Michele Punturo – INFN Perugia and EGO

ET: The Einstein Telescope Design Study

ET currently is

- **ET is a “design study” supported by the European Commission under the Framework Programme 7 (FP7)**
- It is a ~3 years project supported by EC with about 3 M€
- It is started in May 2008 and will end in 2011

ET involves:

- ET design study team is composed by all the major groups leading the experimental Gravitational wave search in Europe:

Participant no.	Participant organization name	Country
1	European Gravitational Observatory	Italy-France
2	Istituto Nazionale di Fisica Nucleare	Italy
3	Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V., acting through Max-Planck-Institut für Gravitationsphysik	Germany
4	Centre National de la Recherche Scientifique	France
5	University of Birmingham	United Kingdom
6	University of Glasgow	United Kingdom
7	NIKHEF	The Netherlands
8	Cardiff University	United Kingdom

ET design study targets

- The ET design study aim is to deliver, at the end of the 3 years, a conceptual design study of a 3rd generation gravitational wave (GW) observatory:
  - Science potentialities
  - New site
  - New infrastructures
  - New detection and analysis technologies

ET EINSTEIN TELESCOPE

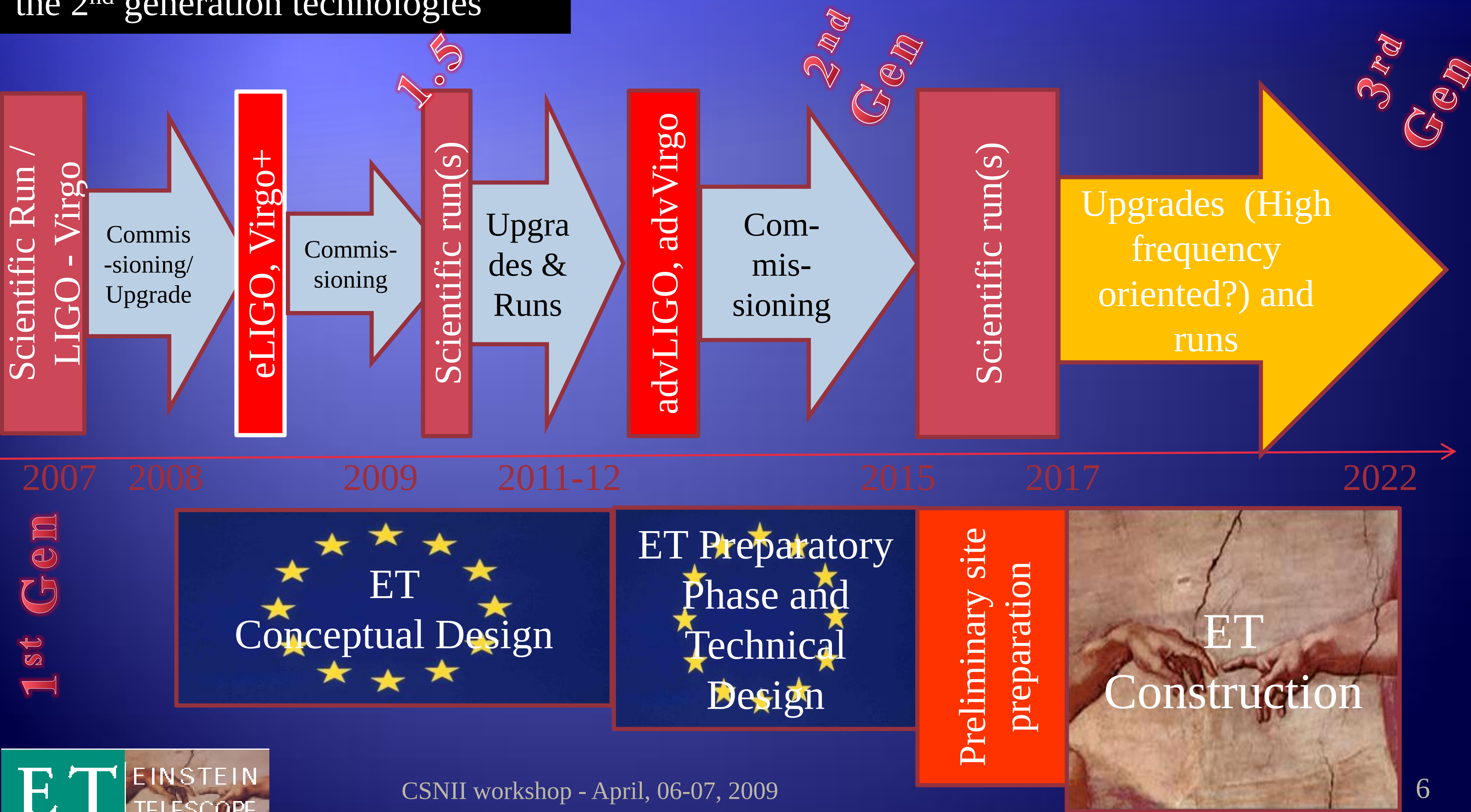
GW detectors evolution path

- To understand the role and the interest about the ET physics , we should have a look to the evolution path of the GW detectors
  - First generation GW detectors reached a major cornerstone of their data taking activity with the joint LIGO-GEO-Virgo run (S5/VSR1) in 2007
  - Subsequently, beside an astro-watch activity, to monitor possible but improbable close events, an intense and worldwide agreed evolution path has been started,
    - upgrading the Virgo and LIGO machines to a 1.5 generation level (Virgo+, GEO-HF and eLIGO)
    - preparing the 2nd generation step with the advanced Virgo and advanced LIGO programmes (see tomorrow presentation at the Virgo site)

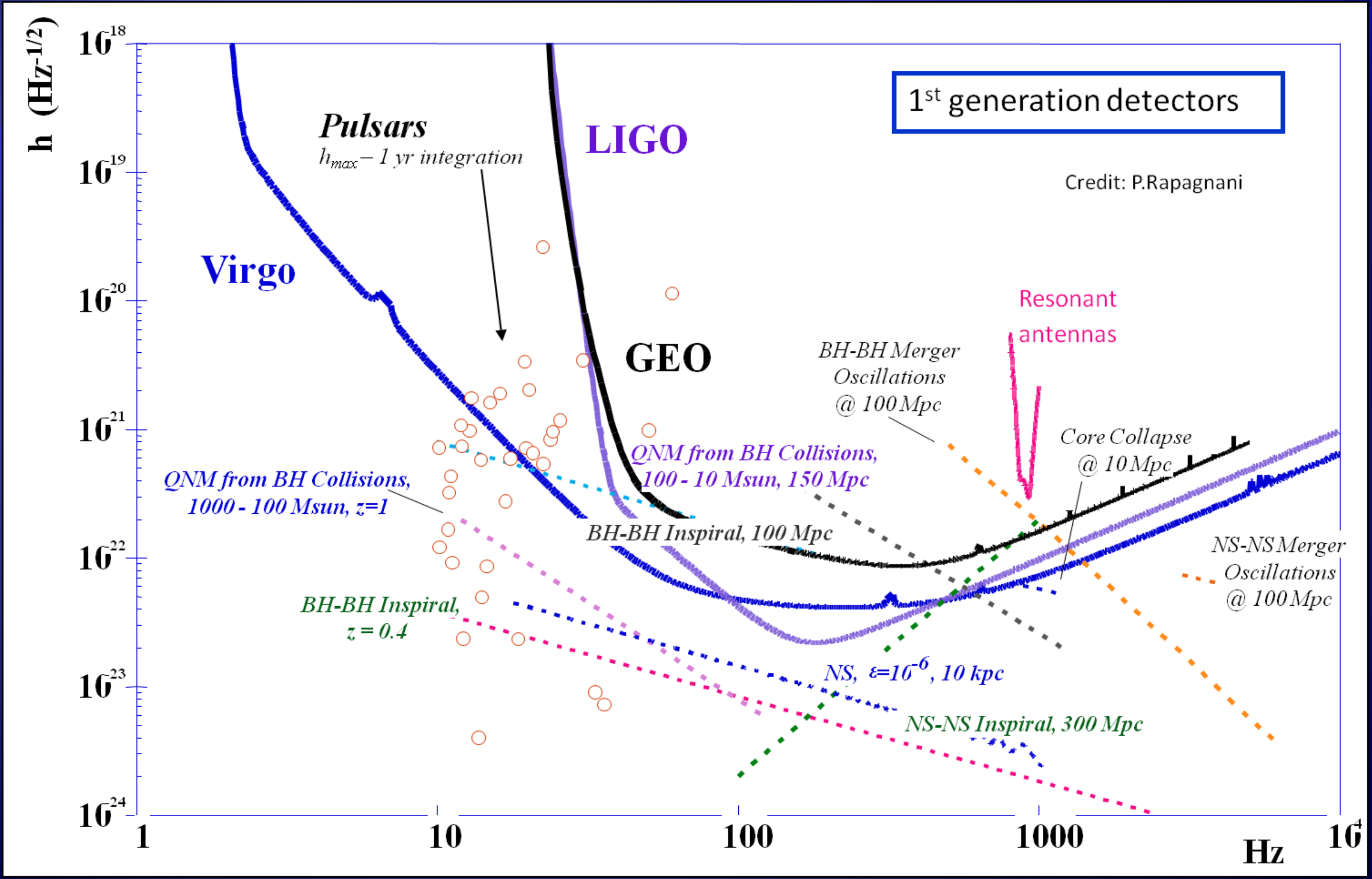
… GW detectors evolution path

Same Infrastructures, improvements of the current technologies, some prototyping of the 2nd generation technologies

