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LISA: From the Quantum to the Cosmos

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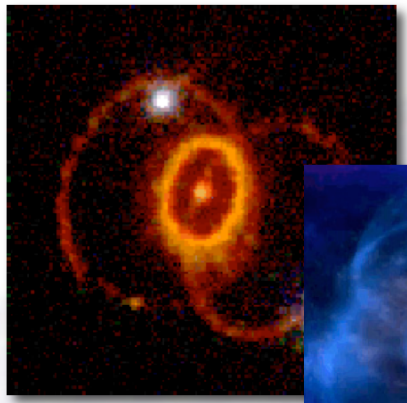
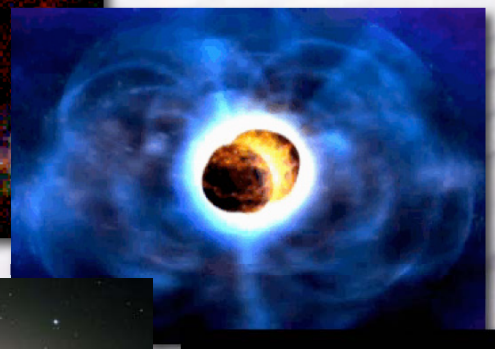
Why Gravitational Wave Probes?

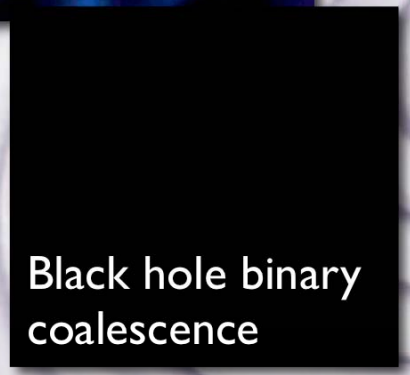
- Strong gravitational wave sources are *compact* with internal bulk motion v ~ c
- Energetic astronomical phenomena involve strong gravitational potentials
  - M/r ~ $(v/c)^2$ ~ 1
- *Gas, dust accumulate in strong potentials, obscure central engine's EM emission*
- *The most energetic phenomena are EM invisible*



Super-, hyper-novae



Neutron star coalescence



Black hole binary coalescence

The universe is transparent to gravitational waves

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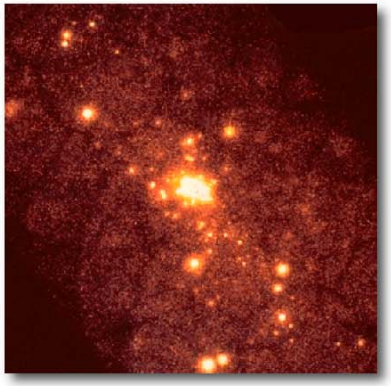
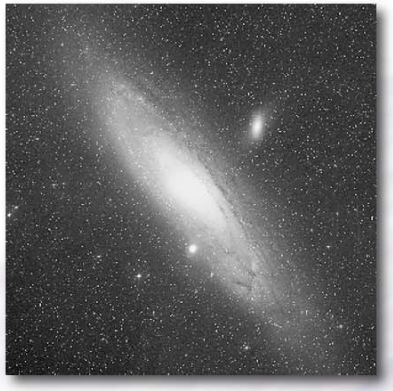
The Universe Today

