The science potential of the Einstein Telescope

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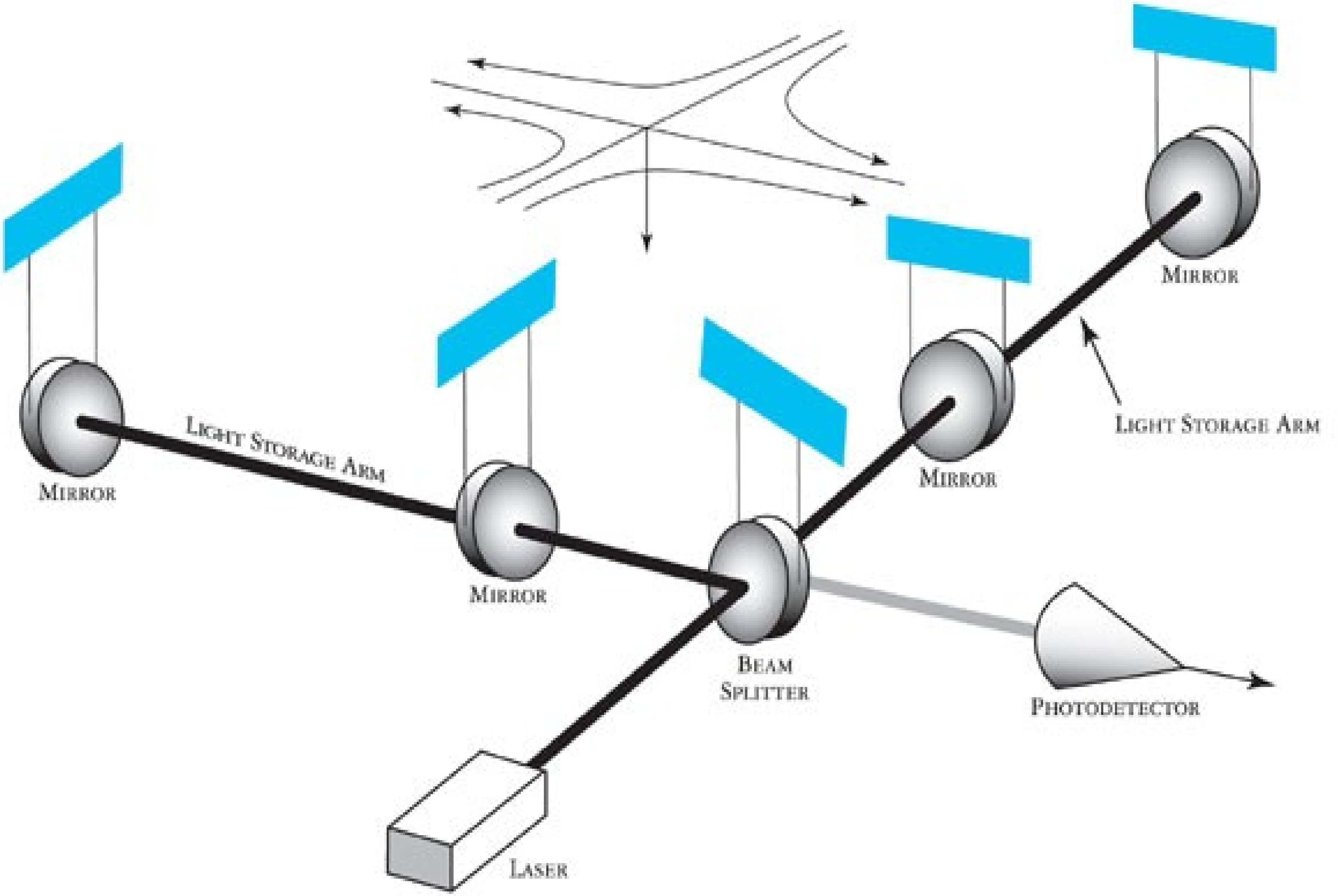
Status of observational gravitational wave astronomy

- Bar detectors
- Interferometers
  - LIGO, Advanced LIGO
  - VIRGO, Advanced VIRGO
  - KAGRA
  - LIGO-India (Indigo)
  - GEO600

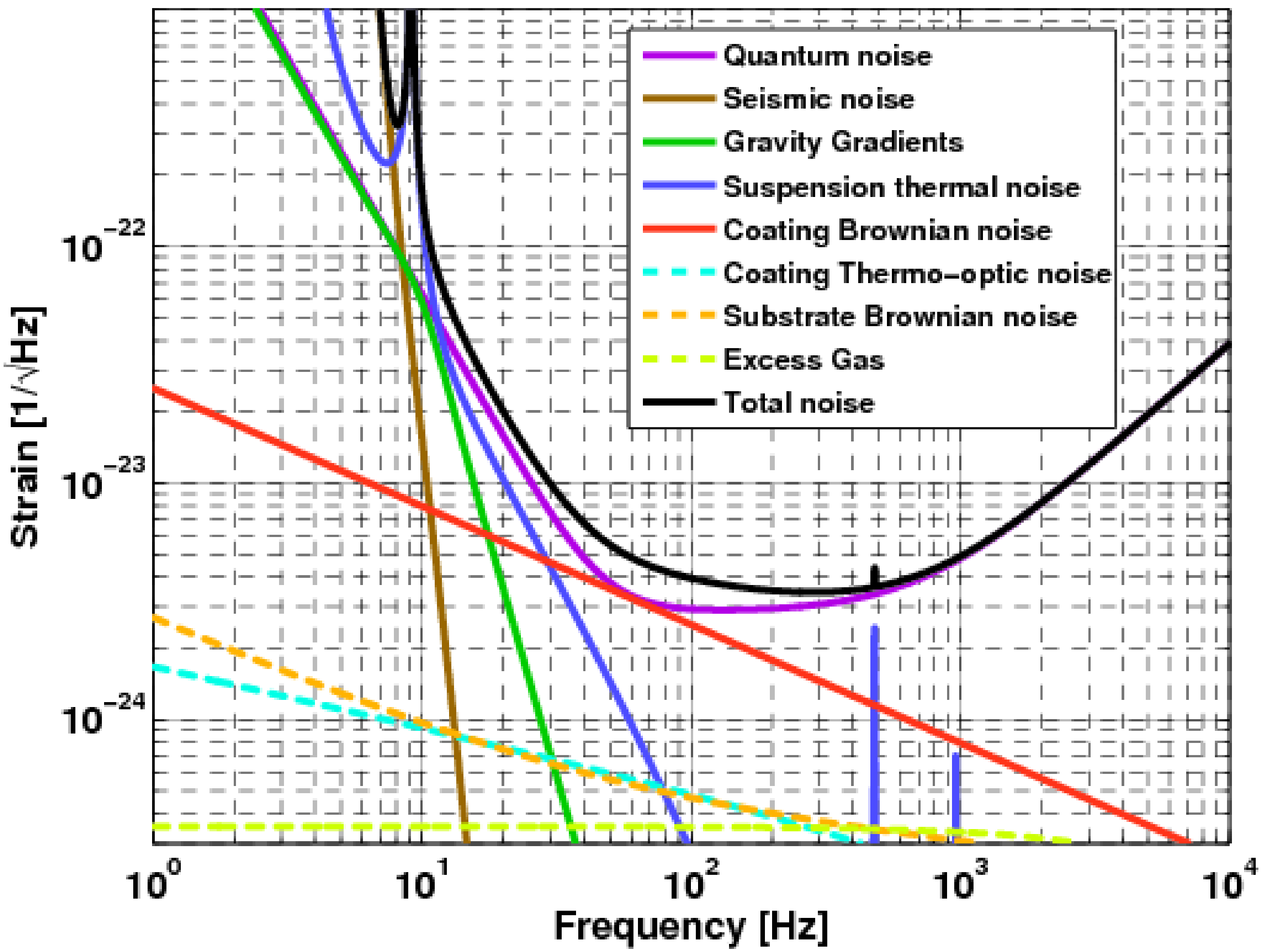
Interferometers



Current detection prospects

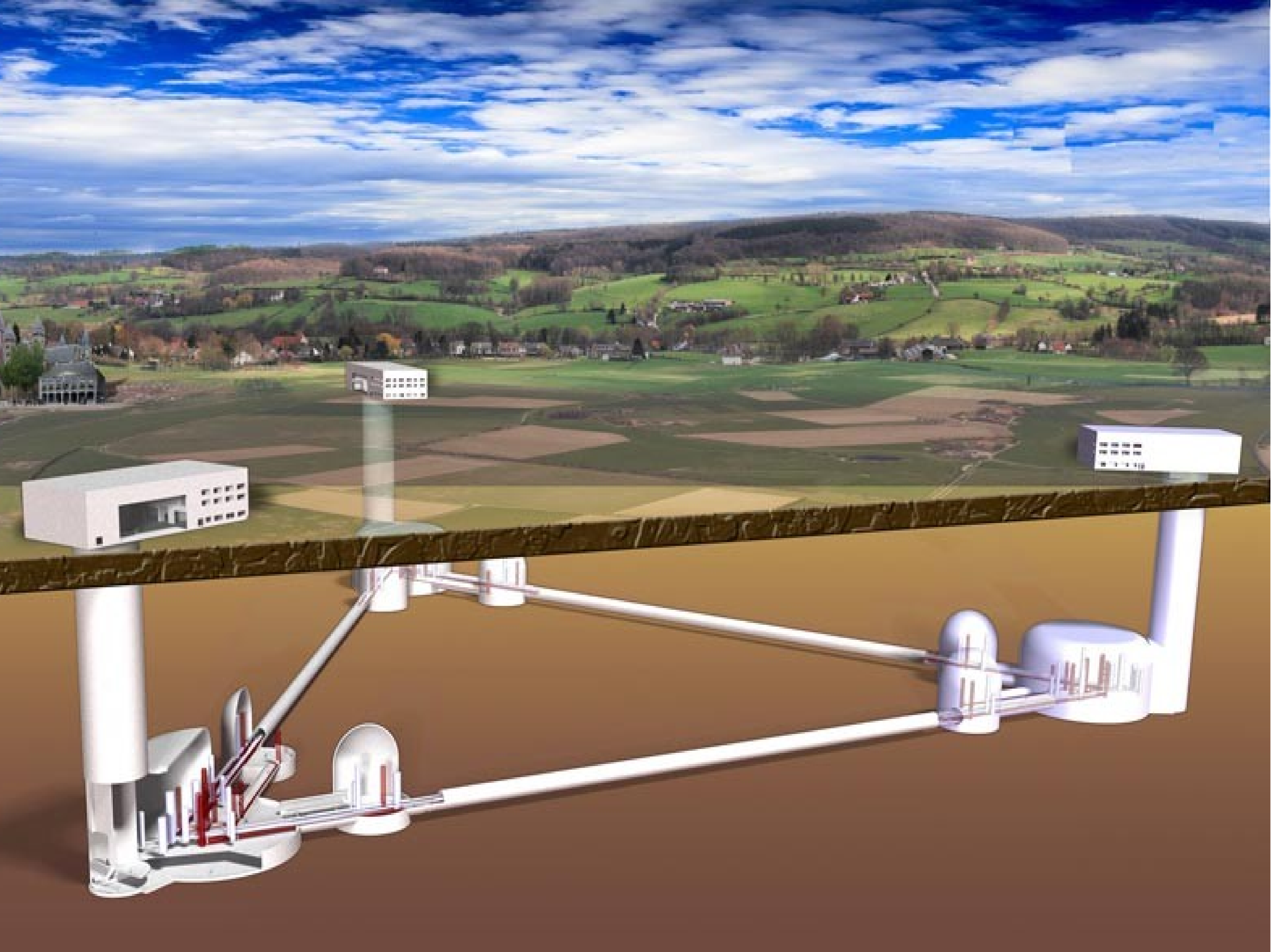
- Range for a DNS coalescence:
  - LIGO , VIRGO – 20Mpc
  - Advanced detectors – 300 Mpc
- Range → Volume → rate
- Expected event rates.
- To be seen

