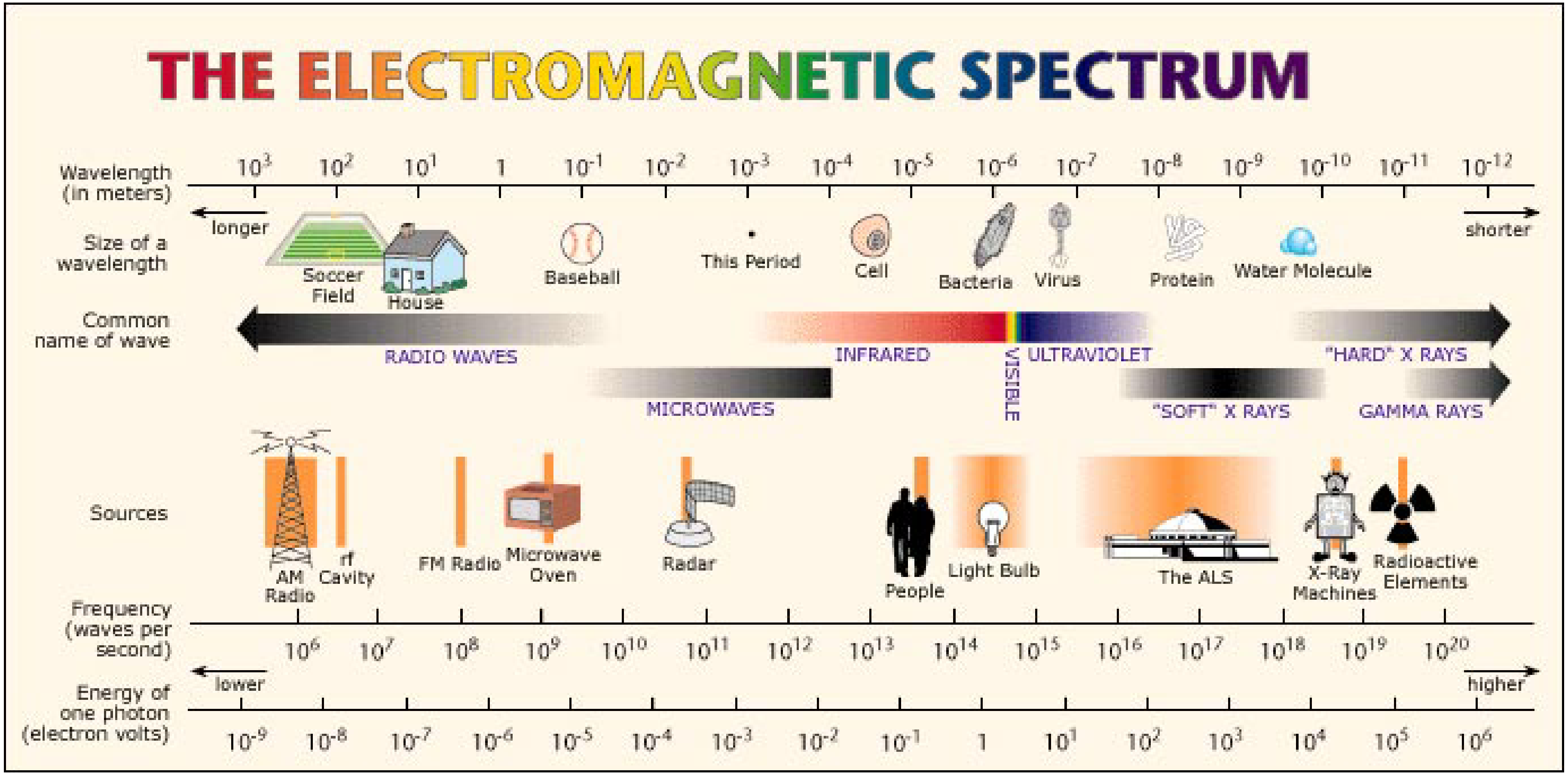
Gravitational Wave Astronomy: opening a new window on the universe

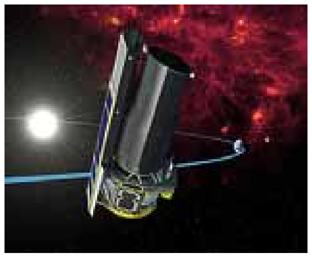
Dr Martin Hendry
&
Dr Stuart Reid

Astronomy and Astrophysics Group
&
Institute for Gravitational Research
Department of Physics & Astronomy
University of Glasgow

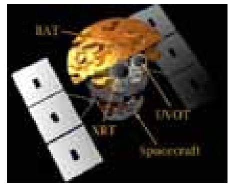
LIGO DCC document (G070011-00)
Can be downloaded from www.ligo.org/lsc_docs.html


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}



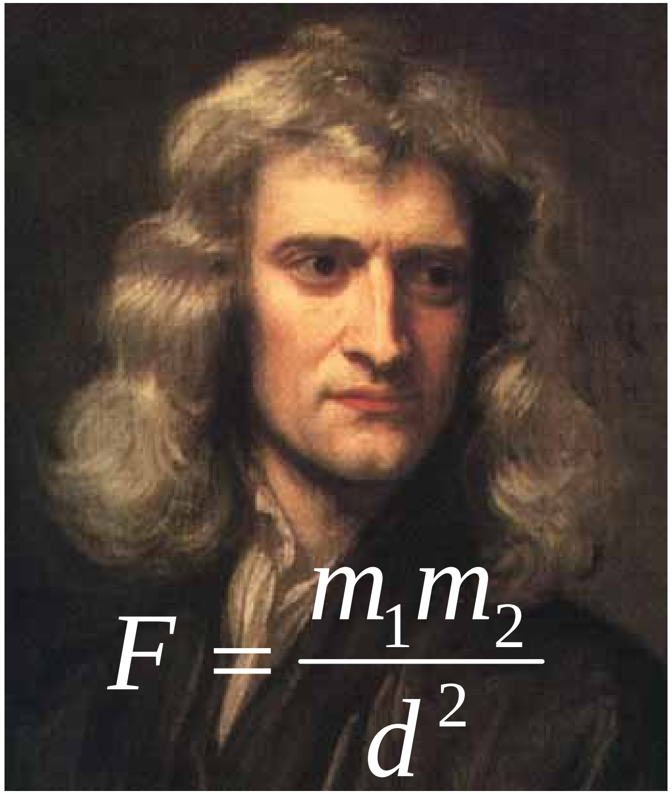






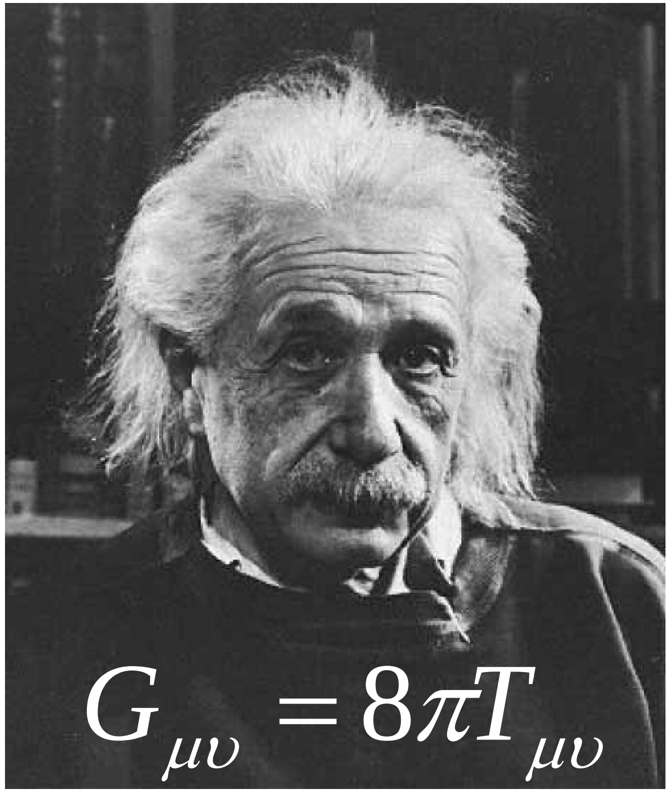
Gravity

Newton



gravity a force

Einstein



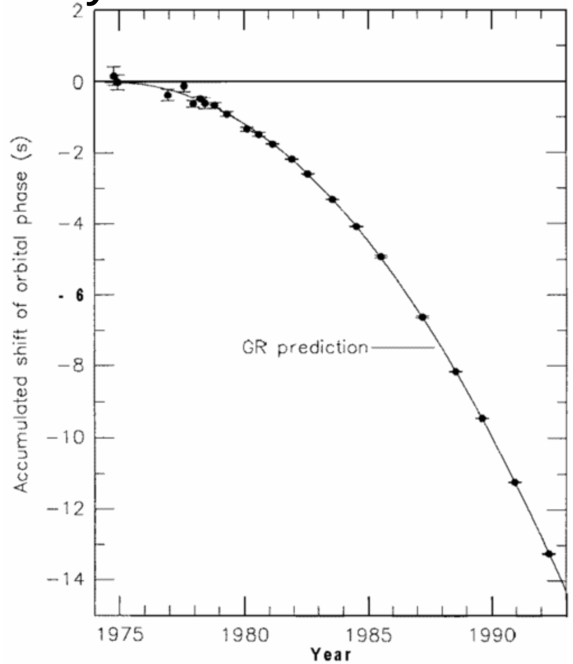
gravity a geometry

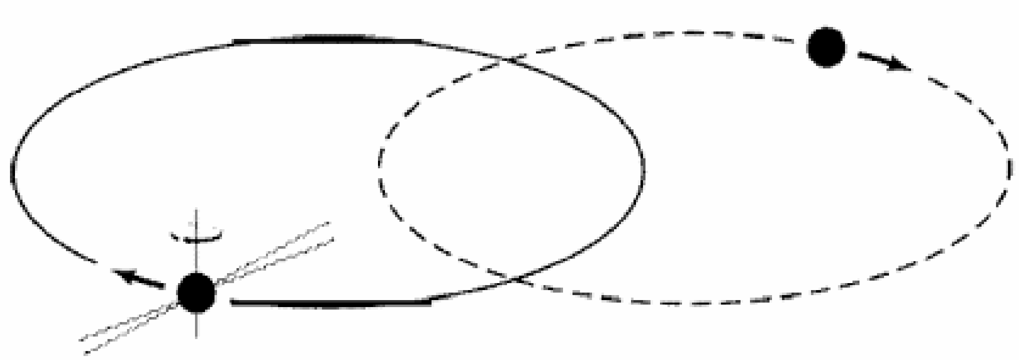
-> prediction of gravitational waves

Evidence of gravitational waves

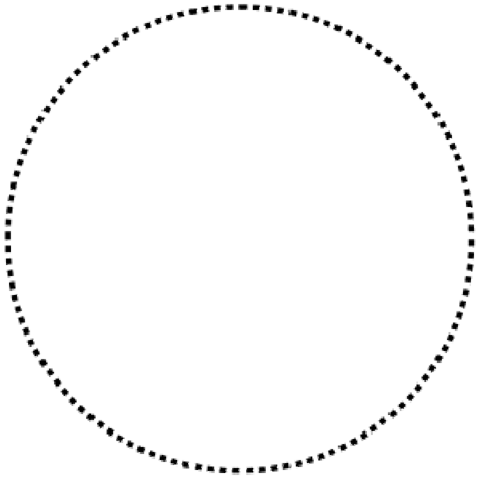
Joseph Taylor & Russell Hulse

Binary Pulsar PSR 1913+16





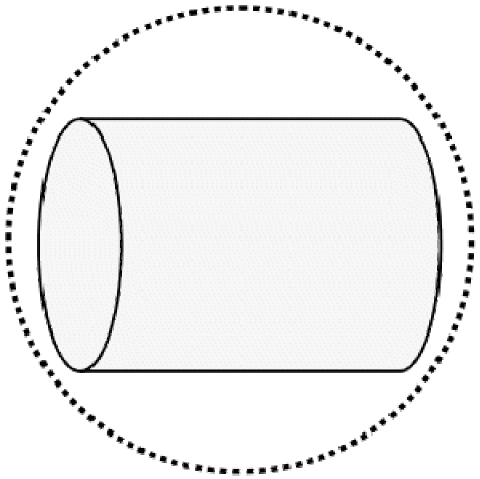
Detection of gravitational waves



In the late 1950s, Joseph Weber of the University of Maryland pioneered the idea that the peculiar nature of the waves could be made measurable by their effect on large test masses.

(sensitivity 10^{-16}m for millisecond pulses)

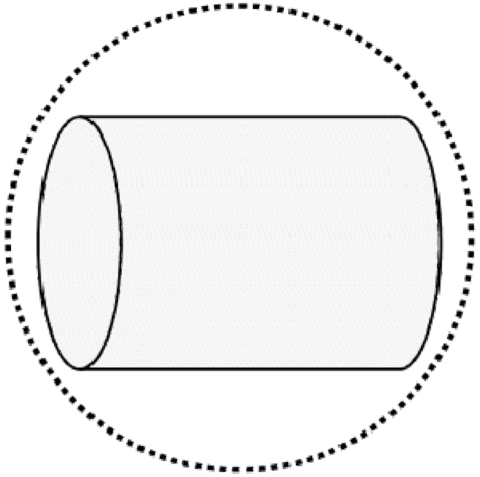
Detection of gravitational waves



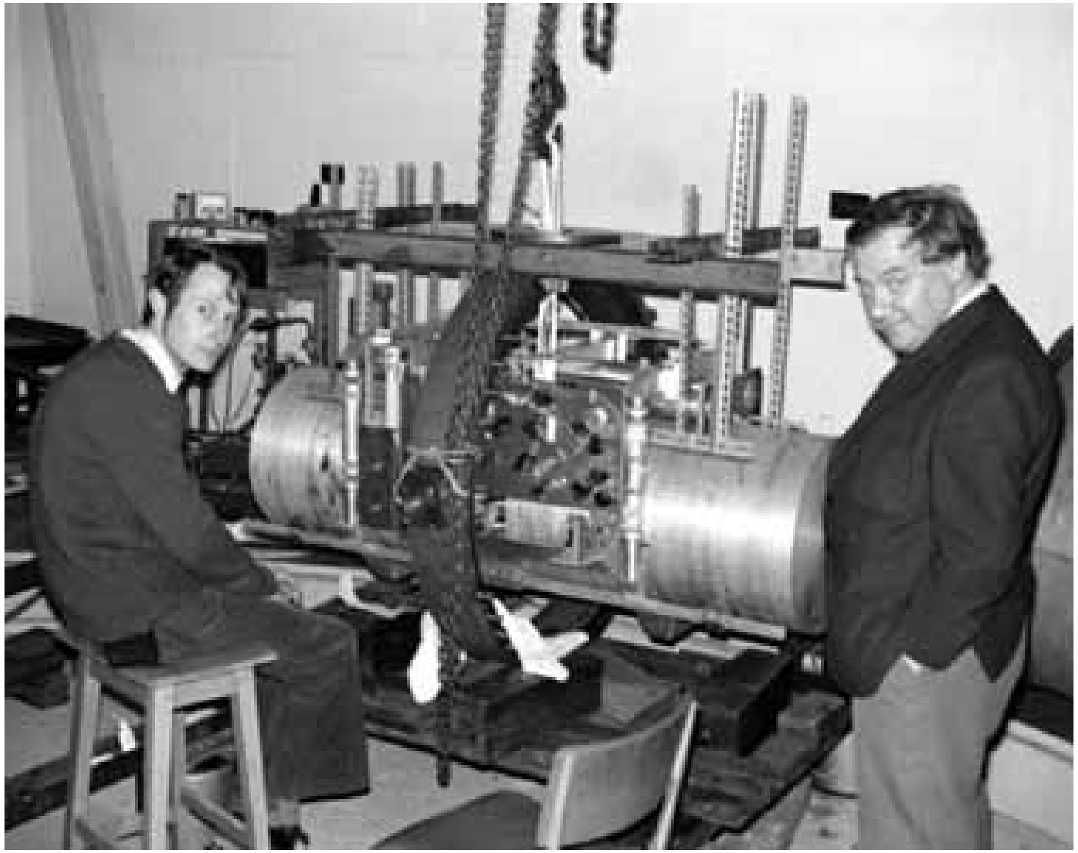
In the late 1950s, Joseph Weber of the University of Maryland pioneered the idea that the peculiar nature of the waves could be made measurable by their effect on large test masses.

(sensitivity 10^{-16}m for millisecond pulses)

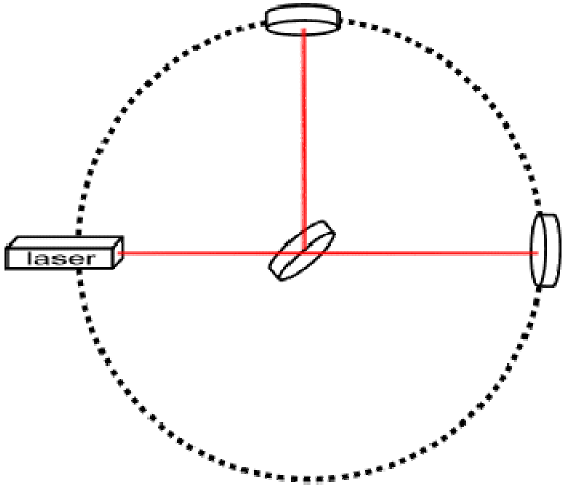
GW research in Glasgow, UK



Prof. James Hough and
Prof. Ron Drever, March 1978.



