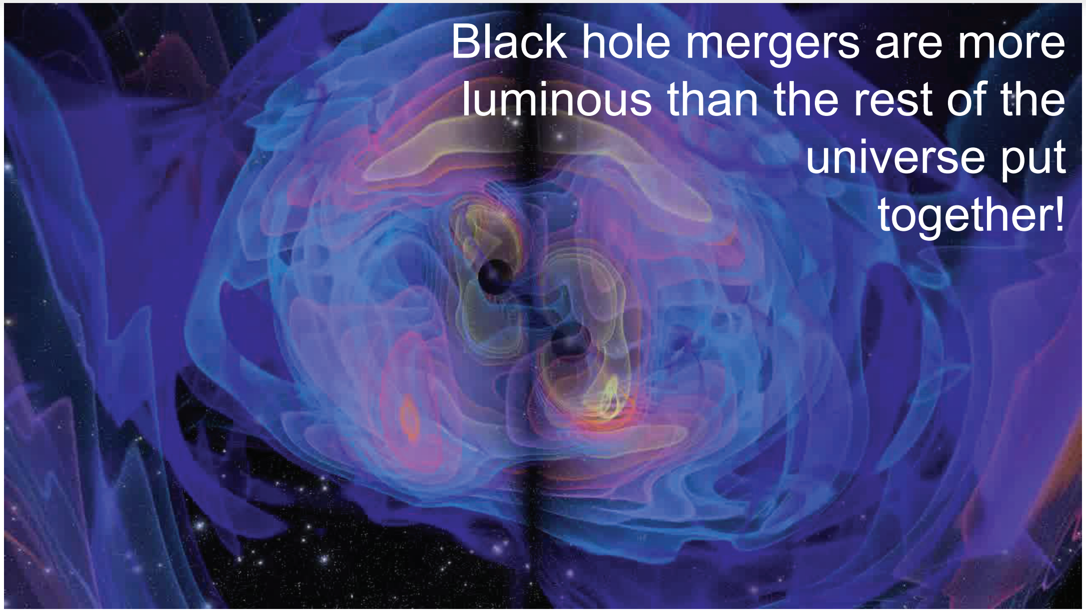
- **Strong analogies with EM radiation**
  - Two transverse polarisations
  - Move at speed of light, follow geometrical optics
  - Same behaviour with gravitational lensing, cosmological redshift

- **Like light, GW phase and polarisation follows source motions**
  - NB: Measuring degree of circular polarisation gives ***binary orbit inclination.***
- **Signal phase encodes large-scale source dynamics.**



But GWs *are* different …

- **Coupling of GWs to matter is very different from EM.**
- **Very weak, $h << \varphi/c^2 = GM/rc^2$**
  - This leads to $\delta L/L \sim h \sim 10^{-21}$ to 10^{-24}.
  - $h \sim 1/r$
- **Weakness □ negligible scatter, absorption: perfect messengers!**
- **Have huge energy flux; luminosity scale is $c^5/G \sim 3.6 \times 10^{59}$ erg/s.**



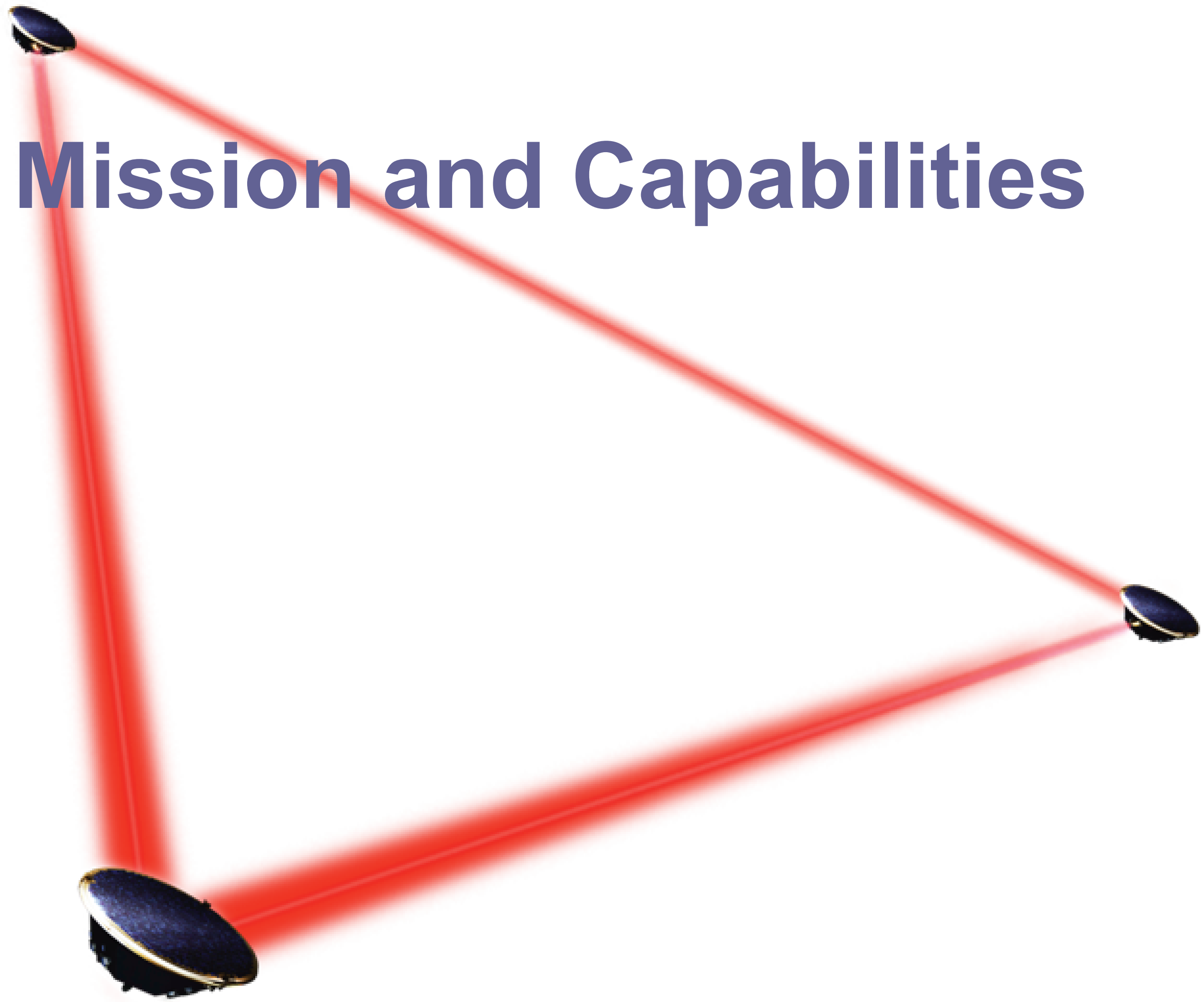
(AEI)

Like *listening* to the universe

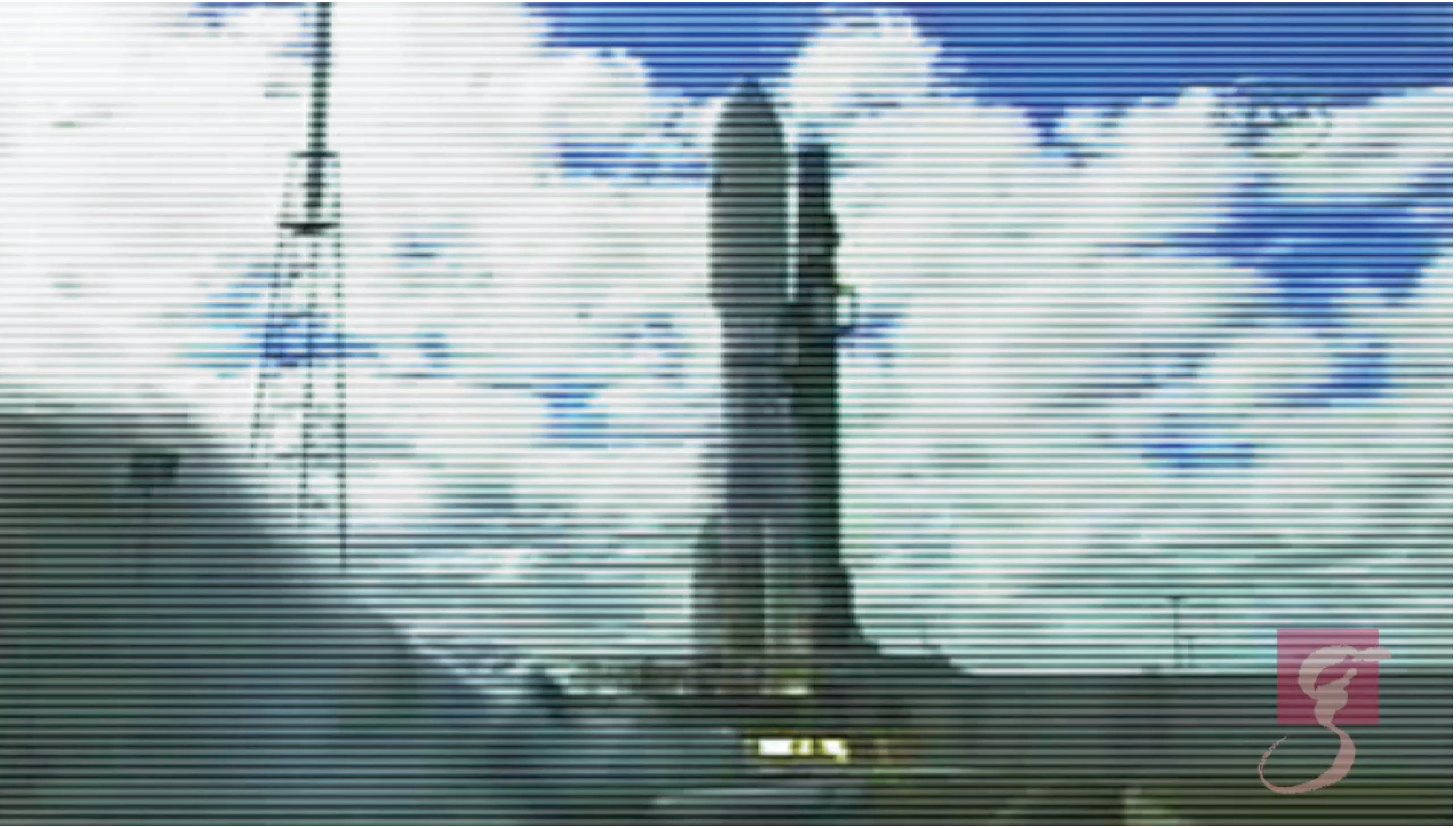
- **GWs have many analogies to sound: waves of spacetime**
- **Detectors are our “microphones”**
  - 1D response, not an image. Converts to sound: you can listen to GWs
  - Record the waves coherently, tracking phase and amplitude
  - Nearly omni-directional, but linearly polarised
- **LISA will add the audio dimension to our ability to monitor the dynamical universe.**

