Ondes gravitationnelles
la physique et les enjeux

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pour le groupe Virgo

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lapp VIRGO

Introduction

Gravitation

Sources

Universe

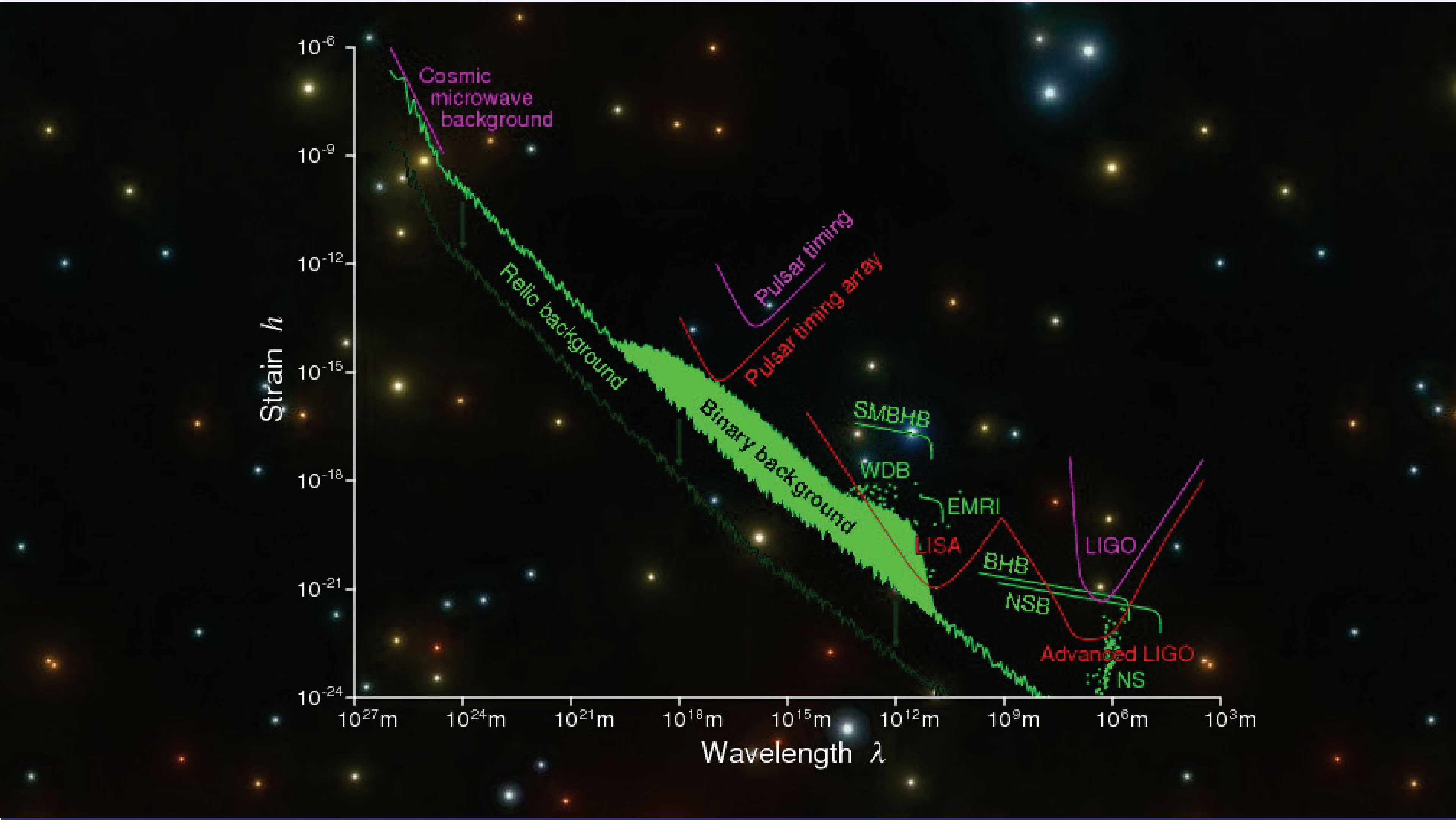
- GW generated by powerful mass acceleration
  - Very energetic events in the Universe
  - GW probe event dynamics
- Gravitation is the only clue to 96% of matter in the Universe
  - GW probe gravitation in new regime

General Relativity

Astrophysics

Cosmology

Gravitational wave spectrum



Ground-based interferomters

- 1st generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

  - Enhanced LIGO, Virgo+

Improved sensitivity

Lay ground for multi-messenger astronomy

- 2nd generation detectors
  - Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA
  - 2.5