29 yrs on - Interferometric ground-based detectors



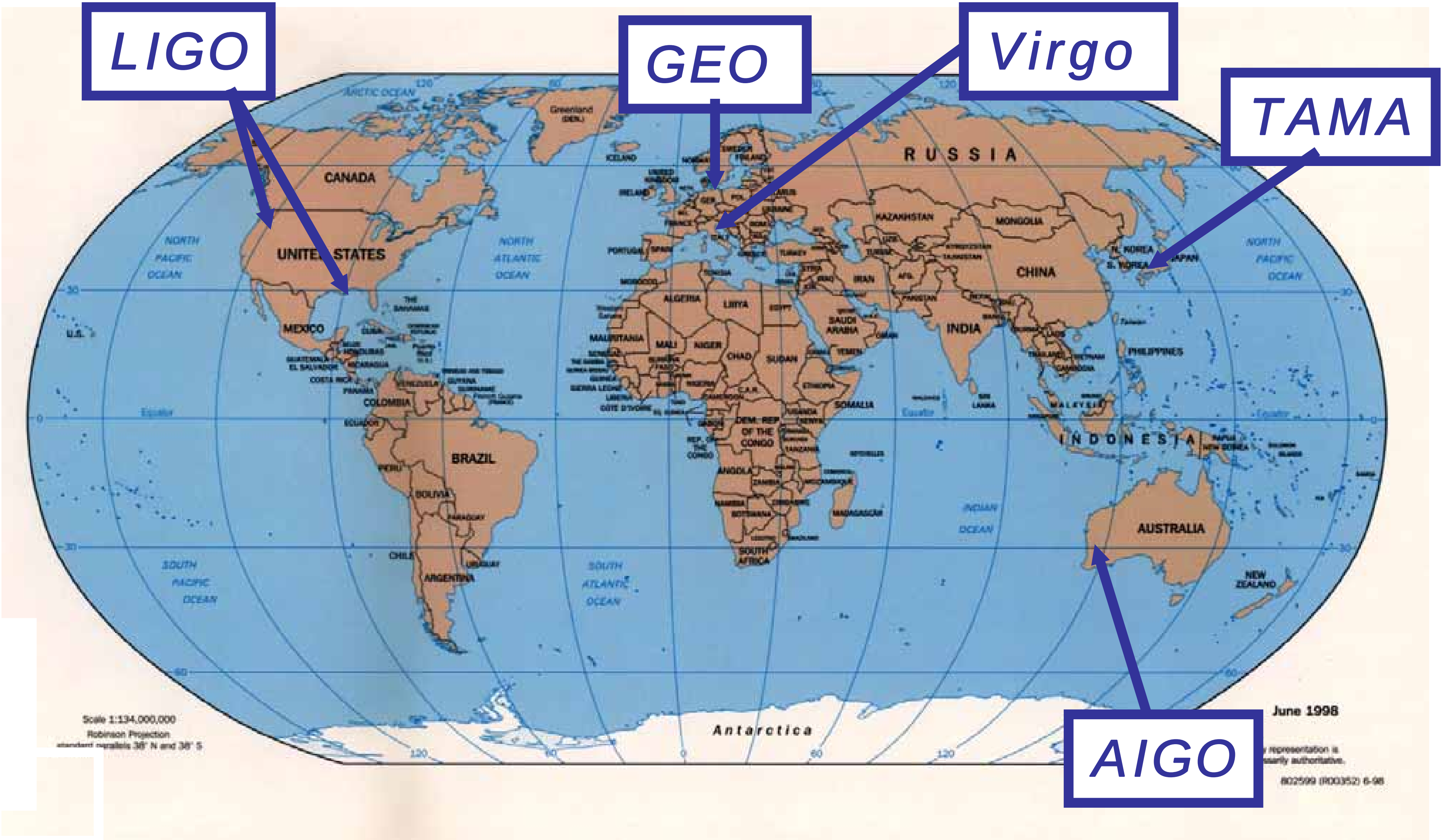
e.g. GEO600.

strain sensitivities reaching 2×10^{-22}m at 500 Hz

Sensitivity limited by
1) shot noise
2) thermal noise

The Michelson Interferometer

Network of Detectors on Earth

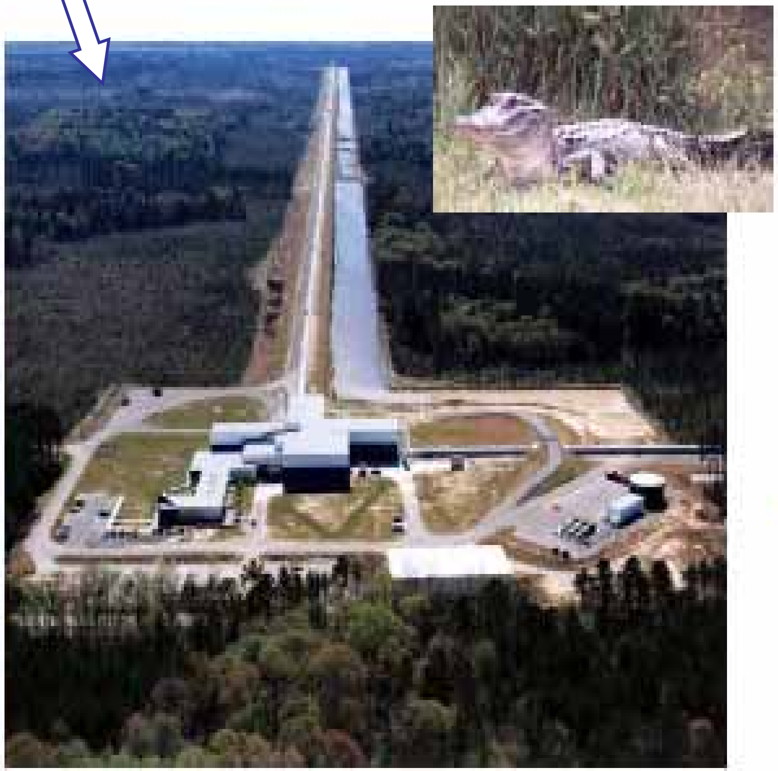


simultaneously detect signals

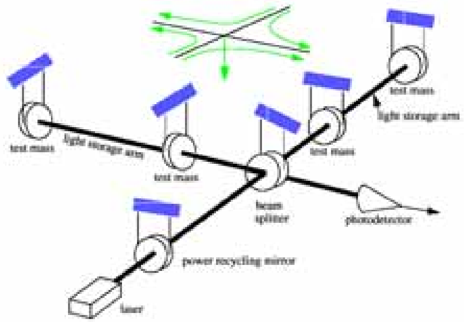
Initial LIGO detectors

LIGO project (USA)

- 2 detectors of 4km arm length + 1 detector of 2km arm length
- Washington State and Louisiana



Each detector is based on a 'Fabry-Perot – Michelson'



Nd:YAG laser 1.064μm

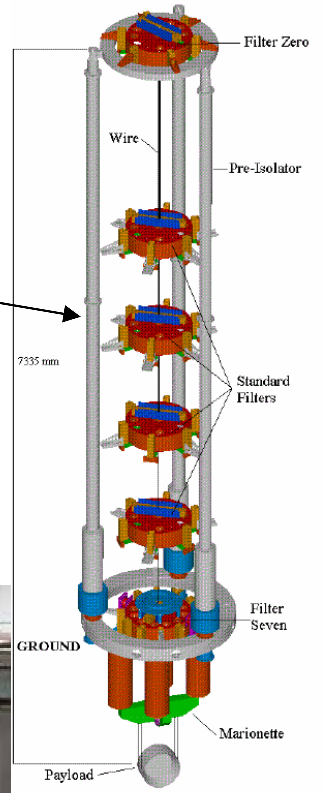
VIRGO: The French-Italian Project 3 km armlength at Cascina near Pisa

designed for enhanced low frequency performance

VIRGO – Cascina

3km beam tube

The 'Super Attenuator' filters the seismic noise above 4 Hz



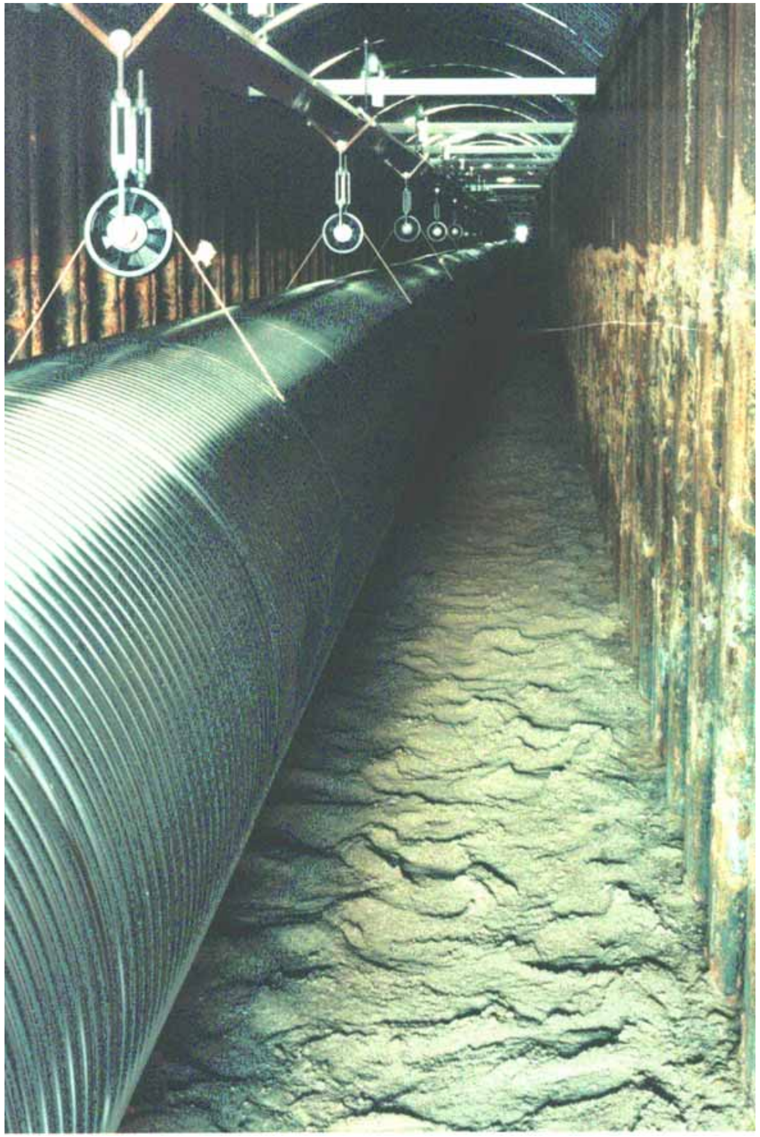
Other Detectors and Developments – TAMA 300 and AIGO

TAMA 300 Tokyo
300 m arms

AIGO Gingin, WA
80 m arm test facility

GEO 600 – German/UK detector at Ruthe

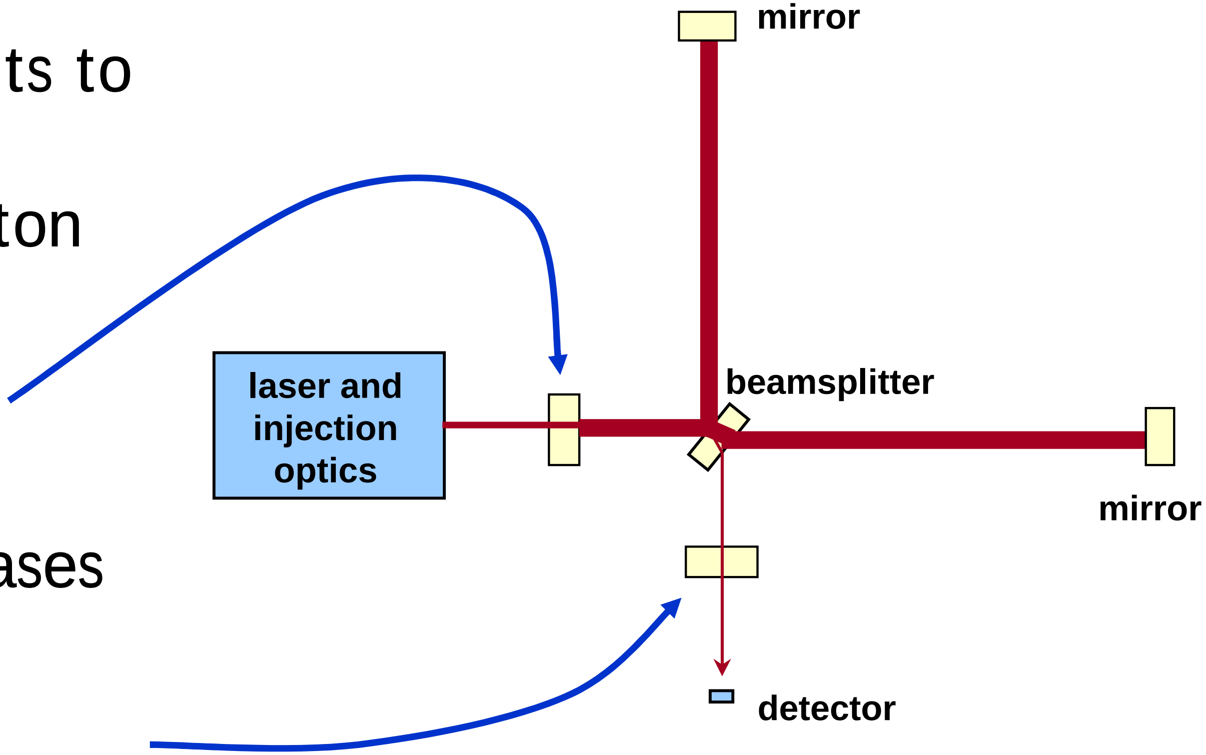
GEO600 Vacuum Tube



Unique GEO Technology 1

Advanced interferometry

- One of the fundamental limits to interferometer sensitivity is photon statistics



- Power recycling effectively increases the laser power
- Signal recycling – a Glasgow innovation – enhances signal size

Standard Quantum Limit

- High frequency sensitivity limited by SHOT NOISE. Counting statistics of N photons gives $\sqrt{N}$ uncertainty.
- Low frequency sensitivity limited by RADIATION PRESSURE NOISE from momentum transfer from photons. Increases as $\sqrt{power}$.

Alternative view: We want to know the position of the test masses at time t. To reduce uncertainty we increase laser power. This kicks the masses and reduces our knowledge of their momentum. Subsequent measurements of position are then less accurate. Follows Heisenberg uncertainty principle

Thermal Noise

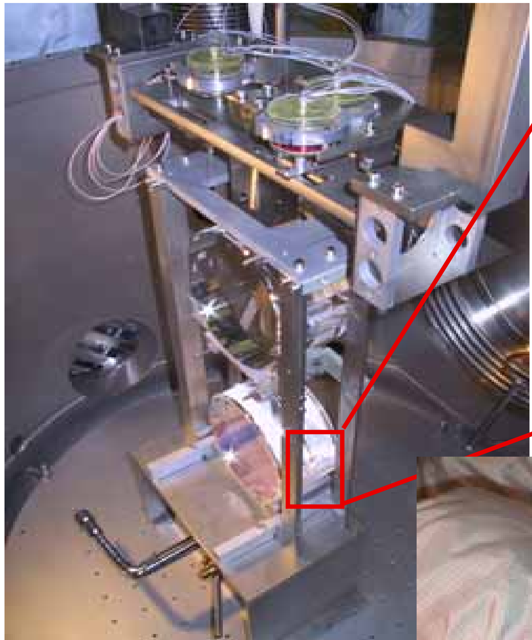
- Results from the thermal energy of the atoms and molecules in test masses and suspensions

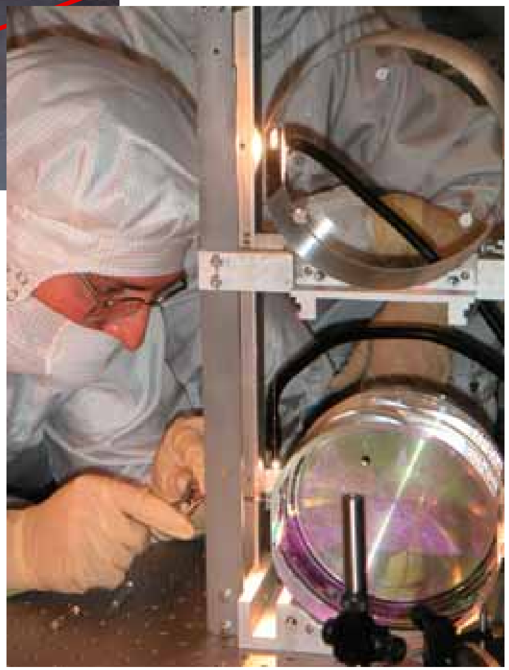
- Appears in two forms
  - Brownian thermal noise (Einstein 1905) since there is ½k_BT energy per degree of freedom in a system
  - Thermo-elastic noise resulting from spatial temperature fluctuations in a system

- Current suspension designs based on modelling the resonant modes of suspensions and masses as damped simple harmonic oscillators of resonant frequency f_0, mass m and loss factor ϕ(f) – then FD theorem gives the power spectral density of the resulting thermal motion as:

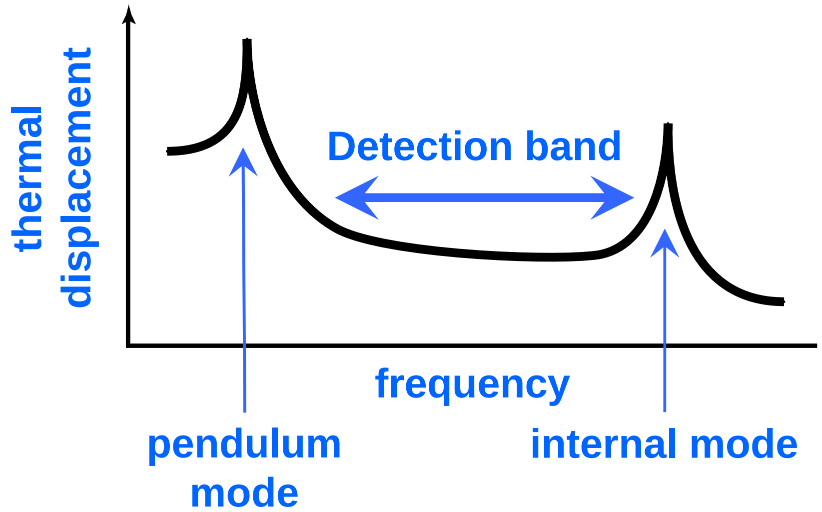
$$S_x(\omega) = \frac{4k_B T \omega_0^2 \phi(\omega)}{\omega m\left[\left(\omega_0{}^2 - \omega^2\right)^2 + \omega_0^4 \phi^2(\omega)\right]}$$

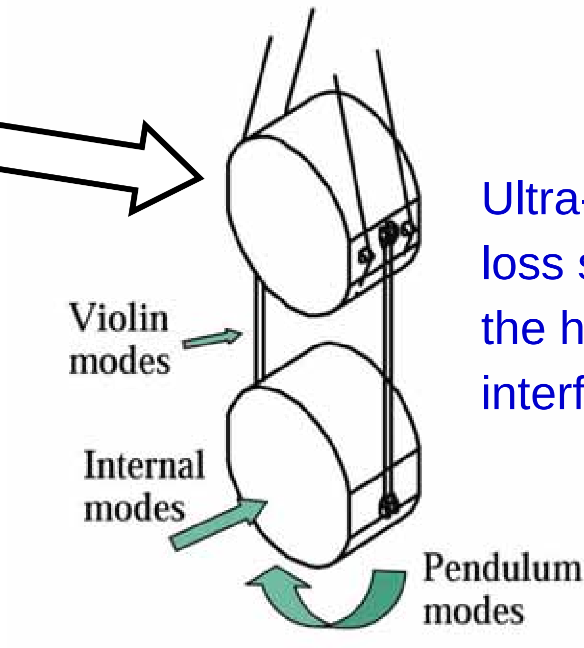
Unique GEO Technology 2 - Monolithic Silica Suspension





– reduces thermal noise





Ultra-low mechanical loss suspension at the heart of the interferometer

Timescales - first detectors

GEO and LIGO

Main interferometers under development in 2001-5

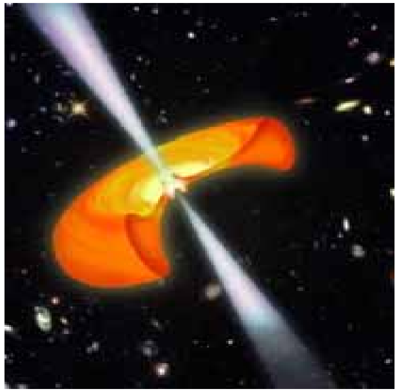
- First science coincident LIGO/GEO data run – September 2002 (17 days)
  - upper limits to signals from particular sources – coalescing compact binaries, pulsars, bursts, stochastic background published in Phys. Rev D.