(AEI/Milde Science Comm/ getye1/Novak/Willmann)

LISA Mission and Capabilities



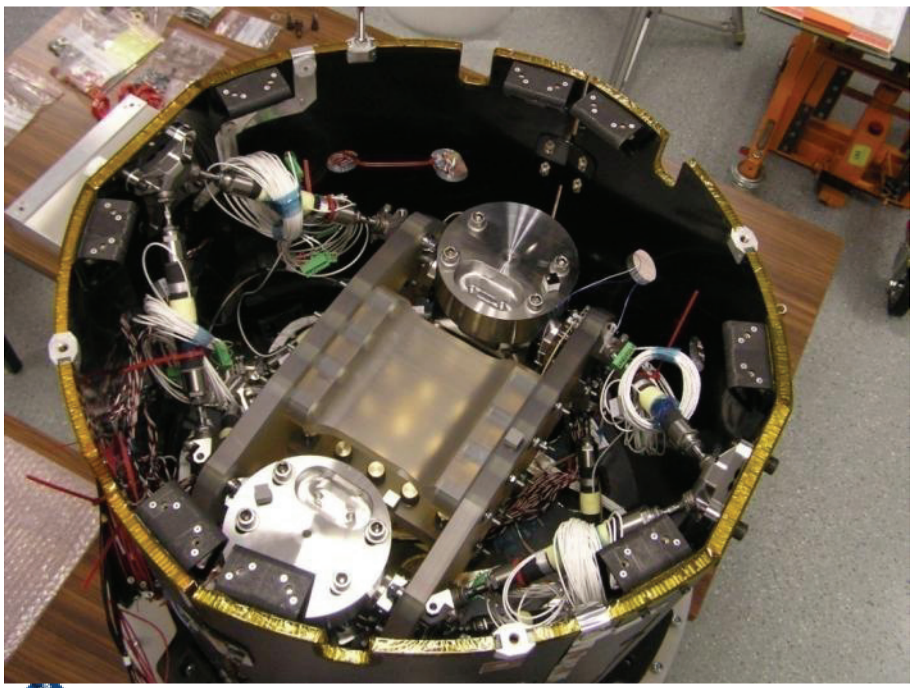
The LISA Mission

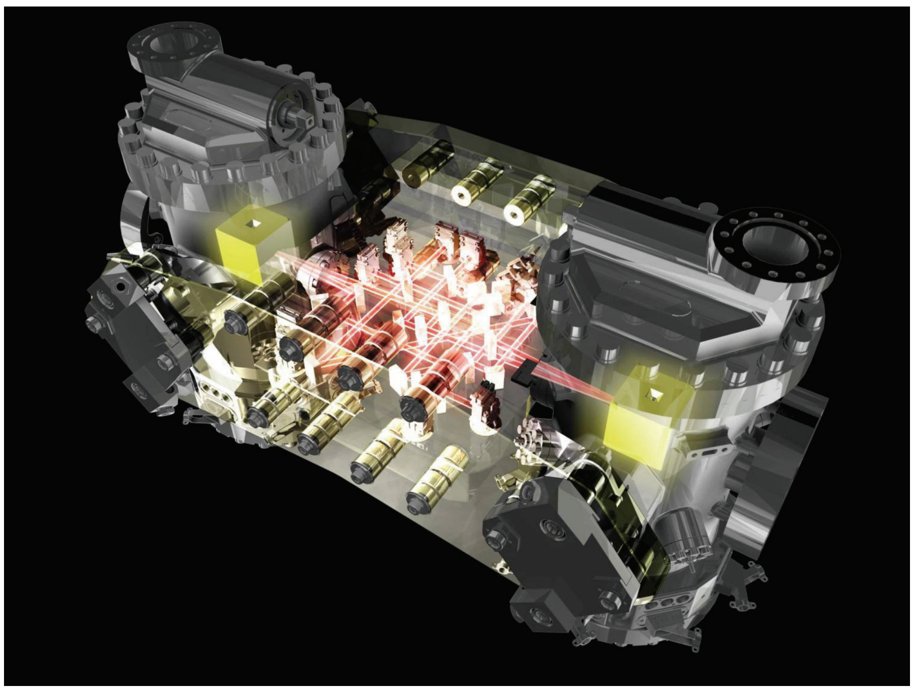


(AEI/Milde Science Communications)

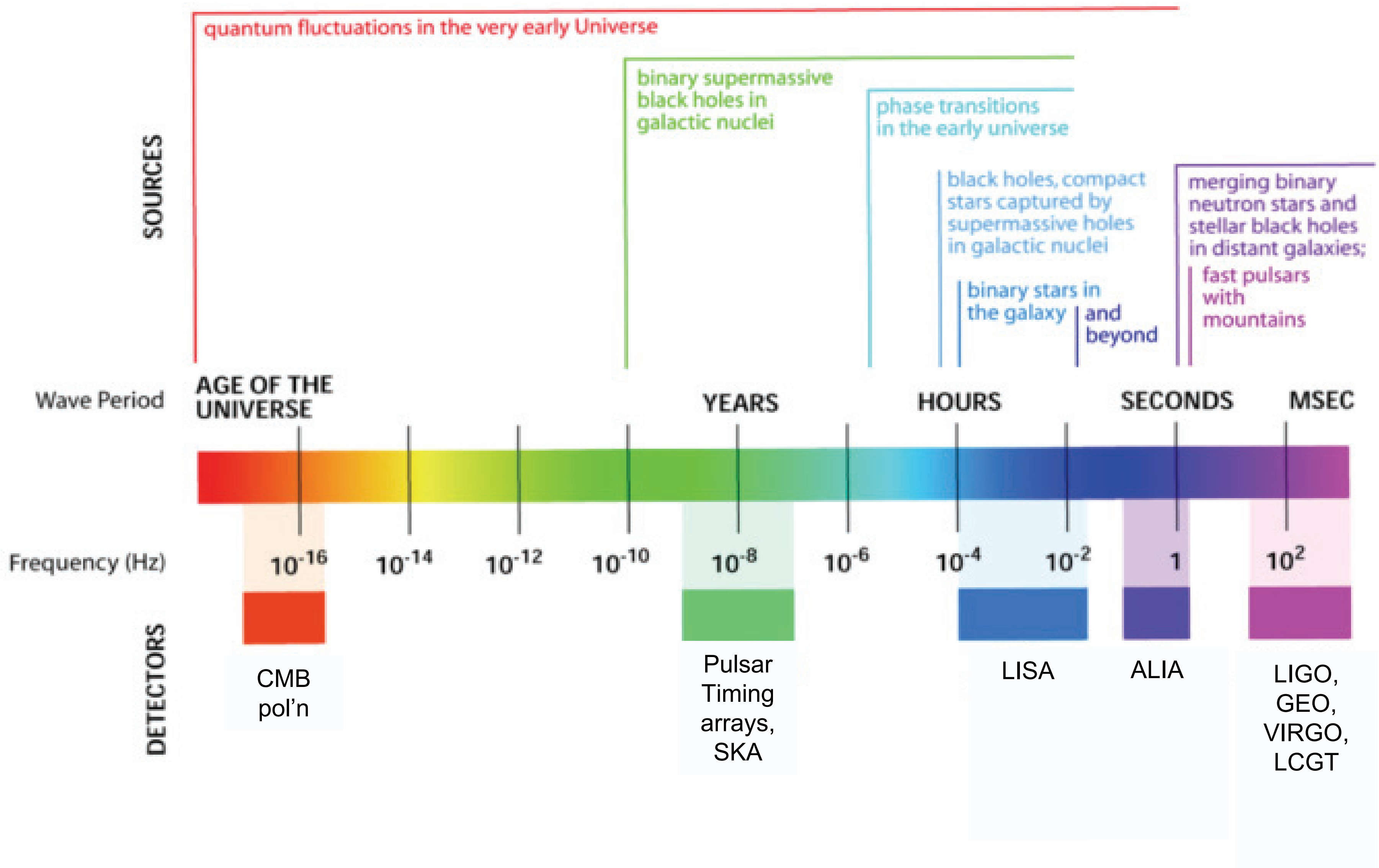
Technology of stillness

- **LISA Pathfinder will fly the LISA isolation and interferometry systems for the first time.**
  - Two proof masses in a single S/C.
  - Will test LISA hardware in a space environment.
  - Proof masses will be the **quietest places in the solar system**.