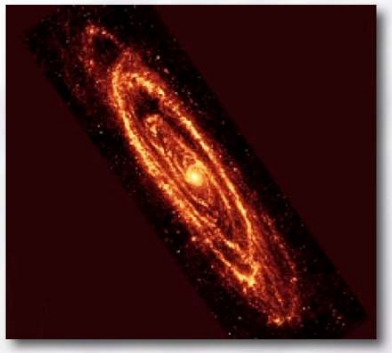


X-ray

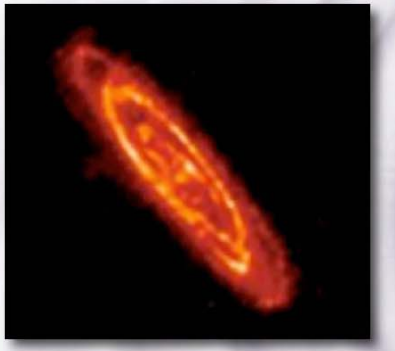
UV



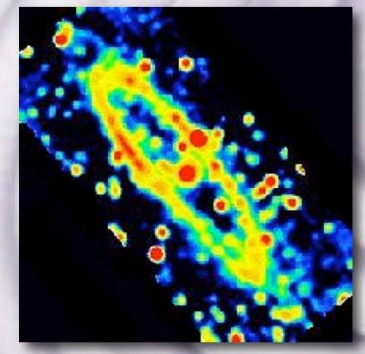
Optical



mid-IR



far-IR



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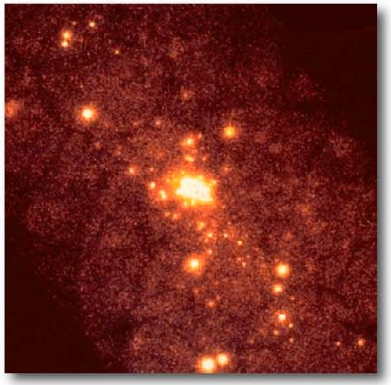
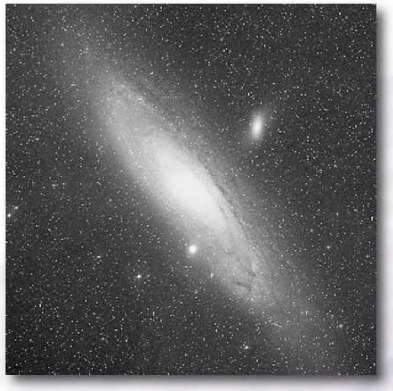
The Universe Tomorrow



X-ray

UV



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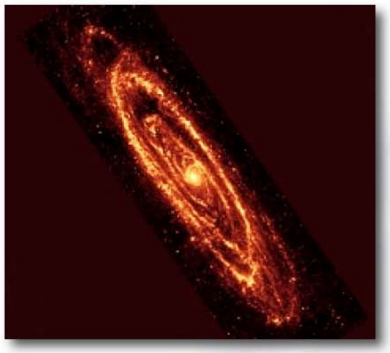
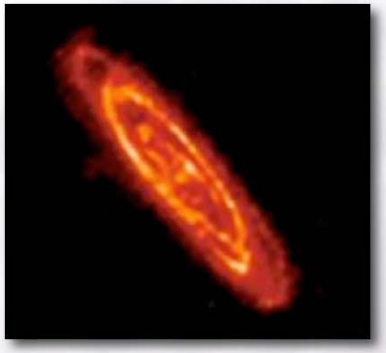
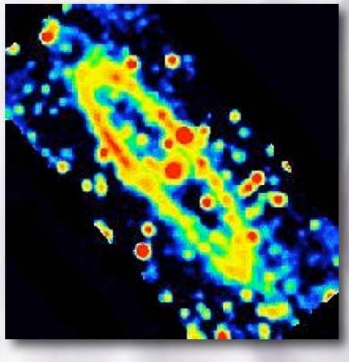


mid-IR



far-IR



Radio

Grav-Wave

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Laser Interferometer Space Antenna

- Three sci-craft constellation in 1 AU circumsolar orbit
  - 5×10^6 km separations
- Measurement: relative velocities to fm/sec precision
  - Grav wave signature: correlated disturbance in relative velocities
- Joint NASA, ESA project
- LISA Pathfinder
  - Technology demonstrator for drag free flight, laser metrology, micropropulsion

Courtesy Rutherford Appleton Laboratory

Science Enabled by LISA

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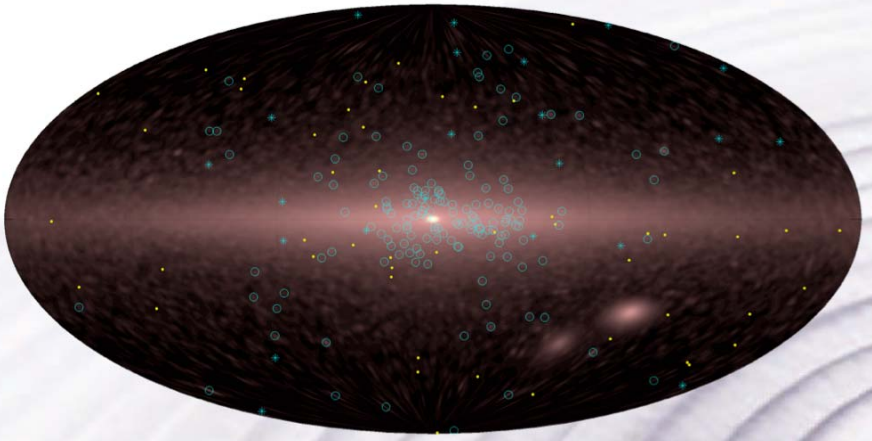
LISA's Science Impact is Broad!