Same Infrastructures, engineering of new technologies developed by currently advanced R&D

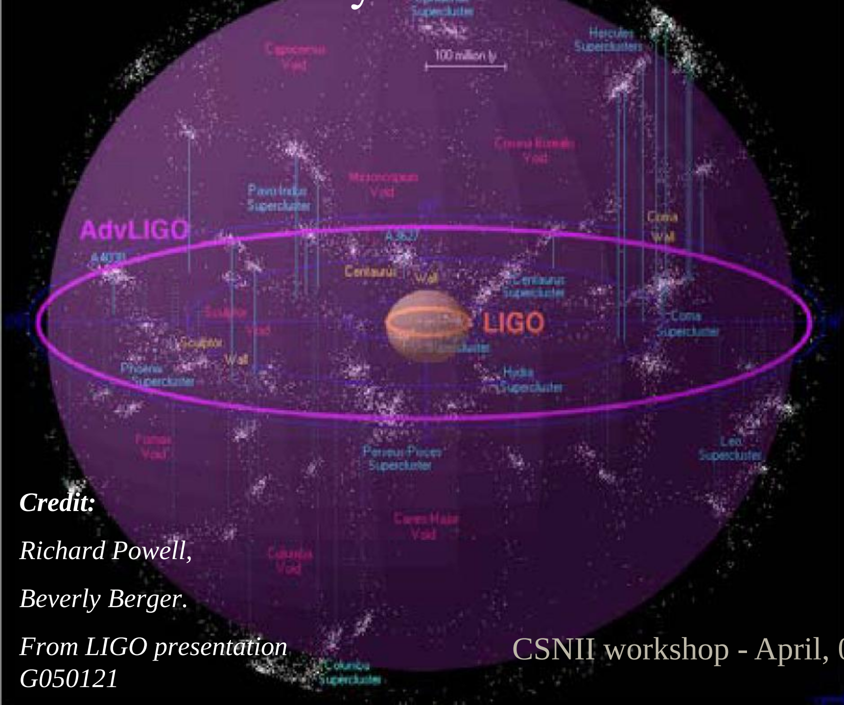


1^{st} generation GW detector nominal sensitivities



Our “standard siren”: Coalescing neutron stars

- The most important source of GW for current and advanced GW detectors are the binary systems of coalescing neutron stars (BNS):
  - Possibility to model the signal in an semi-analytical way
  - Confirmation of the existence of this kind of systems thanks to the “special” pairs where one of the two stars is a pulsar
  - Possibility to “evaluate” the coalescing rate

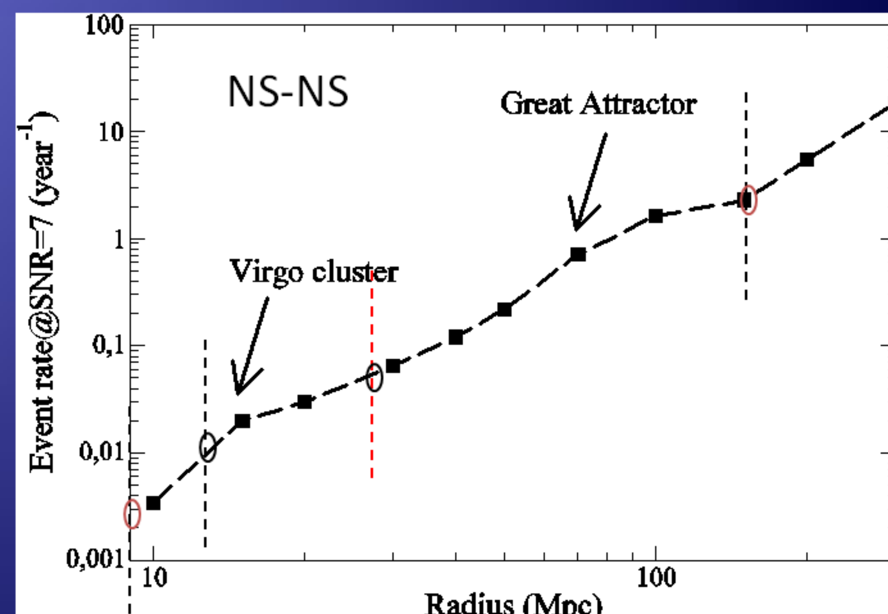


Credit:

Richard Powell,

Beverly Berger.