Advanced detectors noise budget

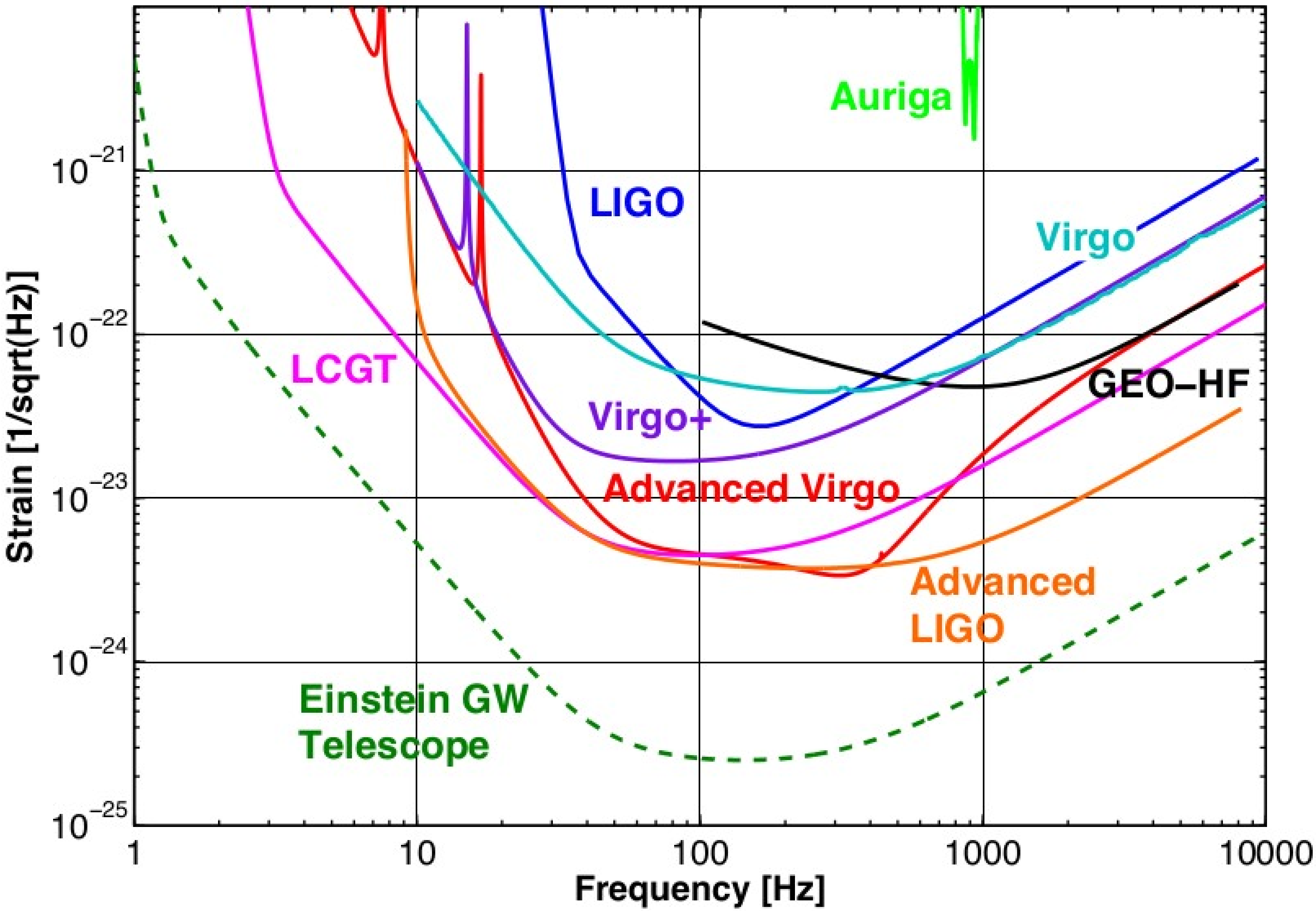


What is ET?

- The third generation gravitational wave detector.
- An underground interferometer.
- Triangle configuration



ET Sensitivity



ET capabilities: summary

- Spectral range: 10Hz-10kHz
- Sensitivity down strain $3x10^{-25}$ $Hz^{-1/2}$ in the best range
- Angular resolution:
  - depend on EM detections
  - long lasting sources – use the Earth motion modulation
  - would be improved by a network
- Excellent spectral resolution

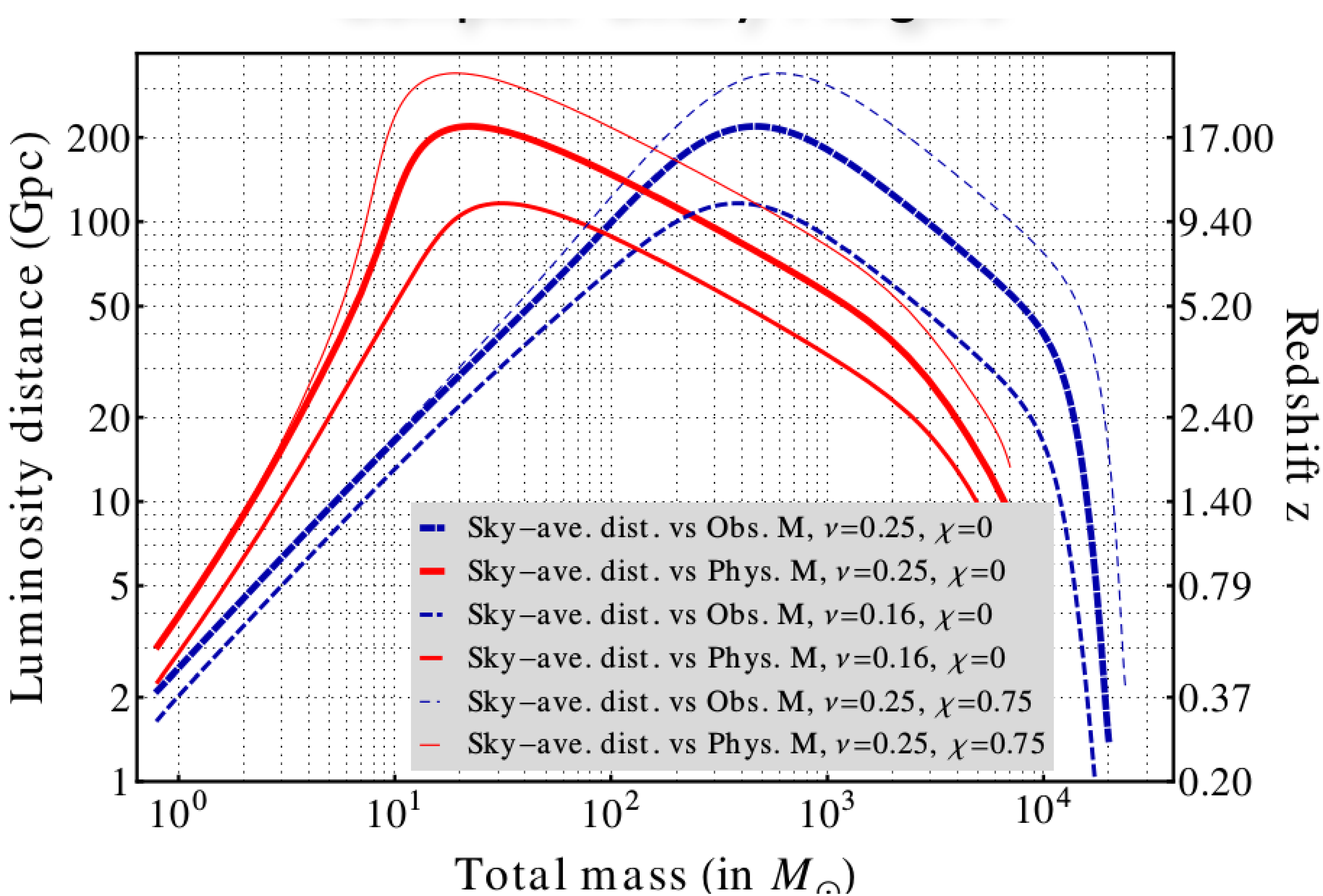
What does it mean?

- Sensitivity ~100 times better than current detectors
- Volume roughly 10^6 times larger
- 30 seconds of ET time is equivalent to 1 year of LIGO/VIRGO data

Astronomical sources

- Compact object binaries
- Core collapse supernovae
- Pulsars
- Backgrounds

ET range for coalescences



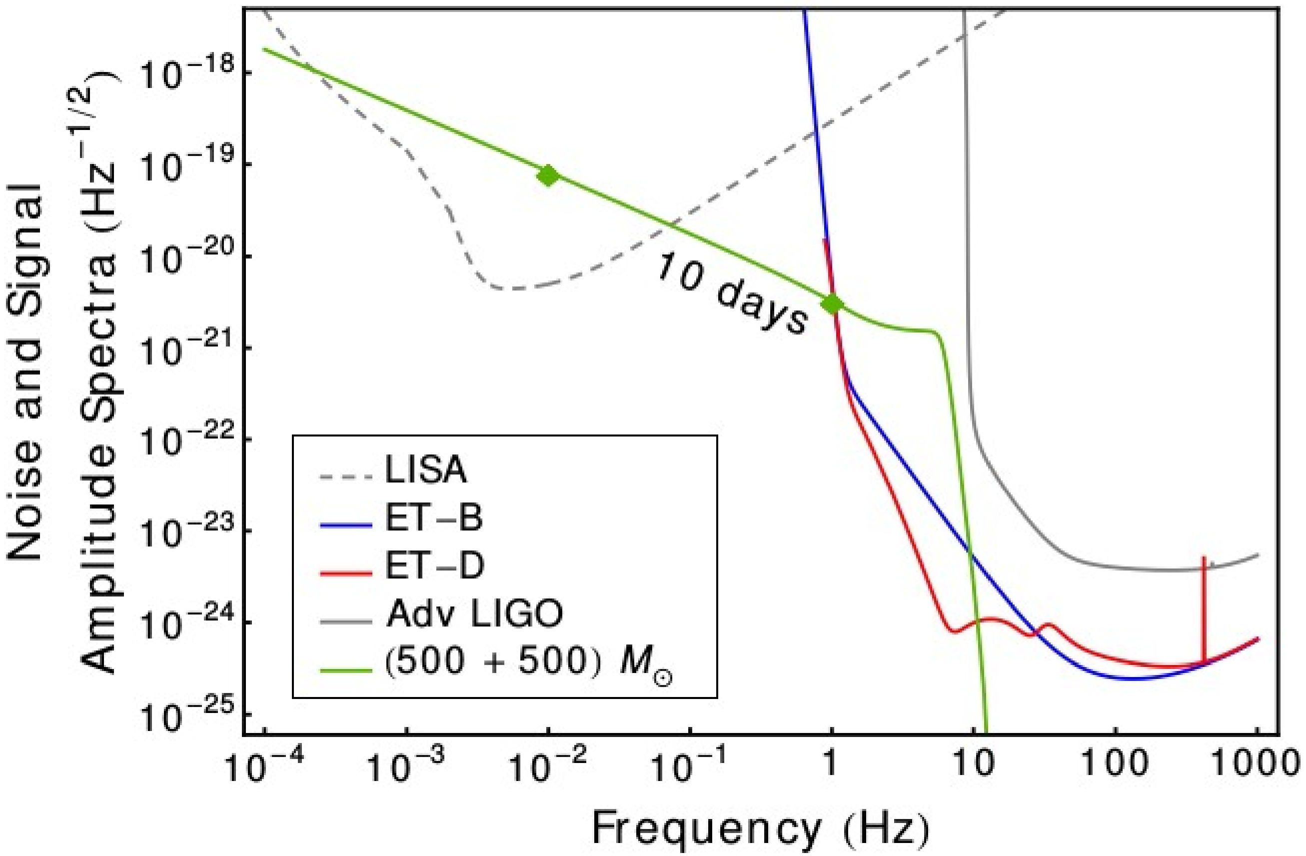
Compact object binaries

- Rates: up to 100s per day
- Large mass range: not only standard stellar sources but also intermediate BHs
- For nearby sources very high S/N – detailed measurement of the waveform.

Astrophysics with compact object binaries

- Cosmology:
  - Standard sirens: amplitude and frequency change depend on the chirp mass only; need an independent redshift estimate
  - Possible measurement of the Hubble constant, w, and their variation with age
  - Anisotropic cosmologies tests
  - EoS of dark energy
- Star formation and compact object mass spectrum
- Gamma ray bursts
- Massive BH formation scenarios
- EoS of ultra dense matter