- Fundamental Physics of Gravity
- Stellar structure & compact binary evolution
- Galactic structure, observation of "hidden" galactic neighborhood
- Dynamics & dissipative processes in galactic nuclei
- Cosmology & Structure Formation
  - *Absolute calibration of distance ladder* lower & upper rungs (galactic & galaxy cluster distances), Galactic nucleus black hole (M, J), merger rates as function of luminosity distance d_L

Stellar Populations

- LISA will identify ~30,00 galactic WD binaries with P_{orb} < 40 min
  - Determine for each l, b, P_{orb}, sin i, M_c/d
- P_{orb}-dot measures mass transfer
  - Probe common envelope evolution
- Some fraction identifiable as spectroscopic binaries
  - Determine *full orbital solution, component masses, absolute distance*
- *Calibrate binary stellar synthesis models*



LISA view of the gravitational wave sky
Open circles are globs; yellow dots are (simulated) isotropic sMBH mergers.
Note LMC, SMC in lower-right quadrant.
(Finn, Holley-Bockelmann, Rubbo)

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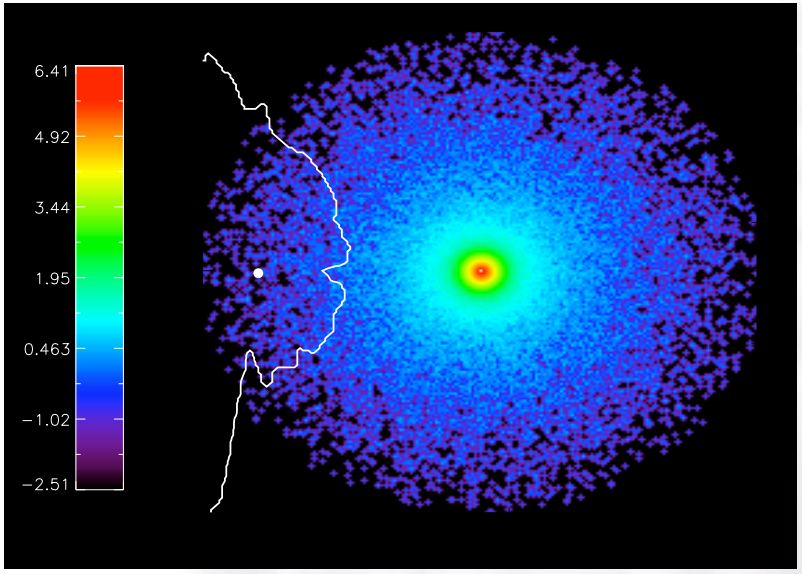
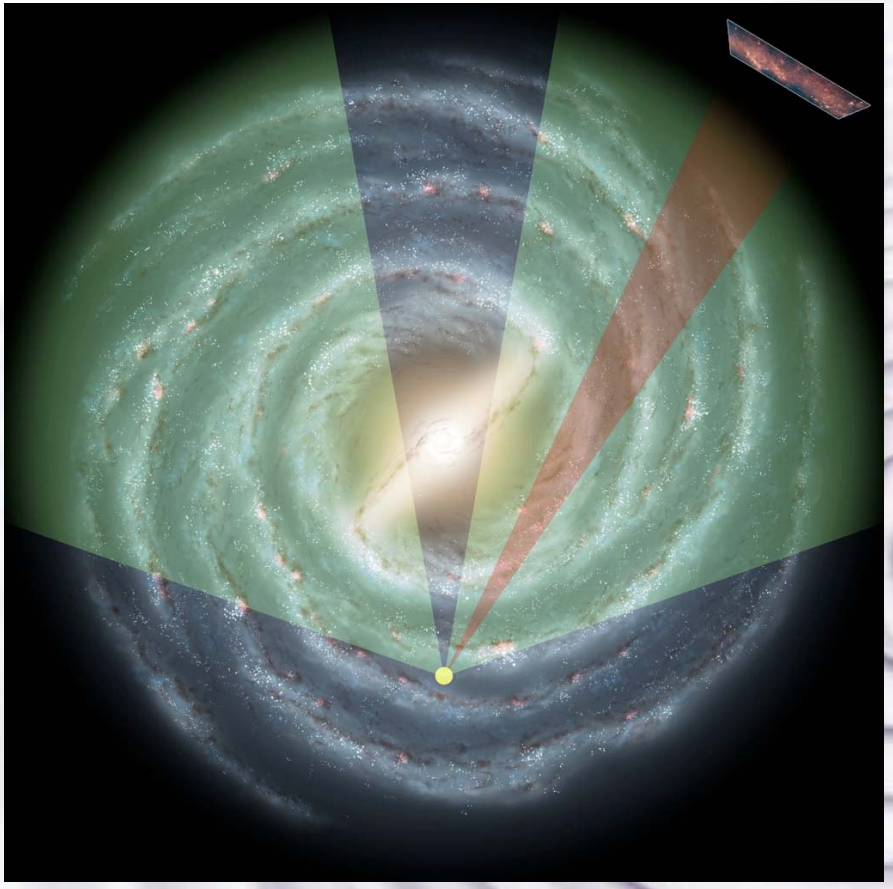
Gravitational waves and galactic structure