- Further runs have been carried out – S2 to S4 (ending March 2005) and results are available in Phys. Rev. Lett., Phys. Rev. D, CQG; see http://www.ligo.org/results/ for details
- S5 science run began Nov 2005 to compile 1 years worth of coincidence data
- LIGO and GEO to run in coincidence, with GEO making upgrades throughout

LIGO/GEO Searches

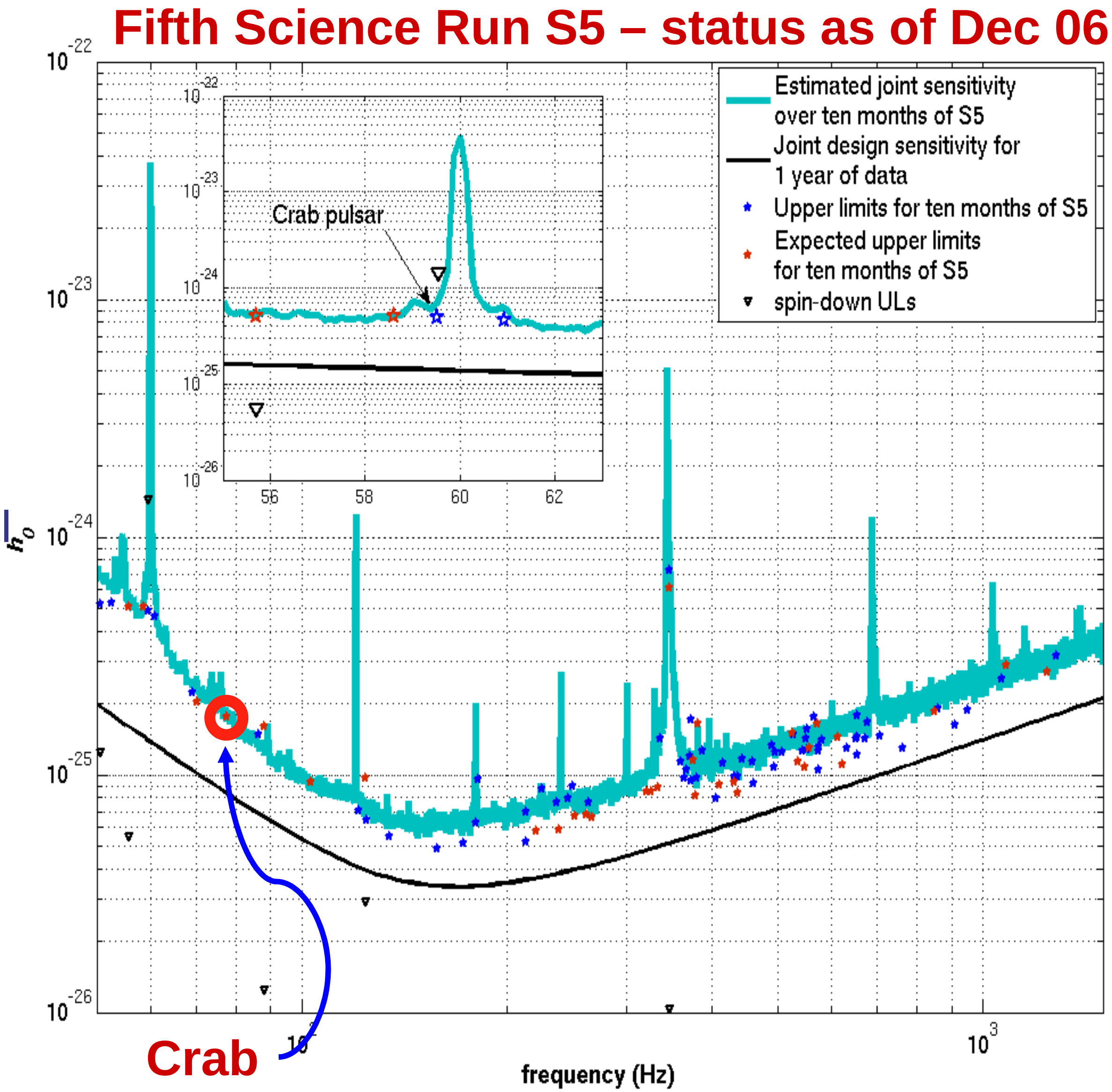
- 'Upper Limits' have been set for a range of signals
  - Coalescing binaries
  - Pulsars
  - Bursts
  - Stochastic background
- Now at an astrophysically interesting level
  - We recently beat the Crab spindown limit and the BBN limit on stochastic background

Pulsar Sources & Science: Science Goals



Goals:

- All-sky surveys for known and unknown pulsars & GRBs
- Constraint on neutron star crustal strength/deformation
- Lowest GW strain upper limit:
  PSR J1802-2124
  (f_{gw} = 158.1 Hz, r = 3.3 kpc)
  $h_0 < 4.9\times10^{-26}$
- Lowest ellipticity upper limit:
  PSR J2124-3358
  (f_{gw} = 405.6 Hz, r = 0.25 kpc)
  $\varepsilon < 1.1\times10^{-7}$

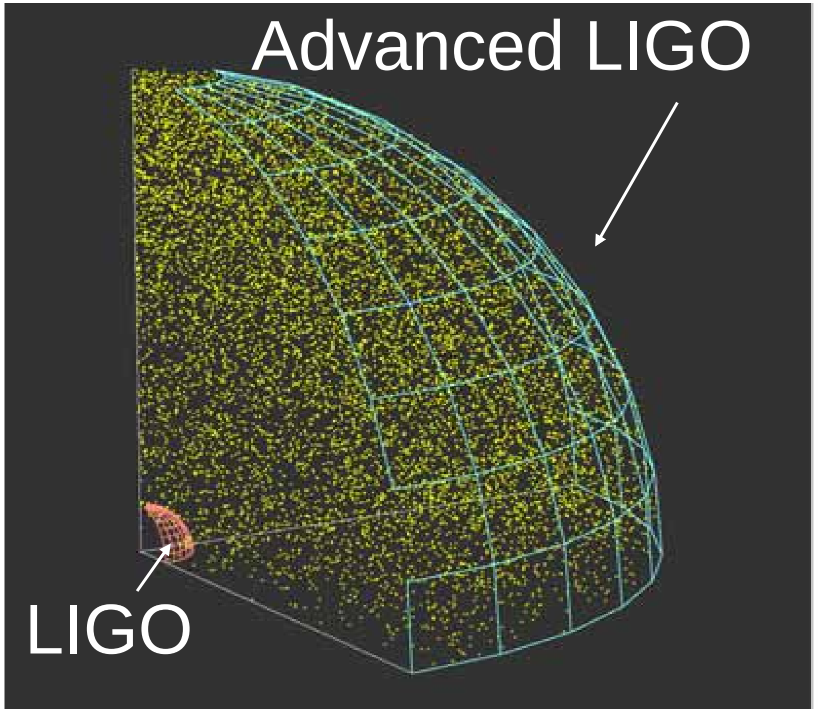


Coalescing compact binaries

- recent discovery of another compact binary system in the galaxy - the double pulsar J0737-3039 – has improved the statistics for the expected rate of binary coalescences by a significant factor
  - the most probable rate of binary neutron star coalescences detectable by the LIGO system is between 1 per 10 years and 1 per six hundred years
- thus detection at the level of sensitivity of the initial detectors is no way guaranteed – Need another X 10

For the Future :

- **Need** to improve sensitivity:
  - try to reach limits set by the Uncertainty Principle and Gravity Gradient noise
- How?
  - can go a long way towards this goal by applying the GEO technology and its extensions to longer detectors
    - Silica Fibres/Ribbons
    - Signal Recycling and injection locked lasers (180W)



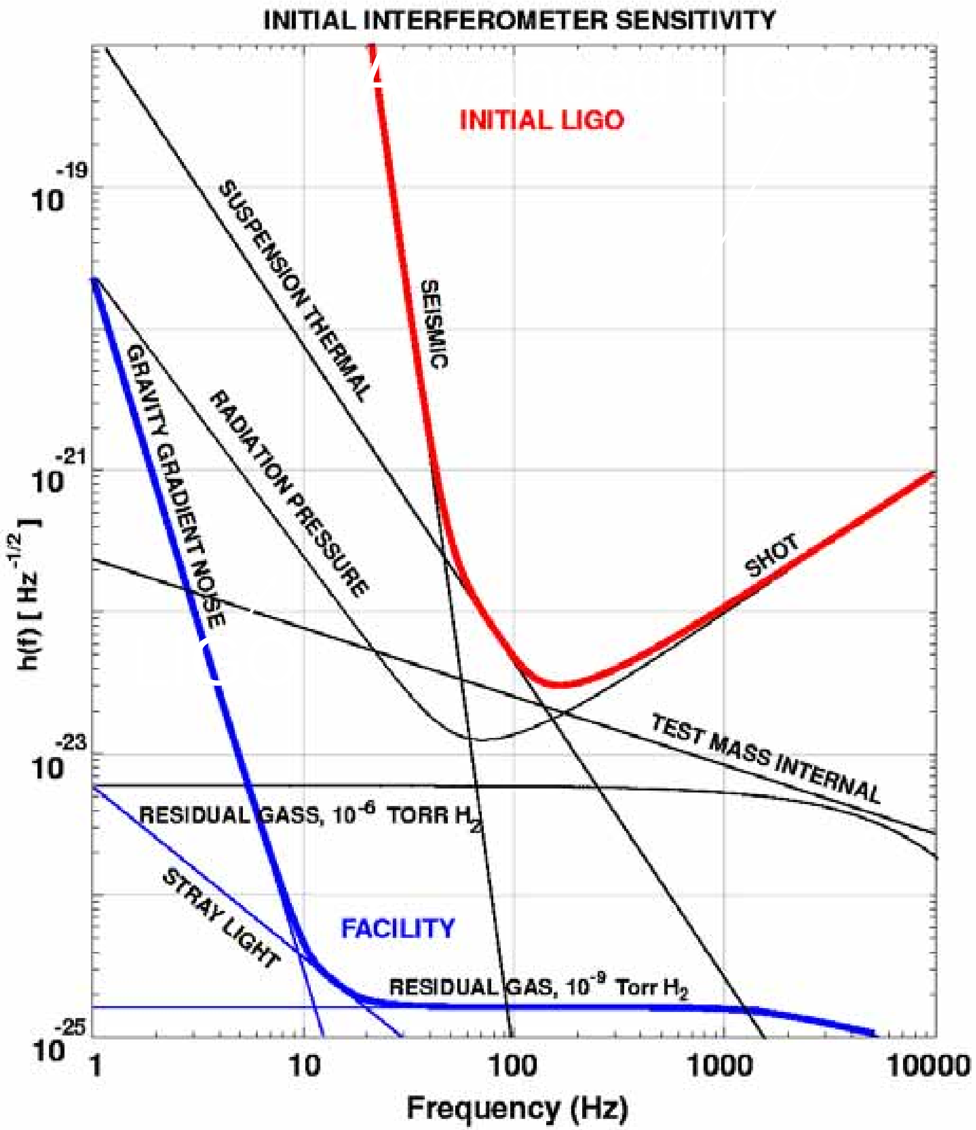
⇒ **'Advanced LIGO' -**

Approved by US National Science Board 2004

In Presidents FY08 budget – 5^{th} Feb 07!

For the Future :

- **Need** to improve sensitivity:
  - try to reach limits set by the Uncertainty Principle and Gravity Gradient noise
- How?
  - can go a long way towards this goal by applying the GEO technology and its extensions to longer detectors
    - Silica Fibres/Ribbons
    - Signal Recycling and injection locked lasers (180W)



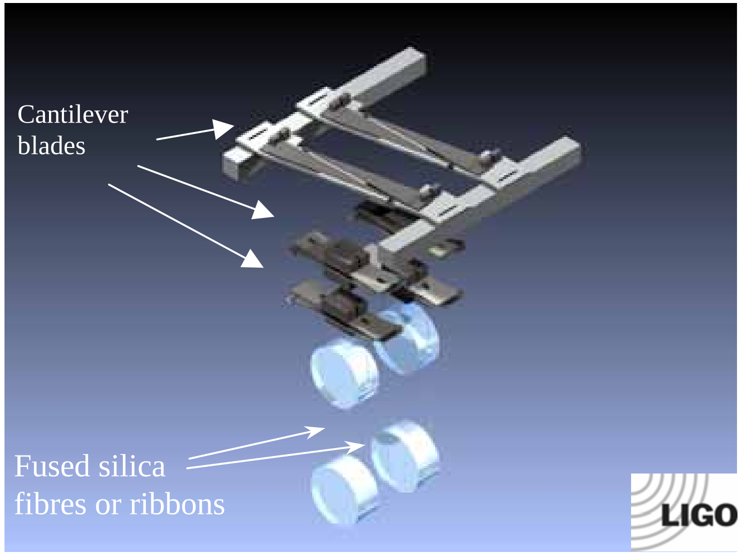
⇒ ‘Advanced LIGO’ -

Approved by US National Science Board 2004

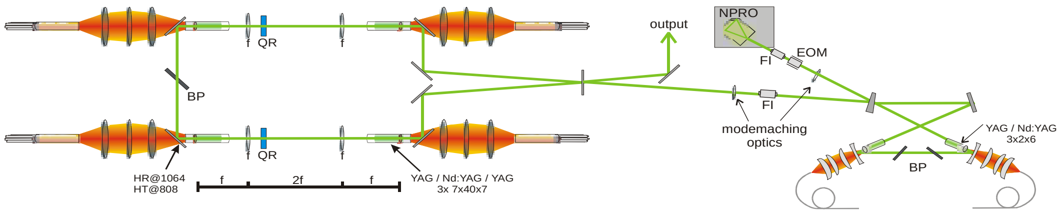
In Presidents FY08 budget – 5^{th} Feb 07!

Advanced LIGO Suspension (Glasgow)

- Advanced LIGO suspension (Glasgow)



- Advanced LIGO Laser Design (GEO/LZH Hannover)
  - Injection locking on a 20 W Master above 200 W single frequency output power possible



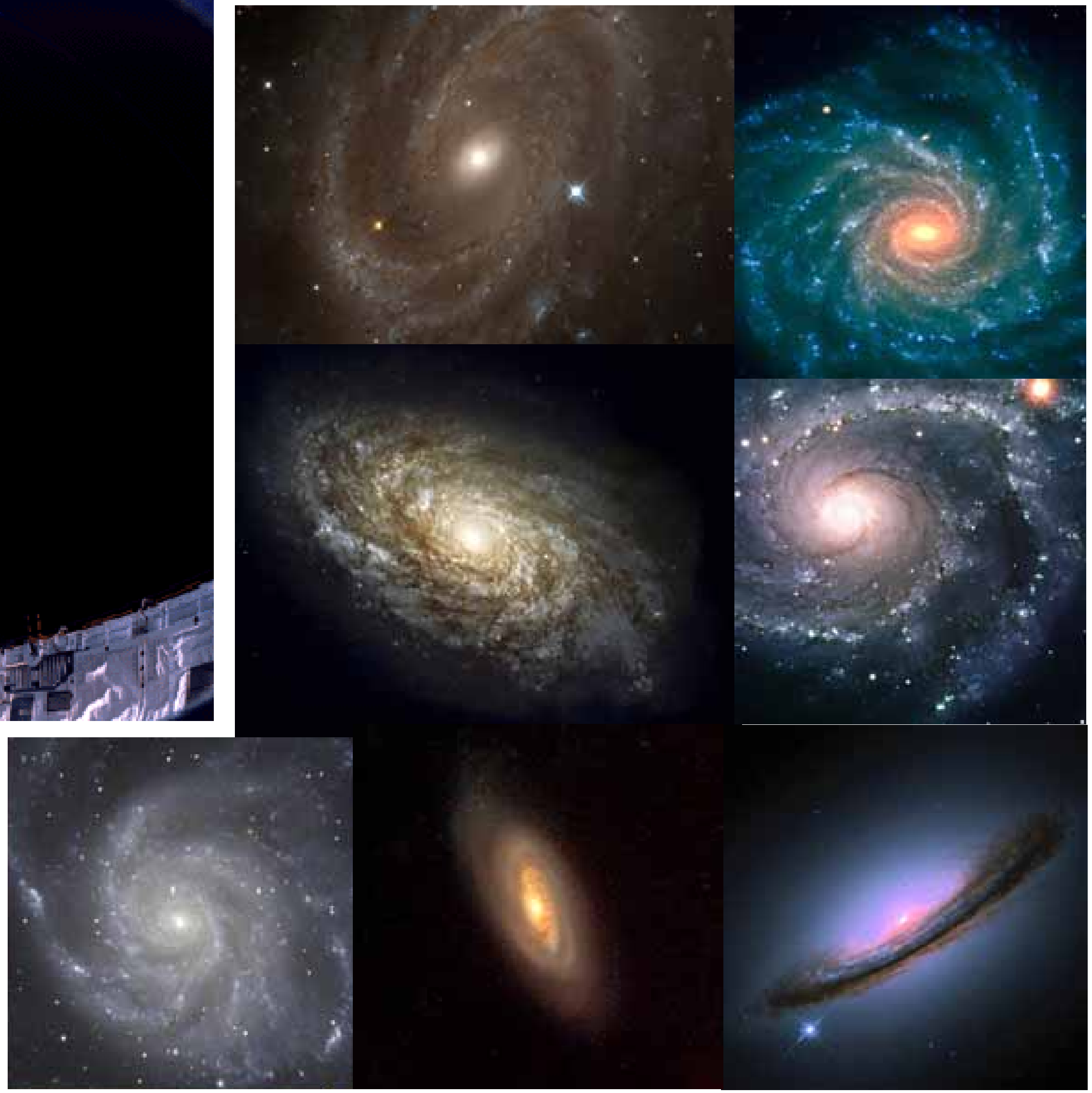
For the Further Future

- Active program of technology research and development for ground based detectors to reduce noise levels and thermal loading effects of high laser power:
  - Other materials for test masses and suspensions – silicon, perhaps at cryogenic temperatures
  - All reflective interferometry
  - Use of 'non-classical' light to get below the Standard Quantum Limit (Quantum Non-demolition, QND)

  Application to:
  - GEO upgrade ('GEO-HF' 2008+), aimed for operation around 2 kHz
  - New '3rd generation' European detector ('EGO'- 2010 onwards?)
  - Any future follow-on to the Advanced LIGO detectors in the US

- LISA – Laser Interferometric Space Antenna (ESA/NASA)
  - Approved as an ESA Cornerstone Mission and as a NASA 'Beyond Einstein Great Observatory Mission' to be launched soon after 2015

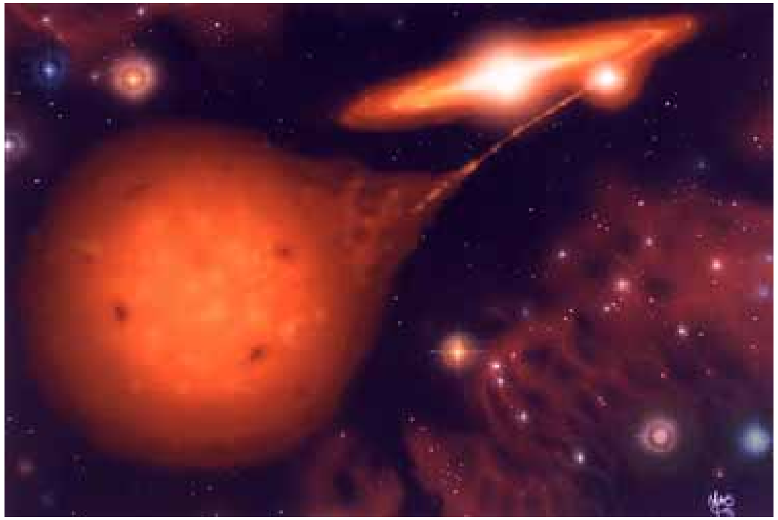
How fast is the Universe expanding?