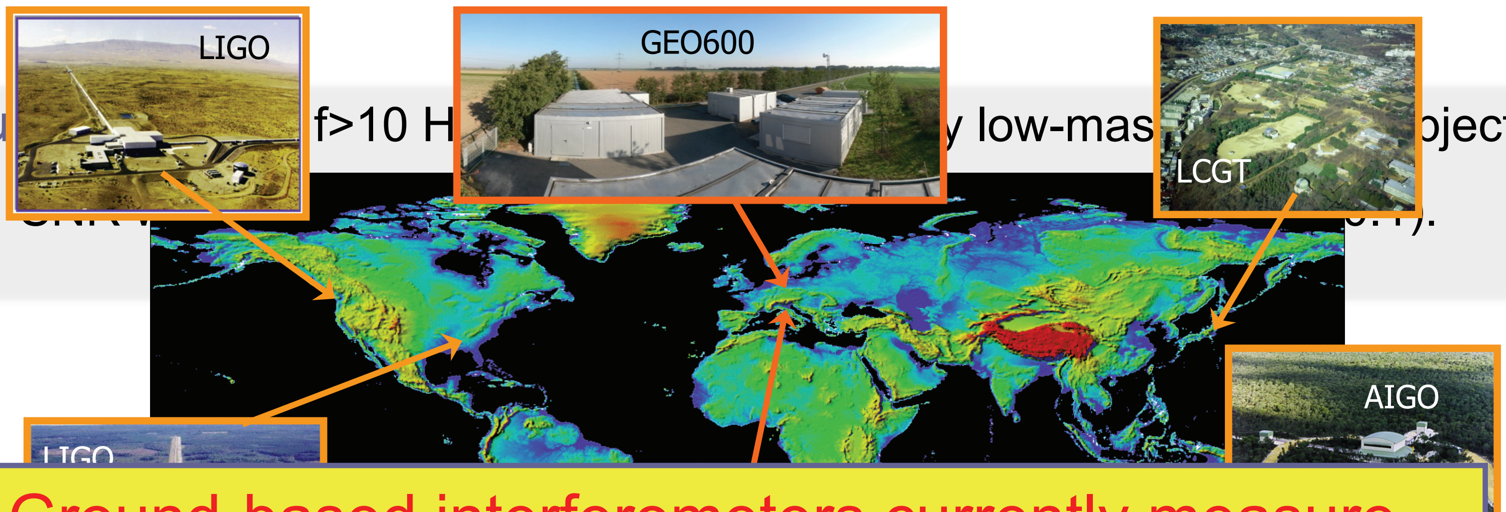


GW searches across the spectrum



Ground-based detection

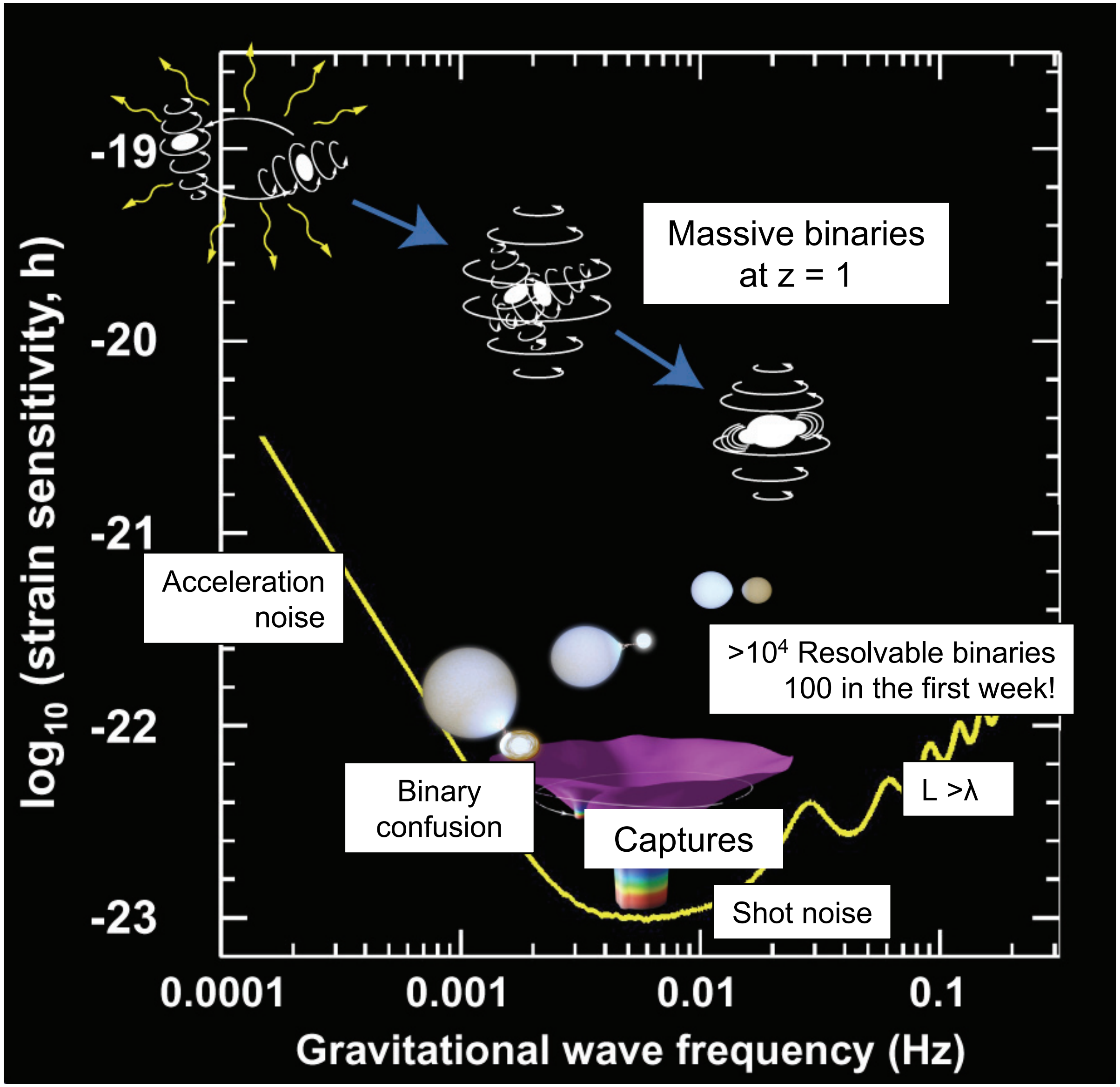
- **Current LSC (LIGO, GEO) and VIRGO progress:**
  - Initial LIGO reached promised sensitivity in 2005-7 observing run (S5).
  - Advanced LIGO, VIRGO expected to make regular observations 2016+
  - Large Japanese detector (LCGT) funded, maybe another in Australia



- **Fu** … f>10 H … y low-mas … bjects
  - – …

Ground-based interferometers currently measure displacements of 10^{-18} m.
LISA only needs to measure 10^{-11} m.

LISA Sensitivity Diagram



LISA measures absolute distances

- **Almost all LISA sources are binary systems.**
- **A system that radiates GWs strongly will "chirp" up in *f*.**
- **Standard sirens: absolute luminosity distances to chirping binary systems can be derived *directly* from**
  - Amplitude
  - frequency f
  - chirp rate df/dt

Apparent magnitude

Absolute magnitude

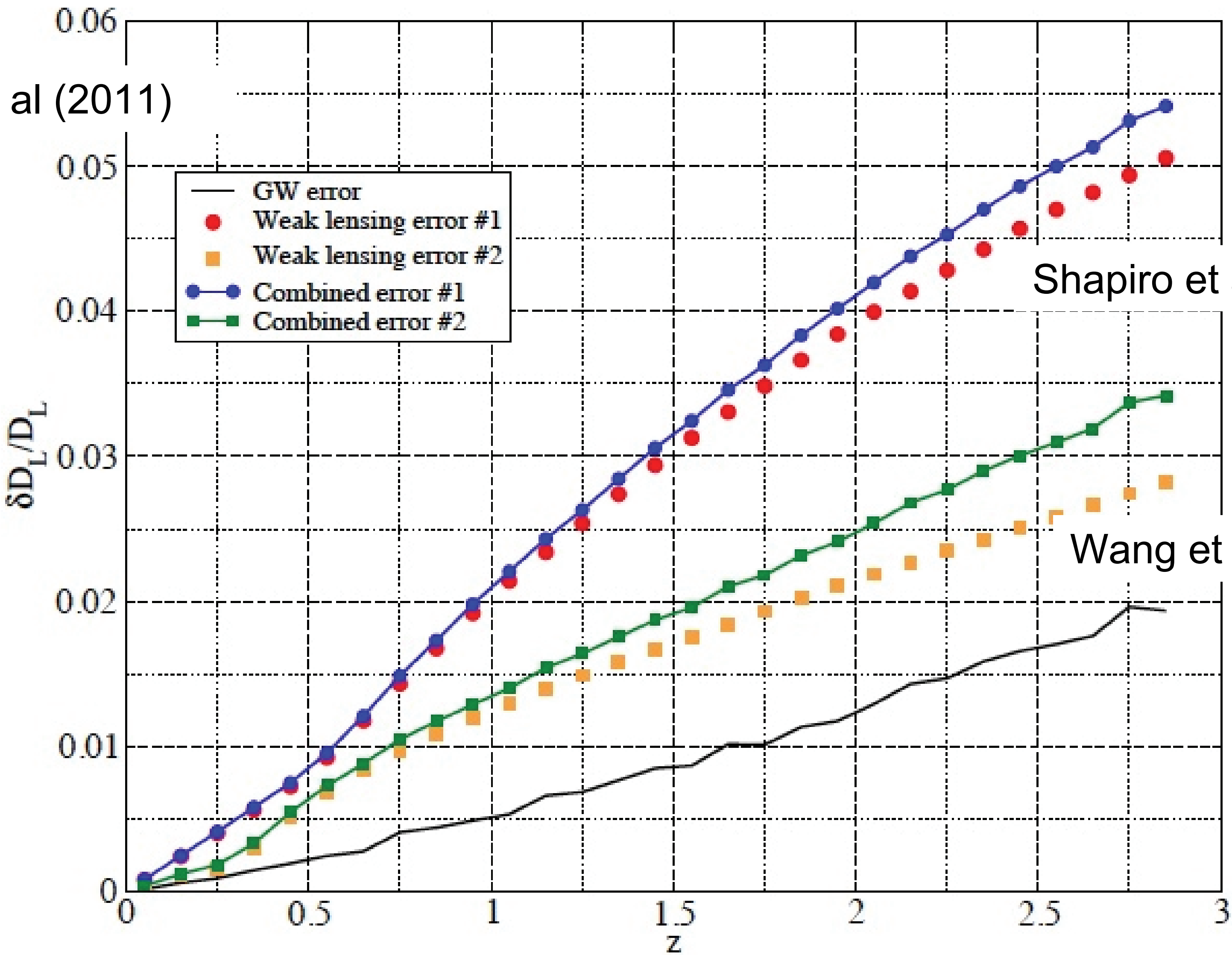
$$\text{Distance} \cong c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}$$