Dust, gas, faintness limit EM observations of galactic stellar density distribution





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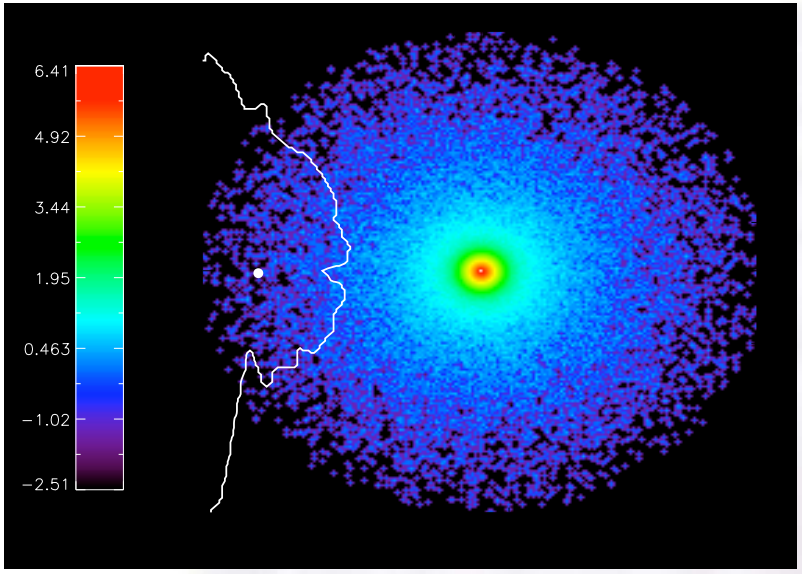
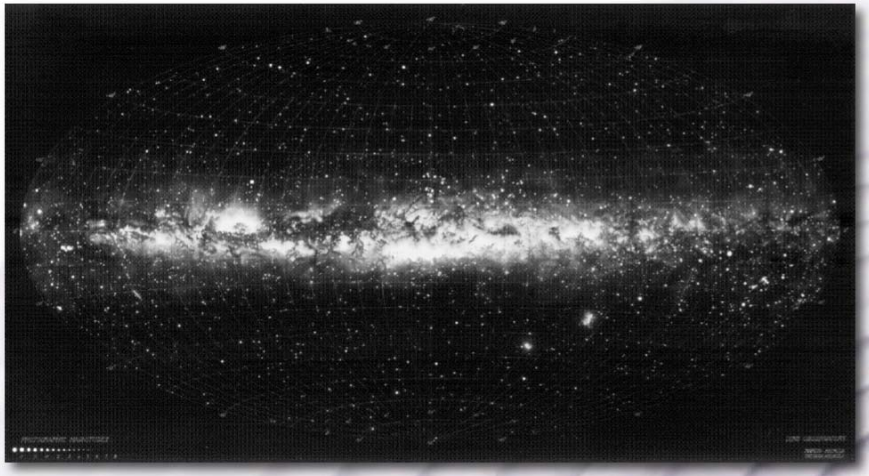
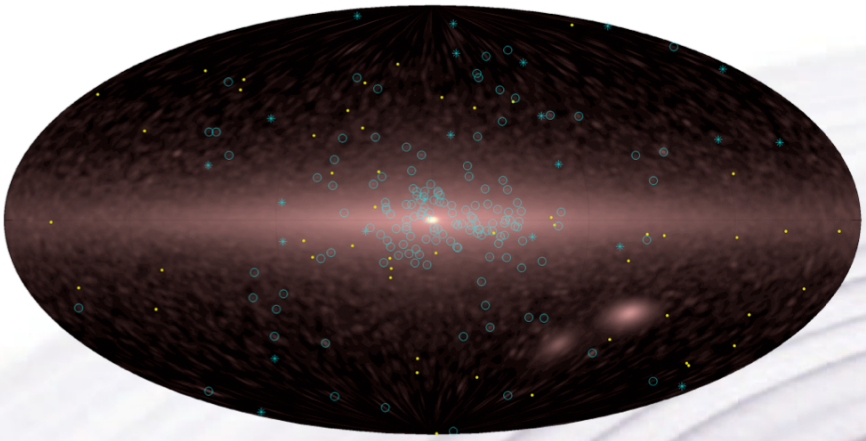