Intermediate mass BH binaries

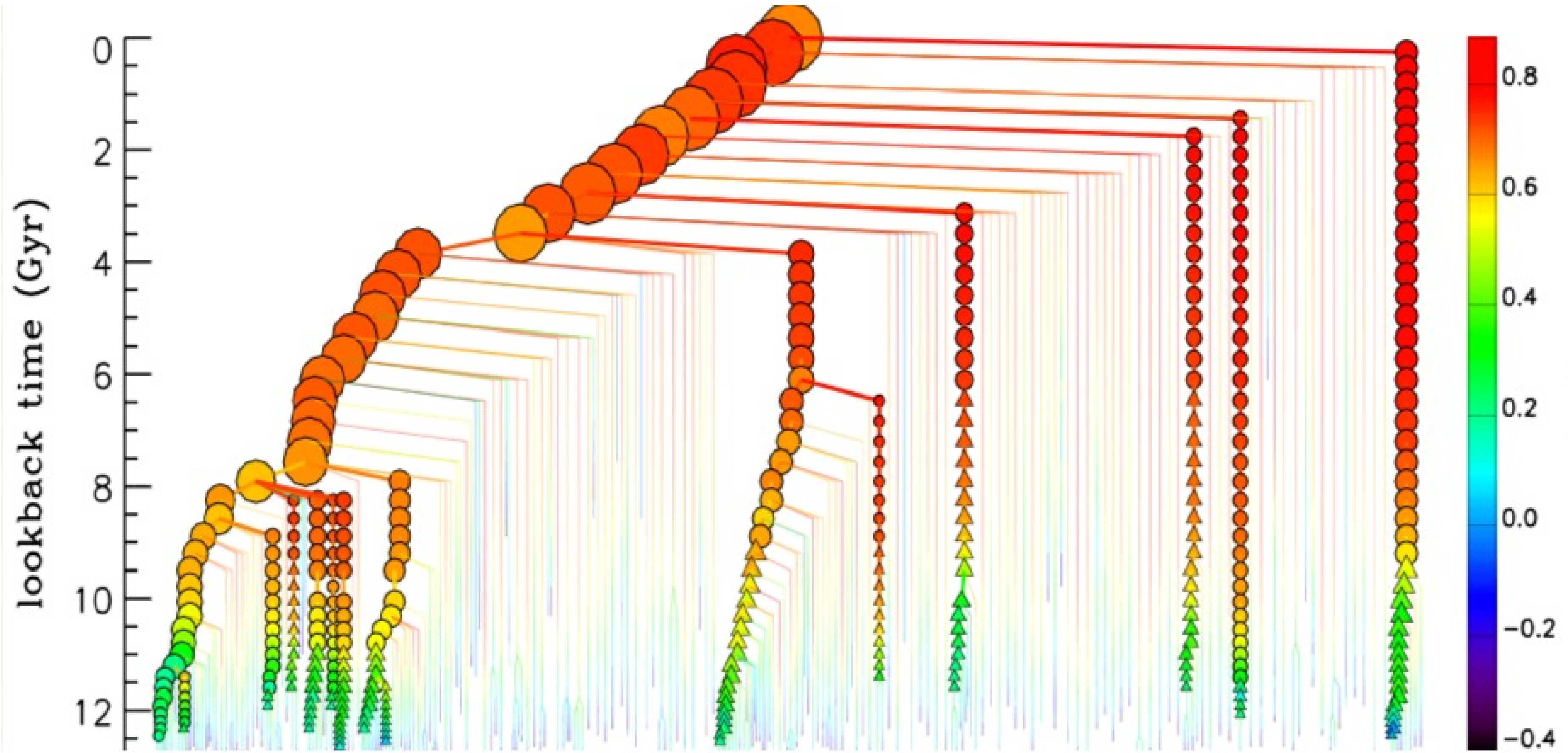


Identifying seeds of galaxy formation

Tracing the population of ULXs

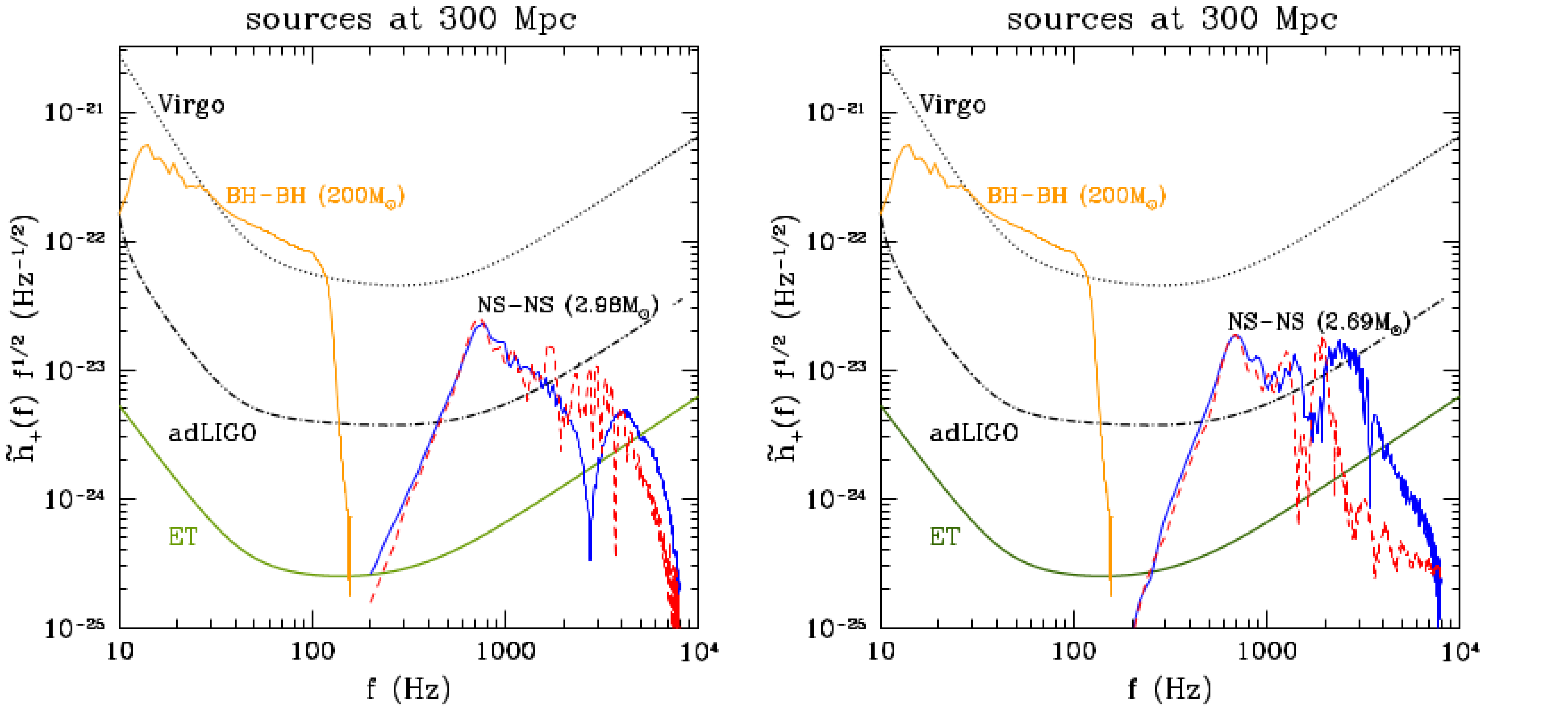
Formation of massive BHs

Formation of BHs in galactic nuclei



Small black holes merger hierarchically into larger ones. ET can detect mergers of black holes up to 1000 solar mass, enabling to trace the formation of massive ones.

Neutron star equation of state



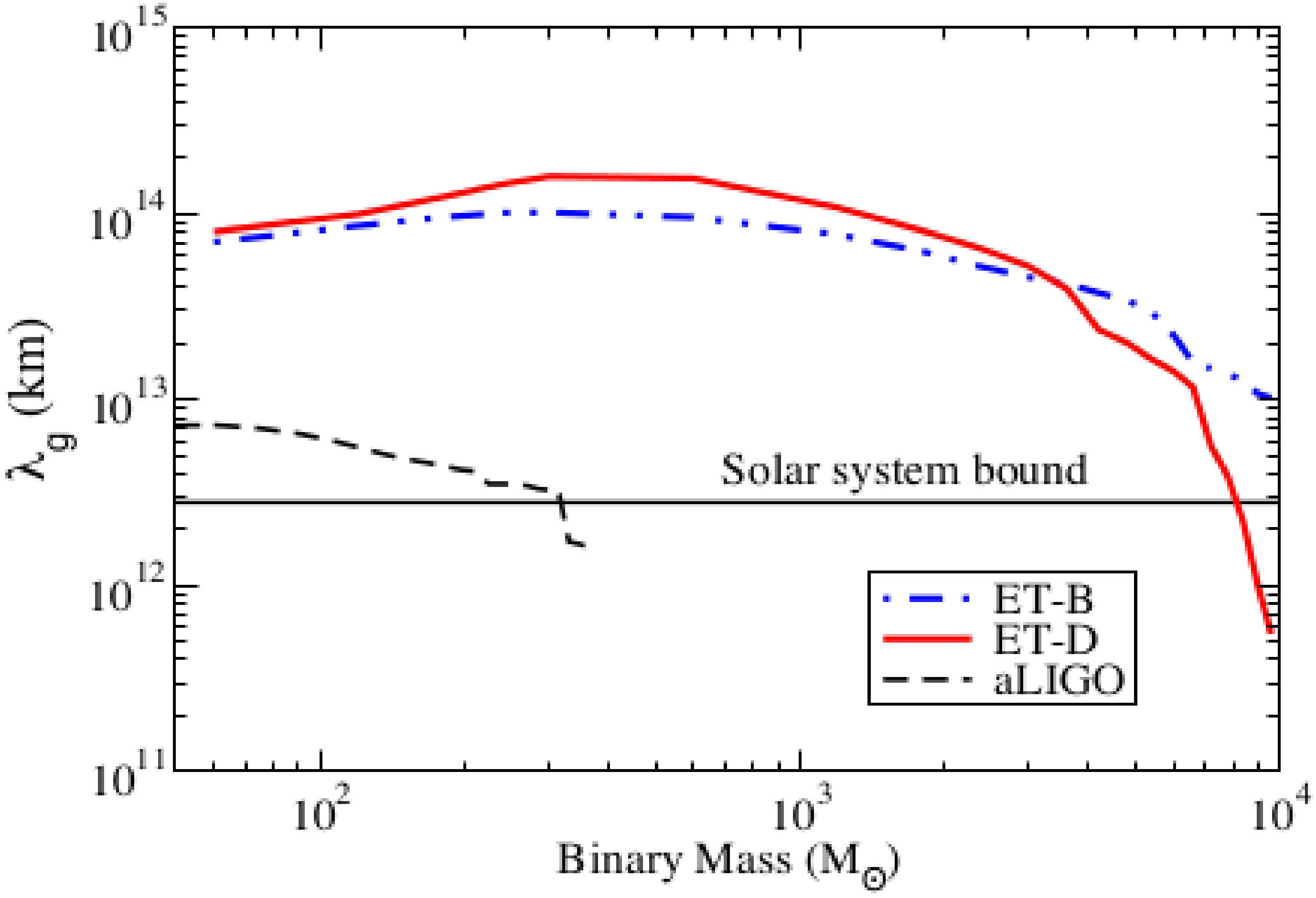
Fundamental physics with binaries

- The speed of gravity:
- Difference in the arrival time of EM (or neutrino) and GW signal

$$\frac{\delta v}{c} = \frac{\delta t}{D/c} \approx 10^{-17} \left(\frac{\delta t}{1s}\right) \left(\frac{1\mathrm{Gpc}}{\mathrm{D}}\right)$$

- Limiting the mass of graviton and it Compton wavelength, from measuring the dispersion
- Testing GW beyond the quadrupole formula
- How many GW polarizations there are?

Bounds on the graviton Compton wavelength



Fundamental physics with binaries

- Testing the no hair theorem:
  - BH spectrography

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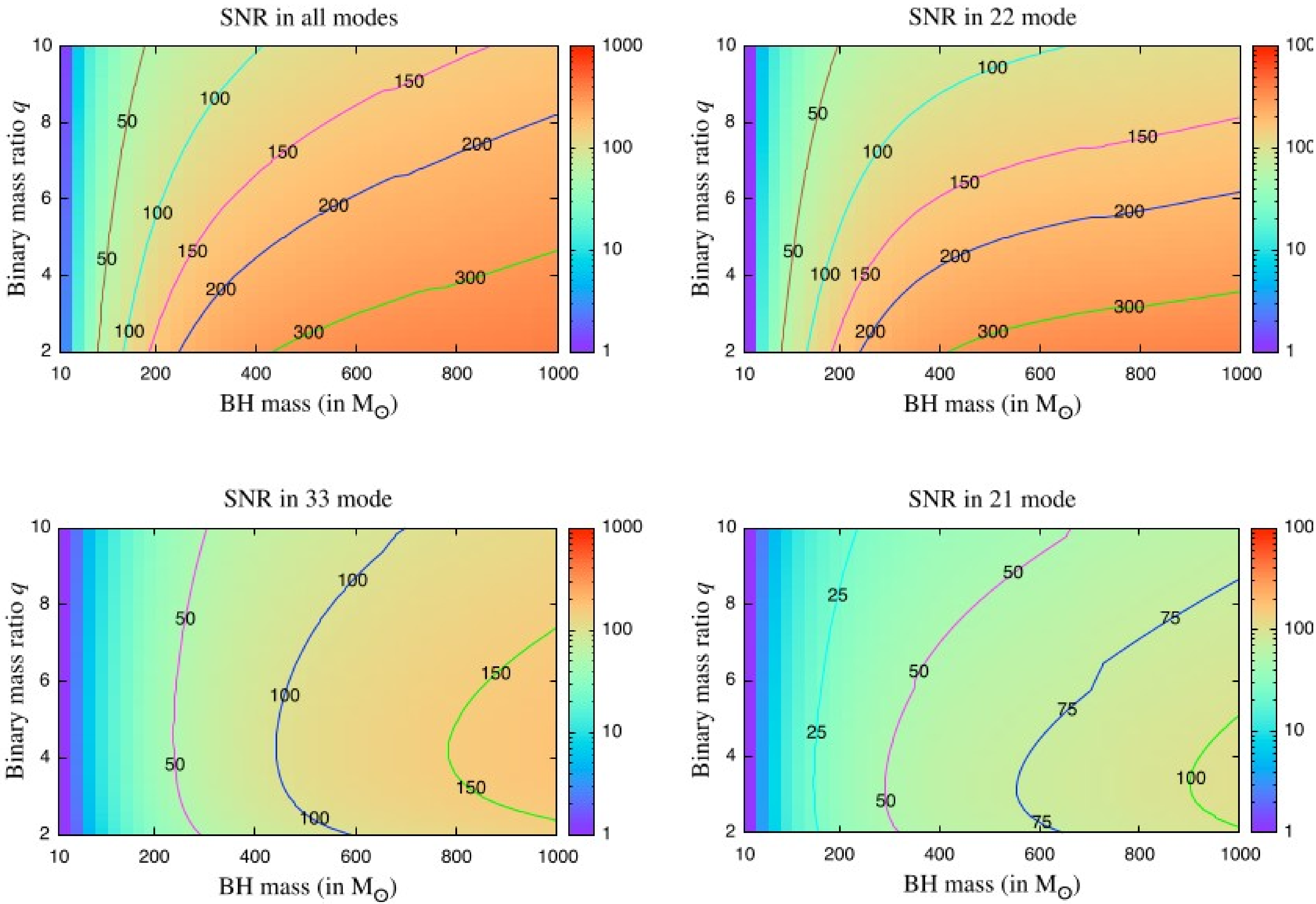
The quasi-normal modes of the Schwarzschild black hole