- **Works for *any* chirping binary (mass ratio, eccentricity, spins)**

- **Distances D_L given in light-seconds: no calibration needed.**
- **Clean systems: high accuracy, few systematic errors.**
- **Completely independent of other astronomical distance ladders**
- **If we assume a cosmology, D_L □ z for each observed system.**
- **With a population, we can measure H_0, w even without z's.**

Accuracy of D_L: weak lensing

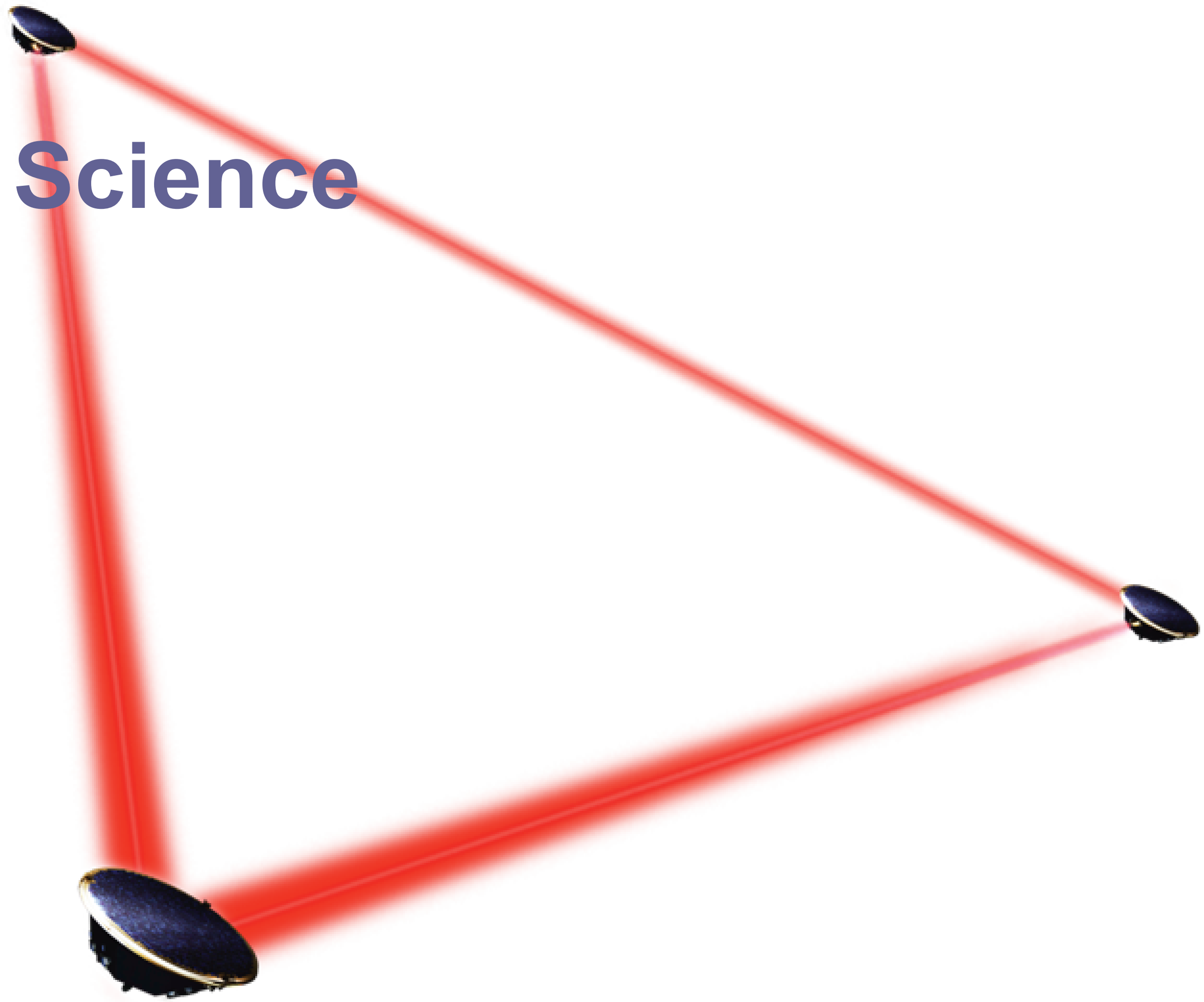
Babak et al (2011)



Shapiro et al (2009)

Wang et al (2003)

LISA Science



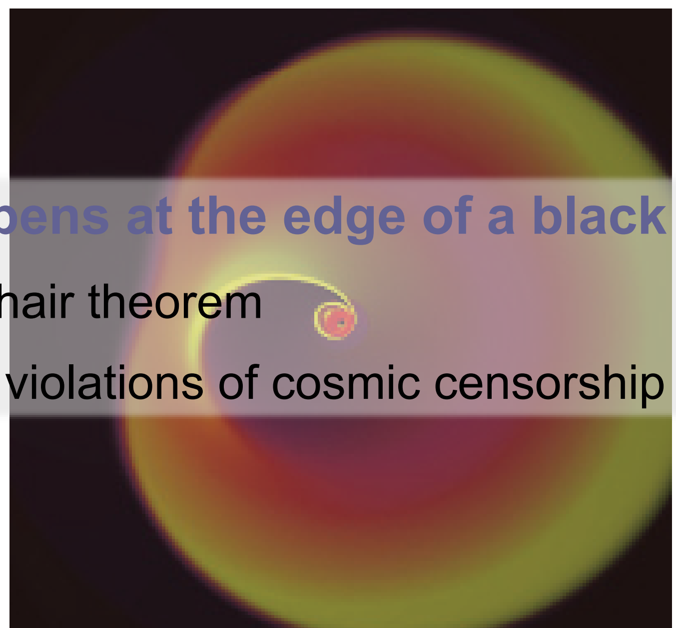
What happens when MBHs merge?

- **LISA should detect handful of 10^5-$10^7 M_\odot$ BH-BH binary mergers at z = 0.5 to 2.**
- **What does galaxy look like? What are the effects of merger?**
  - Notify other observatories (X-ray, optical, IR, radio) up to 3 months in advance, give 1° position 1 day in advance, 10' a few hours in advance. Luminosity distance accurate to ±30-300 Mpc.

Numerical relativity simulation by AEI; viz by M Koppitz, Milde Science Comms, ExozetBabelsberg

Black hole science with SNR = 10^4

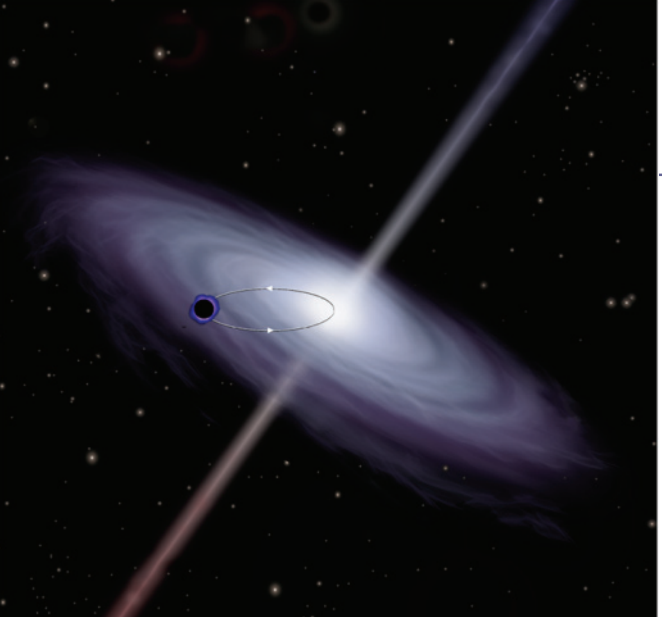
- **Masses to ±0.1%**
- **Spin *vectors* to ±3-5%**
  - Alignment: wet or dry merger
- **Distance to ±1-4% depending on z.**
- **Much work now on counterpart identification: what is the signature of a galaxy containing a merger?**