- Barred or unbarred?
- Spiral arms?
- Disk scale height(s)?
- Halo dimensions?

Galactic structure

Galaxy is transparent in gravitational waves, allowing detailed projected imagery of bulge, disk, halo...



LISA resolvable compact binaries

Type	Resolved	With df/dt
(wd, wd)	$>10^4$	~600
AM CVn	$>10^4$	~50
(ns,wd)	21	3
Other	2	0

Nelemans 2003

- Bar dimensions, orientation, disk & halo scales, spiral arms, etc.
- "Zone of avoidance" dwarf/satellite galaxies, globular clusters...
- Binary mass function from consistency with galactic model...

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Extra-galactic astronomy

- Massive black holes are ubiquitous in galactic centers
  - At least, we see evidence for them wherever we are able to ...
- Every galaxy has undergone a major merger in its past
  - Black holes sink to potential center and coalesce
  - *Dissipative processes by which black holes traverse final parsec are not understood*
- LISA can localize BH mergers to cluster (& possibly galaxy) scale
  - *Morphology at merger measures dissipative process timescales*

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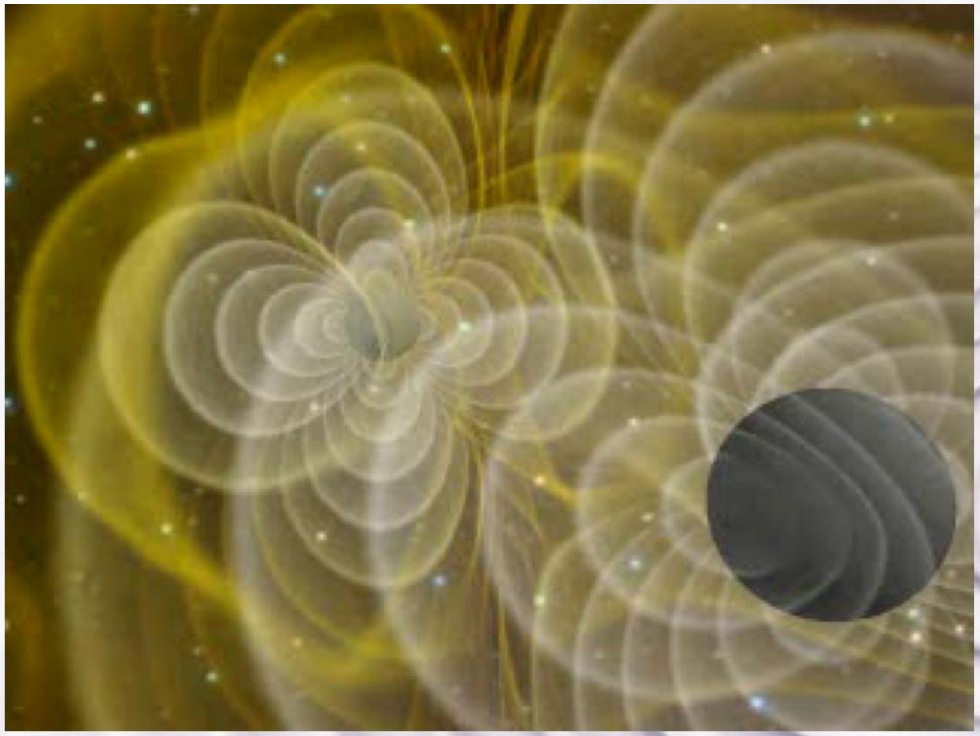
Measuring Black Hole Hair