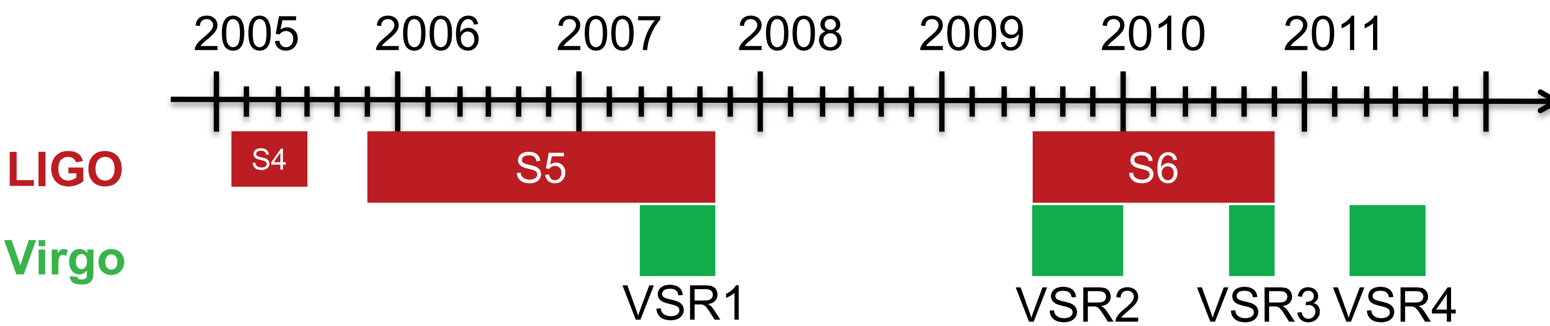
Likely detection

Routine observation
➔ GW astronomy

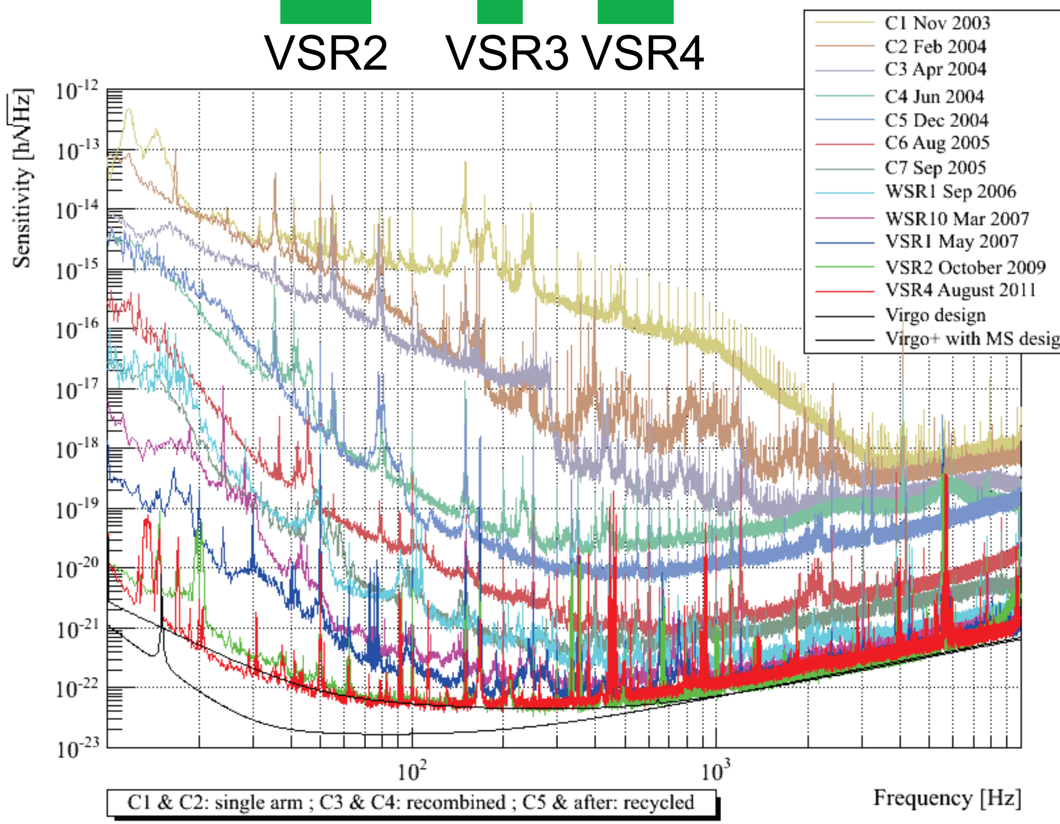
- 3rd generation detectors
  - Einstein Telescope, US counterpart to ET