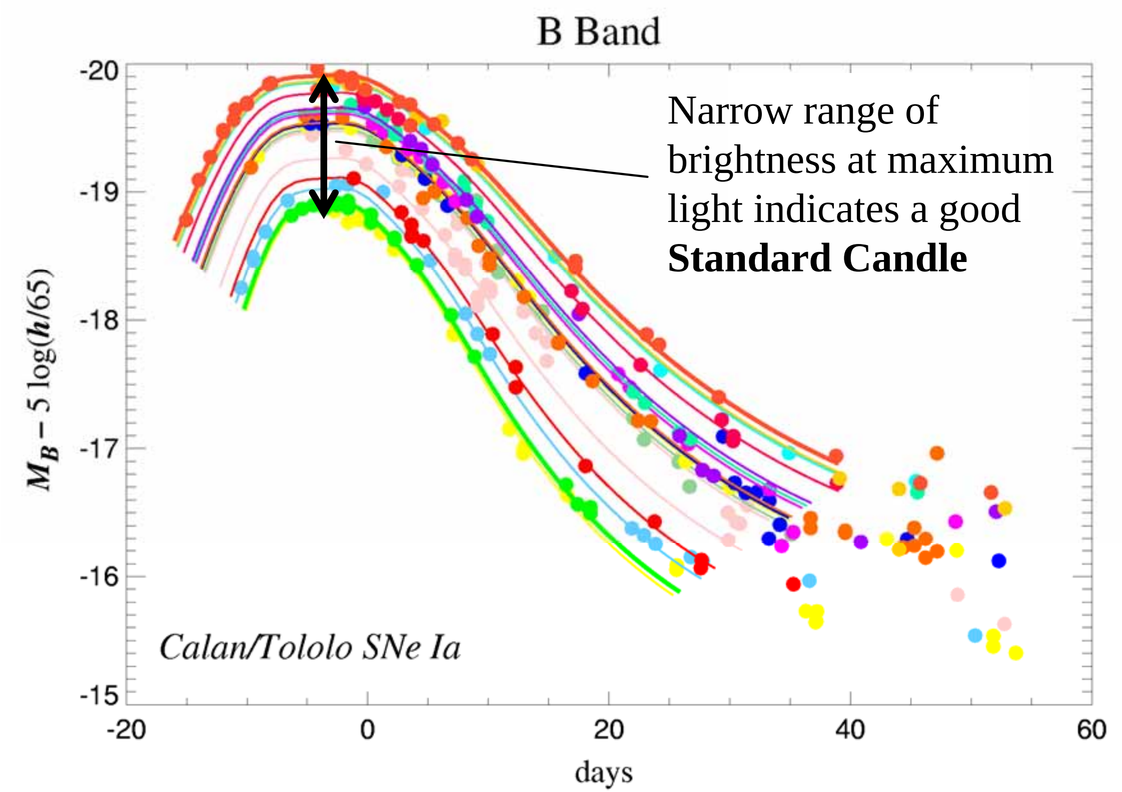


Hubble space Telescope Key Project: 1990-2000

Cepheid distances to ~30 galaxies, linking to secondary distance scale

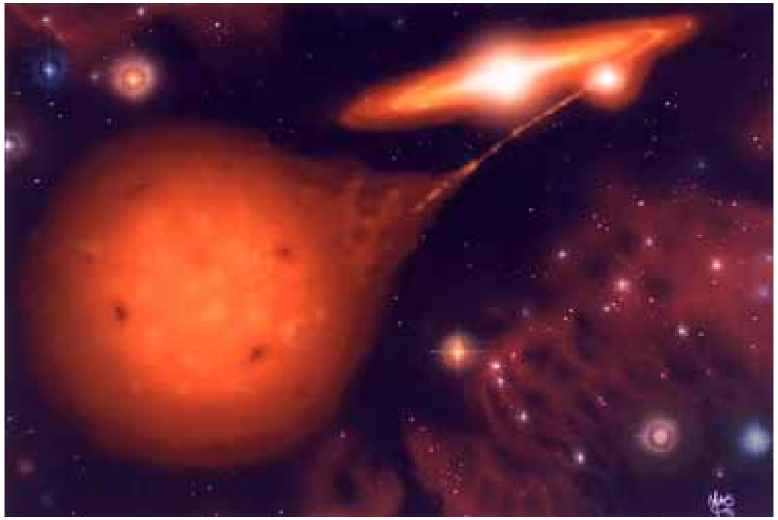
Is the Universe speeding up or slowing down?



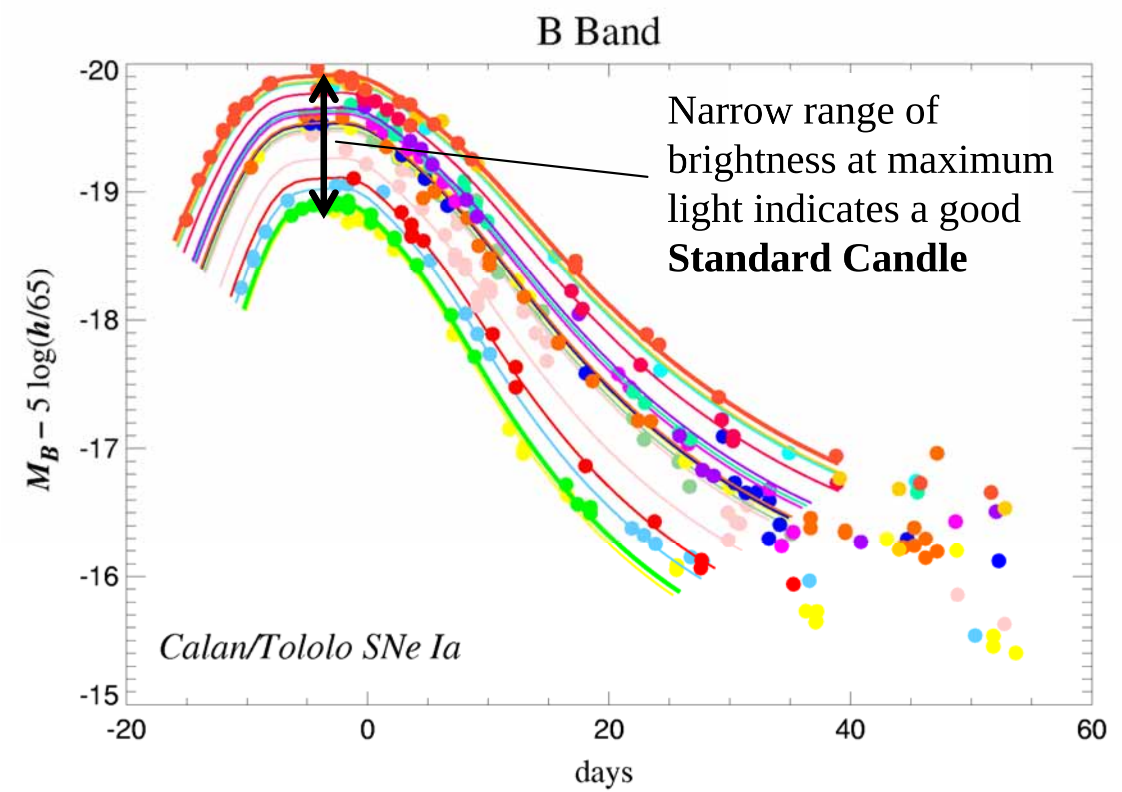


We can answer this question using **type Ia supernovae**

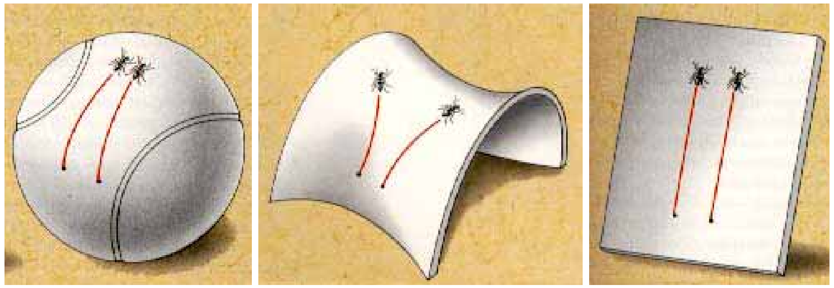
Is the Universe speeding up or slowing down?



We can answer this question using **type Ia supernovae**

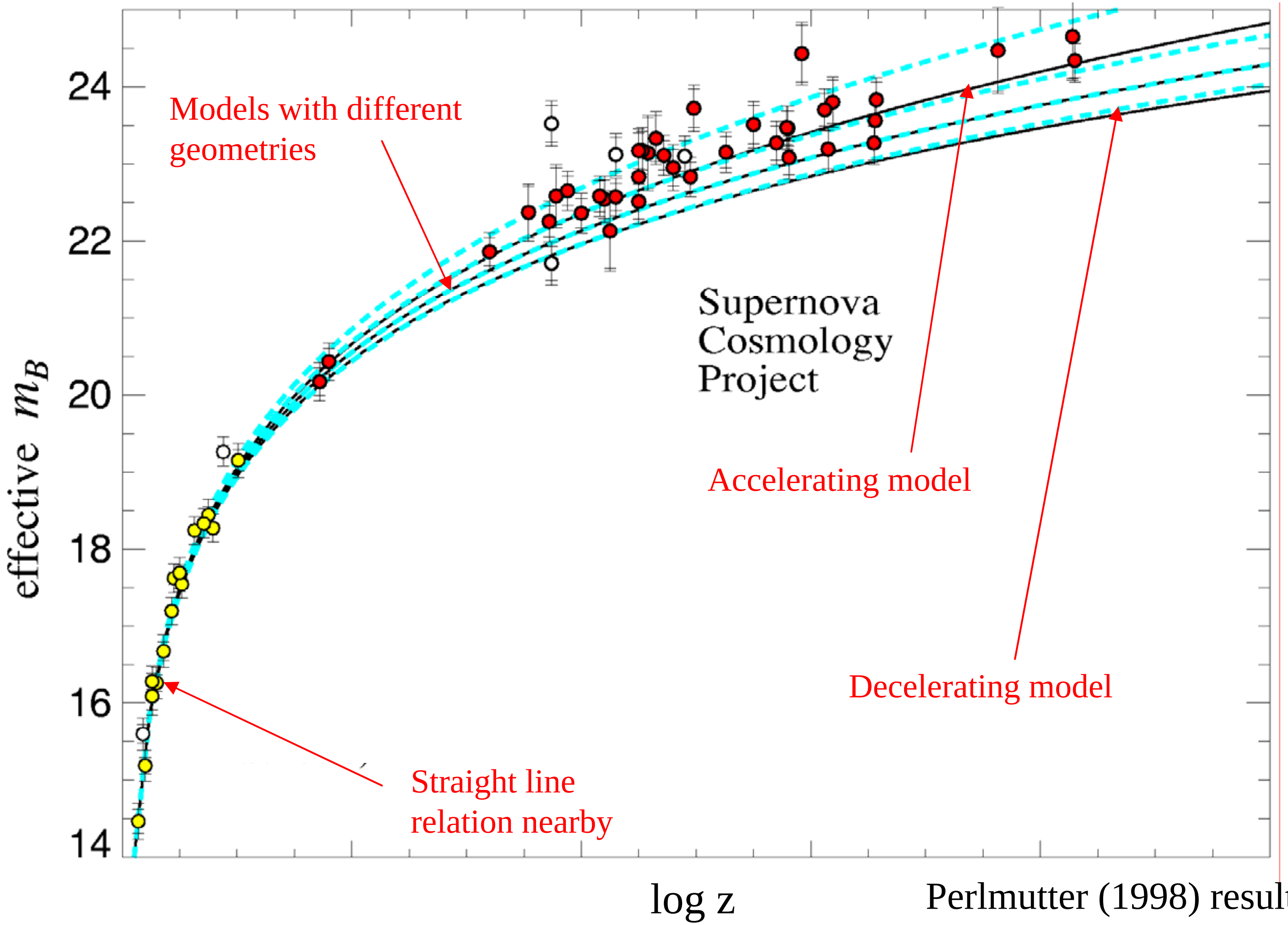


Geometry of the universe affects the relationship between redshift and luminosity distance of distant supernovae



Closed   Open   Flat

Hubble diagram of distant supernovae



Perlmutter (1998) results

Re-expressing Friedmann's Equations:-

Consider *pressureless* fluid (dust); assume *mass conservation*

$$\rho R^3 = \rho_0 R_0^3 = \text{constant} \quad \Rightarrow \rho = \rho_0 \, R_0^3 \big/ R^3 = \rho_0 (1+z)^3$$

and

$$\Omega_m = \rho \big/ \rho_{crit} = \frac{8\pi G \rho_0 (1+z)^3}{3H^2} \frac{H_0^2}{H_0^2} = \Omega_{m0} \frac{H_0^2}{H^2} (1+z)^3$$

More generally:-

$$H = H_0 \left(\sum_i \Omega_{i0} (1+z)^{n_i} \right)^{1/2}$$

	n_i
Matter	3
Radiation	4
Curvature	2
Vacuum	0

Expansion rate dominated by different terms at different redshifts

Can also consider more general Dark Energy or Quintessence models:

Evolving scalar field which 'may track' the matter density

Convenient parametrisation: 'Equation of State'