Credit: GSFC Gravitational Physics Lab

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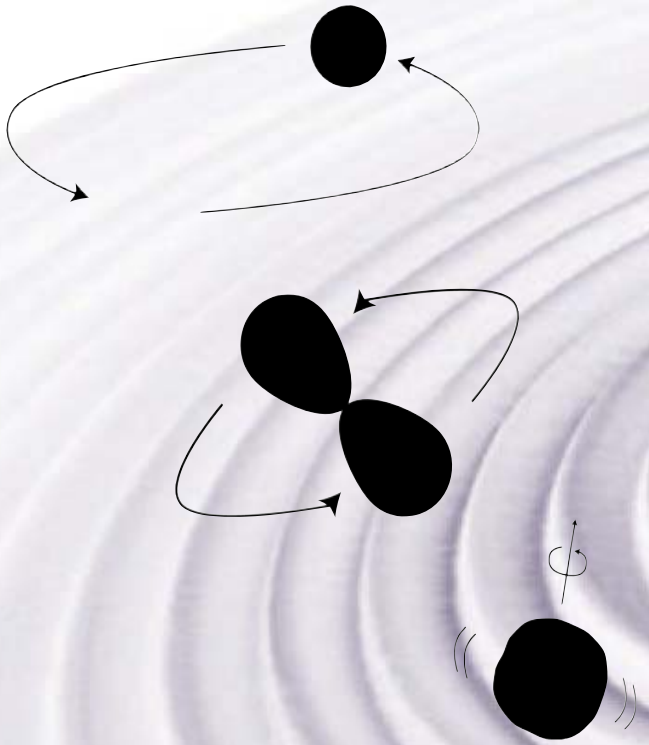
Measuring Black Hole Hair

- What distinguishes between black holes? Hair!
  - "Ringdown": damped sinusoidal signal

    $s(t) \sim \Sigma \exp(-\pi f_k t/Q_k) \sin 2\pi f_k t$
  - Einstein: Ringdown f_k, Q_k depend uniquely on M, J/M^2
  - *Other length scales will disturb relationship*



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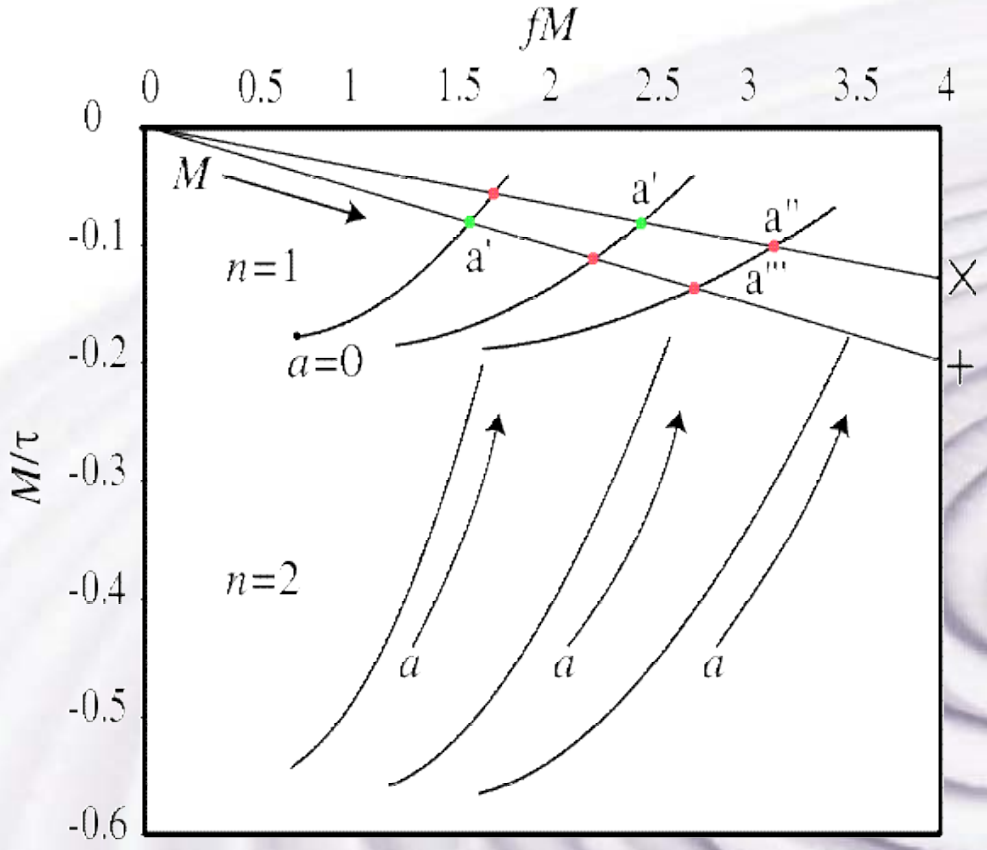
  - *Other length scales will disturb relationship*
- Observe (f,Q) pairs
  - Each pair suggests set of (M,a,n,l,m) n-tuples