Thorough observation of Universe with GW

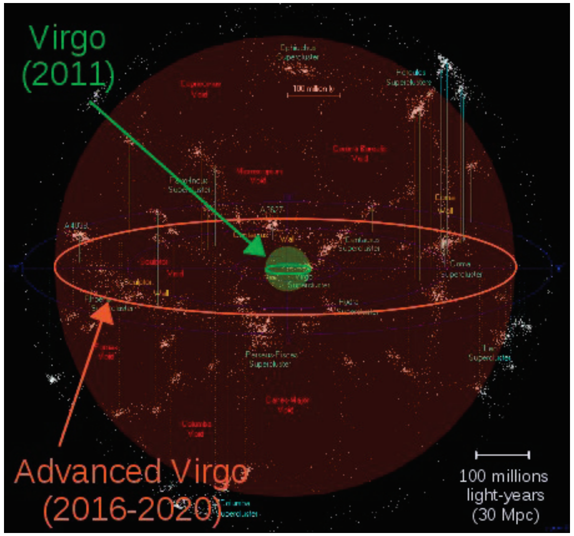
1st generation



- Operating detectors at their nominal sensitivities took years of effort
- Long science data taking
- No detection, but some science!
  - More later…

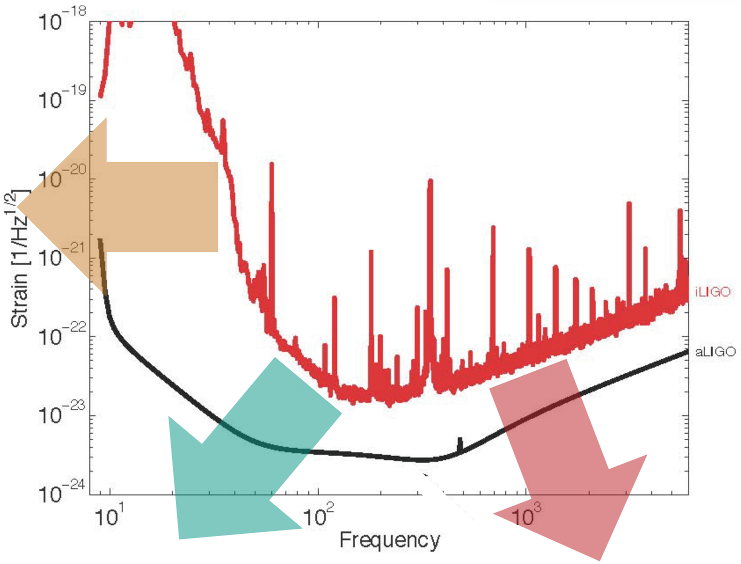


2nd generation (I)



Seismic noise
Improved seismic isolation

See Romain's talk for experimental challenges…



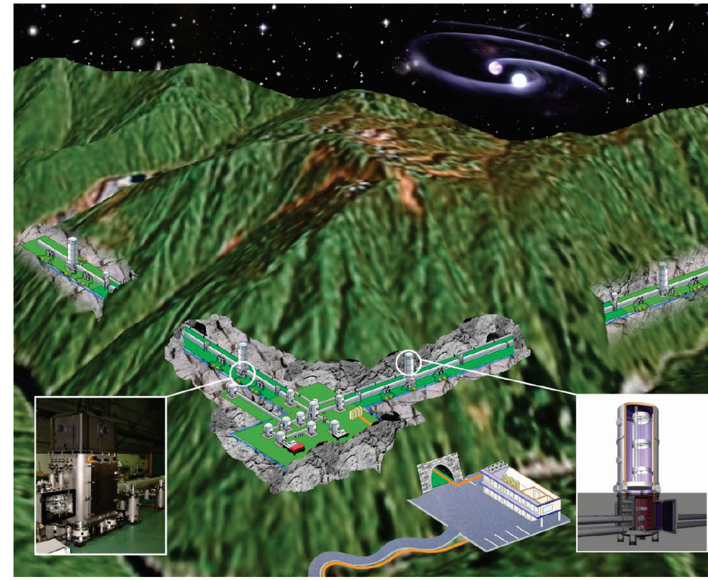
x10 distance
x1000 volume
More in a day of observation than in a year…