By S. Chandrasekhar, F.R.S. and S. Detweiler
University of Chicago, Chicago, Illinois, 60637

(*Received 6 December* 1974)

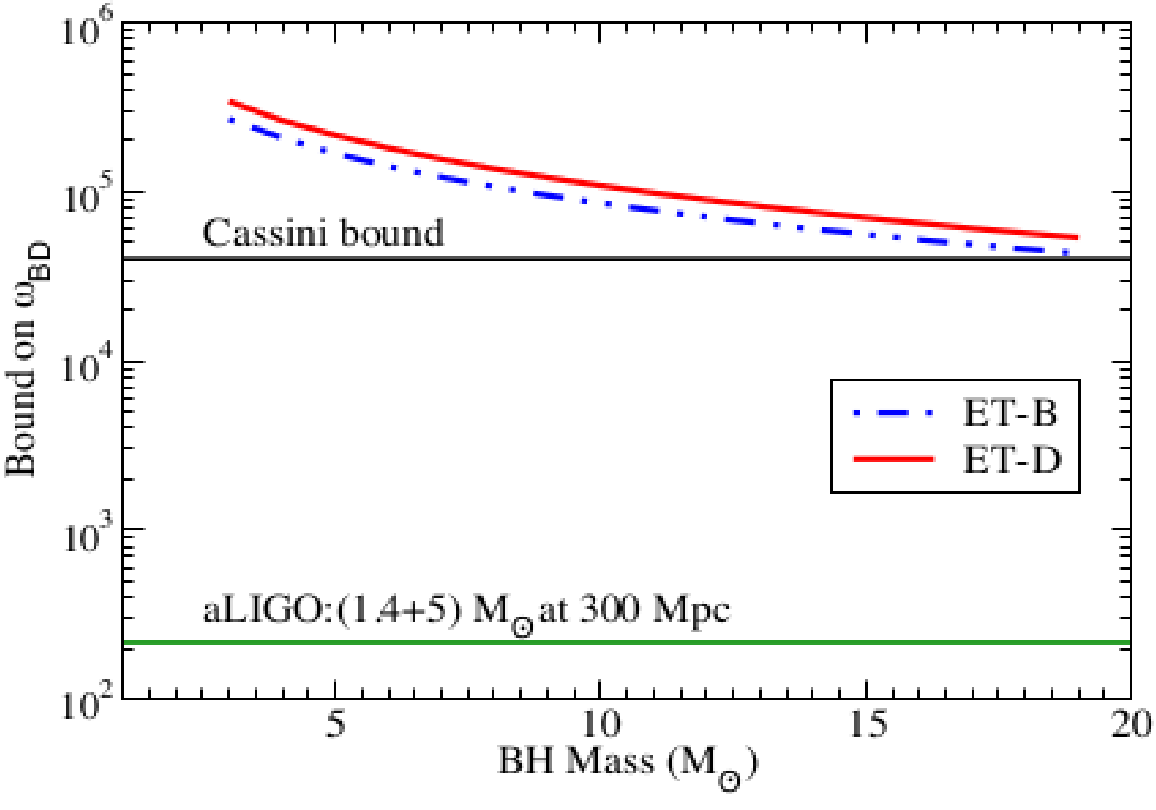
The quasi-normal modes of a black hole represent solutions of the relevant perturbation equations which satisfy the boundary conditions appropriate for purely outgoing (gravitational) waves at infinity and purely ingoing waves at the horizon. For the Schwarzschild black hole the problem reduces to one of finding such solutions for a one-dimensional wave equation (Zerilli's equation) for a potential which is positive everywhere and is of short-range. The notion of quasi-normal modes of such one-dimensional potential barriers is examined with two illustrative examples; and numerical solutions for Zerilli's potential are obtained by integrating the associated Riccati equation.

Visibility of QNM in ET: Formation of BHs at $z=1$



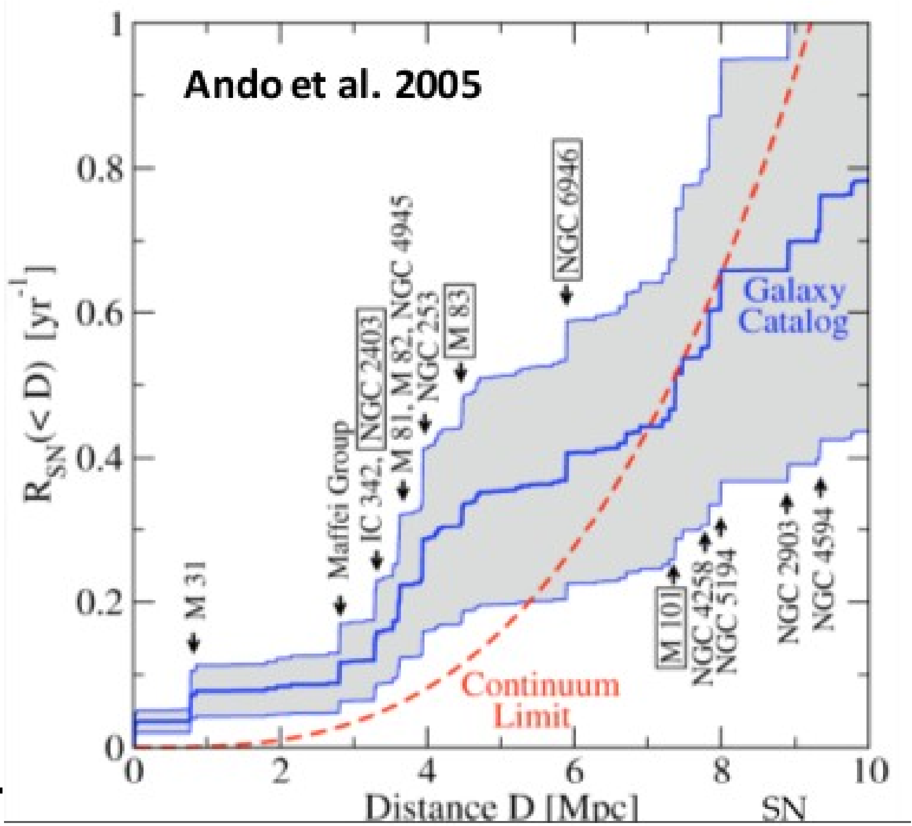
Alternative gravity

Potential bounds on the Brans-Dicke gravity parameter. The bound stems form the existence of a dipolar term in the BD theory.

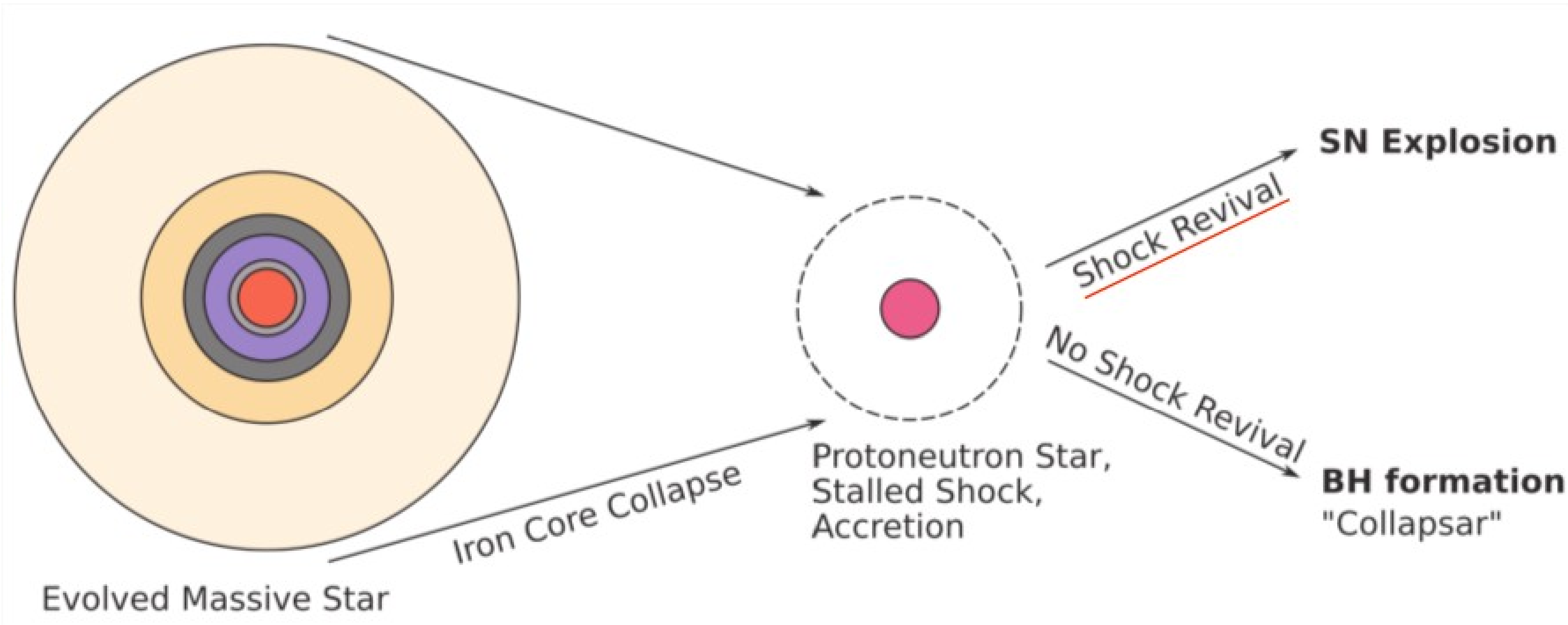


Core collapse supernovae

- Rates: current LIGO/VIRGO range in the Milky Way.
- Advanced LIGO/VIRGO will reach M31
- ET – up to 5Mpc
- Rates up to one per year – optimistic.



Core collapse supernova



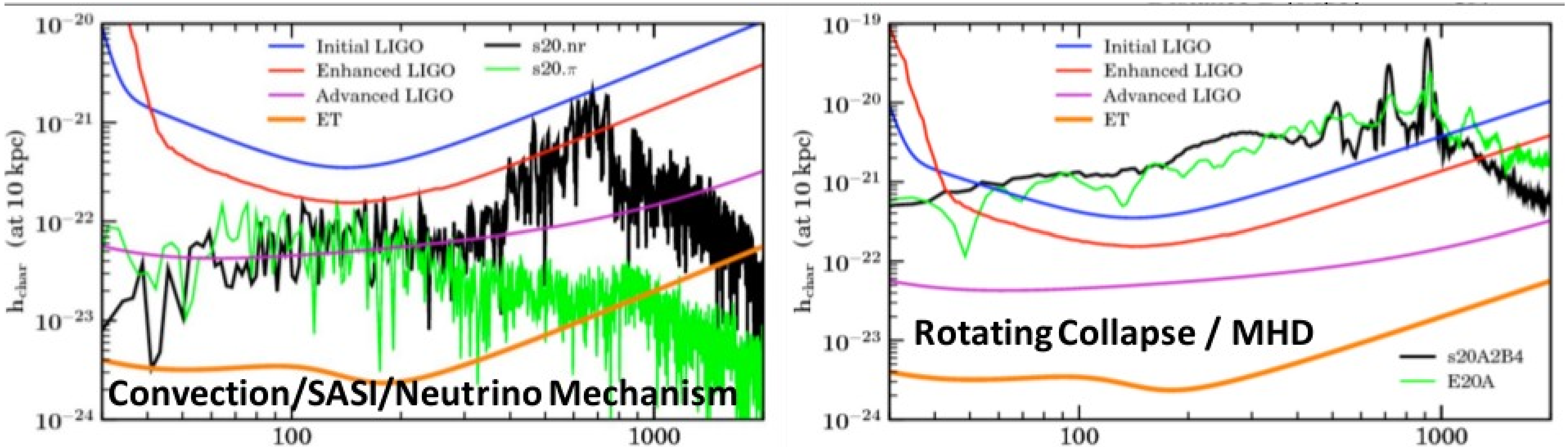
Energy up to 10^{51} erg.