From LIGO presentation G050121



Binary Systems (BS) in adVirgo

- The detection rates (from VIR-089A-08) with advanced Virgo are reported in the following tables
  - Considering a network of similar and well aligned detectors and a coherent analysis that rates could be increased by about a sqrt(n) factor

model	merger rate ($Myr^{-1}MWEG^{-1}$)	detection rate (yr^{-1})	comments
empirical	3 - 190	0.4 - 26	empirical model
A	12 - 19	1.6 - 2.6	reference model
B	7.6 - 12	1 - 1.6	full CE accretion
C	68 - 101	9.2 - 14	CE for HG stars

Table 4: Expected rate of BNS events for Advanced Virgo, in the different empirical and theoretical scenarios for the coalescence rates.

Model	$\mathcal{M}/M_{\odot}$ range	$d_{eff-sight}$Mpc	merger rates Myr^{-1}	AdV detection rate yr^{-1}
A	$2.5-3$	300	$0.07-0.11$	$0.08-0.12$
C	$1.5-4$	286	$3.2-4.8$	$3.1-4.7$

Table 5: BH-NS results from population synthesis models

Model	$\mathcal{M}/M_{\odot}$ range	$d_{eff-sight}$Mpc	merger rates Myr^{-1}	AdV detection rate yr^{-1}
A	$5-8$	613	$0.02-0.03$	$0.2-0.3$
C	$2.5-8.5$	545	$7.7-11$	$52-75$

Table 6: BBH results based on population synthesis models

What ET adds to the BS physics

- Advanced detectors will be able to determine BNS rates in the local Universe
  - “Routine” detections at low to medium SNR
  - But high precision fundamental physics, astrophysics and cosmology may not be possible
    - would require good quality high-SNR events
- ET sensitivity target aims to decrease the noise level of about one order of magnitude in the full 1-10000Hz range
- It will permit to access a larger amount of information embedded in the BS (BNS, BH-NS, BH-BH) chirp signal
  - Higher harmonics
  - Merging phase

Credits: B. Sathyaprakash

…What ET adds to the BS physics

- A coalescing binary emits most of its GW radiation at twice of the orbital frequency
- Current (an partially advanced) interferometers, basing the detection upon the matched filtering technique, far more sensitive to phasing than amplitude modulation, privilege the correct phase reconstruction of the signal (PN approximations) rather than the amplitude modulation
- PN approximation is currently known to 3.5 PN in phase and 3 PN in amplitude and up to eight harmonics of the orbital frequency

$$h(t) = \frac{2M\eta}{D_{\mathrm{L}}} \underbrace{\sum_{k=1}^{7}}_{\text{Harmonics}} \underbrace{\sum_{n=0}^{5}}_{\text{PN corrections}} A_{(k,n/2)} \cos\left[k\Psi(t) + \phi_{(k,\,n/2)}\right] x^{\frac{n}{2}+1}(t)$$