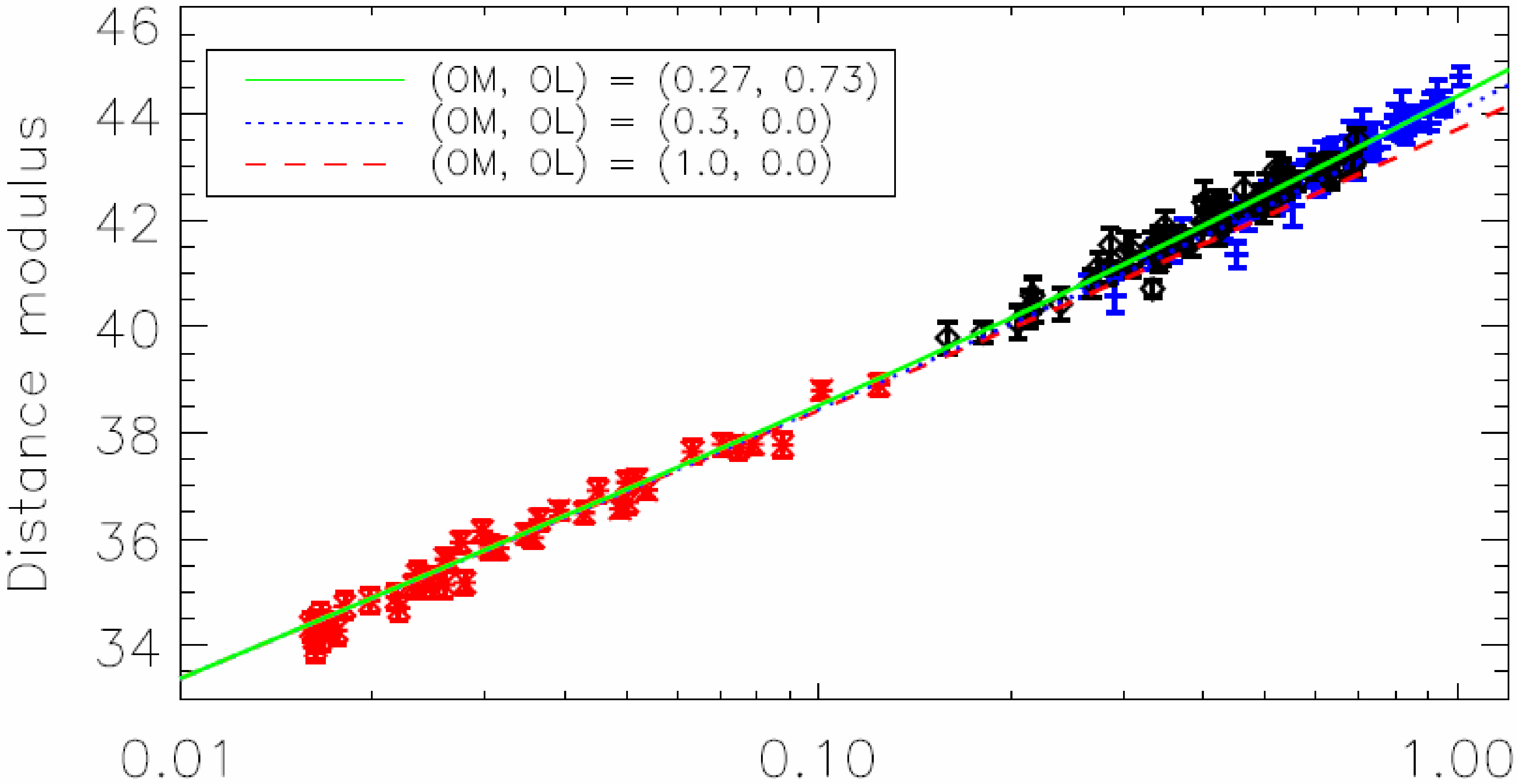
$$P = w\rho$$

$$H = H_0 \left(\sum_i \Omega_{w_i 0} (1+z)^{3(1+w_i)} \right)^{1/2}$$

	w_i
Matter	0
Radiation	1/3
Curvature	-1/3
'Lambda'	-1
Dark energy	*w(z)*

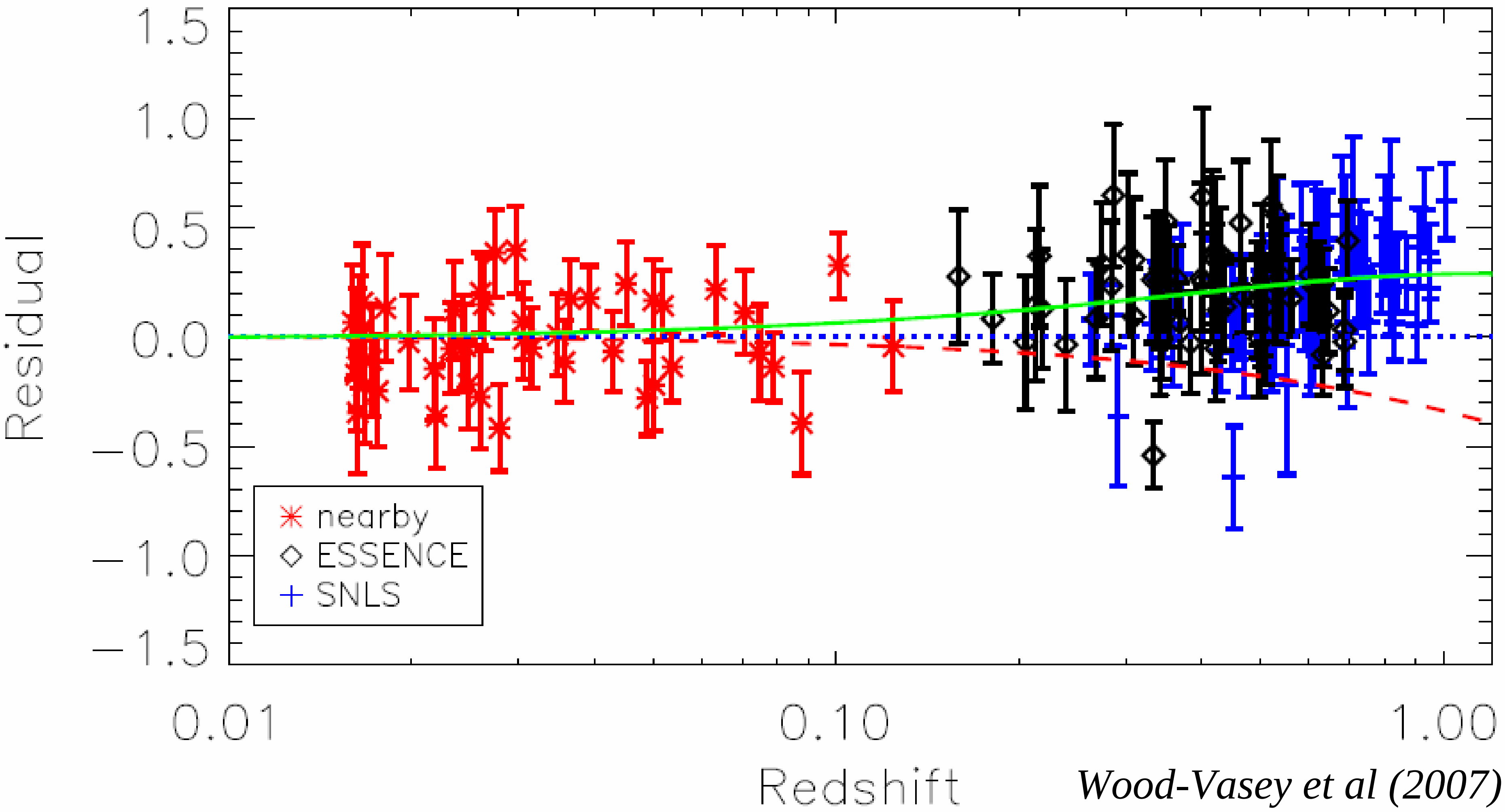
Can we measure $w(z)$?

Latest results…



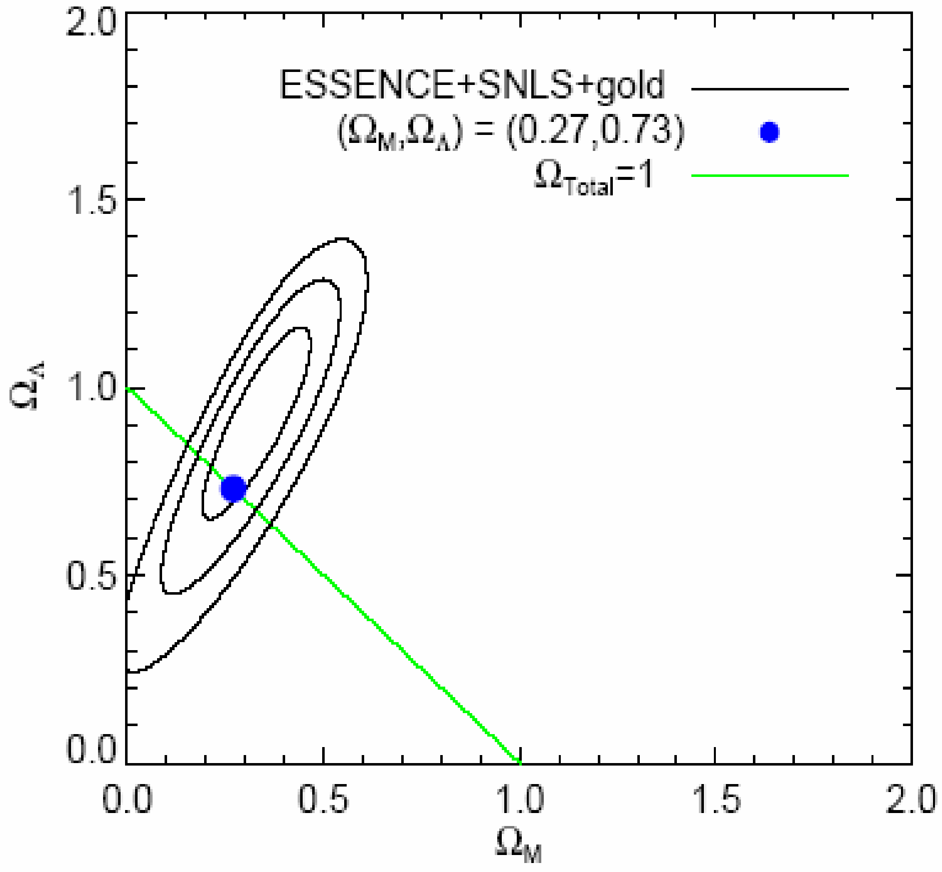
Wood-Vasey et al (2007)

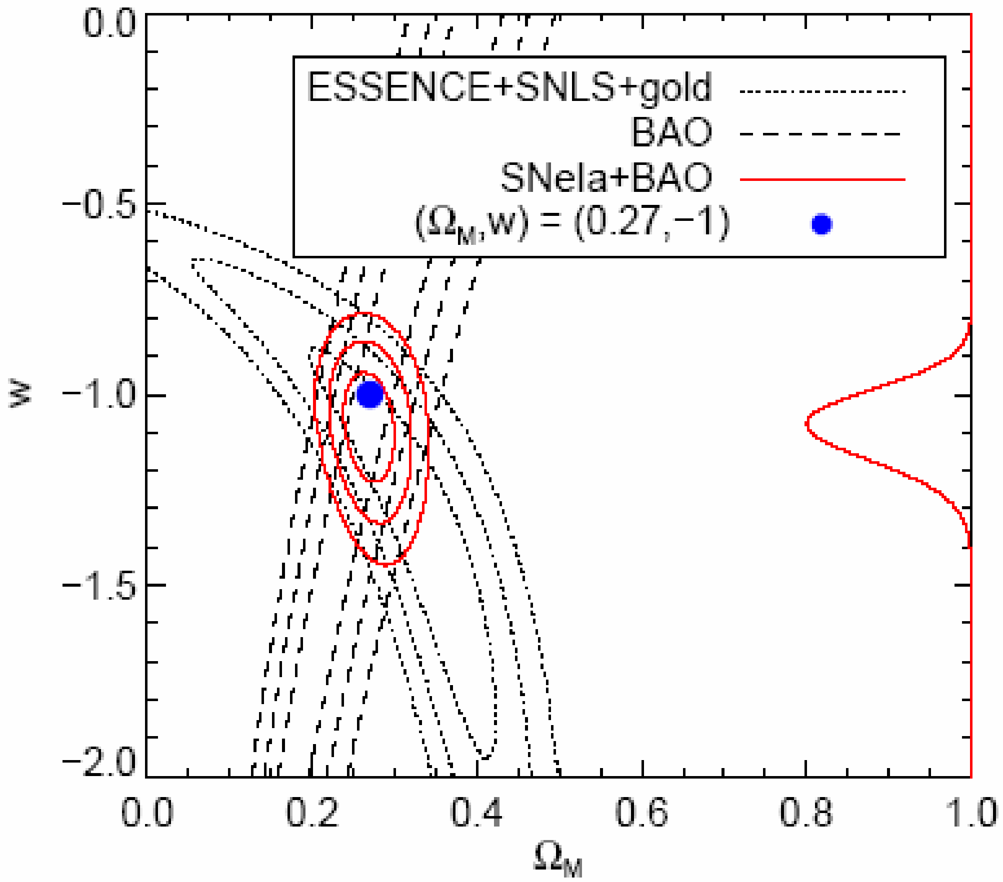
Latest results…



Wood-Vasey et al (2007)

Latest results…

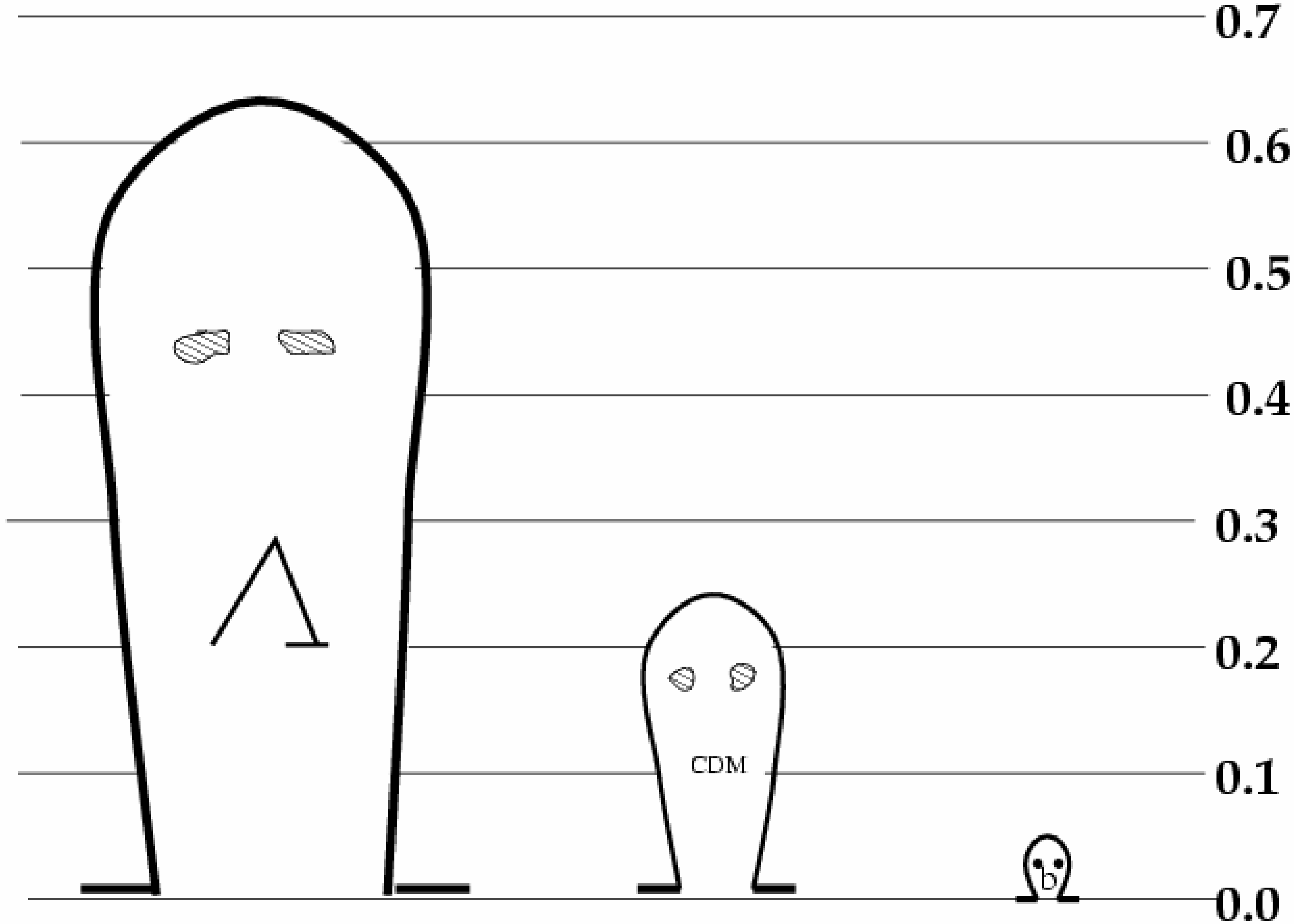




Wood-Vasey et al (2007)

ΛCDM

Cosmology's Most Wanted

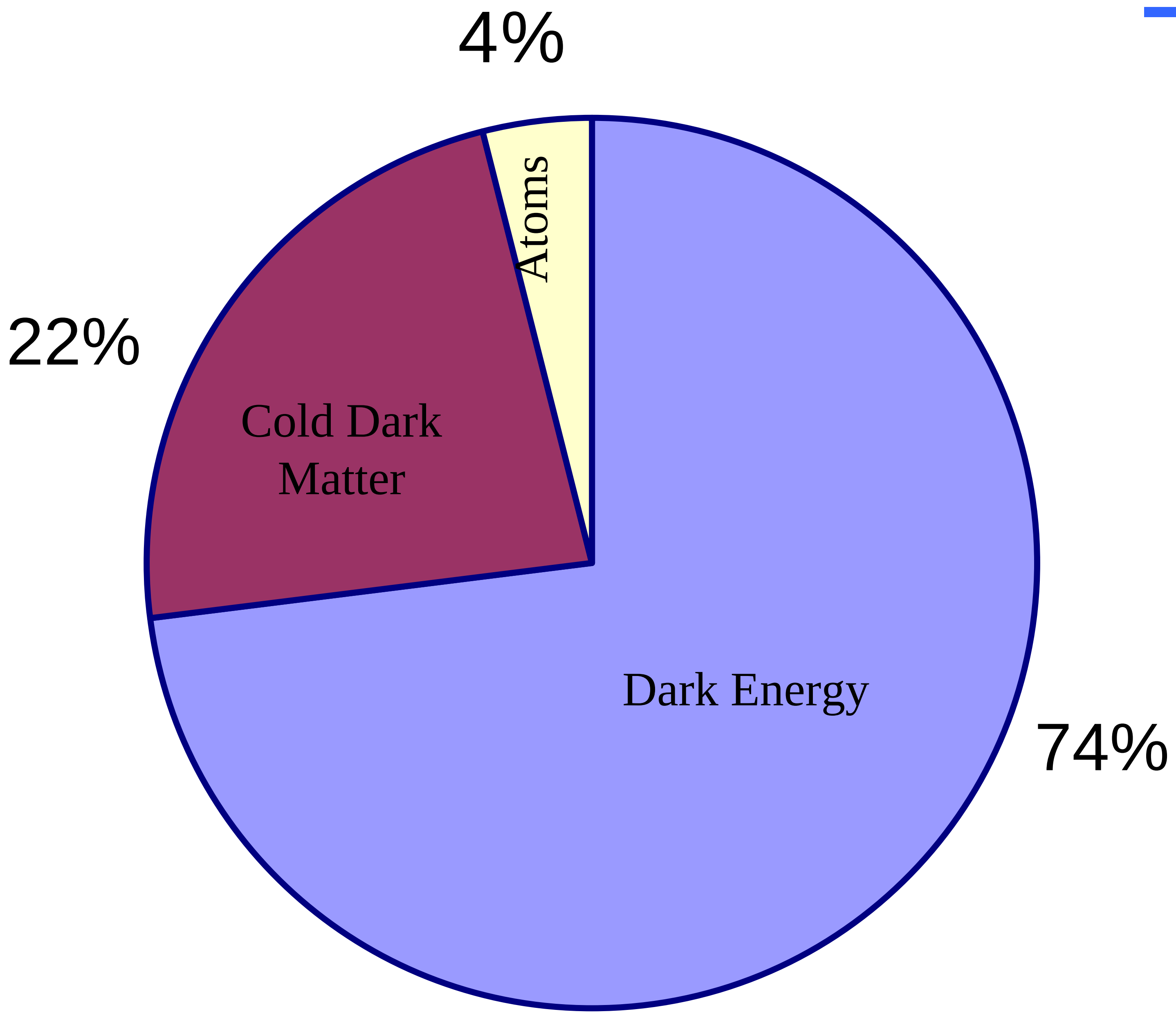


Ω_Λ	Ω_{CDM}	Ω_b
cosmological constant energy of the vacuum He never clumps His evil plan is to blow up the Universe	cold dark matter He likes to clump but has never been detected directly His evil plan is to make the Universe collapse	normal baryonic matter a pawn in the cosmic game who just follows CDM around. He thinks he's a complex life form but is really just a bunch of hydrogen

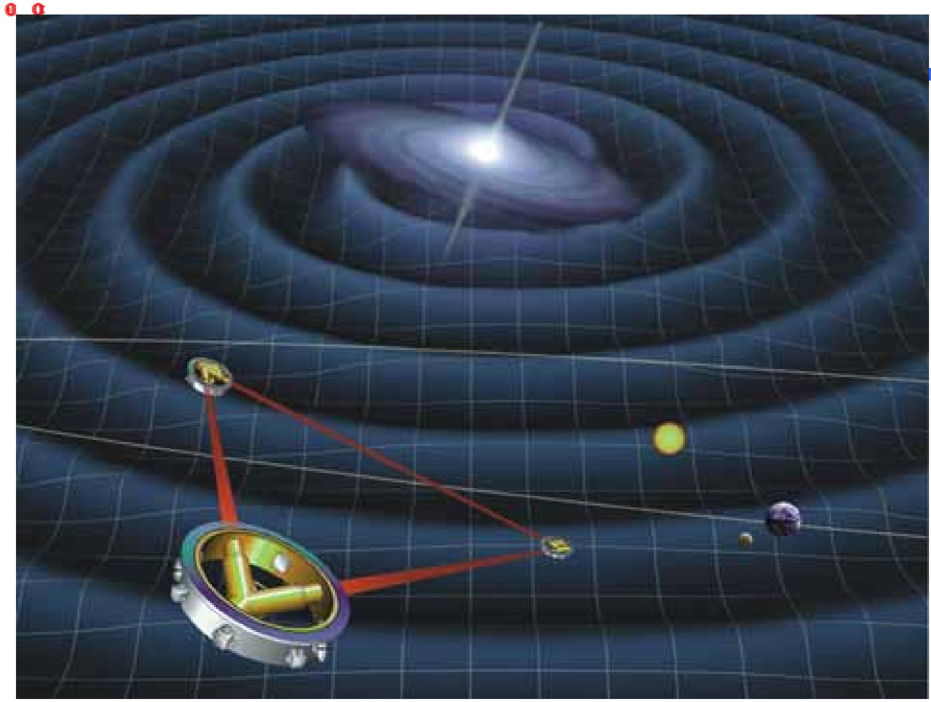
Figure 3. A line up of cosmological culprits Ω_Λ is the big shot controlling the Universe. He's going to make it blow up. Ω_{CDM} would like to make the Universe collapse but can't compete with Ω_Λ. Ω_b just follows Ω_{CDM} around. Like all dangerous criminals, one can never be sure of Ω_Λ until he is behind bars. The CMB police is being beefed up. Hundreds of heroic CMB observers are now planning his capture.