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Measuring Black Hole Hair

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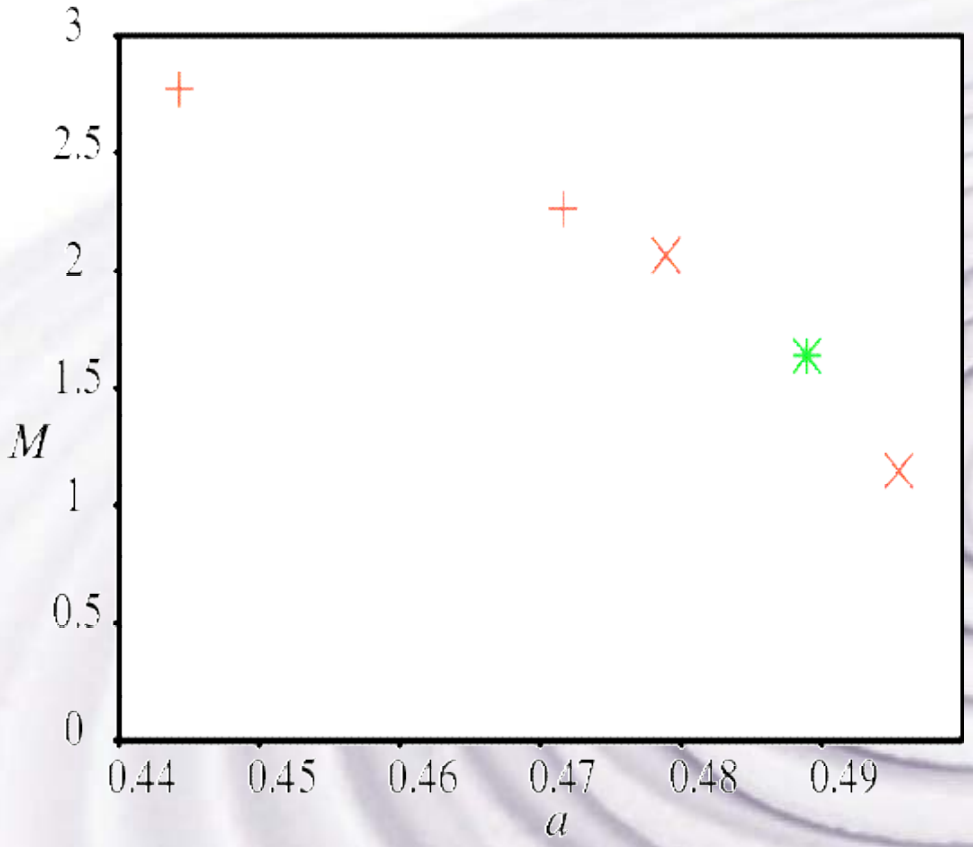
  - Einstein: Ringdown f_k, Q_k depend uniquely on M, J/M^2
  - *Other length scales will disturb relationship*
- Observe (f,Q) pairs
  - Each pair suggests set of (M,a,n,l,m) n-tuples
- "No-hair" theorem: "Einstein consistent" (in M, J/M^2) f, Q pairs
  - Deviations are evidence for other length scales



"Demonstration touchant le mouvement de *la attraction universelle*"