$M = m_1 + m_2,$

total mass

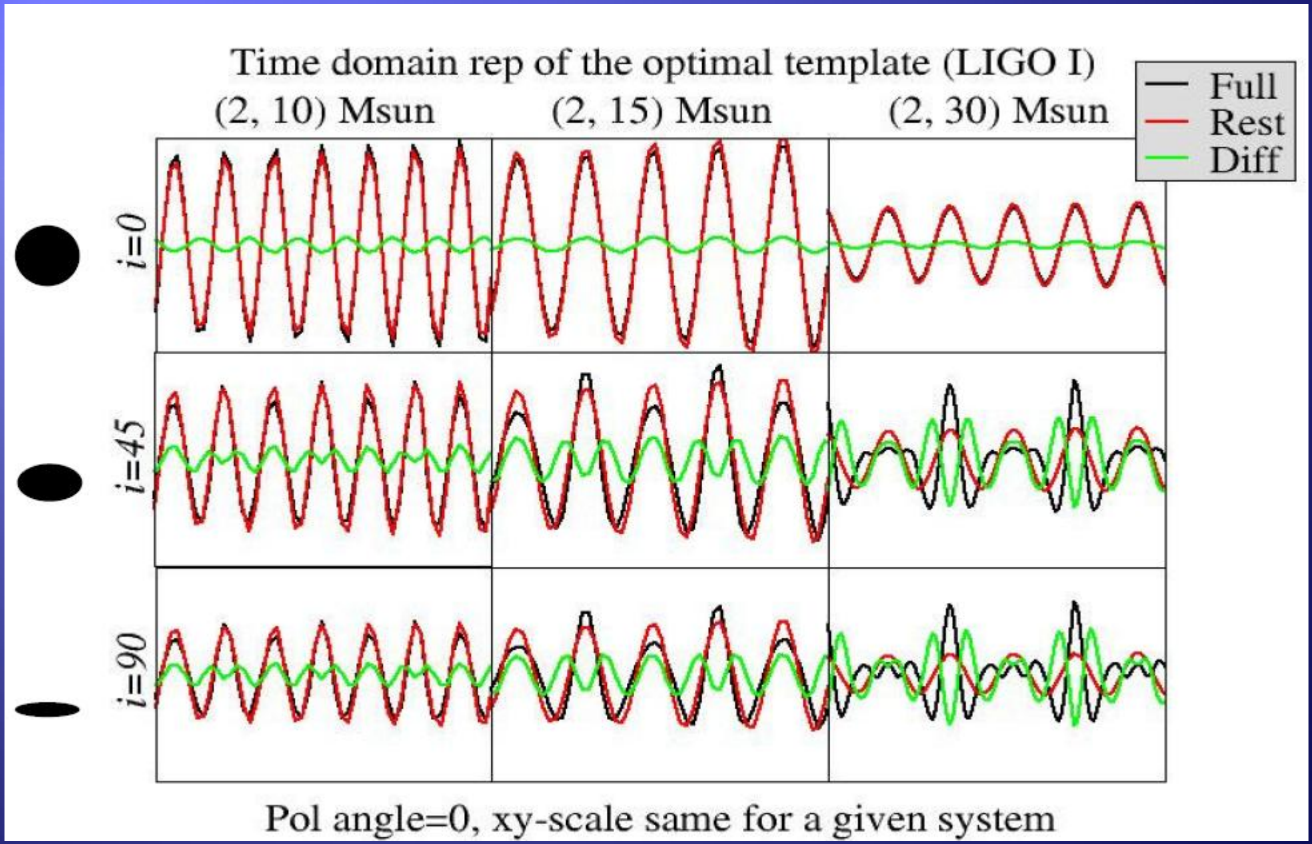
$\eta = \frac{m_1 m_2}{M^2}$

symm. mass ratio

- The so-called restricted waveform uses only the dominant harmonic
- The full waveform includes radiation emitted at other frequencies
  - These higher harmonics are due to higher multipole moments associated with the source

Higher harmonics role

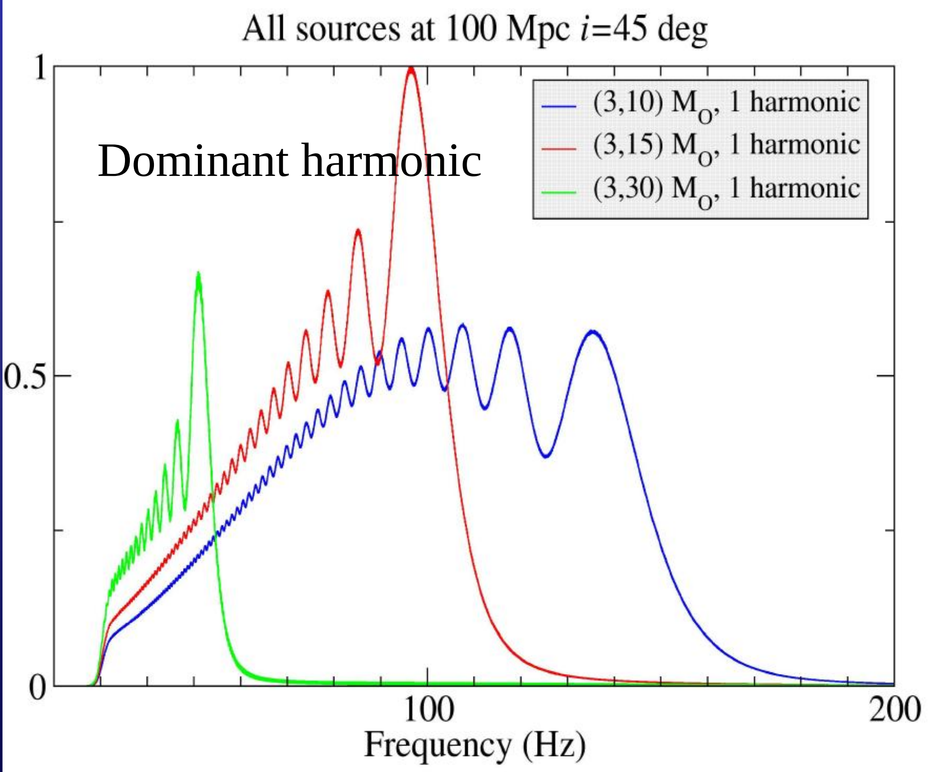
- Higher harmonics could have an important role depending on the masses, mass asymmetry and the inclination angle