Delay 1-2 seconds after bounce

Formation of BH – and its mass growth

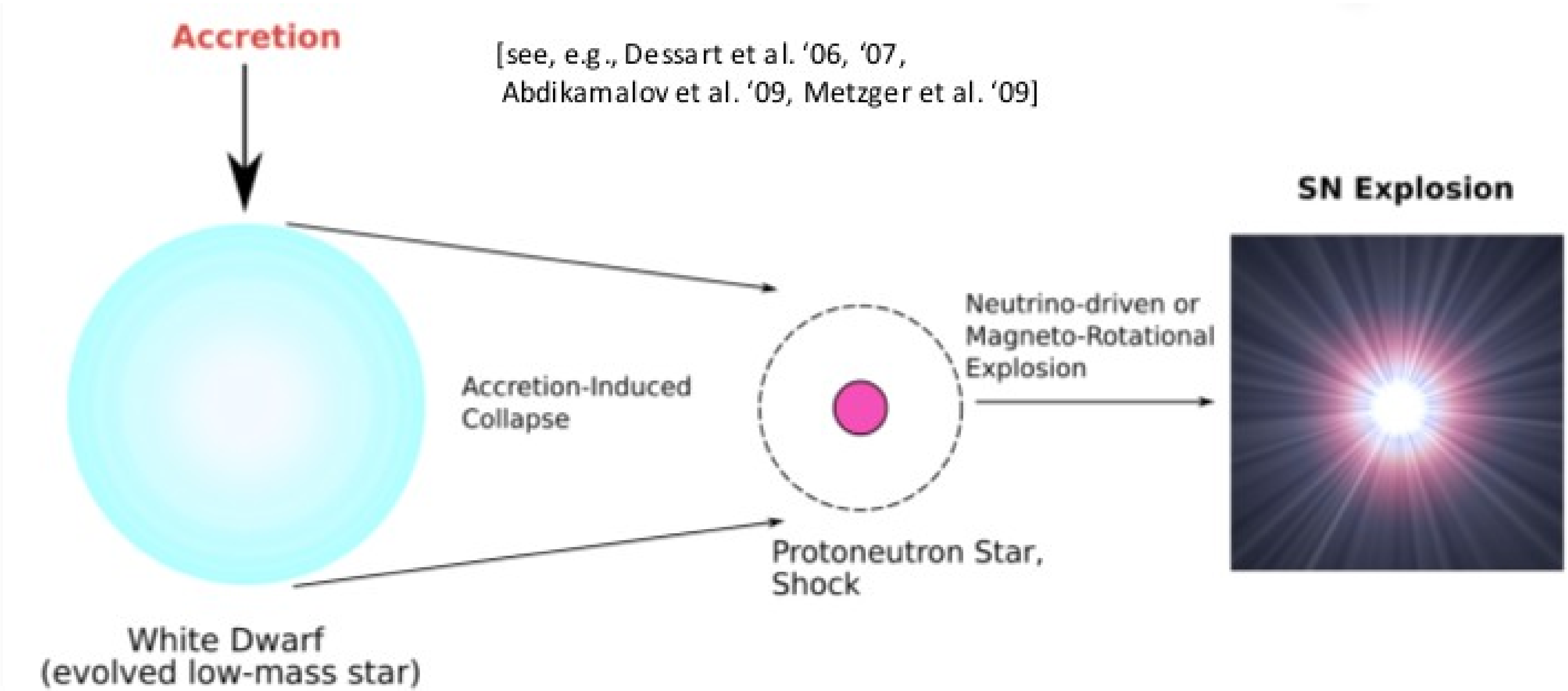
Physics with core collapse supernovae

- Mechanism of supernovae explosions
- Formation of a BH
- Quasi normal modes and BH spectrography
- Could allow the measurement of neutrino mass.



Example spectra for a SN in the center of the Milky Way

Accretion induced collapse

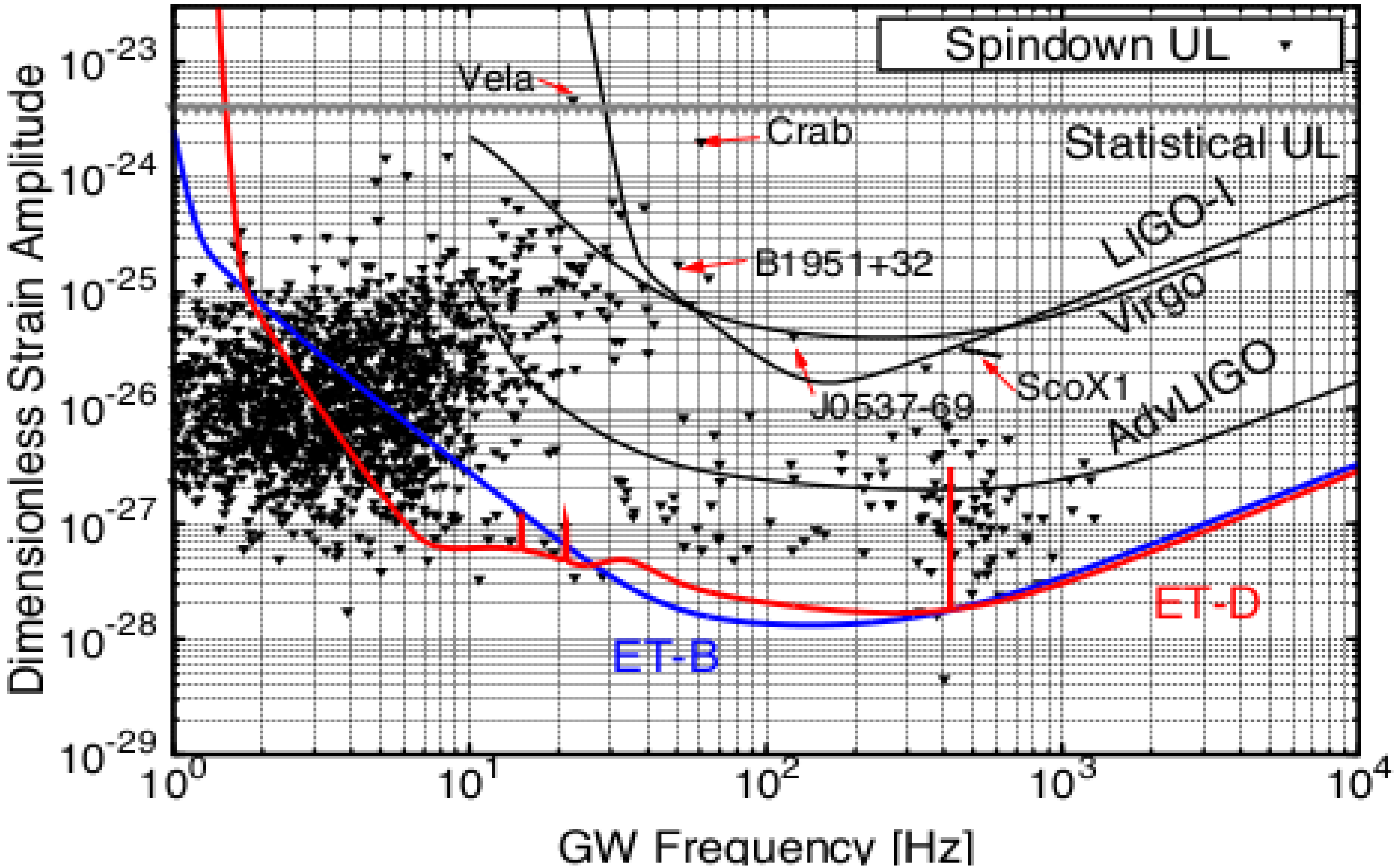


- Collapse of accreting, probably rotating White Dwarfs
  - Neutrino-driven or magneto-rotational explosion
- Explosion probably weak, sub-luminous
  - Might not be seen in optical
- Potential birth site of magnetars - highly (10^{15}- 10^{16} G) magnetized neutron stars

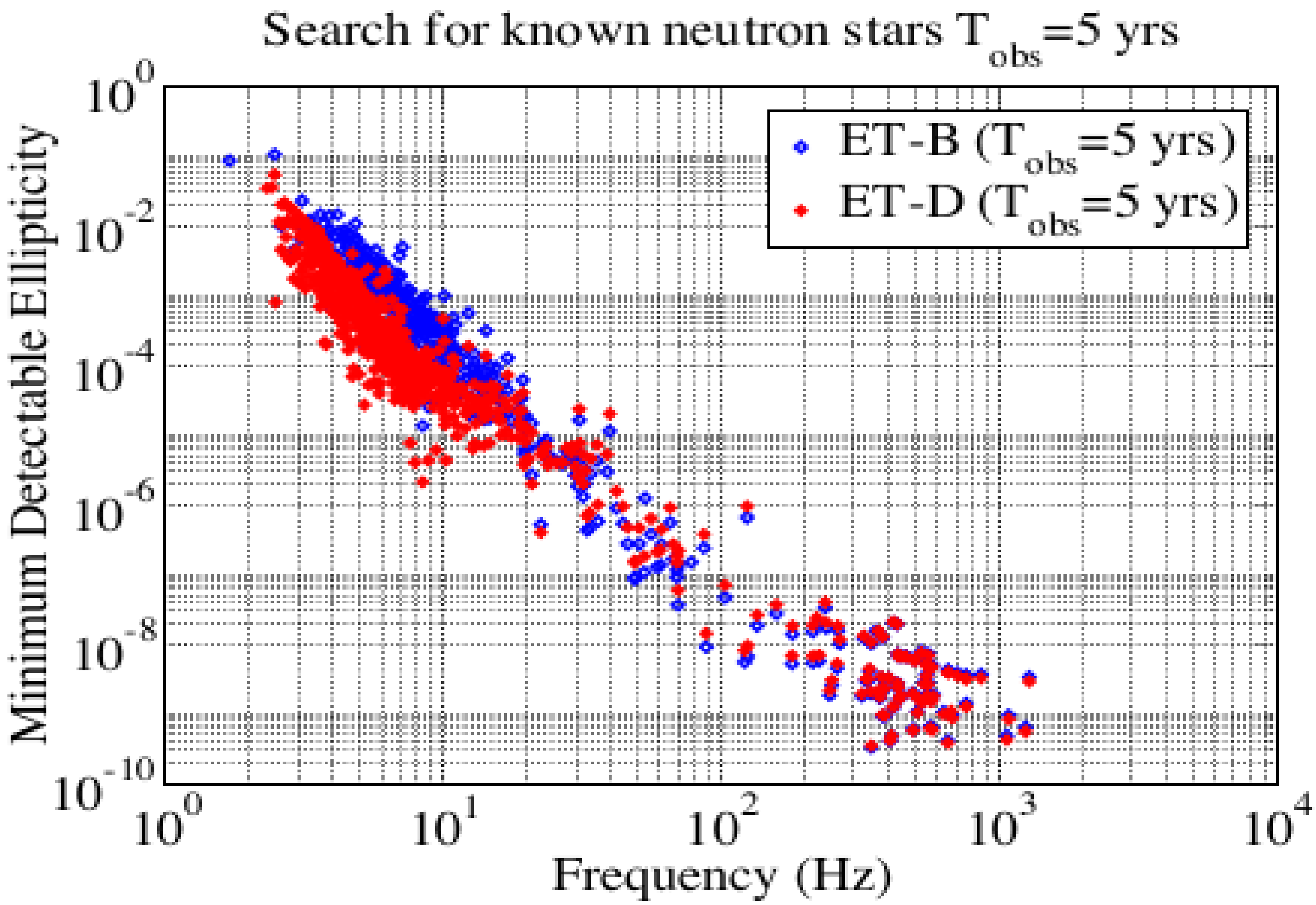
Rotating neutron stars

- Will emit GW if asymmetric
- All astrophysical objects are non spherical to some degree
- Can form mountains on the crust of a NS
- Supported by magnetic fields
- Glitches as NS asymmetry indicators

Spin down limit for pulsar luminosity



ET sensitivity



Mountains as small as 10um can be detected !