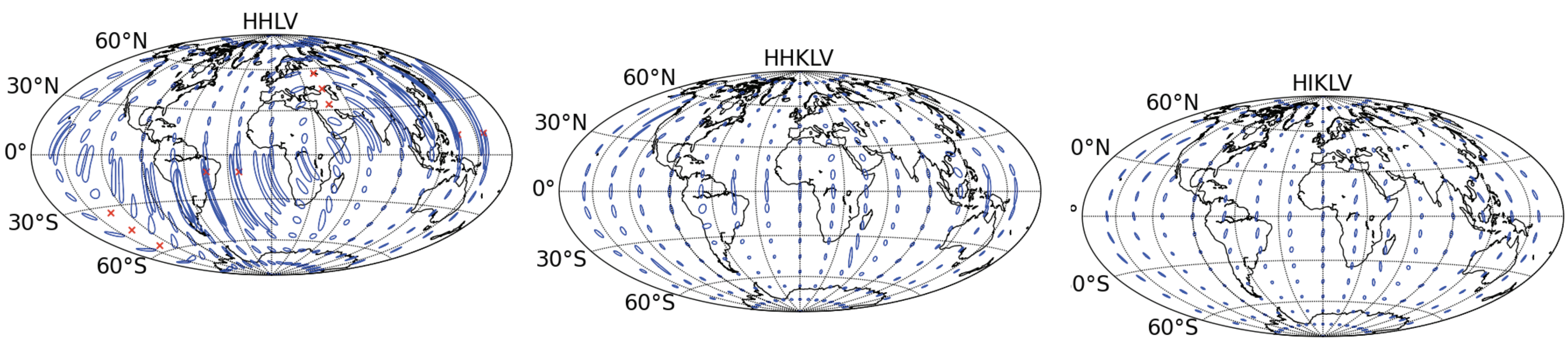
Thermal noise
Monolithic suspensions
Improved mirror coatings
Larger beam size

Quantum noise
Higher laser power
Thermal compensation
Signal recycling
DC detection

2nd generation (II)

- Toward an extended detector network
  - KAGRA in Japan
  - Third LIGO detector probably located in India
  - Duty cycle
    - ~80% at best for one detector
    - ~50% for three detectors in coincidence
  - Sky coverage
  - Source localization capability

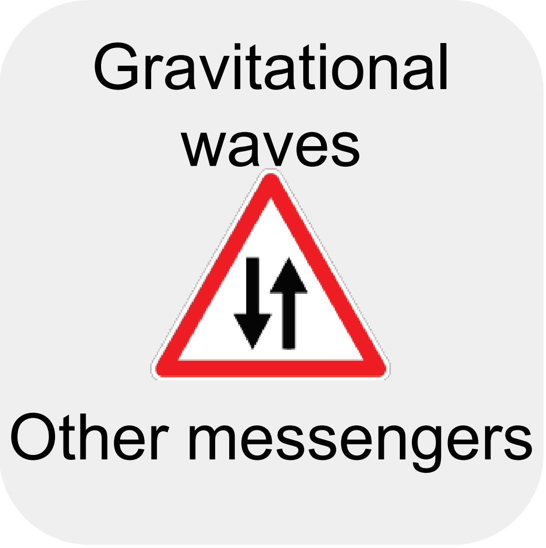




Science, from 1st to 2nd generation

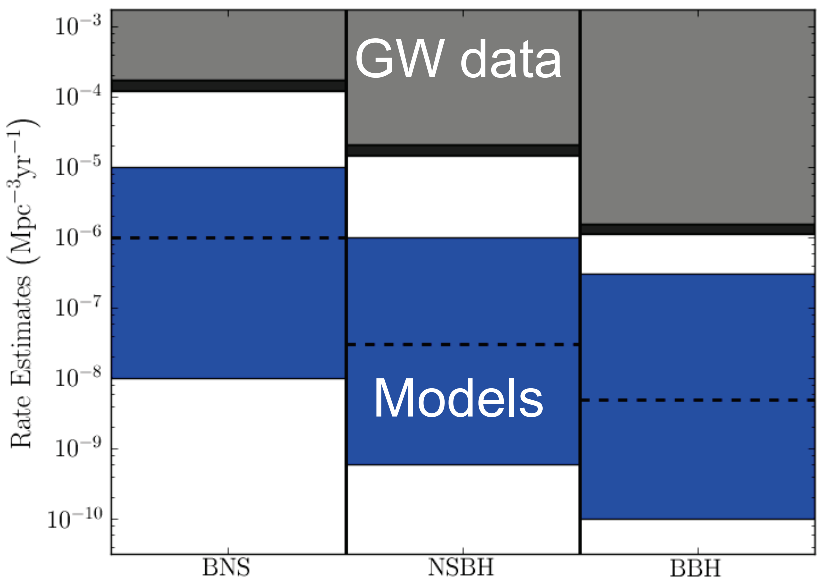
LAPP

- All sky searches
  - Compact coalescing binaries
  - Burst sources
    - Supernovae, cosmic strings…
  - Continuous waves (spinning neutron stars)
  - Stochastic background
- Targeted searches
  - Known pulsars
  - Neutron star oscillations
    - SGR flares, pulsar glitches
  - Gamma ray bursts
    - Long & short
  - High energy neutrinos
- Search for electromagnetic counterparts to GW



CBC: initial detector rates

IFO	Source[a]	$N_{\rm low}$ yr^{-1}	$N_{\rm re}$ yr^{-1}	$N_{\rm pl}$ yr^{-1}	$N_{\rm up}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]