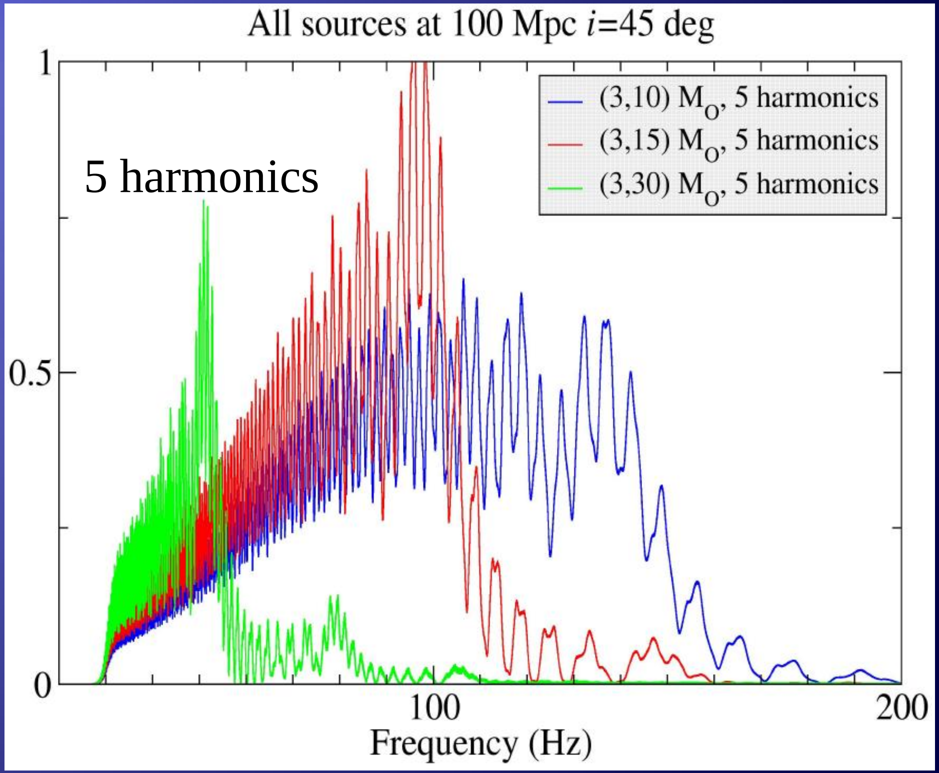


McKechan et al (2008)

Higher harmonics effects

- The first consequence of the higher harmonics is a richer spectrum of the signal detected by the ITF