- **What happens at the edge of a black hole?**
  - Test no-hair theorem
  - Look for violations of cosmic censorship

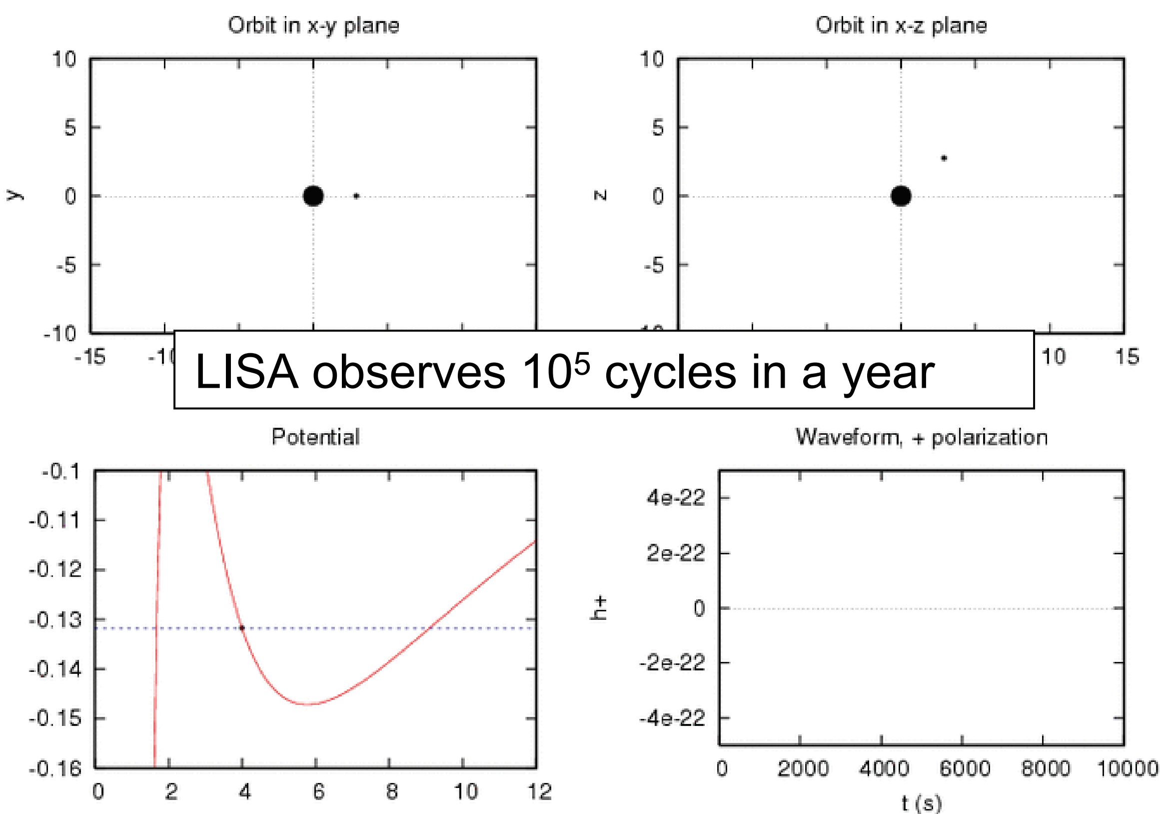
(Rossi, et al)

BH Geodesy: EMRIs

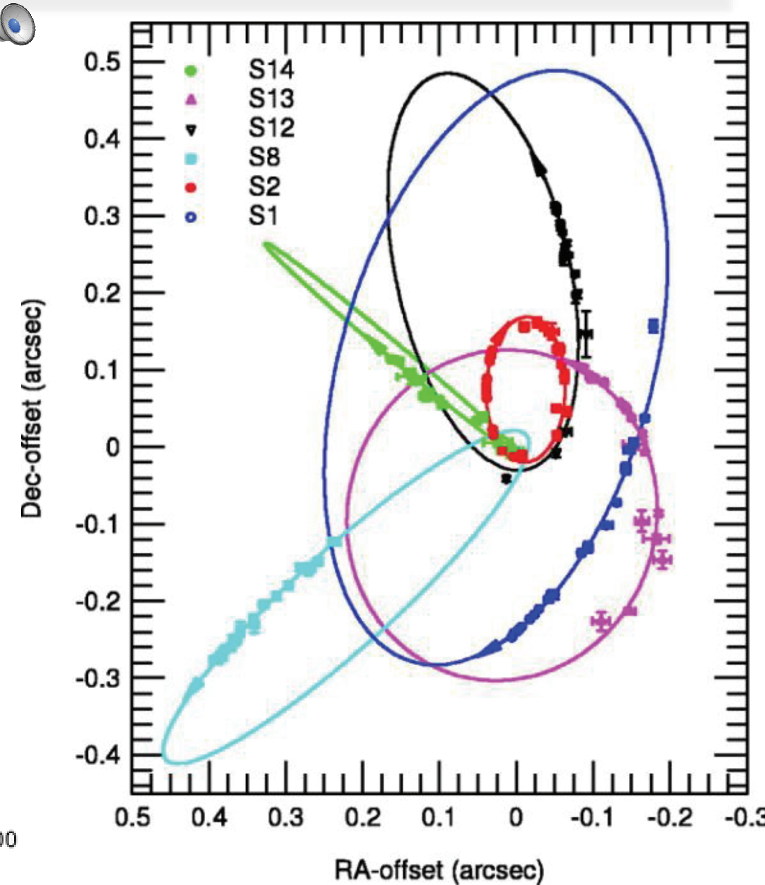


- Stellar BH in-spiral into a massive BH
- Map of near-horizon geometry: relativistic geodesy (GRACE/GOCE for black holes)
- Test the no-hair theorem to 1%

J. Gair



LISA observes 10^5 cycles in a year



Studying central MBH environments

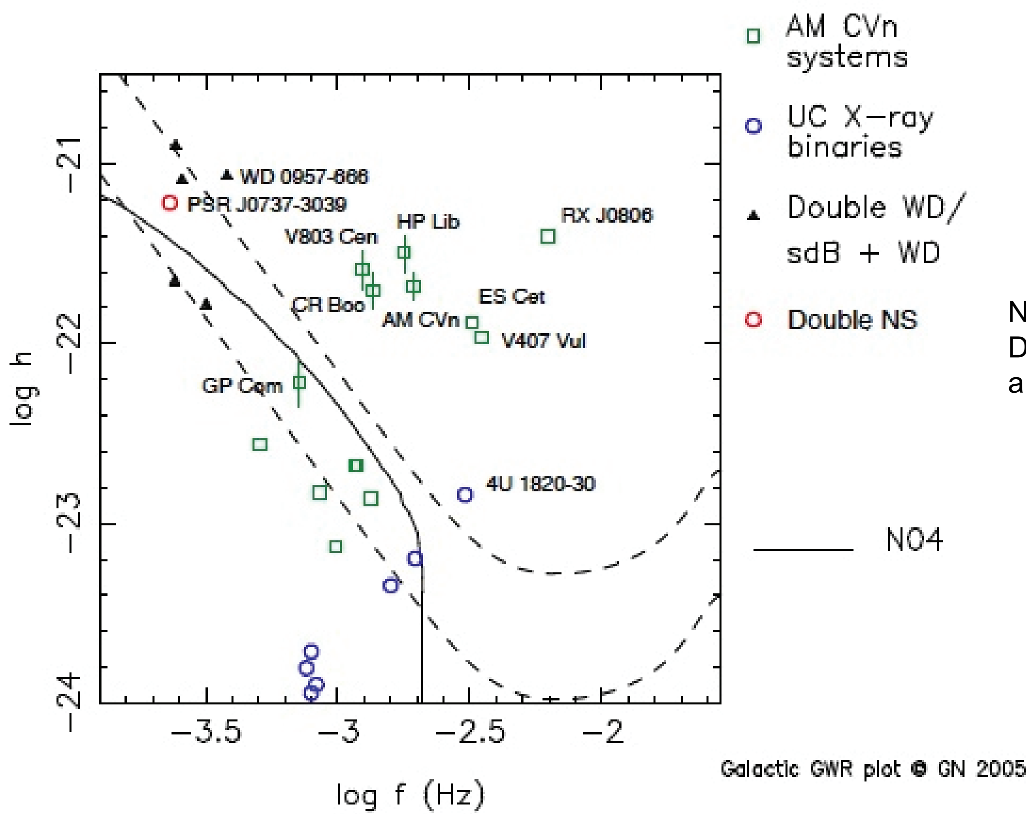
- Captures of stellar-mass black holes by single central massive black holes (~$10^6 M_\odot$) are called Extreme Mass-Ratio Inspirals (EMRIs)
- LISA will detect ~100 per year out to z ~ 0.2, SNR ~ 100, locations to ~ 0.5°.

- Rich survey of local MBH population in normal galaxies (not AGNs)
  - Measure central mass, spin to 1%; captured mass to 1% and spin to 10%.
  - First survey of the stellar-origin BH population near central BHs in galaxies: important for our own Galactic central BH.
- In our own GC, we see only 5% of the stars, no stellar BHs. Cusp?

- LISA will also detect any captures of larger BHs, up to $10^3 M_\odot$.