From Lineweaver (1998)

State of the Universe – Jan 2007



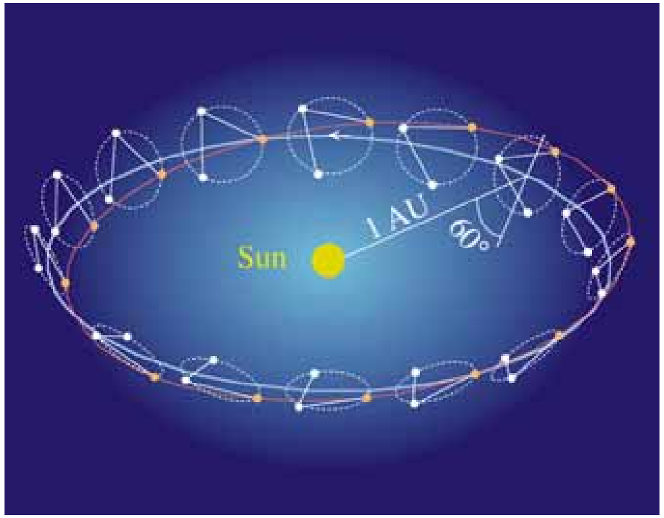
The LISA Mission



- ***Mission Description***
  - 3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.
  - Gravitational waves are detected by measuring changes in proper distance between fiducial masses in each spacecraft using laser interferometry
  - Partnership between NASA and ESA
  - Launch date: soon after 2015
- ***Observational Targets***
  - *Mergers of supermassive black holes*
  - *Inspiral of stellar-mass compact objects into massive black holes*
  - *Gravitational radiation from thousands of compact binary systems in our galaxy*
  - *Possible gravitational radiation from the early universe*

(Following Prince 2005)

- Directions (to about 1 degree) : 2 methods: AM & FM



- FM: Frequency modulation due to LISA orbital doppler shifts
  - *Analogous to pulsar timing*
  - *FM gives best resolution for f > 1 mHz*
- AM: Amplitude modulation due to change in orientation of array with respect to source over the LISA orbit
  - *AM gives best resolution for f < 1 mHz*
- **Summary: LISA will have degree level angular resolution for many sources (sub-degree resolution for strong, high-frequency sources)**
  - See e.g. Cutler (98), Hughes (2002), Cornish & Rubbo (2003), Vecchio (2004), Lang & Hughes (2006)

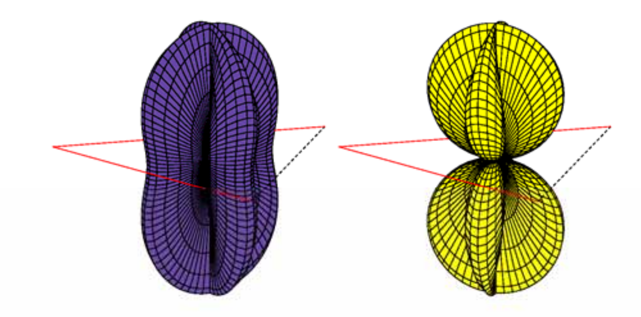
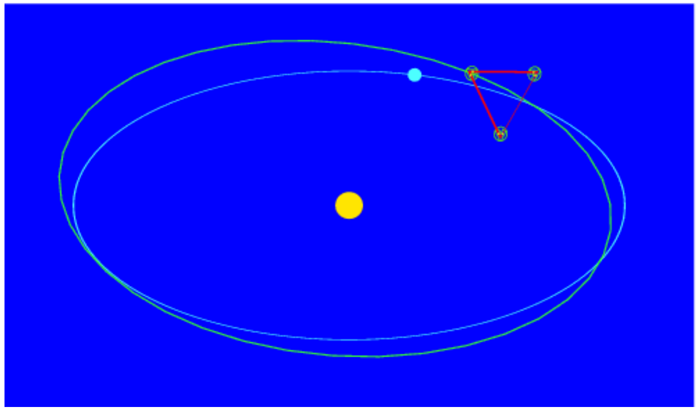


Figure 3. The magnitudes of the detector response functions $F^{+}(\hat{\Omega}, f)$ and $F^{\times}(\hat{\Omega}, f)$ in the low frequency limit.

- Directions (to about 1 degree) : 2 methods: AM & FM
- FM: Frequency modulation due to LISA orbital doppler shifts
  - *Analogous to pulsar timing*
  - FM gives best resolution for f > 1 mHz
- AM: Amplitude modulation due to change in orientation of array with respect to source over the LISA orbit
  - AM gives best resolution for f < 1 mHz
- **Summary: LISA will have degree level angular resolution for many sources (sub-degree resolution for strong, high-frequency sources)**
  - See e.g. Cutler (98), Hughes (02), Cornish & Rubbo (03), Vecchio (04)



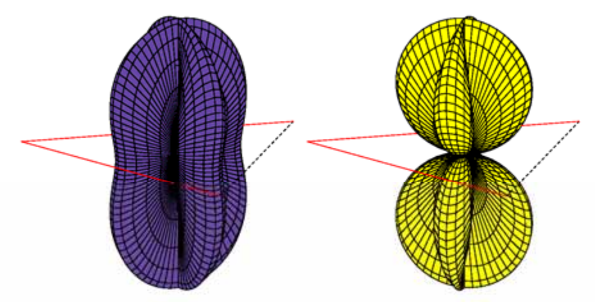
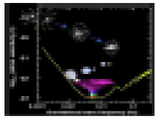
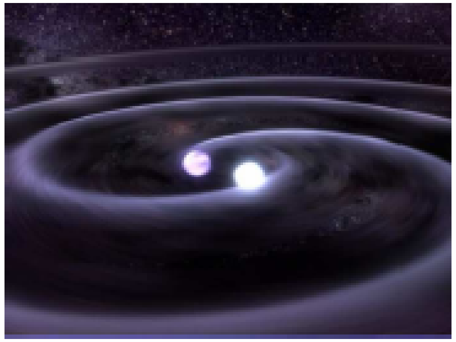


Figure 3. The magnitudes of the detector response functions $F^{+}(\hat{\Omega}, f)$ and $F^{\times}(\hat{\Omega}, f)$ in the low frequency limit.

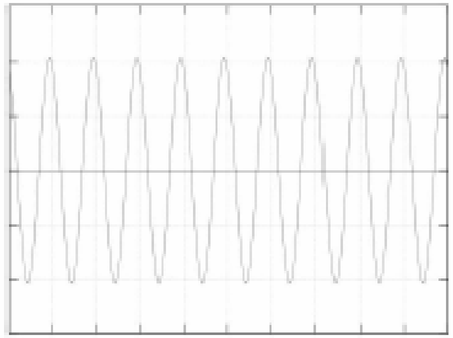


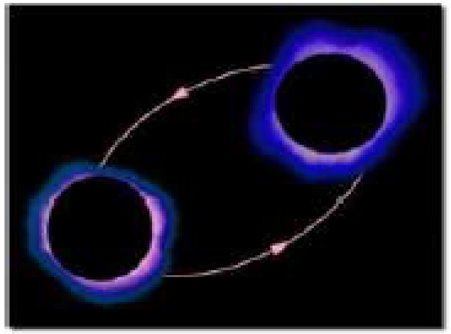
Event Rates and Waveforms



Galactic Binaries

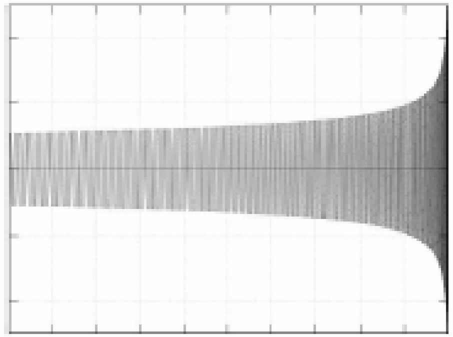
$\sim 10^8$ ever present signals

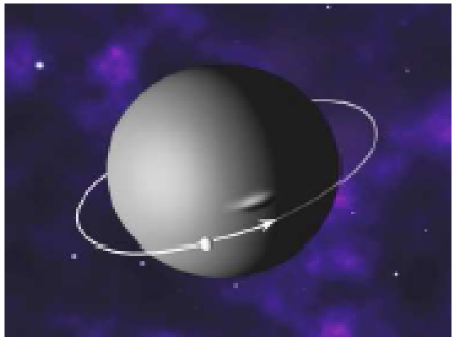




Supermassive Black Hole Binaries

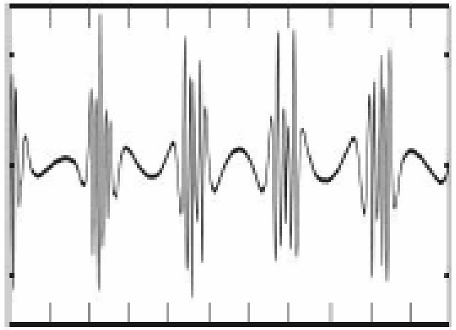
0.1 to 10^3 per year





Extreme Mass Ratio Inspirals

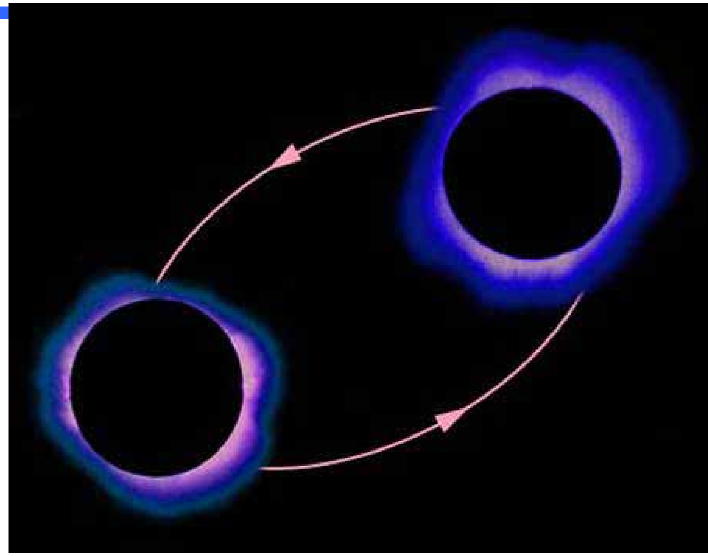
10^2 to 10^3 per year



Gravitational Wave Sources as Cosmological Probes

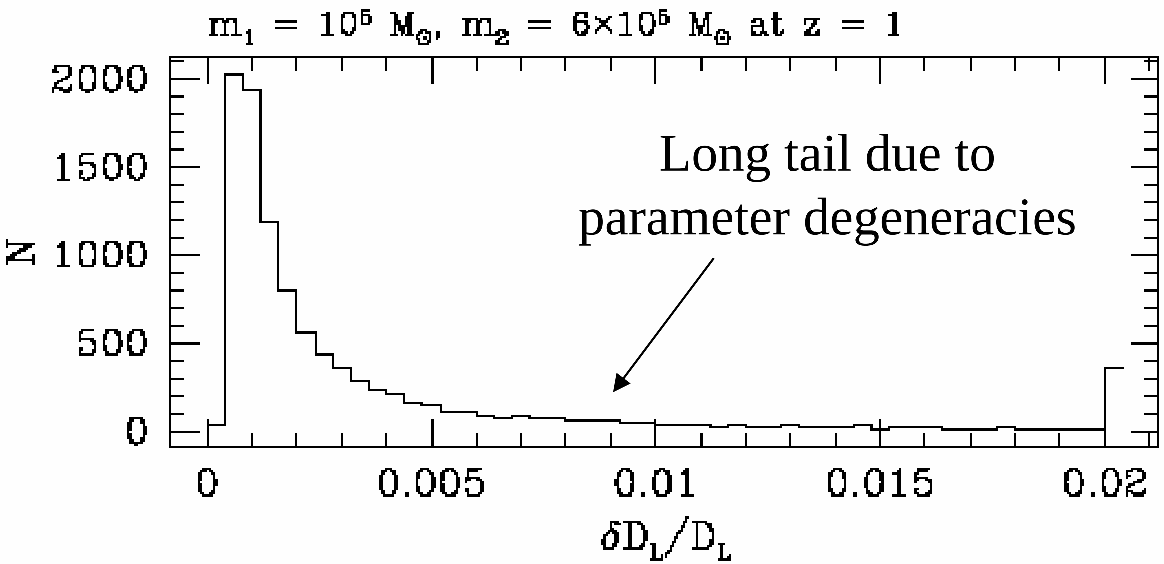
Recent interest in 'Standard Sirens':

SMBHs at cosmological distances, for which D_L can in principle *be determined to exquisite accuracy.*



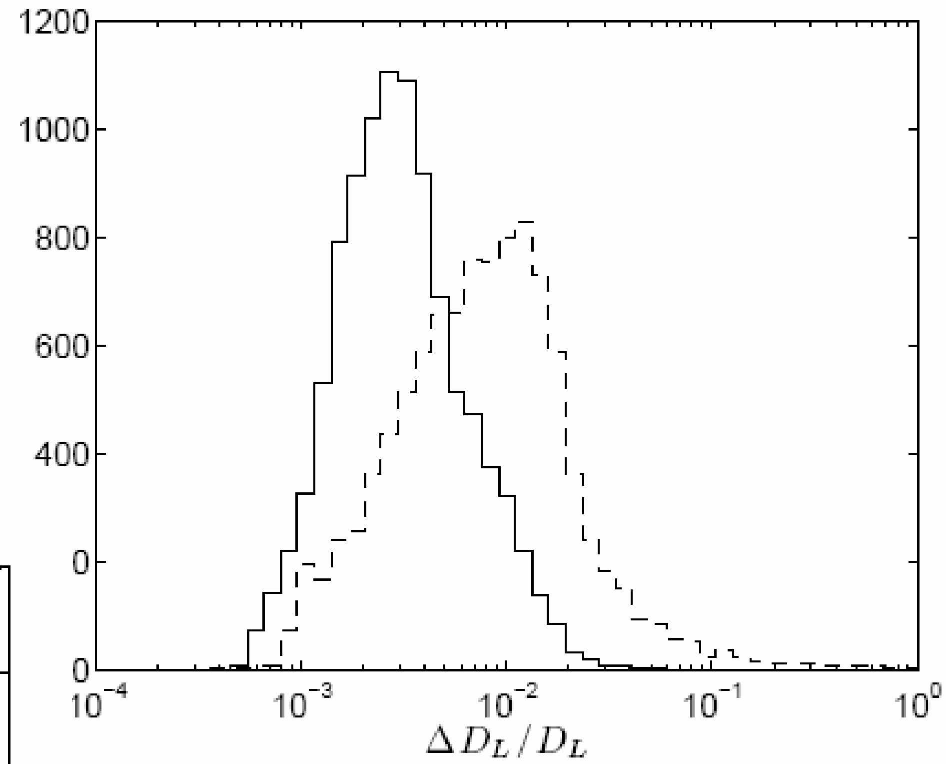
Inspiral and ringdown waveform strongly dependent on SMBH masses.

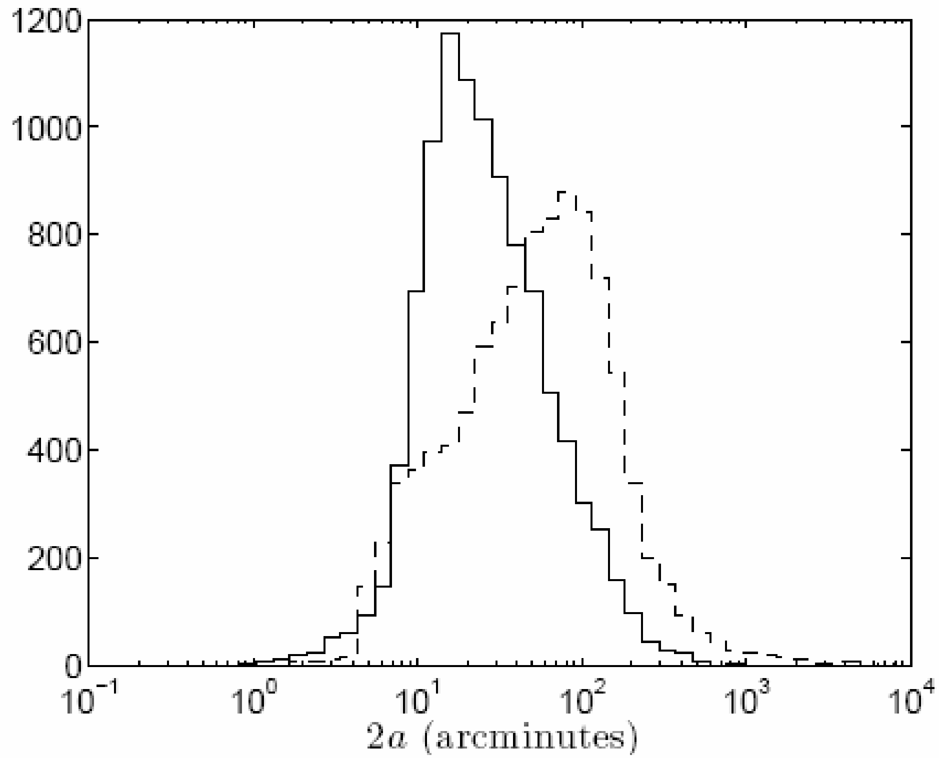
Since amplitude falls off linearly with (luminosity) distance, measured strain at LISA determines the distance of the source.