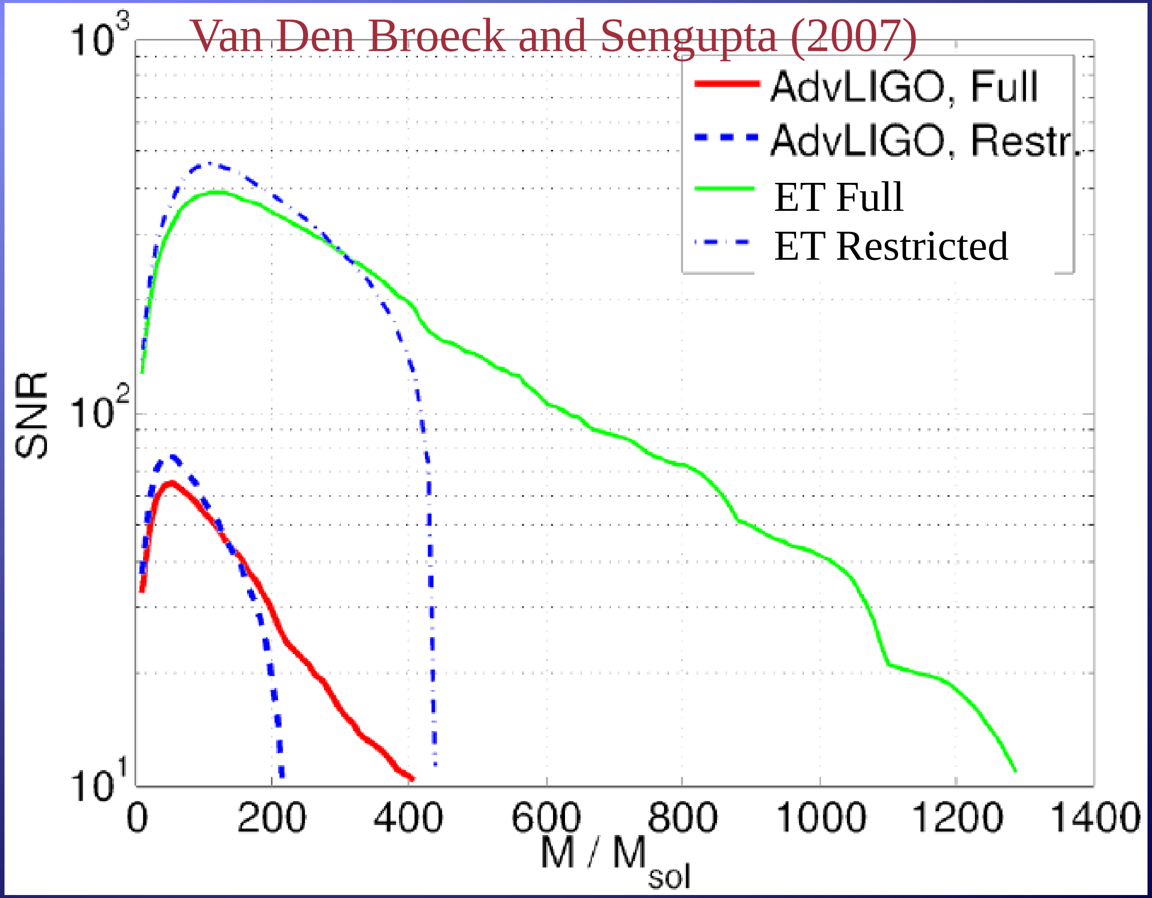




McKechan et al (2008)
Plots referred to LIGO I

… Higher harmonics effects

- Higher harmonics do not greatly increase overall power, but move power toward higher frequencies, which can make higher-mass systems detectable even if quadrupole signal is outside the observing band
  - BBH improved identification



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… Higher harmonics effects

- Harmonics do increase structure, greatly enhance parameter determination, by breaking degeneracy between parameters

- Antenna response is a linear combination of the two polarizations: $$h(t) = A_+ H_+ + A_\times H_\times$$
- H_+ and $H_\times$ contain the "physics of the source" (masses and spins) and time and phase at coalescence
- $A_+(\alpha, \delta, \psi, D_L, i)$ and $A_\times(\alpha, \delta, \psi, D_L, i)$ contain the "geometry of the source-detector system"
  - Right ascension
  - Declination
  - Polarization angle
  - Luminosity distance
  - Orientation of the binary wrt the line of sight