Pulsar glitches

Sudden changes in the spin period

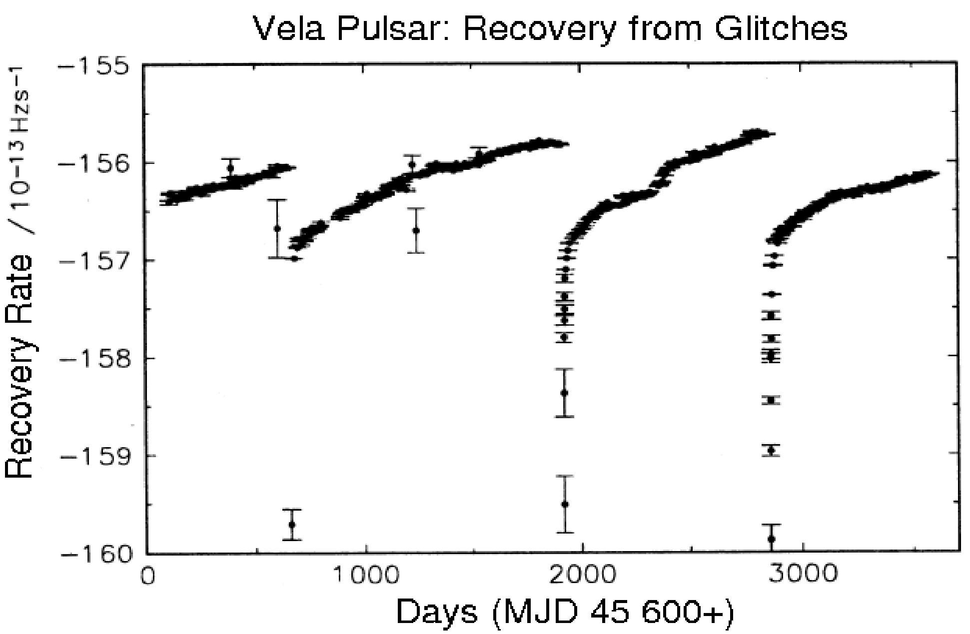
Appear every few years in Vela pulsar

Transfer of angular momentum between core and crust

Crust deformation

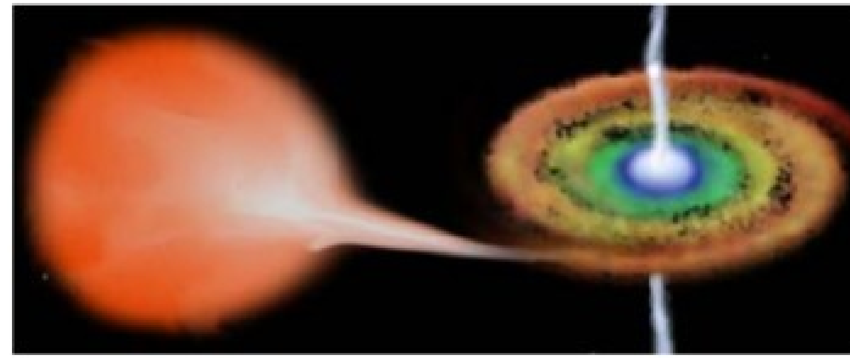
Very likely accompanied by GW emission

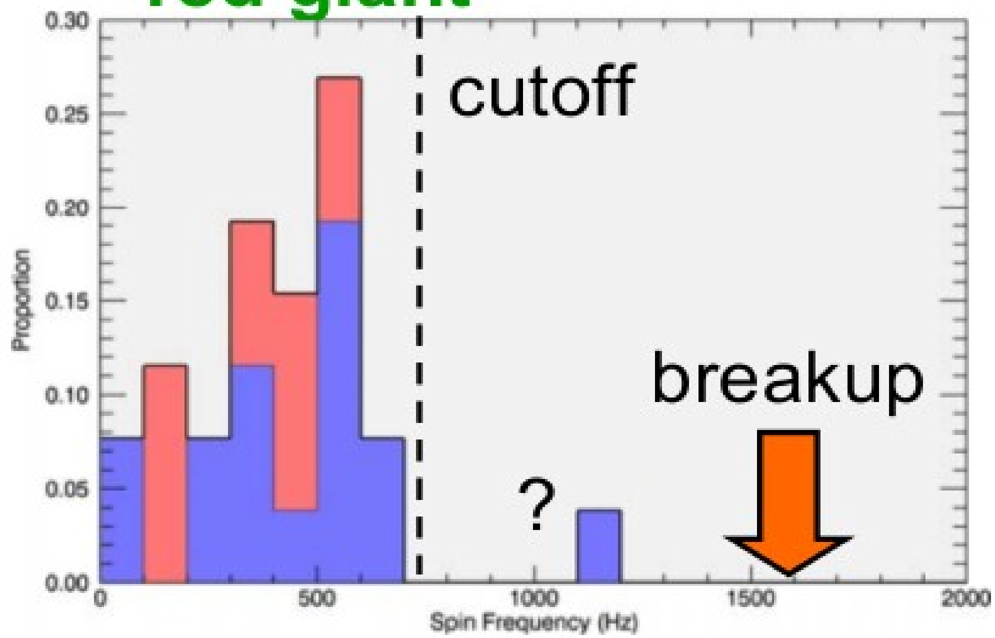
ET will be able to detect GWs and possibly find the glitch mechanism.



Accreting Neutron Stars

- Spin frequencies of accreting NS seems to be stalled below 700 Hz
  - Well below the break-up speed
- What could be the reason for this stall?
  - Balance of accretion torque with GW back reaction torque
- Could be explained if ellipticity is ~ 10^{-8}
  - Could be induced by mountains or relativistic instabilities, e.g. r-modes





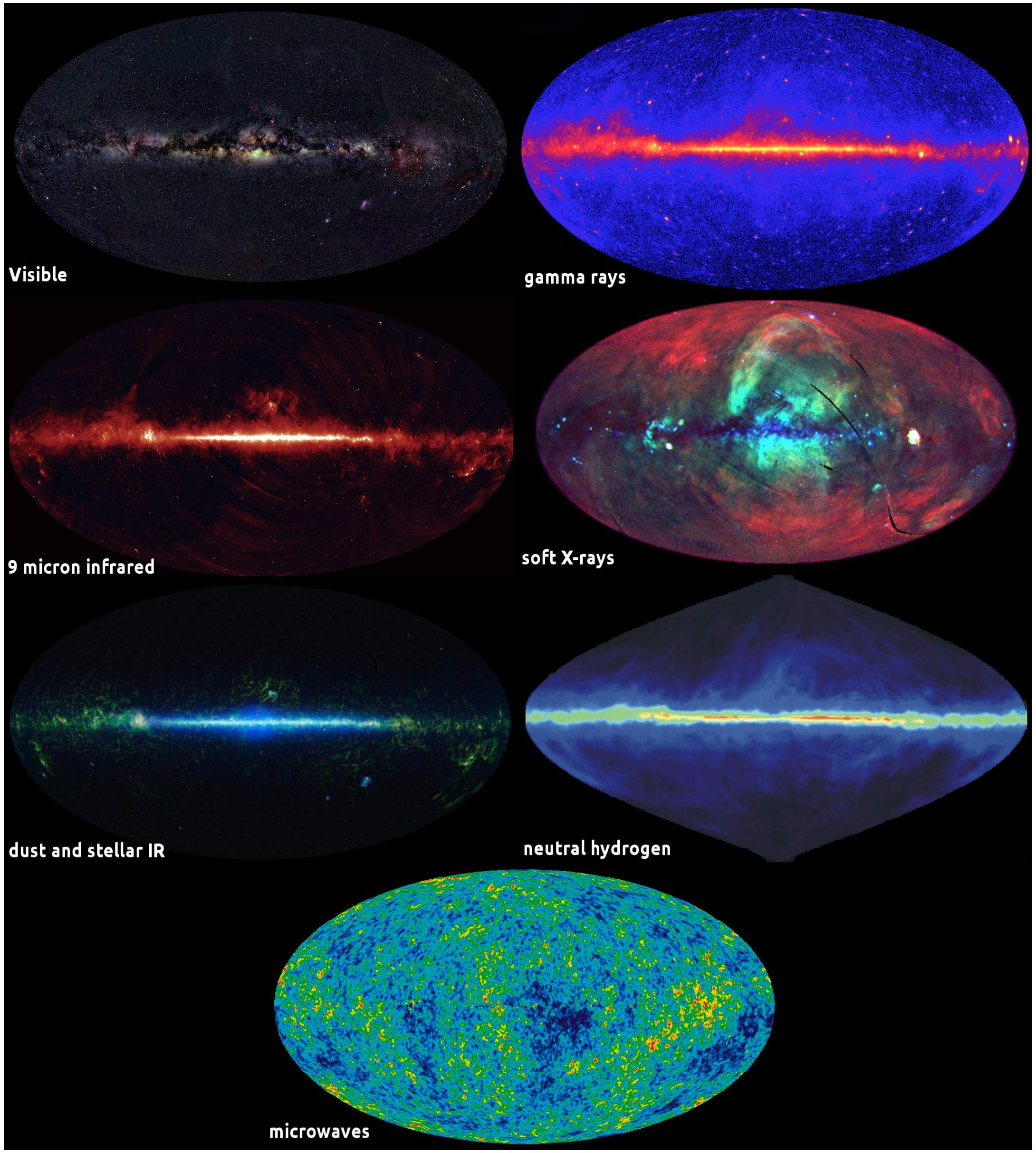
pulses & burst oscillations

Pulsar collective background

The signal from the ensemble of NS in the Milky Way will for a background

The shape and spectrum of the background is a product of interplay of the NS evolution, period decay, asymmetry evolution, and spatial distribution.

The measurement of the background will constrain NS evolution beyond the radio death line.

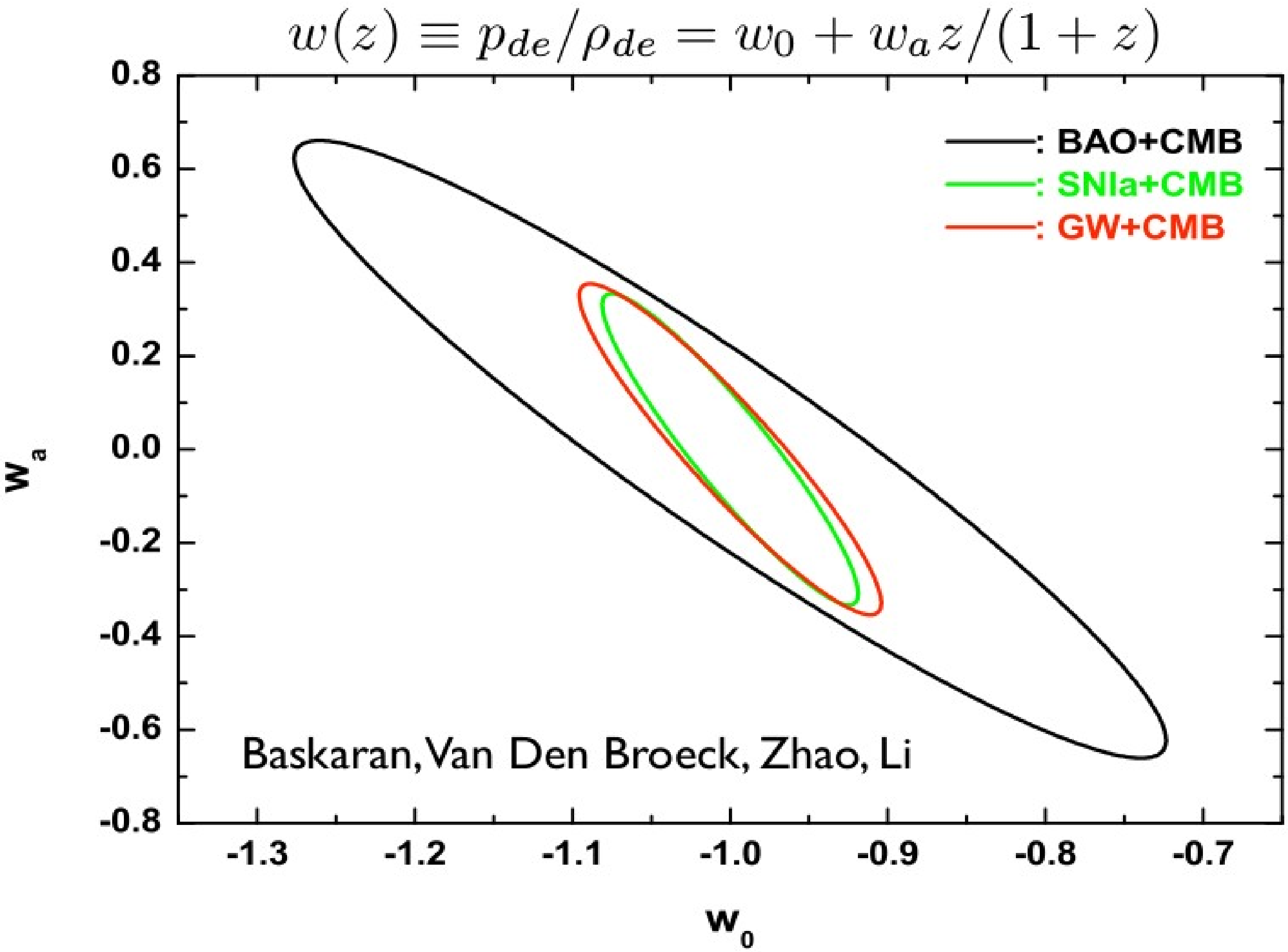


Cosmology

- Cosmography – tracing the evolution of cosmic expansion
- Anisotropy of the Hubble expansion
- Primordial gravitational waves
- Emission of GWs during phase transitions in the early Universe

Cosmology

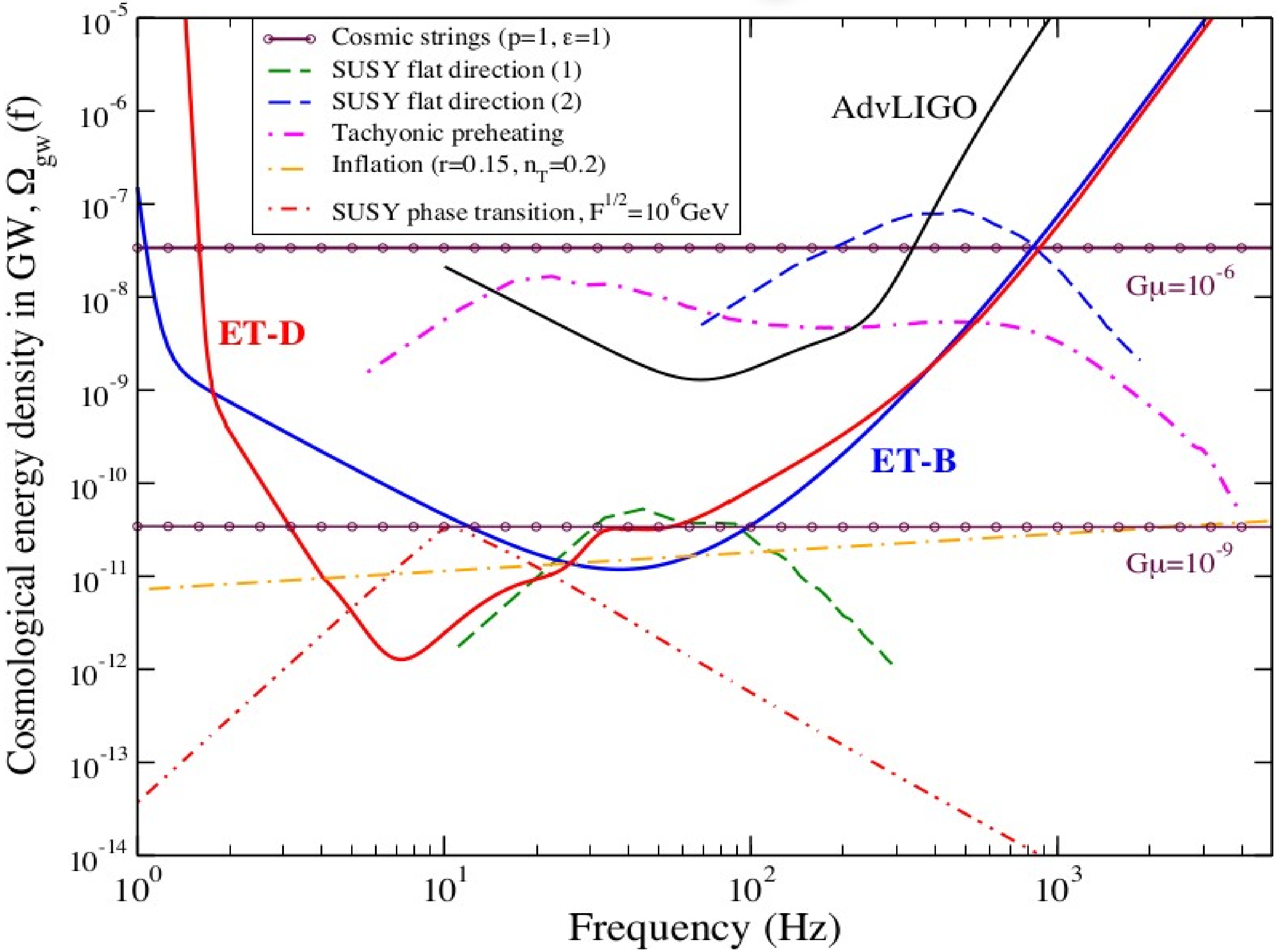
An example of w(z) possible mesasurment with ET:



Backgrounds

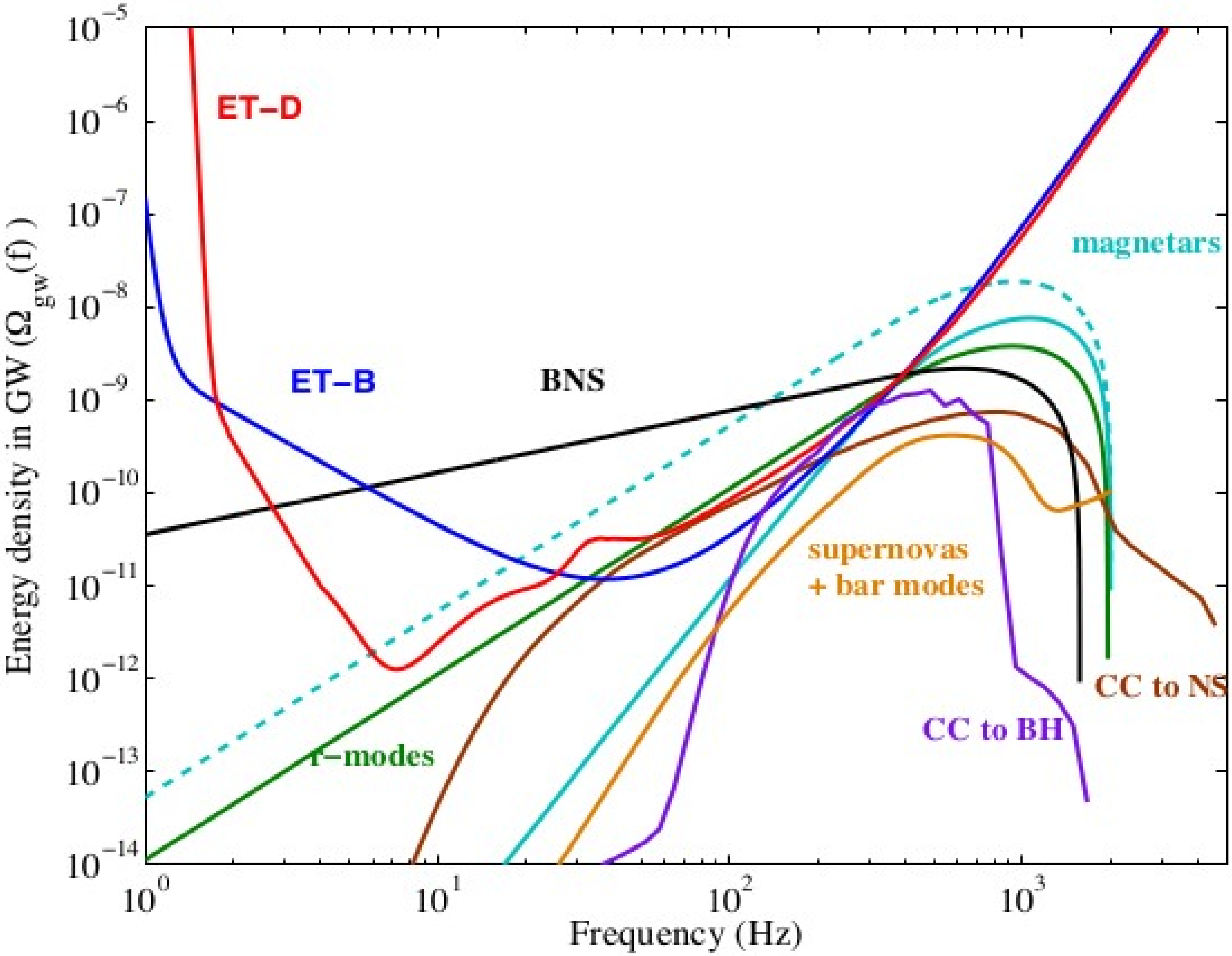
- Stochastic backgrounds can be detected by correlating signals from independent interferometers
- Compact object background
- Primordial background from the early Universe.

Primordial backgrounds



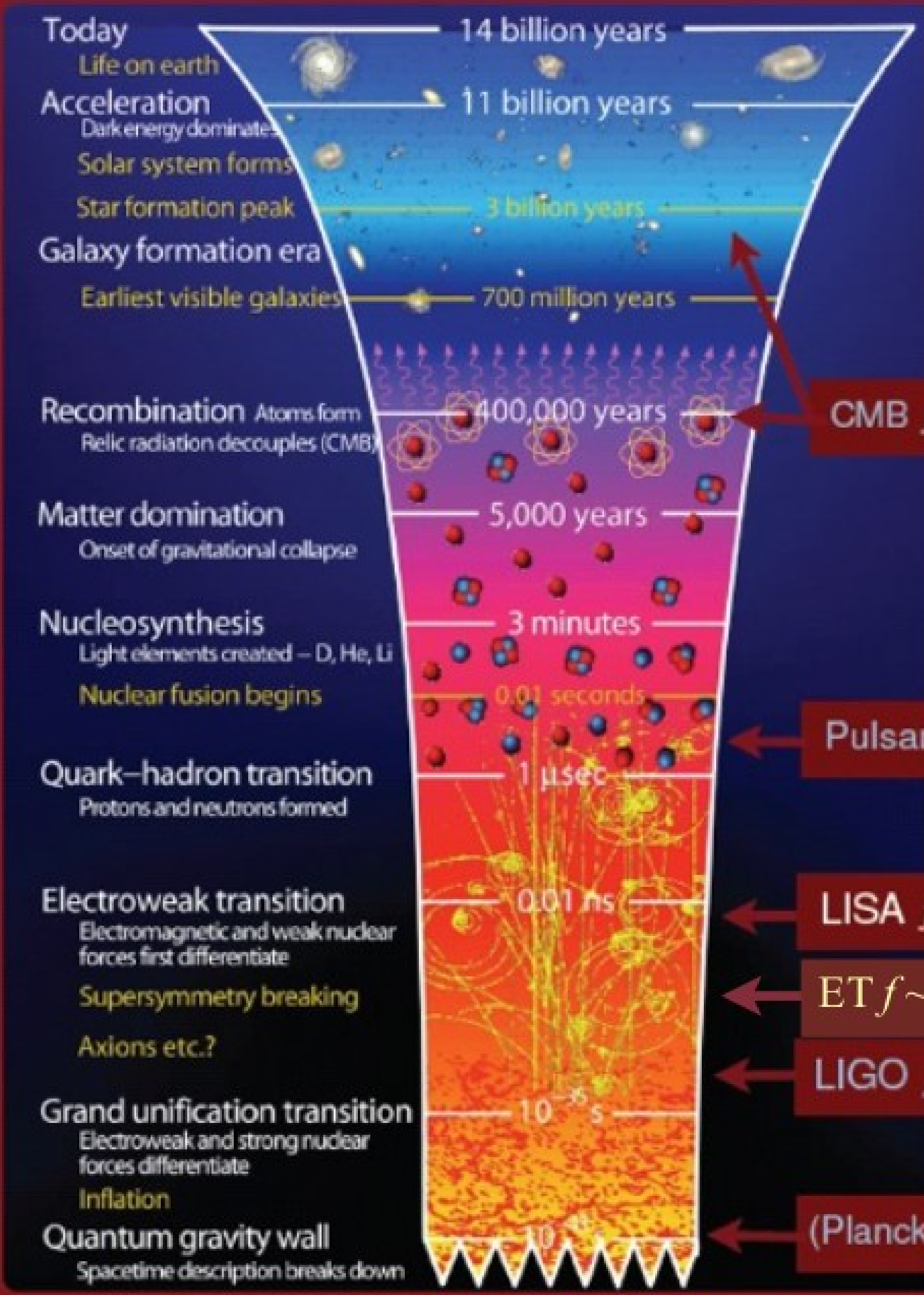
Insight into the phase transitions at the early Universe, however need to subtract the foreground!

Astronomical foregrounds



Slide from Shellard

A brief history of the Universe



CMB $f < 3 \times 10^{-17} h$ Hz probes $300{,}000$yrs $< t_e < 14$ Gyrs

Pulsars $f \sim 10^{-8}$Hz probe $t_e \sim 10^{-4}$s ($T \sim 50$MeV)

LISA $f \sim 10^{-3}$Hz probes $t_e \sim 10^{-14}$s ($T \sim 10$TeV)

ET $f \sim 10$ Hz probes $t_e \sim 10^{-20}$ s ($T \sim 10^6$ GeV)

LIGO $f \sim 100$ Hz probes $t_e \sim 10^{-24}$s ($T \sim 10^8$GeV)

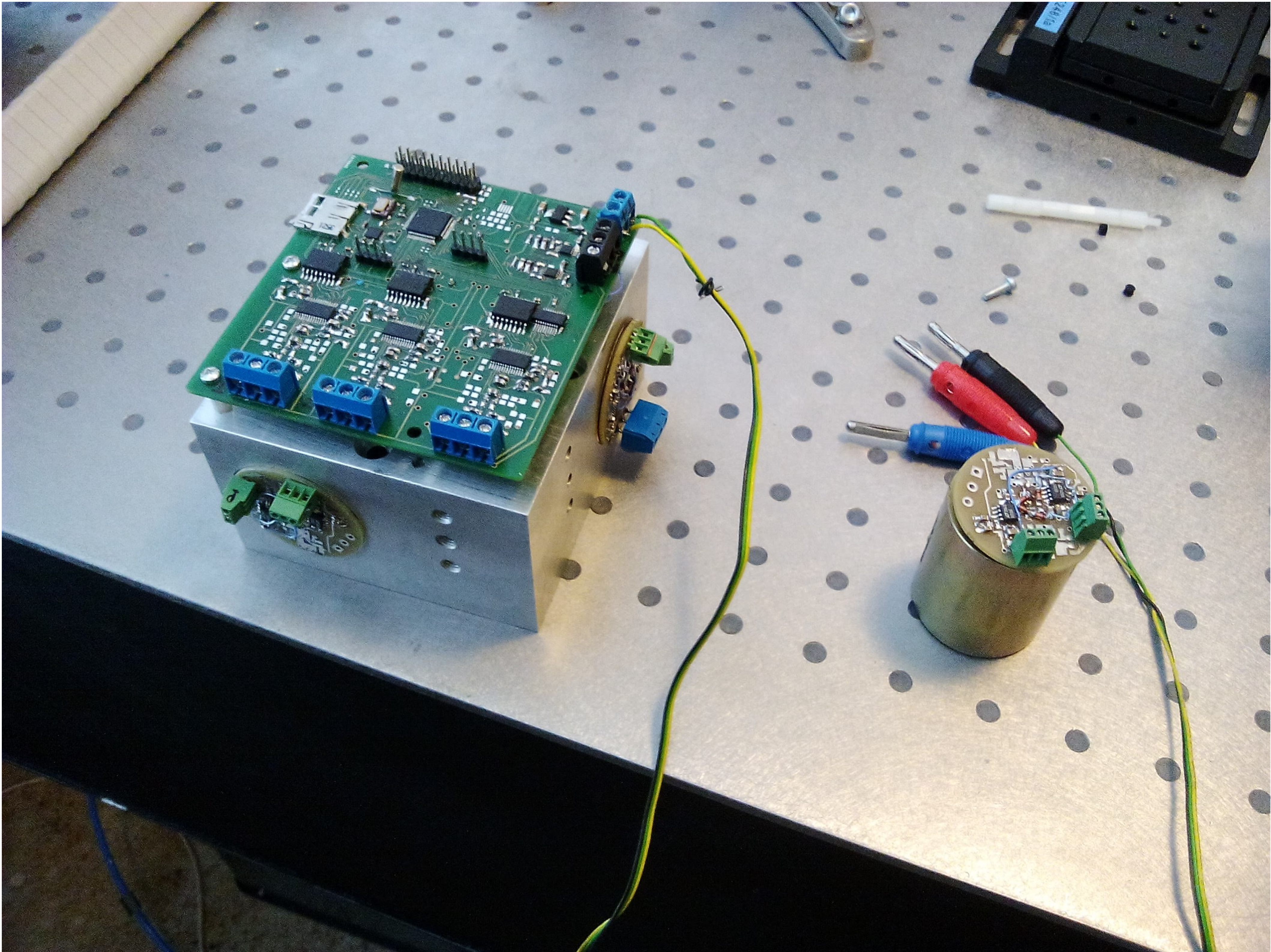
(Planck scale $f \sim 10^{11}$Hz has $t_e \sim 10^{-43}$s ($T \sim 10^{19}$GeV)