Holz and Hughes 2005

Lang and Hughes (2006) use spin-induced precession to break degeneracies, significantly improving distance determination, and sky location.





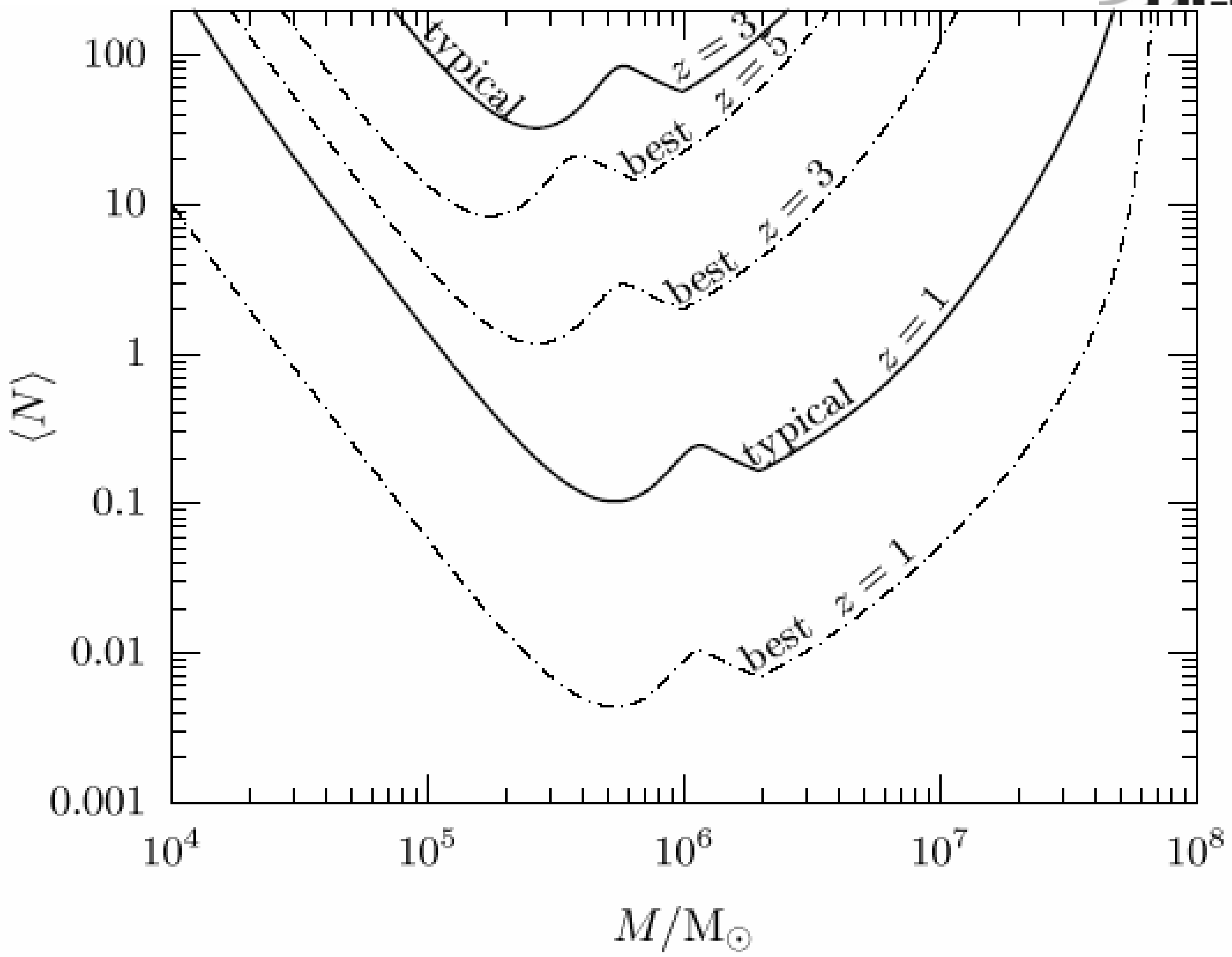
But the GW waveform is redshifted, so we also need to know the redshift of the sources.

Optical counterpart?...

Kocsis et al (2006)

Good prospects for unique identification of E-M counterpart, at least to z~1.

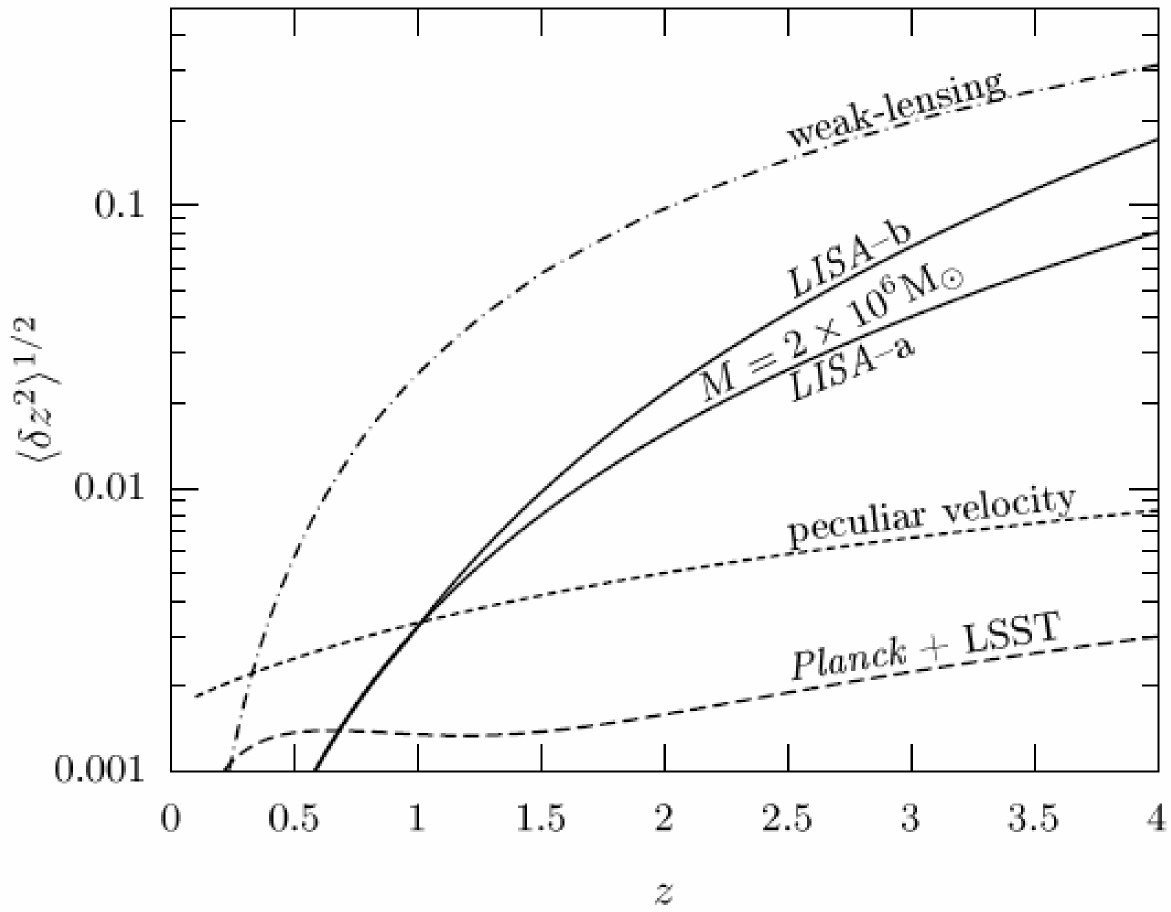
Confirm conclusions of Holz & Hughes (2005), Lang & Hughes (2006) that dominant systematic error will be gravitational lensing.



Kocsis et al (2006)

Good prospects for unique identification of E-M counterpart, at least to z~1.

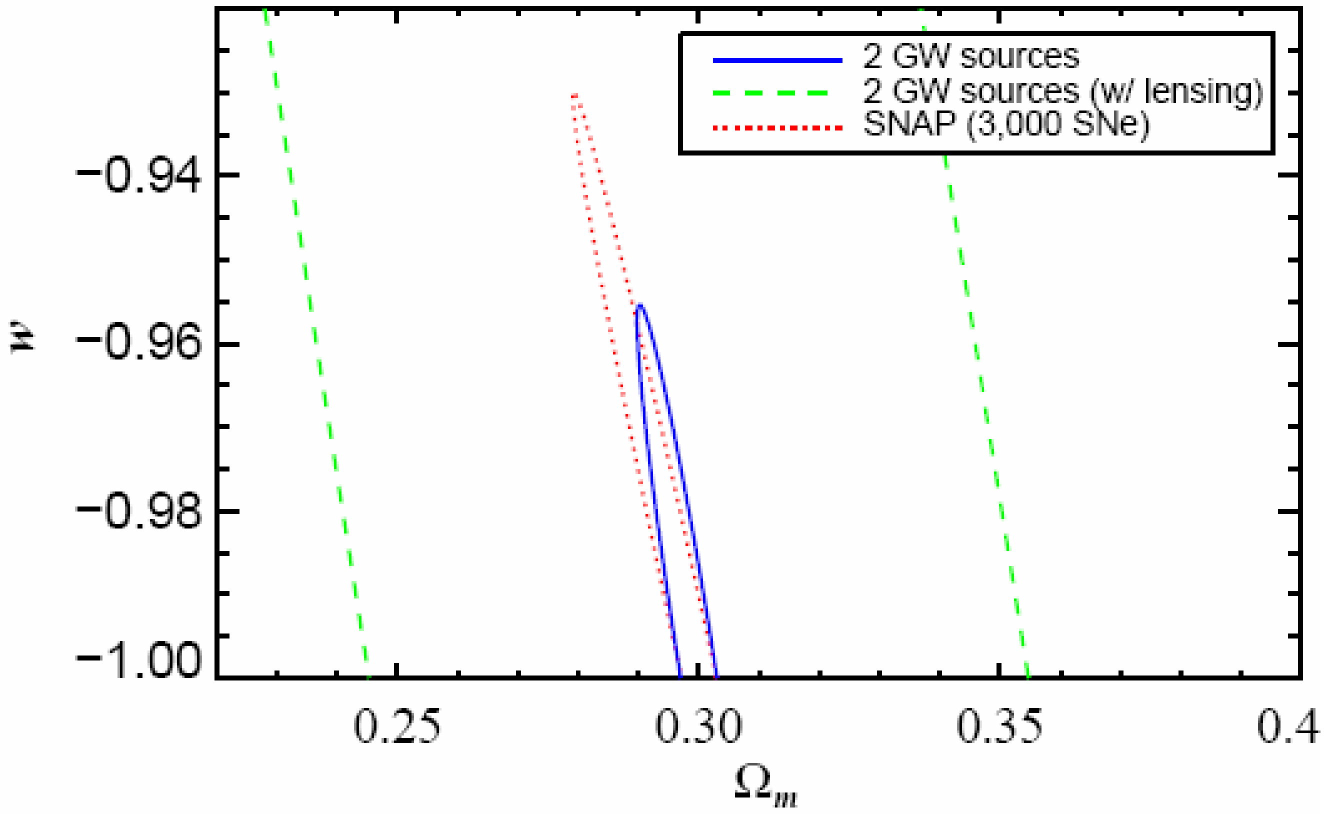
Confirm conclusions of Holz & Hughes (2005), Lang & Hughes (2006) that dominant systematic error will be gravitational lensing.



Kocsis et al (2006)

Good prospects for unique identification of E-M counterpart, at least to z~1.

Confirm conclusions of Holz & Hughes (2005), Lang & Hughes (2006) that dominant systematic error will be gravitational lensing.

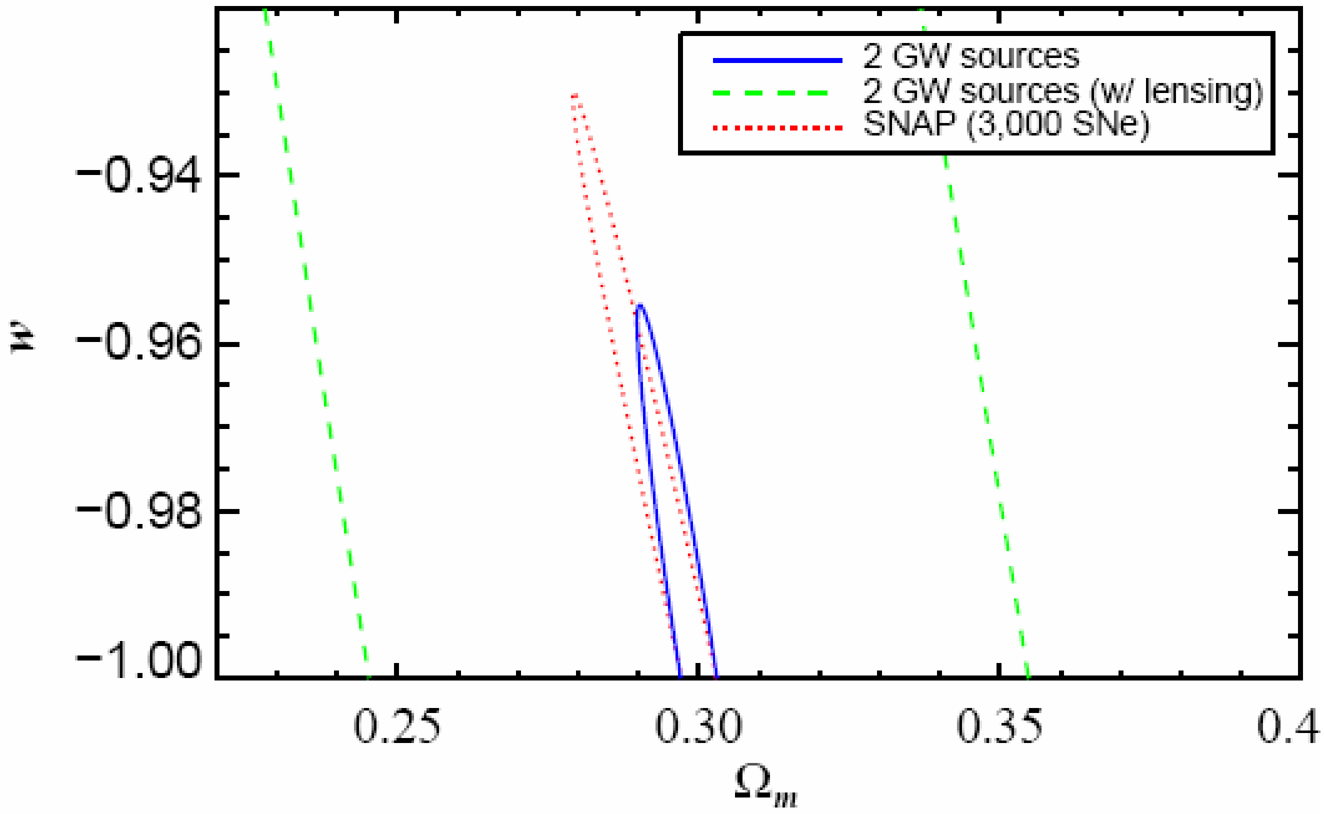


Holz & Hughes (2005)

Kocsis et al (2006)

Good prospects for unique identification of E-M counterpart, at least to z~1.

Confirm conclusions of Holz & Hughes (2005), Lang & Hughes (2006) that dominant systematic error will be gravitational lensing.



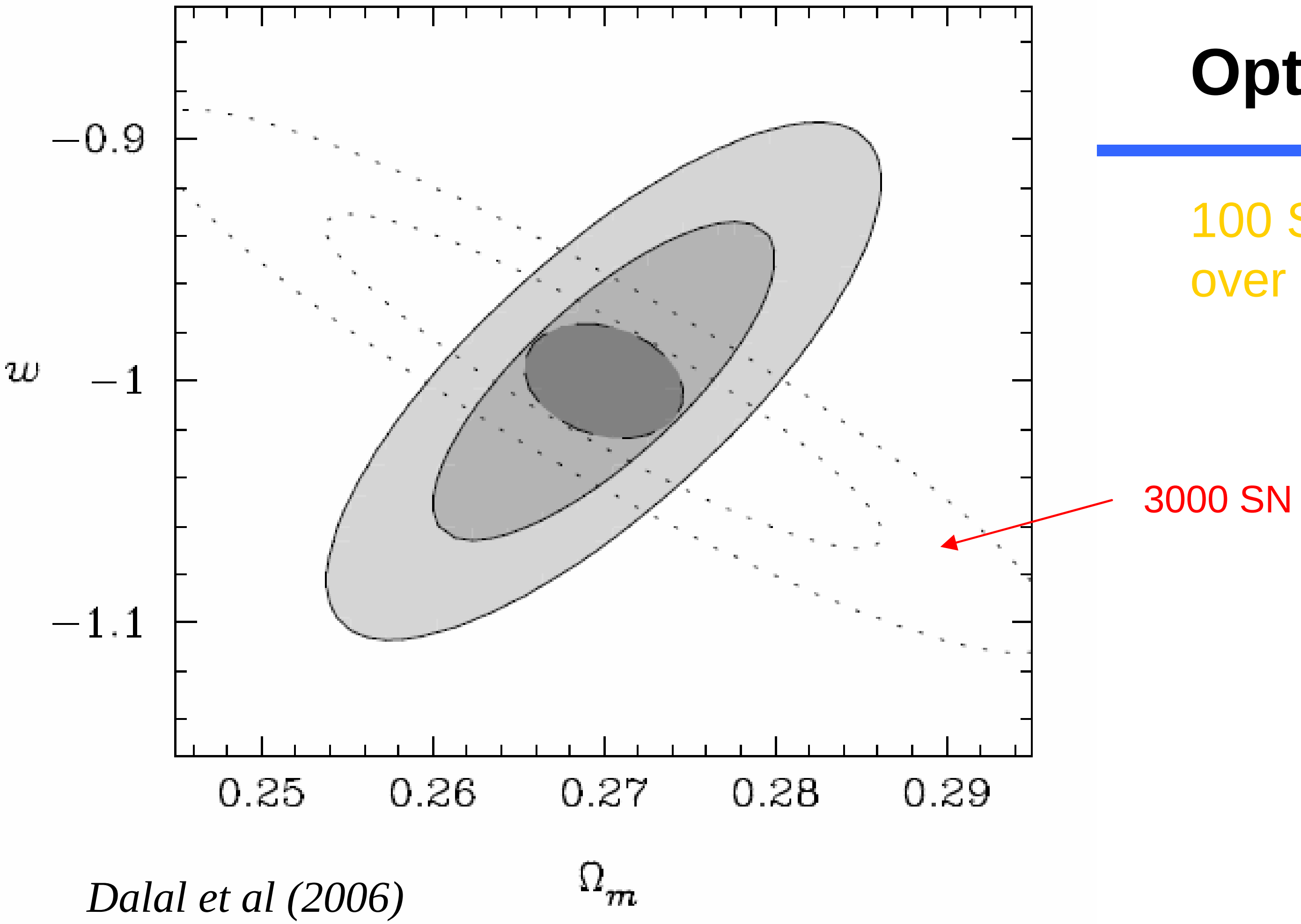
Holz & Hughes (2005)