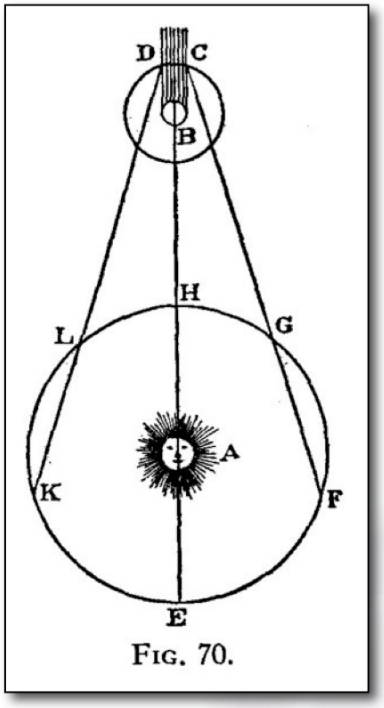


FIG. 70.

- 1676: Roemer measures c from "Galilean Clock" arrival time variations over Jovian synoptic year
- GW observation of a pulsar, or binary measures c_g:
  - $c_g = \frac{8\pi}{\Delta\Phi_{\rm PP}} \frac{R \sin\theta}{P_{\rm NS}}$
  - LISA + WD Binary: $\frac{\Delta c_g}{c} < 10^{-3}$
  - LIGO + Pulsar: $\frac{\Delta c_g}{c} < 10^{-6}$

cf. Roemer *Journal des Sçavans* 7 Dec 1676, pg 233-6;
Finn & Romano, Woan & Hendry, in preparation

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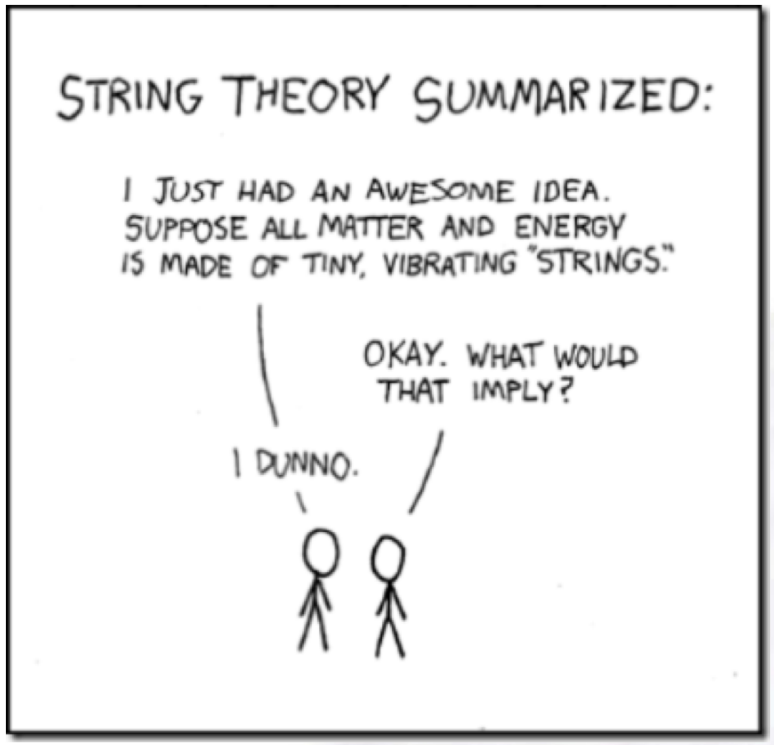
String theory and quantum gravity



- Consistency of string theory, standard model extension gravity require GR quantum correction
  - Chern-Simons term *affects only gravitation sector*
  - Affects propagation: a wavenumber dependent *birefringence* amplifies one (circular) polarization, suppresses other
- Wavenumber of ~10^6 $M_\odot$ inspiraling binary signal changes adiabatically by x100 over observation
  - "Apparent" anomalous binary precession
- LISA can observe cosmological binary coalescences (z up to 30!)
  - Bound/measure *form-factors* associated with cosmologically averaged CS correction!

LISA

- Exceptionally broad Science Impact & Discovery Potential
  - Truly from the Quantum to the Cosmos!
- Observations enable scientific investigations not otherwise possible
- Pathfinder verifies critical technologies
- Superior discovery potential in frontier science for the next decade!