- Rate upper limits from LIGO-S6/Virgo-VSR2-3 data
- ~1 order of magnitude above optimistic estimates

CBC: advanced detector rates

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{pl}$ yr^{-1}	$\dot{N}_{up}$ yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Realistic rates do get substantial for advanced detectors

BBH visible up to 1 Gpc

Science with GW from compact binaries

- General Relativity
  - Test theory in strong field
  - Test/constrain alternative gravity theories
- Astrophysics
  - Measure merger rates
    - As a function of parameters
  - Inform source distribution
    - Masses, spins, spatial distribution
  - Study effect of matter in BNS waveform
  - Short, hard GRBs
    - Confirm or rule out merger progenitor
- Cosmology
  - CBC inspirals as standard sirens
    - Independent measurement of Hubble constant

Challenges

→ Sensitivity

→ Waveforms

Known, but large parameter space, not fully explored yet

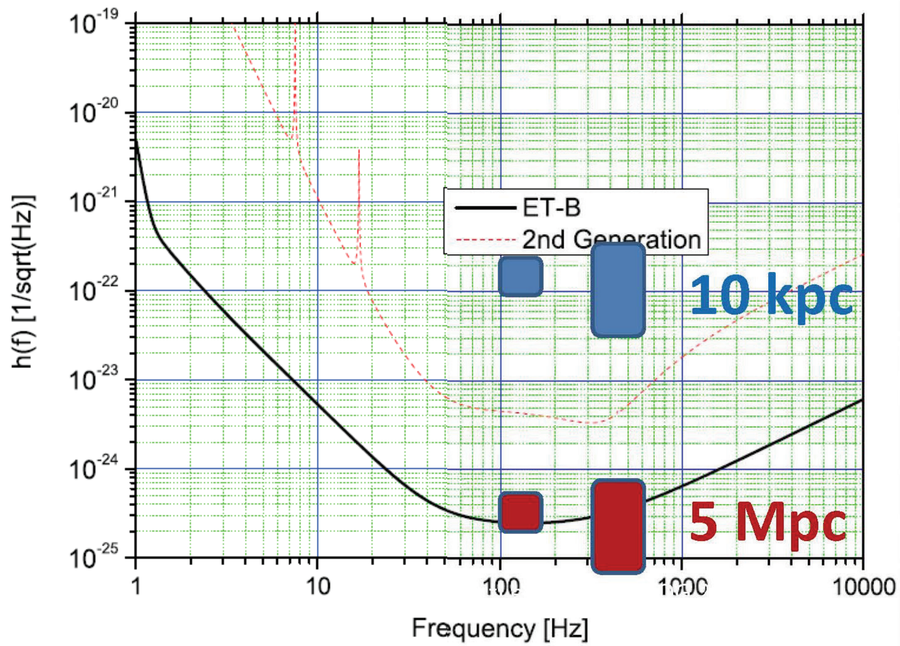
→ Multi-messenger astronomy

Many of the science goals require combining information from GW, electromagnetic and/or particle observations.

Burst GW: supernovae

- Galactic rate of core-collapse SN ~1 per 30-50 years
  - Within reach of 2nd generation detectors, but rare
  - (Lack of) detection will constrain SN mechanisms
- Expect 1 within 5 Mpc every 2-5 years
  - Needs 3rd generation detectors

Sensitivity estimated with Dimmelmaier et al. waveforms (bounce mechanism)



Continuous waves: initial detectors

GW upper limits beating spin-down limit for two pulsars

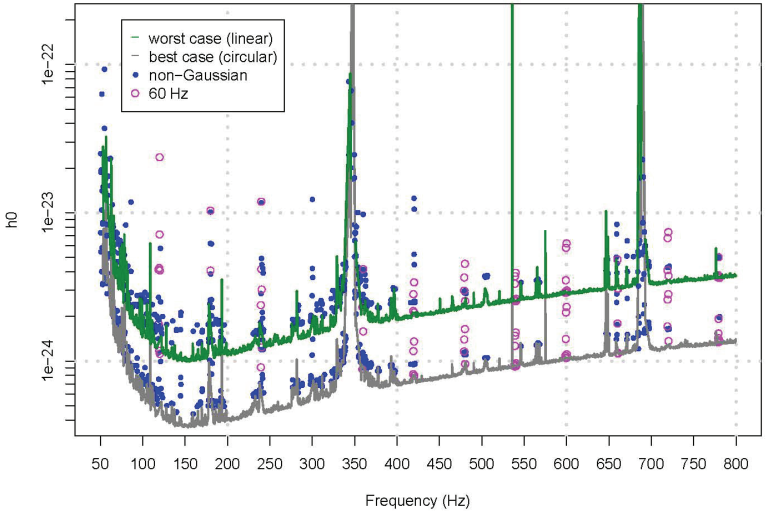
- Crab @ ~60 Hz (LIGO data)
  - » GW energy < 2% of spin-down energy
  - » $\varepsilon < 1.3\times10^{-4}$
- Vela @ ~22 Hz (Virgo data)
  - » GW energy < 35% of spin-down energy
  - » $\varepsilon < 1.1\times10^{-3}$