Much depends on the merger rate of SMBHs

(see also Hendry and Woan 2007 for further discussion)

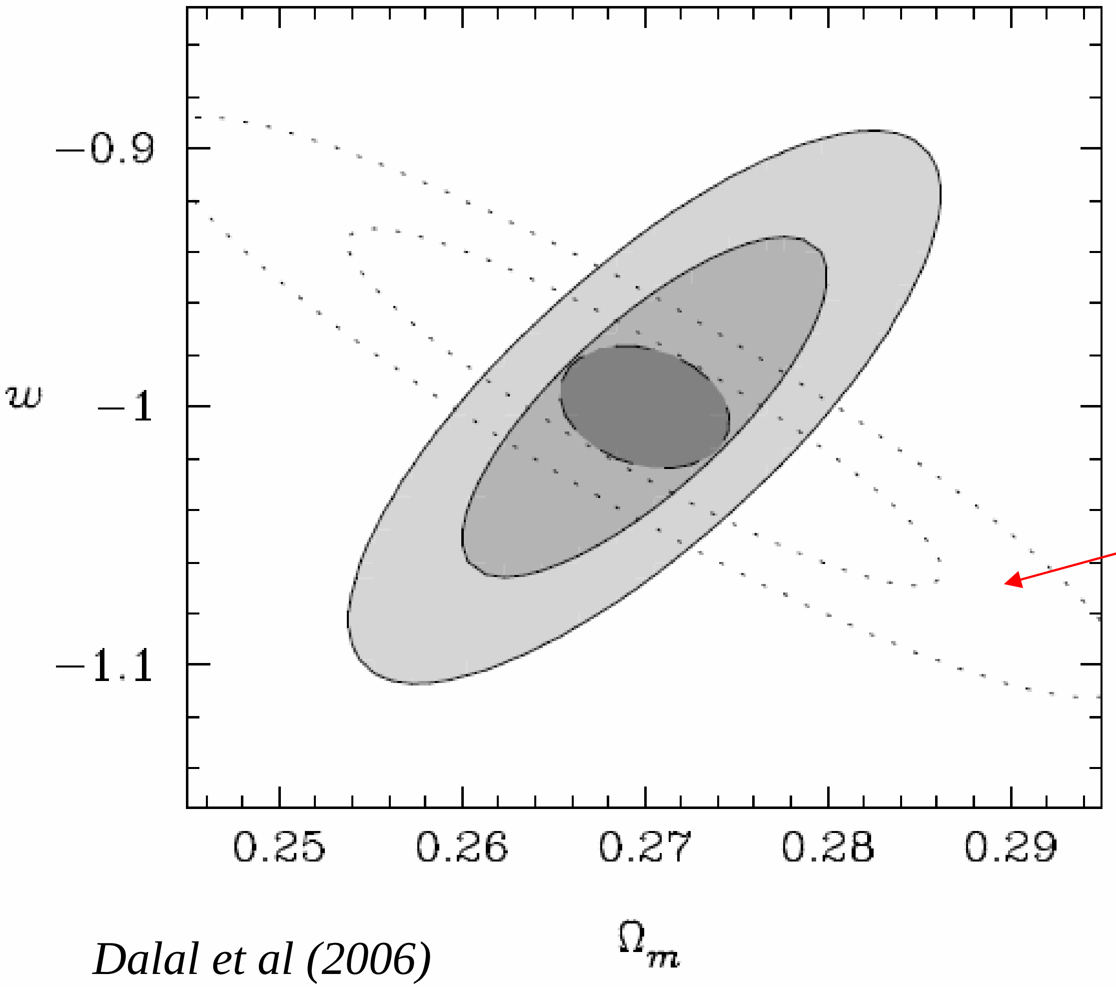
Optimistic limits!

100 SMBHs, $0 < z < 2$
over LISA lifetime.



Dalal et al (2006)

Optimistic limits!



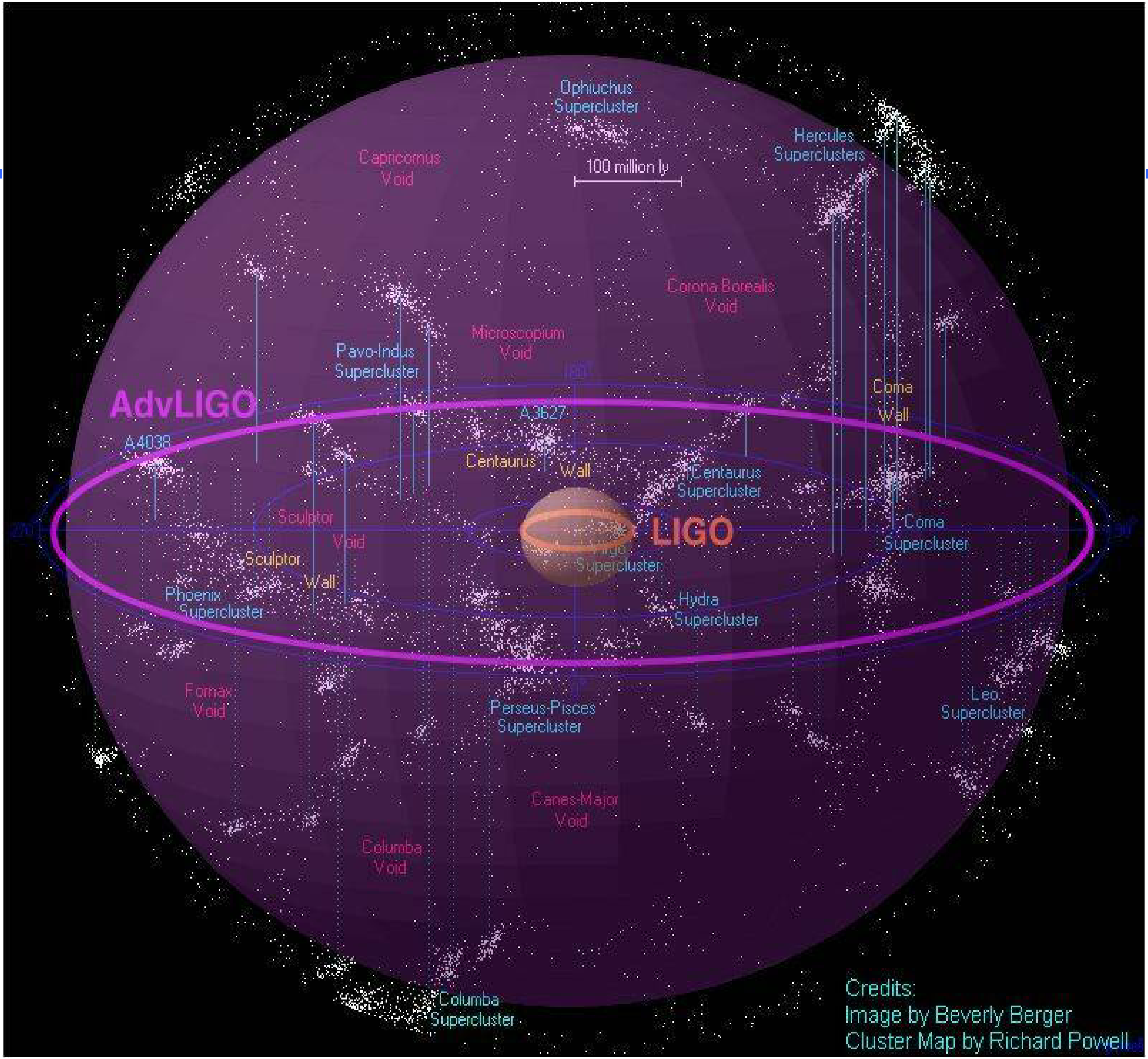
Dalal et al (2006)

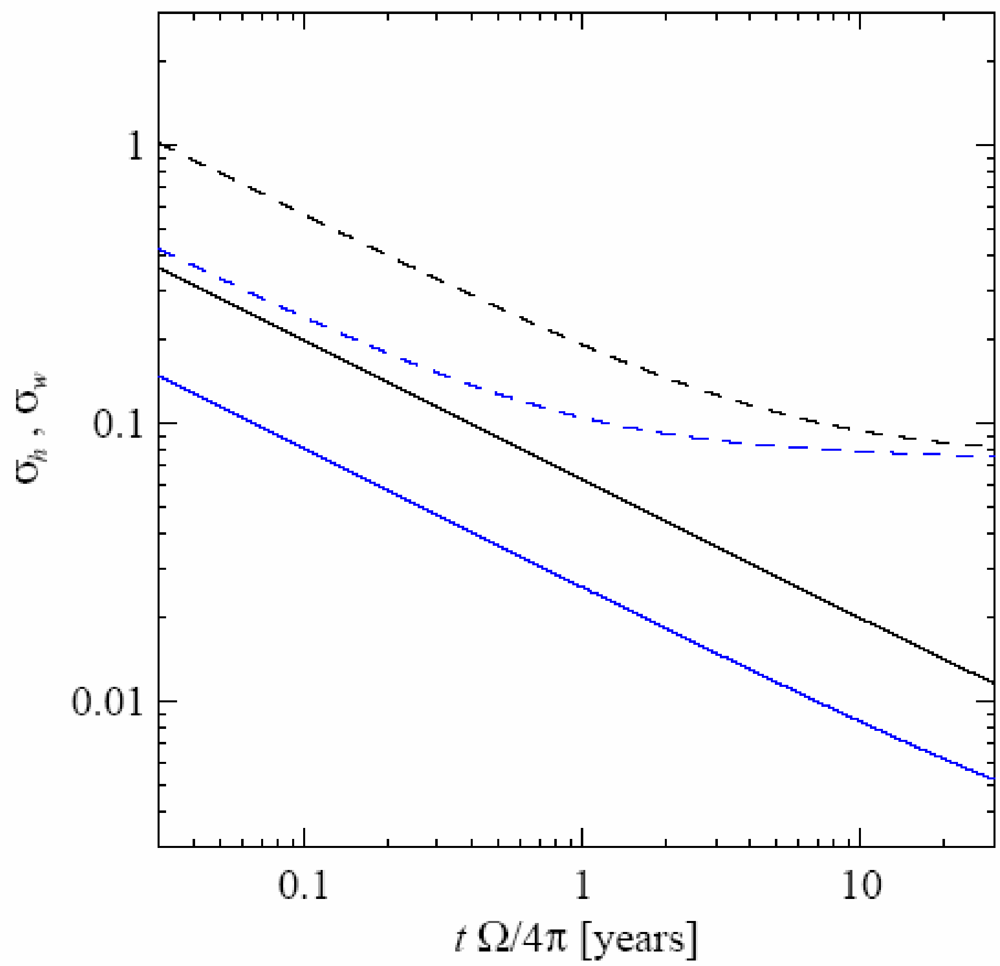
100 SMBHs, 0 < z < 2
over LISA lifetime.

3000 SN

But what about Short burst GRBs? e.g. NS-NS merger

Dalal et al (2006): Detectable with LIGO2 to ~250Mpc.


Ophiuchus Supercluster
Hercules Superclusters
100 million ly
Capricornus Void
Corona Borealis Void
Microscopium Void
Pavo-Indus Supercluster
Coma Wall
AdvLIGO
A3627
A4038
Centaurus Wall
Centaurus Supercluster
Sculptor Void
LIGO
Coma Supercluster
Sculptor Wall
Supercluster
Phoenix Supercluster
Hydra Supercluster
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Canes-Major Void
Columba Void
Columba Supercluster
Credits:
Image by Beverly Berger
Cluster Map by Richard Powell



Dalal et al (2006)

Expected fractional distance errors for a single GRB source, observed by Advanced LIGO, GEO, VIRGO.

Averaged over source direction and orientation.

Note, growth at large distance: decreasing S/N, gravitational lensing

Expect E-M emission to be colimated with orbital angular momentum vector (beamed)

For realistic event rates, Advanced LIGO design sensitivity, Dalal et al. find H_0 to ~2% → w to ~9%

Prospects for cosmology?...

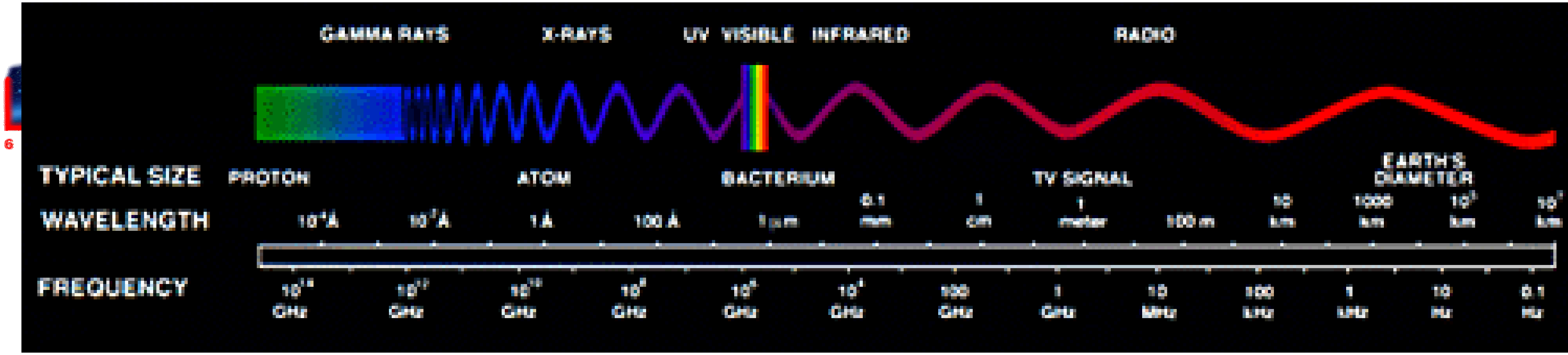
Are 'standard siren' limits on w competitive?

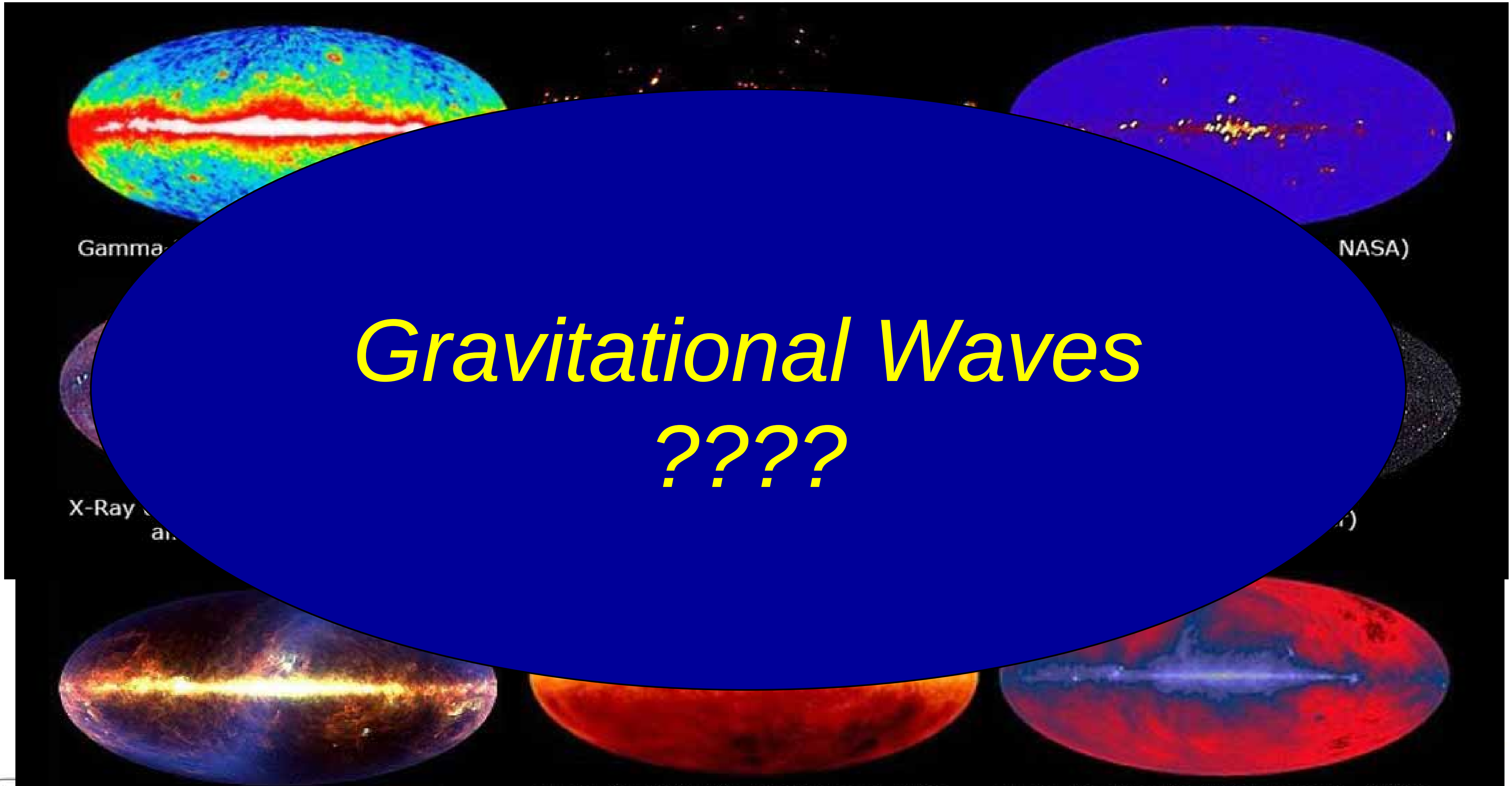
- Yes, provided we observed enough SMBHs, and/or gravitational lensing systematics can be controlled.

BUT in any case…

- GW constraints on dark energy are also a valuable sanity check – completely different systematic errors. **Absolute calibration at cosmological distances**

- Can turn problem around. e.g. assuming H(z) known, SMBH standard sirens to z~5 will provide exquisite probe of dark matter distribution along line of sight.





Gamma

NASA)

X-Ray

Infrared (DIRBE Team, COBE, NASA)

Radio 1420MHz (J. Dickey et.al. UMn. NRAO SkyView)

Radio 408MHz (C. Haslam et al., MPIfR, SkyView)

Gravitational Waves

????