Compact binaries

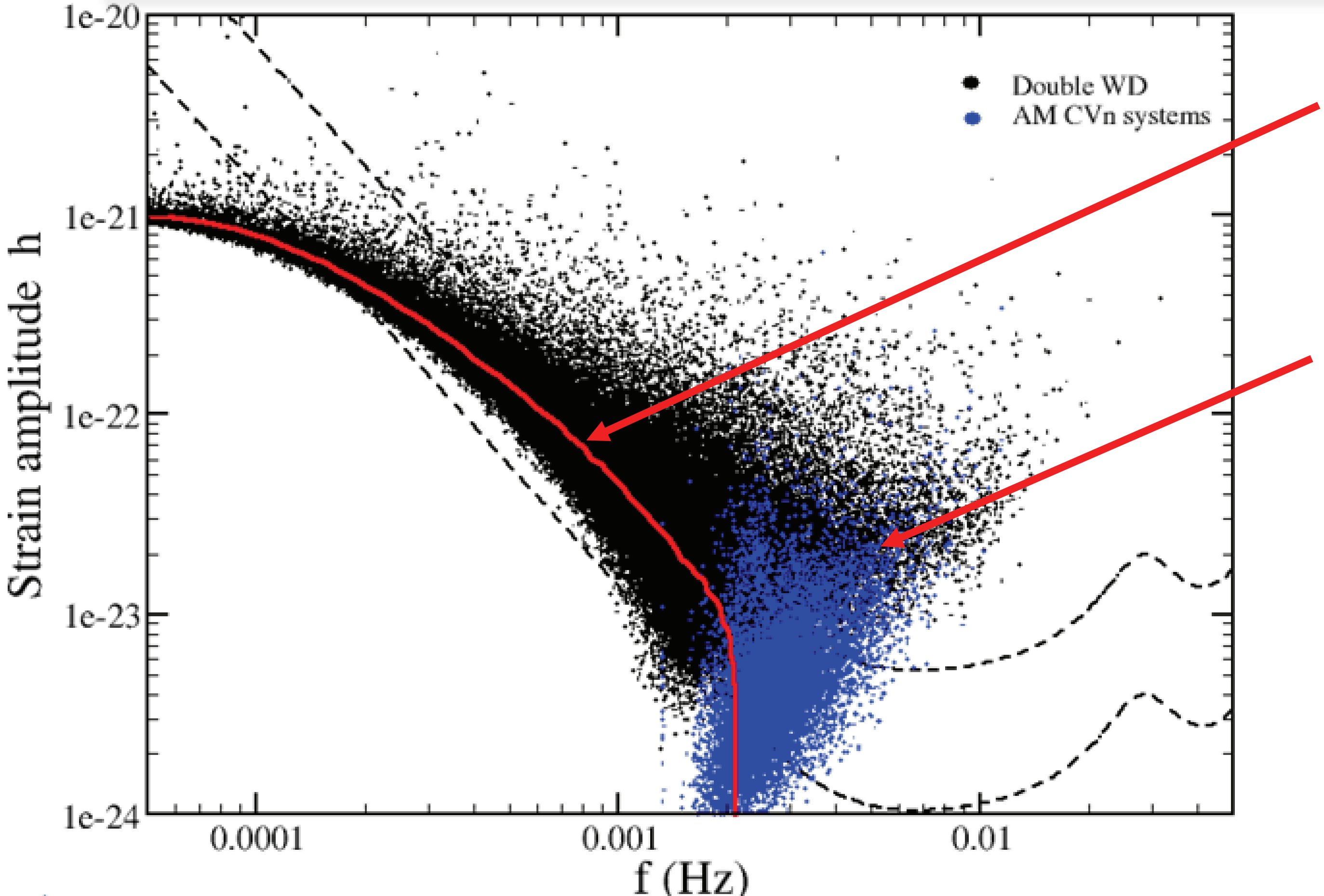
- **LISA will make major contributions to the study of binary evolution and the endpoint of stellar evolution.**
  1. LISA has guaranteed (known) sources: verification binaries



Nelemans et al, Decadal white paper arXiv:0902.2923v1

Compact binaries (2)

2. Hundreds of thousands of binaries in the LISA band.
3. LISA identifies tens of thousands of them, incl. *all* with P <30 m.



Unresolved double WD background

Above and at high f systems are resolved: ~10,000 of both double WD and AM CVns

(Nelemans et al. 2004)

At least several hundred will be observed optically

(Nelemans et al. 2009)

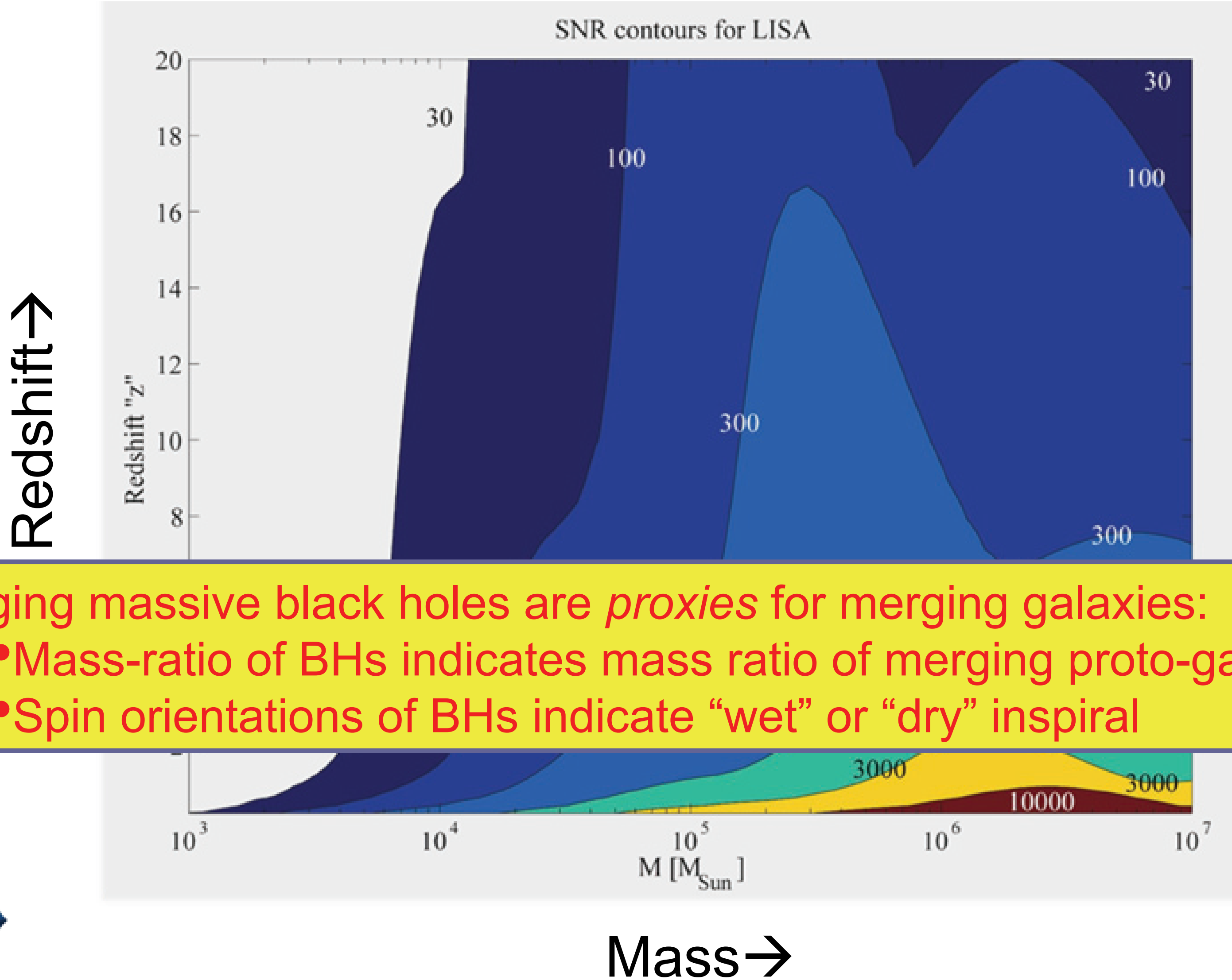
Compact binaries (3)

- **Synergy with GAIA, upcoming large-area surveys, radio pulsar binary surveys**
- **LISA supplies unique new information:**
  - Orbital inclination (helps determine masses)
  - Accurate distance (for known masses, or for chirping systems)

- **These observations address key astrophysics issues, e.g.:**
  - Binary evolution, common envelope evolution
  - Precursors of Type Ia supernovae in the Galaxy
  - Population studies of Galaxy, tracers of star formation
  - Interacting binaries, mass transfer, tides
  - Population studies of NS-NS, NS-BH, BH-BH binaries

The high-z universe: LISA's playground

Contours of LISA SNR, equal mass merger (optimal)



Merging massive black holes are *proxies* for merging galaxies:

- Mass-ratio of BHs indicates mass ratio of merging proto-galaxies
- Spin orientations of BHs indicate "wet" or "dry" inspiral

LISA's wide spectrum of masses

At z = 15	$2.5\times10^{6}M_o$	$2.5\times10^{5}M_o$	$2.5\times10^{4}M_o$	$2.5\times10^{3}M_o$	$250\ M_o$
At z = 2	$1.3\times10^{7}M_o$	$1.3\times10^{6}M_o$	$1.3\times10^{5}M_o$	$1.3\times10^{4}M_o$	$1.3\times10^{3}M_o$
LSO mass	$4\times10^{7}M_o$	$4\times10^{6}M_o$	$4\times10^{5}M_o$	$4\times10^{4}M_o$	$4\times10^{3}M_o$