Other targeted searches

- 116 known millisecond and young pulsars with LIGO S5 data
  - » Best h limit 2.3×10^{-26}
    - » J1603−7202, 135 Hz
  - » Best ε limit 7.0×10^{-8}
    - » J2124−3358, 406 Hz, 0.2 kpc

All-sky searches

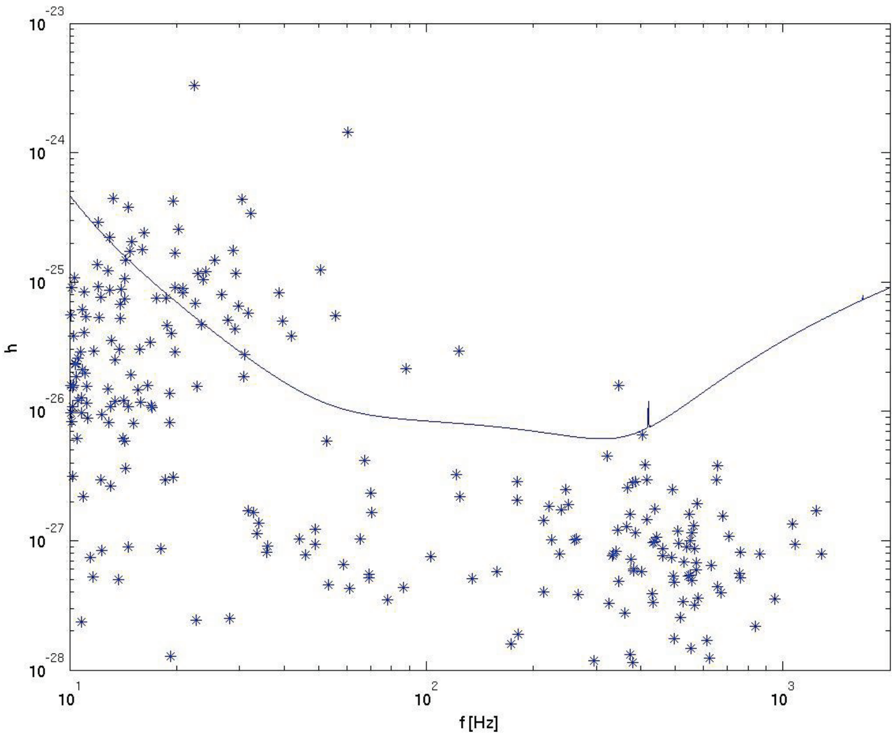
- S5 LIGO data
- At high frequency, sensitive to $\varepsilon = 10^{-6}$ up to ~500 pc

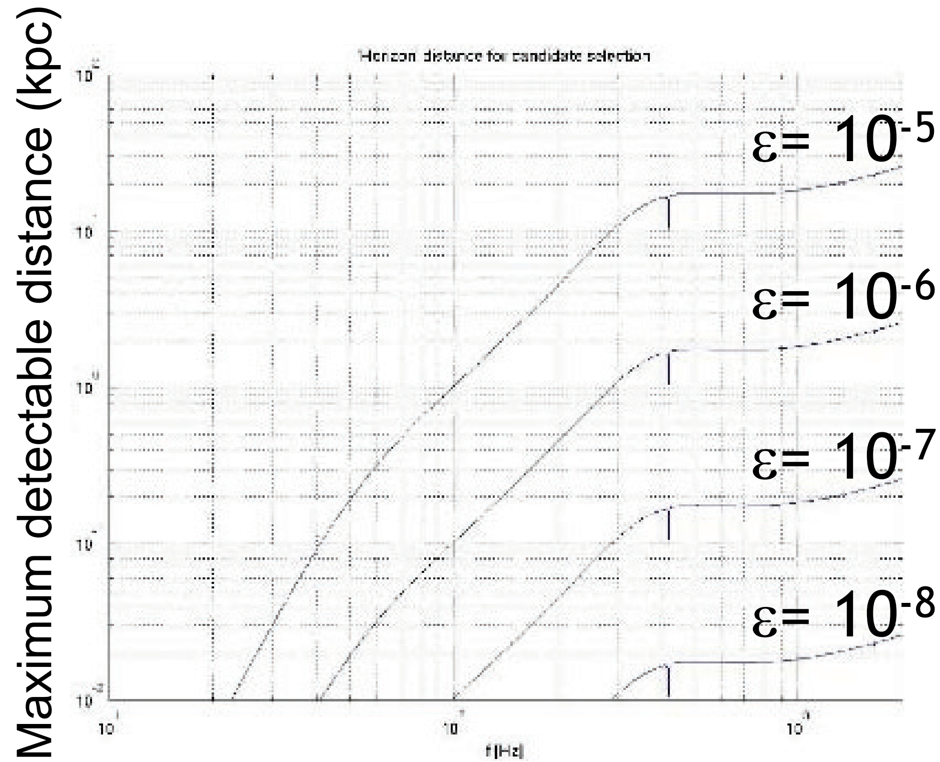


Continuous waves: advanced detectors

Minimum detectable amplitude with 1yr observation of Advanced Virgo, compared to spin-down limits of known pulsars