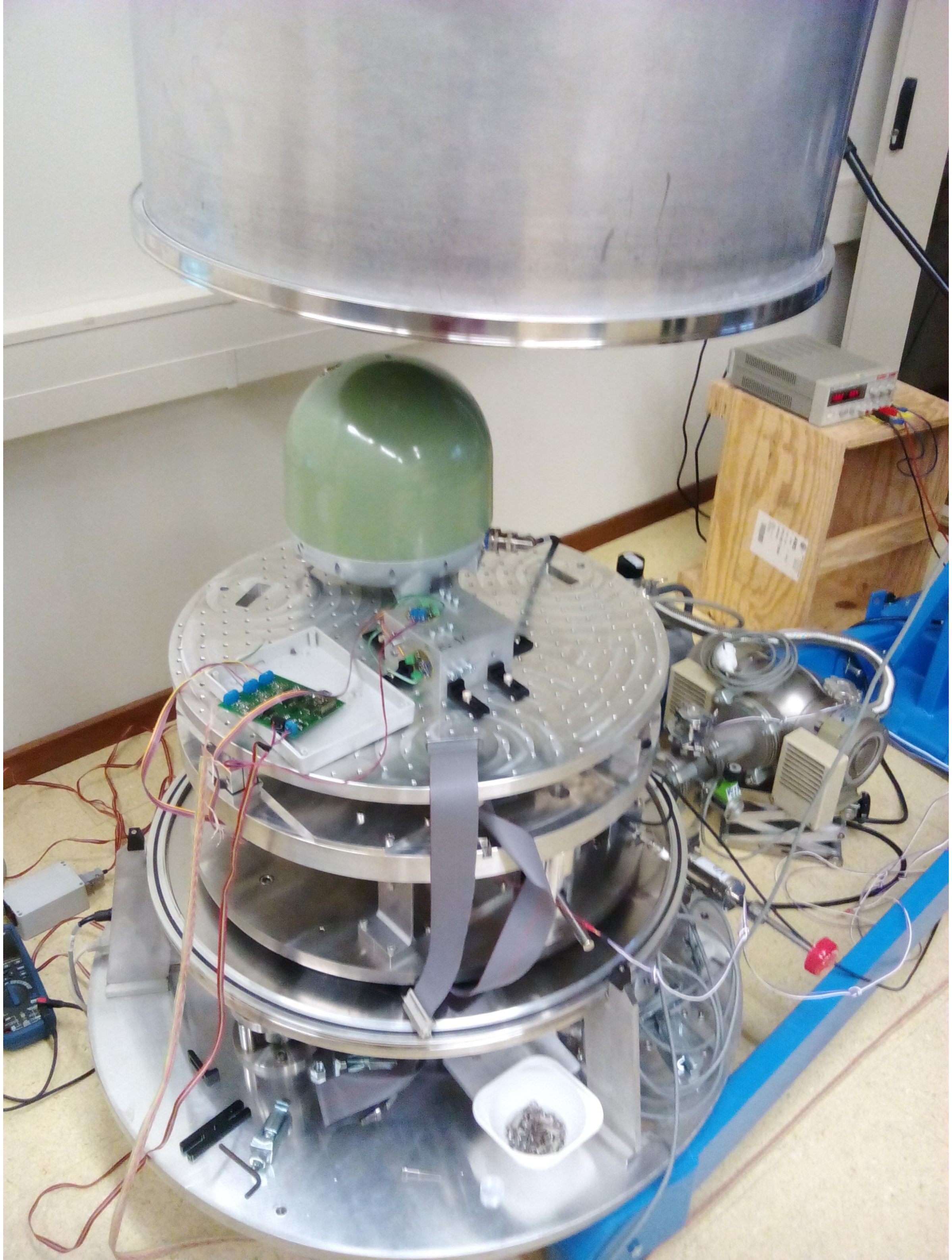
Summary

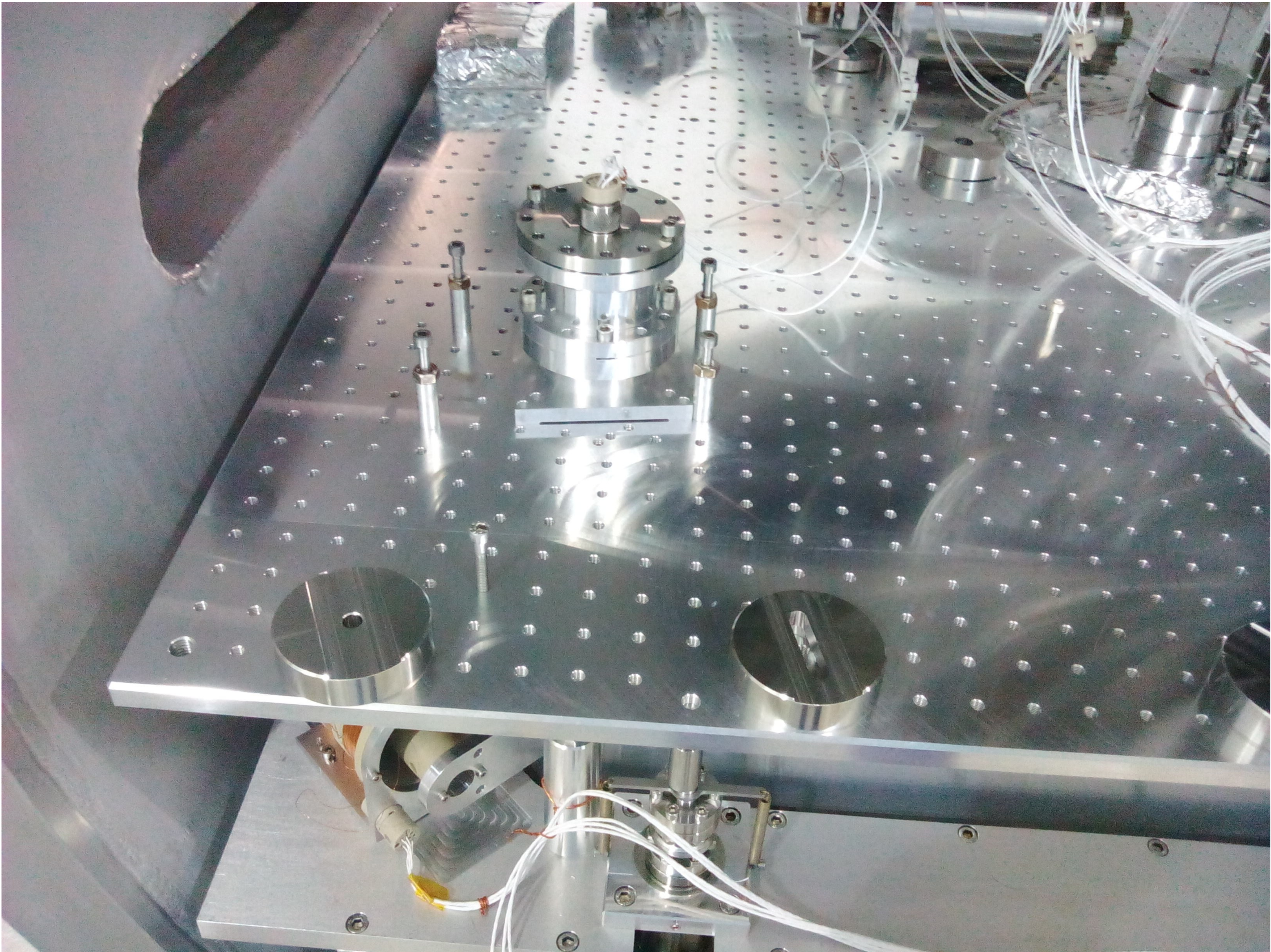
- Astrophysics:
  - The mechanism of SN
  - The origin and mechanism of gamma ray bursts
  - Formation history of compact objects: BH and NS
- Fundamental physics:
  - The nature of gravitational waves?
  - Is GR the correct theory of gravity
  - Are black holes hairy?
- Cosmology:
  - Is the Universe anisotropic?
  - What was the evolution of cosmic expansion?
  - What is the nature of dark energy?
  - What phase transitions took place in the early Universe?

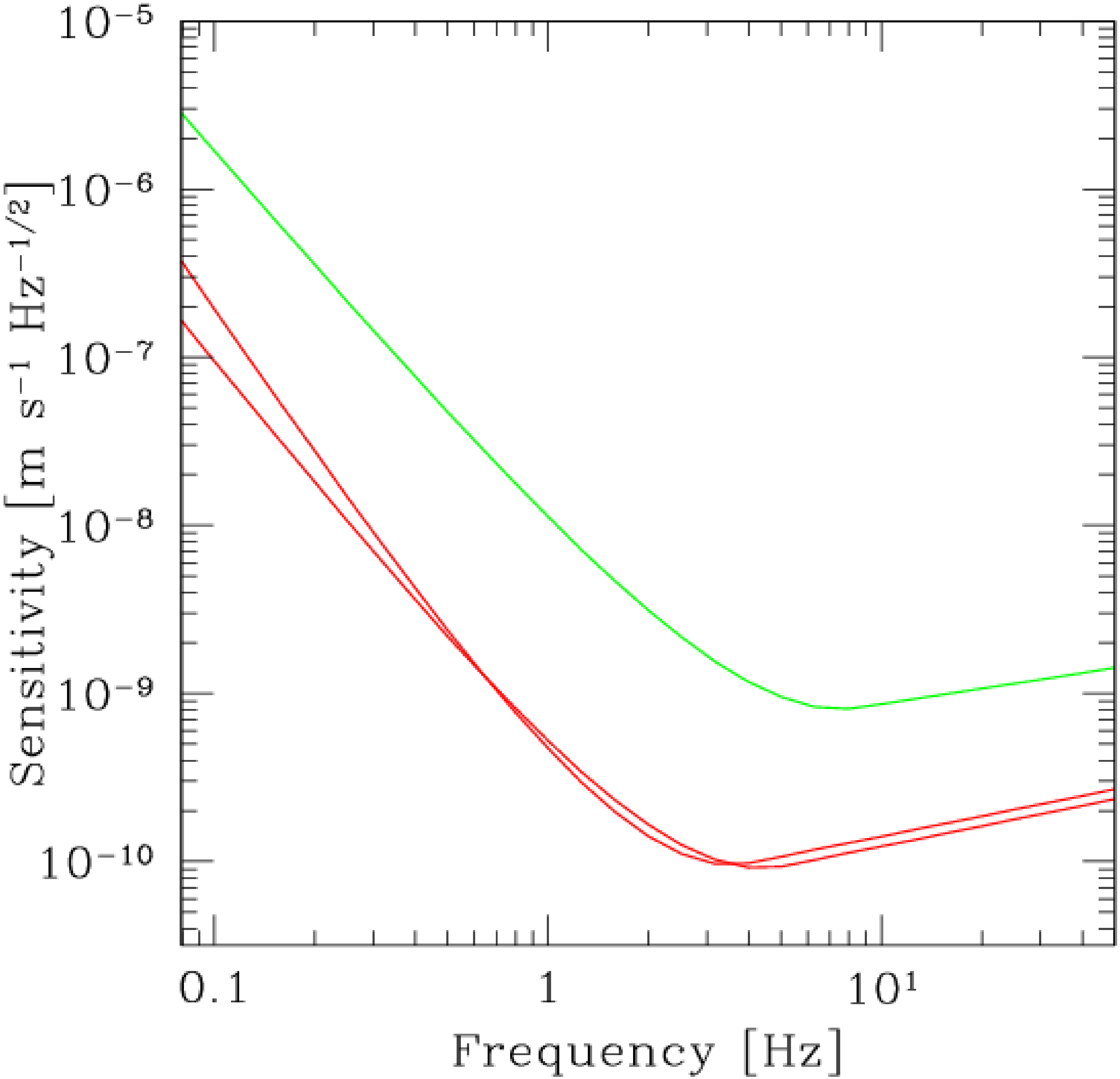
Polish ET Consortium

- UW (Coordinator), PW, UZG, UwB, CAMK, IMPAN, UŚ
- Theory
- Design and construction of seismometers, site characterization
- Investigation of possible sites in around Europe including Poland









Sensitivity [m s^{-1} Hz$^{-1/2}$]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10^{1}
Frequency [Hz]

For more information see the ET Design Study Document

http://www.et-gw.eu/etdsdocument