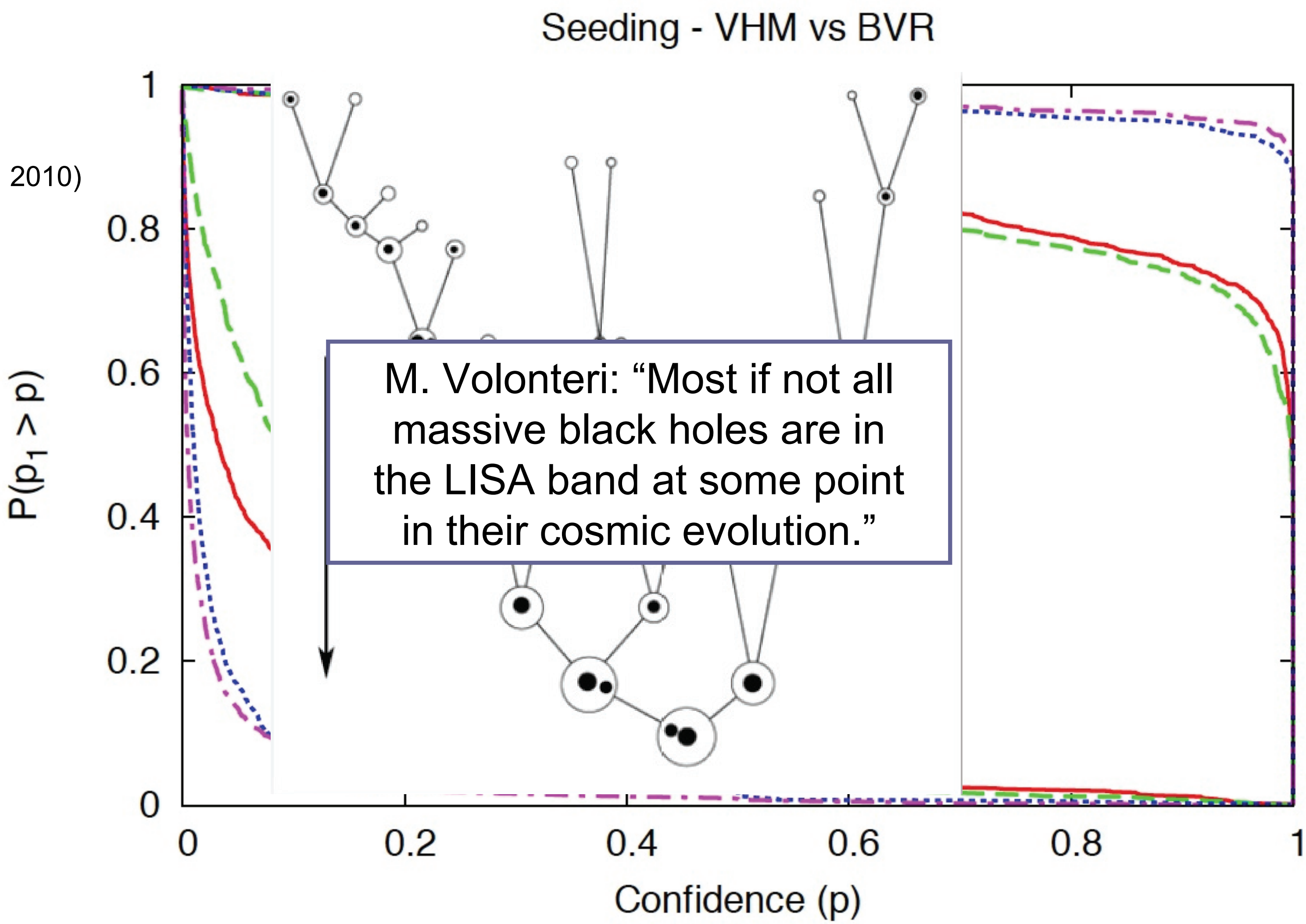
$10^5 + 10^5\ M_\odot$ at z=20!

Area between signal (blue) and noise (black) determines SNR

How did SMBHs form and grow?

- **LISA will detect enough mergers to z = 15 to discriminate among different seeds, accretion models, metallicities.**

(Sesana, et al, 2010)

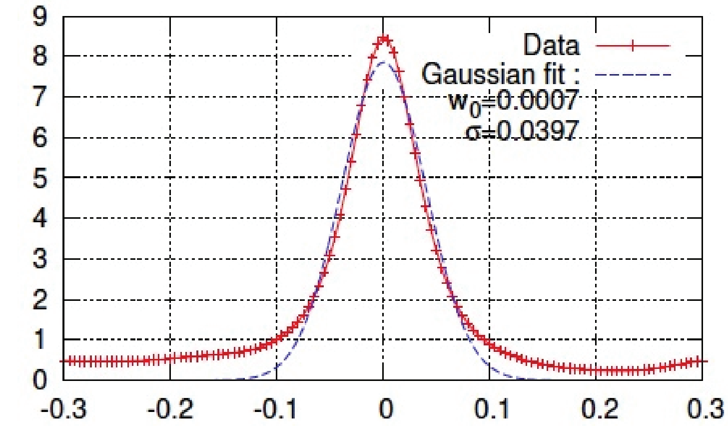


M. Volonteri: “Most if not all massive black holes are in the LISA band at some point in their cosmic evolution.”

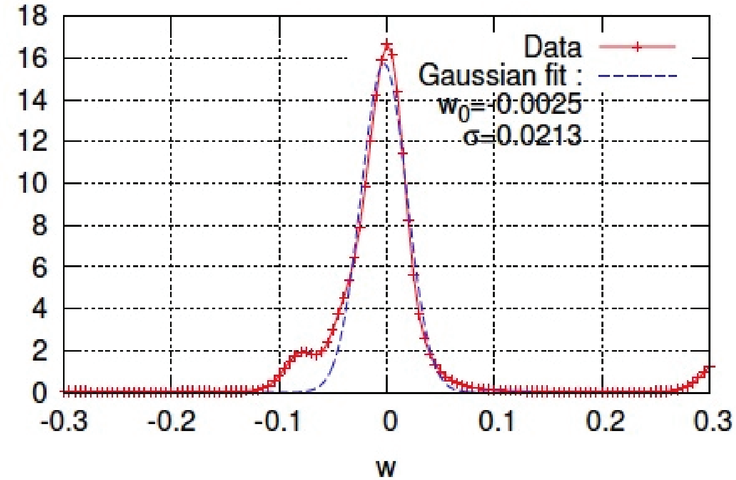
Cosmology with standard sirens

- **With luminosity distances, LISA can provide accurate and independent measurements of H_0 and w.**
- **Using EMRIs, *without* identifications, LISA can determine H_0 to ±0.4% = ±0.3 km s^{-1} Mpc^{-1} after just 20 EMRI detections: ~3 months LISA data. (MacLeod & Hogan, PRD, 2008; SDSS) Today (WMAP) ±1.2 km s^{-1} Mpc^{-1}.**
- **Using massive mergers out to z = 3, again with *no* identifications, LISA can (in 3 years) determine dark energy equation of state parameter w to ±2-4%. (Petiteau et al, ApJ, 2011; Millennium). Compare EUCLID ±2%.**