Significant fraction of the Galaxy probed for large ellipticities



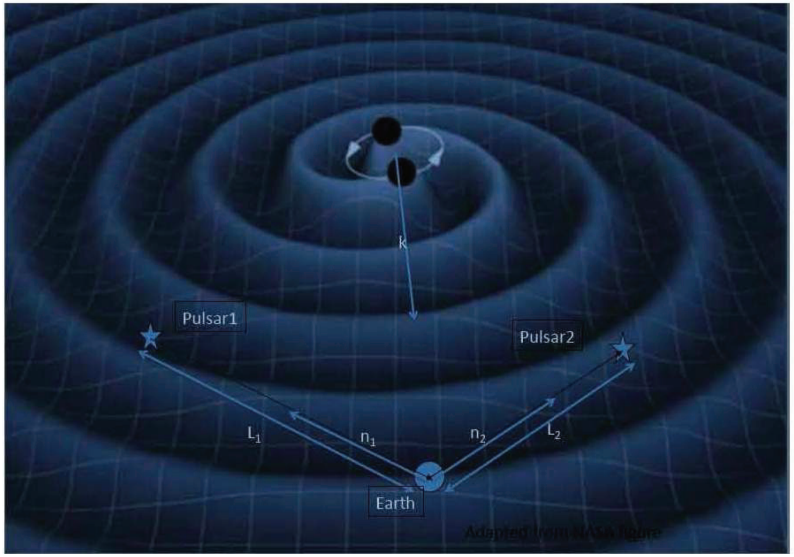


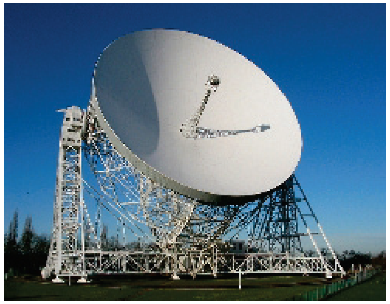
Conclusion

- GW promise a new, powerful tool for fundamental physics, astrophysics, cosmology
- Field & community matured with 1st generation ground-based detectors
- Second generation detectors coming online soon
  - Go through construction, commissioning, observation and… detections!
  - Multi-messenger key ingredient for successful science
  - Prepare the future: 2.5 and 3rd generations…

Pulsar timing arrays

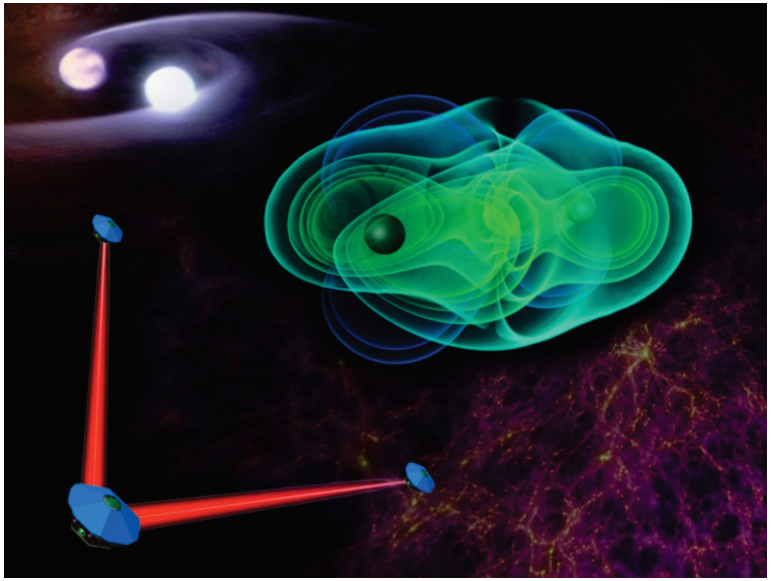
- A galactic scale detector
  - Pulsars = cosmic clocks
  - nano-Hz band
- Probe stochastic background of super-massive black hole binaries
  - Upper limits for past 20 years
  - Ruled out SMBH binary in 3C66B





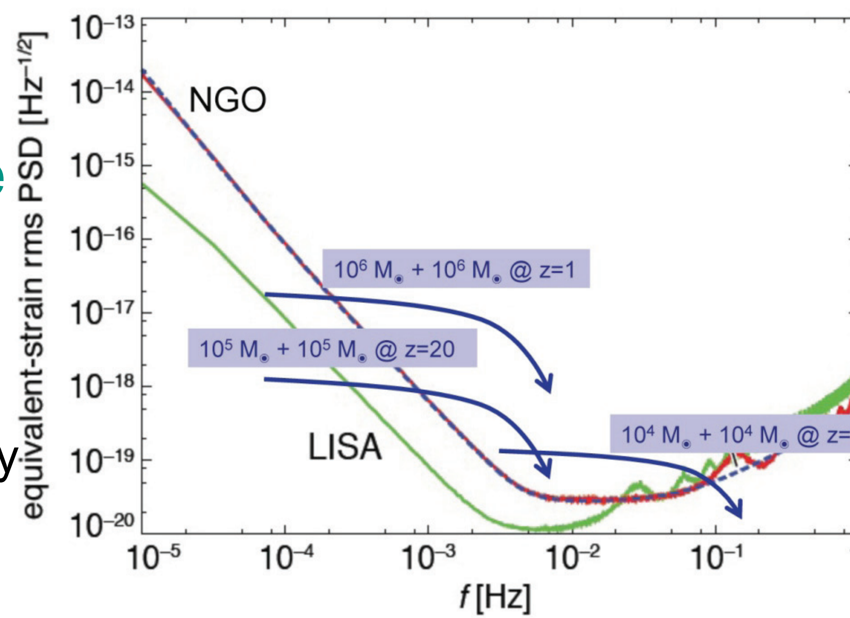
- Goal : weekly observations of ~20 millisecond pulsars over 5 - 10 years with TOA precisions of ~100 ns
  - International Pulsar Timing array

eLISA-NGO

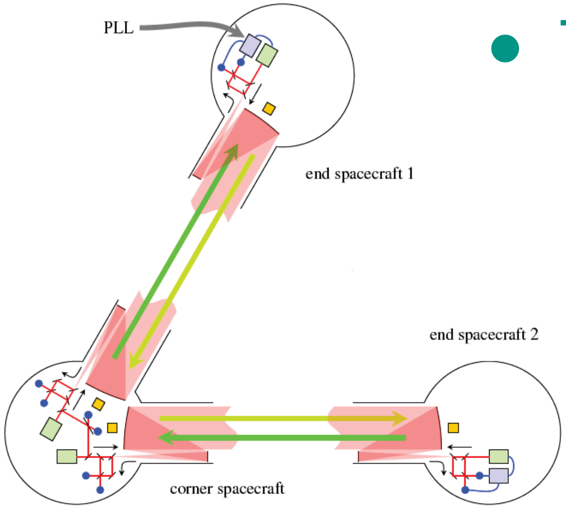


- European avatar of the LISA project
  - Reduced size and bandwidth
  - Will apply for L2 mission selection in ESA Cosmic Vision program
    - » Launch ~2028

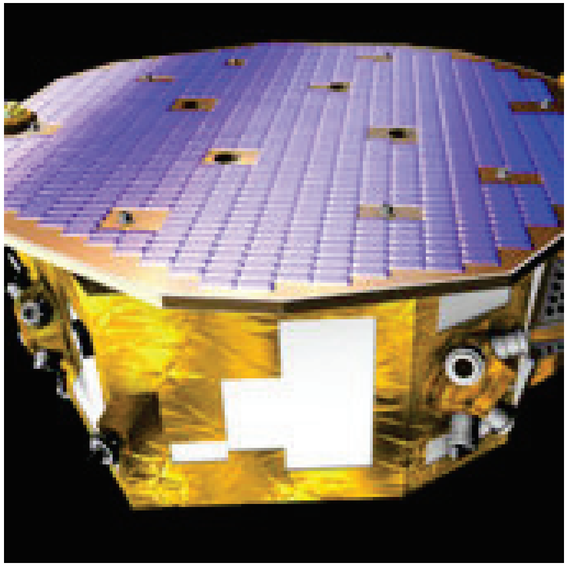
- Guaranteed sources, rich science program
  - Super-massive black holes and large structure formation
  - White-dwarf binary systems in the Galaxy
  - Cosmology, ultra-strong gravity tests



LISA Pathfinder



- Technical challenges
  - eLISA-NGO = constellation of 3 satellites, 2 arms
  - Drag-free control
    - » Control satellites around free-falling masses
  - Laser interferometry to measure distances between test masses
    - » ~10 pm over 10^6 km



- LISA Pathfinder: technology demonstrator
  - Inertial sensors, thrusters
  - Laser interferometry, at same accuracy level as eLISA-NGO
  - Will be launched in 2015