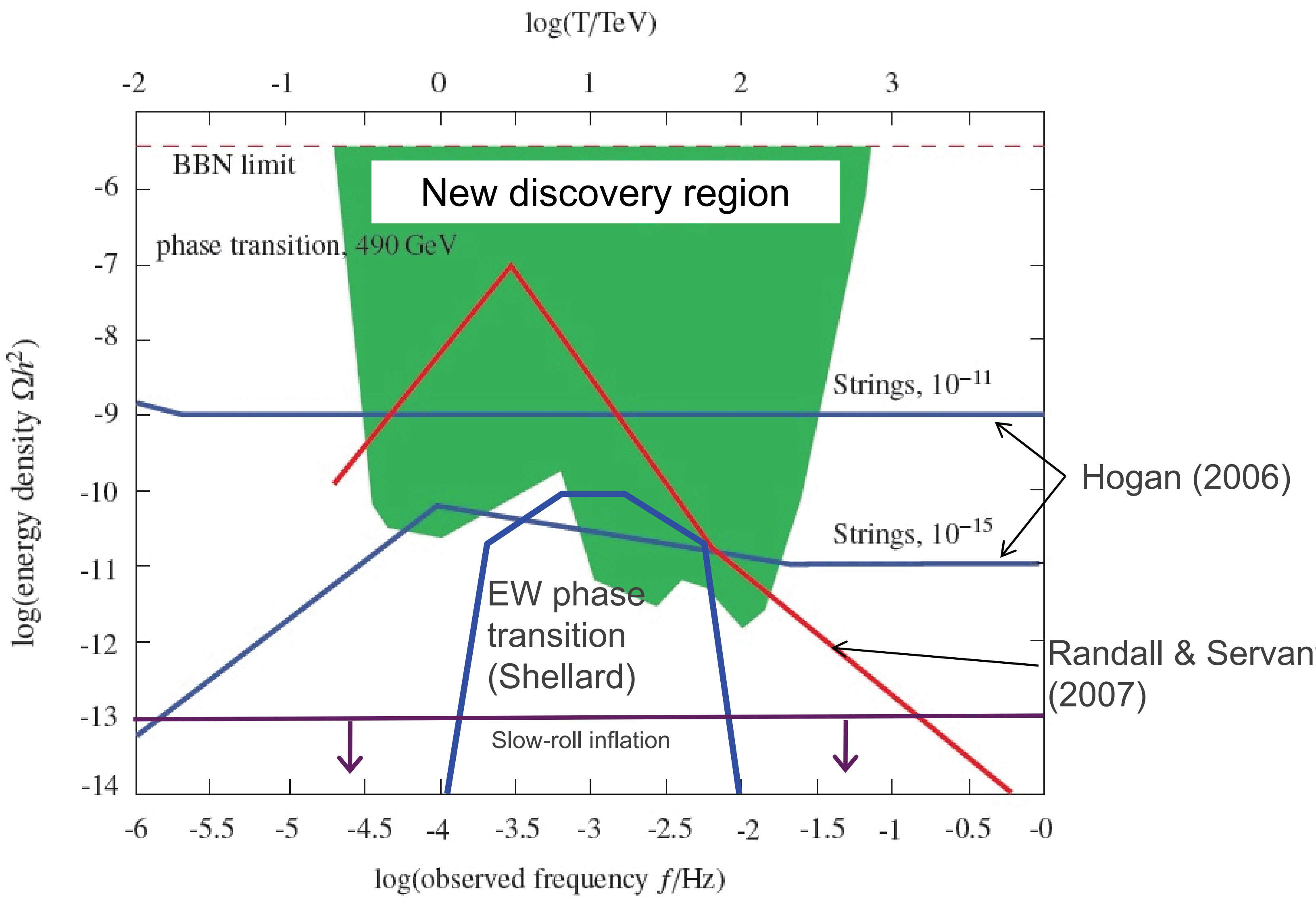
No identifications



With identifications



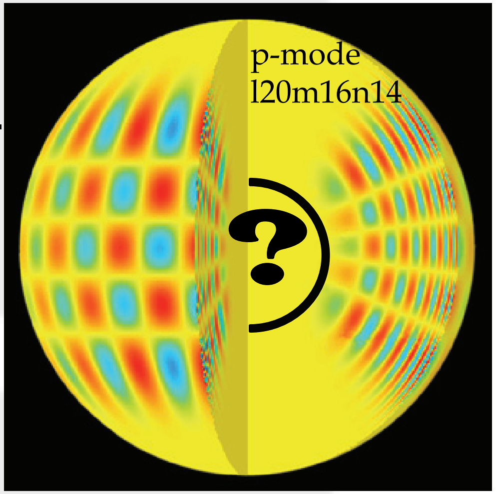
Symmetry breaking after Big Bang



LISA's solar-system science

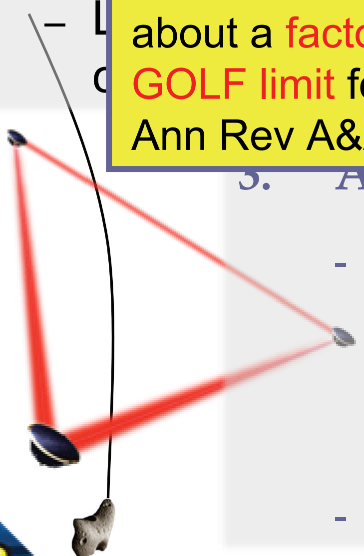
LISA responds to any time-dependent changes in gravity.

1. **Solar g-modes:**
   - LISA responds to any time-dependent change in gravity.
   - Still big questions about solar model, opacity, rotation.
   - g-modes probe the interior where density is high



2. S
   - L y fluctuations
   c

> … the LISA mission may provide a lower detection limit than the current classical helioseismic techniques … about a factor five lower in amplitude than the actual GOLF limit for modes of *m* = ±2. [T. Appourchaux et al, Ann Rev A&A 18, **197** (2010)]



3. Asteroids (Close & Schutz 2011)
   - Disturbed by a body of size L, speed v, passing a distance d from one of its S/C, LISA will have a SNR

$$\mathrm{SNR} = 500 \left(\frac{L}{1\,\mathrm{km}}\right)^{3} \left(\frac{v}{25\,\mathrm{km\,s^{-1}}}\right)^{-2} \left(\frac{d}{10^{6}\,\mathrm{km}}\right)^{-3/2}$$

   - Detect 1-10 events/yr with L between 10 and 100 m.

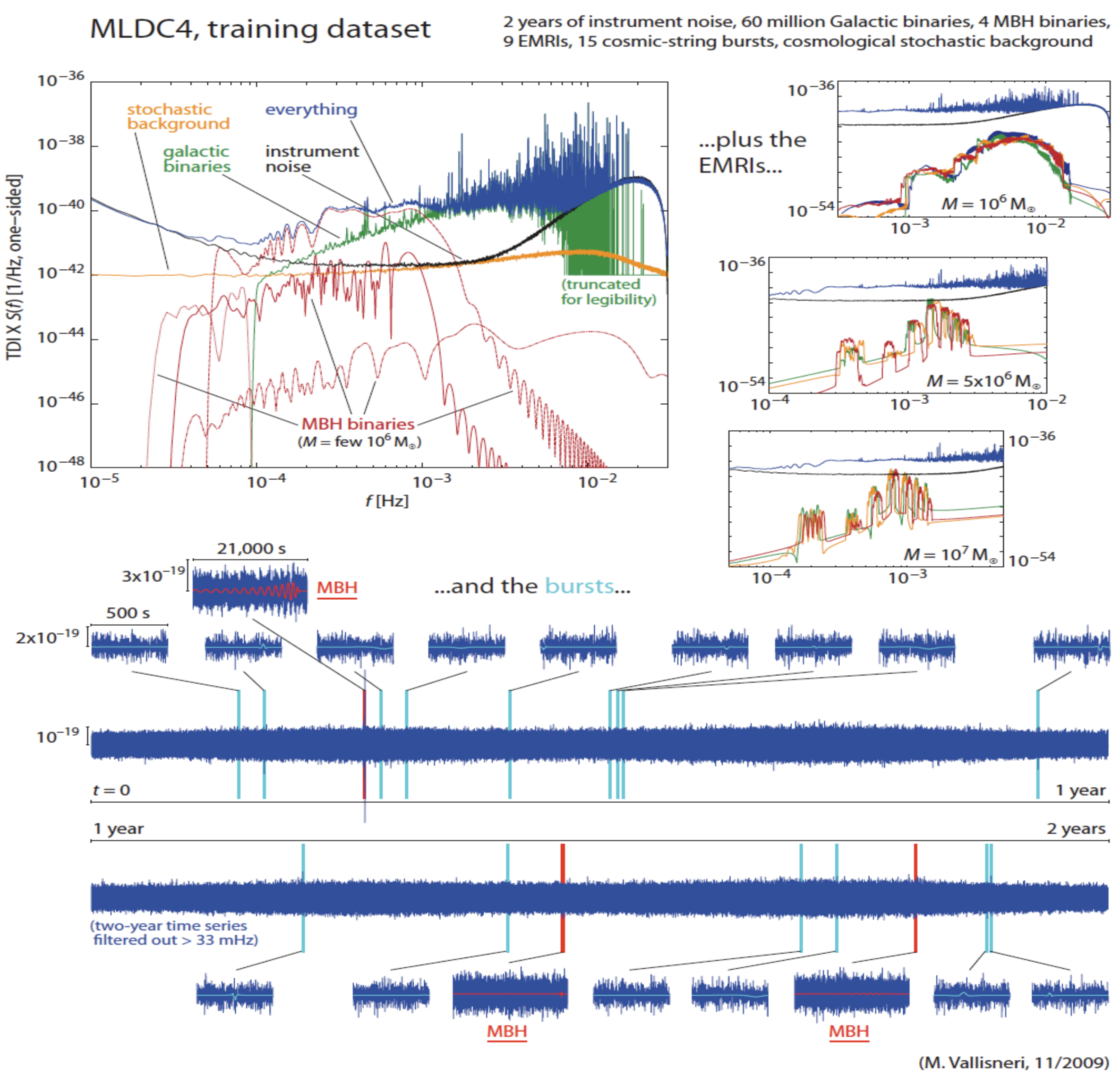
LISA data analysis

- **Analysis is challenging because of confusion problem.**
  - Heritage in well-understood ground-based data analysis problem: matched filtering based on well-understood waveform predictions.
- **LISA signal data set small: 5 years would fit on an iPod.**
- **Data analysis for the mission will require closely integrated pi … data w … ly.**

MLDC a great success: the community has learned how to resolve the confusion problem.

- **Mission will have low-latency data service when major events are expected, such as a BH-BH coalescence at z = 1.**
- **MLDC – Mock LISA Data Challenge – creates test data sets containing simulated signals. Results of analysis by competing groups are published.**
- **Latest challenge identified 20,000 individual sources.**

Mock LISA Data Challenge



LISA addresses priority astronomy

- **USpartners: Decadal Review Astro2010 advised NASA that LISA is among the top 3 “large” mission priorities:**
  - “… the recommendation and prioritization for LISA reflect its compelling science case and the relative level of technical readiness.”
- **This echoed NASA’s Beyond Einstein Program Assessment Committee (BEPAC) in 2007:**
  - “… the committee gave LISA its highest scientific ranking.”
- **A large community of astrophysicists is developing a deeper and deeper understanding of LISA’s science potential**
  - The literature contains ~1500 papers on LISA science (ADS)
  - The bi-annual LISA Symposium attracts hundreds of participants
  - New research started by the stimulus of LISA, eg EM counterparts of mergers
- **LISA targets high-priority astronomy: massive black holes, stellar evolution, the high-redshift universe, cosmology.**

- **LISA’s astronomy is timely. Now is the time for LISA!**