Credits: B.Sathyaprakash

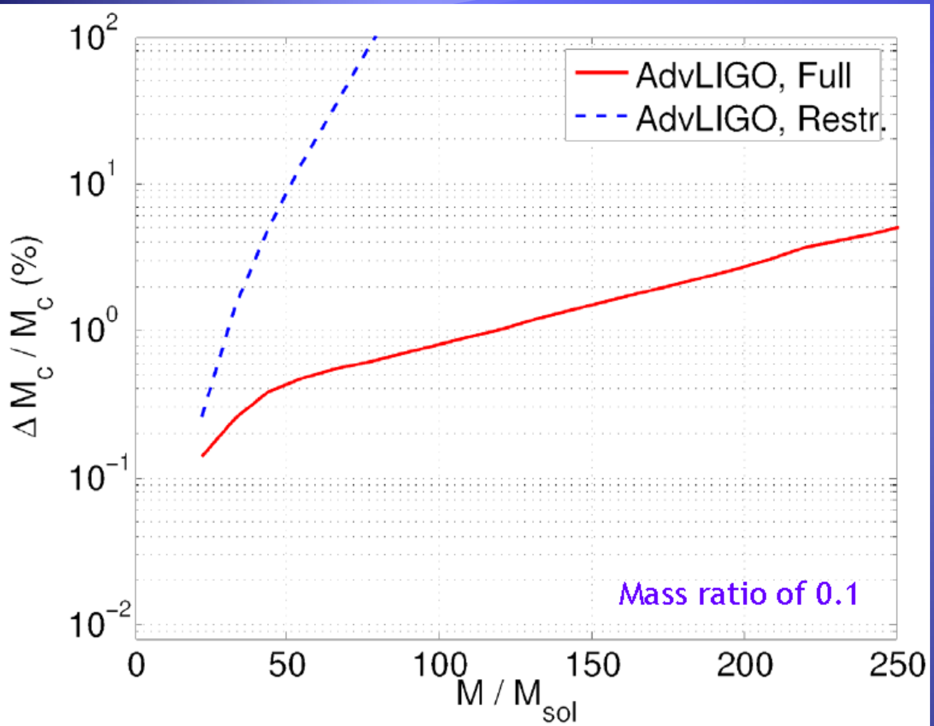
…Higher harmonics effects

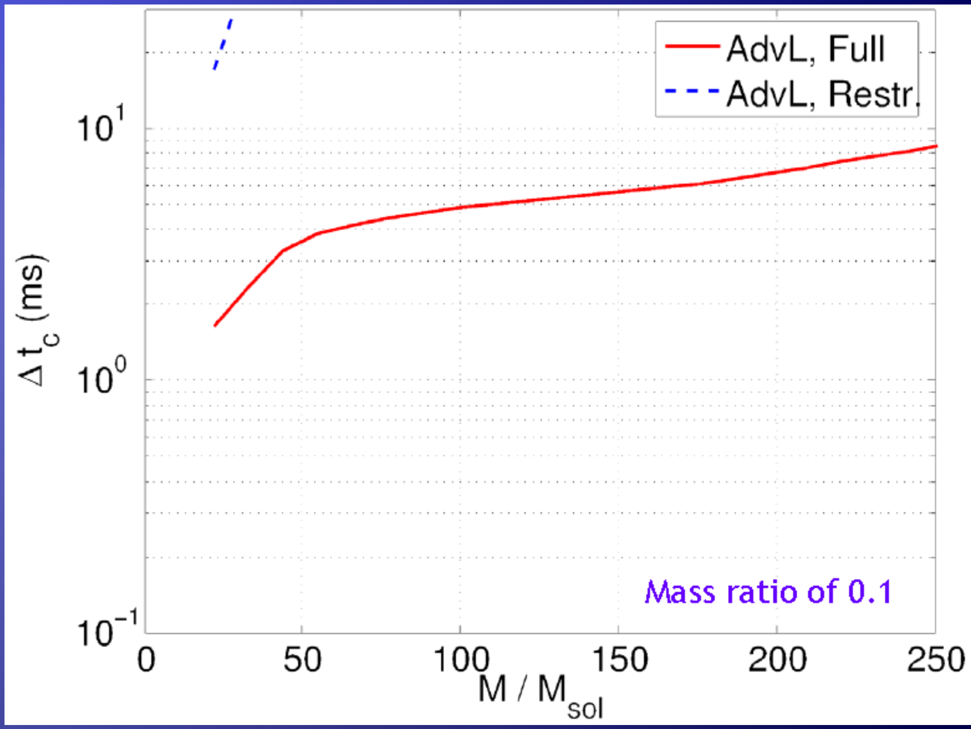
- To fully reconstruct the wave one would need to make five measurements: $(\alpha, \delta, \psi, D_L, i)$
- Restricted PN approximation can only measure the random phase of the signal at the coalescing time
  - To fully determine a source are needed
    - either 5 co-located detectors ("a la sphere")
    - or 3 distant detectors (3 amplitudes, 2 time delays)
- Detecting the harmonics one can measure the random phase of the signal with one harmonic, orientation of the binary with another and the ratio $A_+/A_\times$ with the third
- Two detectors at the same site in principle allow the measurement of two amplitudes, the polarization, inclination angle and the ratio $A_+/A_\times$ – the source can be fully resolved
- In practice, because of the limited accuracy, two ET observatories could fully resolve source:
  - 4 amplitudes from two sites, one time delay

Credits: B.Sathyaprakash

…Higher harmonics effects

- Better determination of the parameters of the source: Mass and arrival time

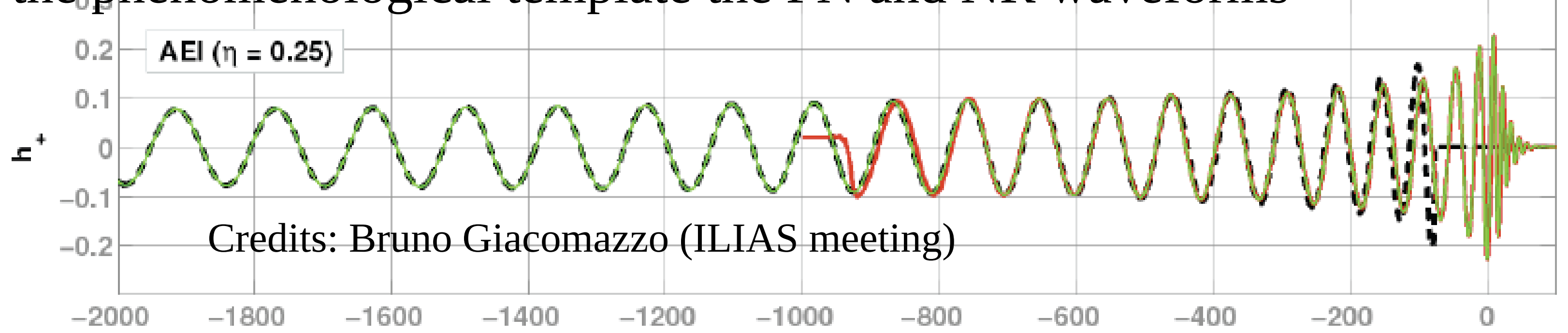




Van Den Broeck and Sengupta (2007)

Learning more from the coalescence

- In principle, the correct way to model the merging of a black holes binary is to fully use the General Relativity (GR)
  - Unable to analytically solve the Einstein Field Equation:
    - Use of the Numerical Relativity (NR)
- There is no fundamental obstacle to long-term (i.e. covering ~10+ orbits) NR calculations of the three stages of the binary evolution: inspiral, merger and ringdown
- But NR simulations are computationally expensive and building a template bank out of them is prohibitive
- Far from the merging phase it is still possible to use post-Newtonian approximation
- Hybrid templates could be realized and carefully tested with ET overlapping in the phenomenological template the PN and NR waveforms



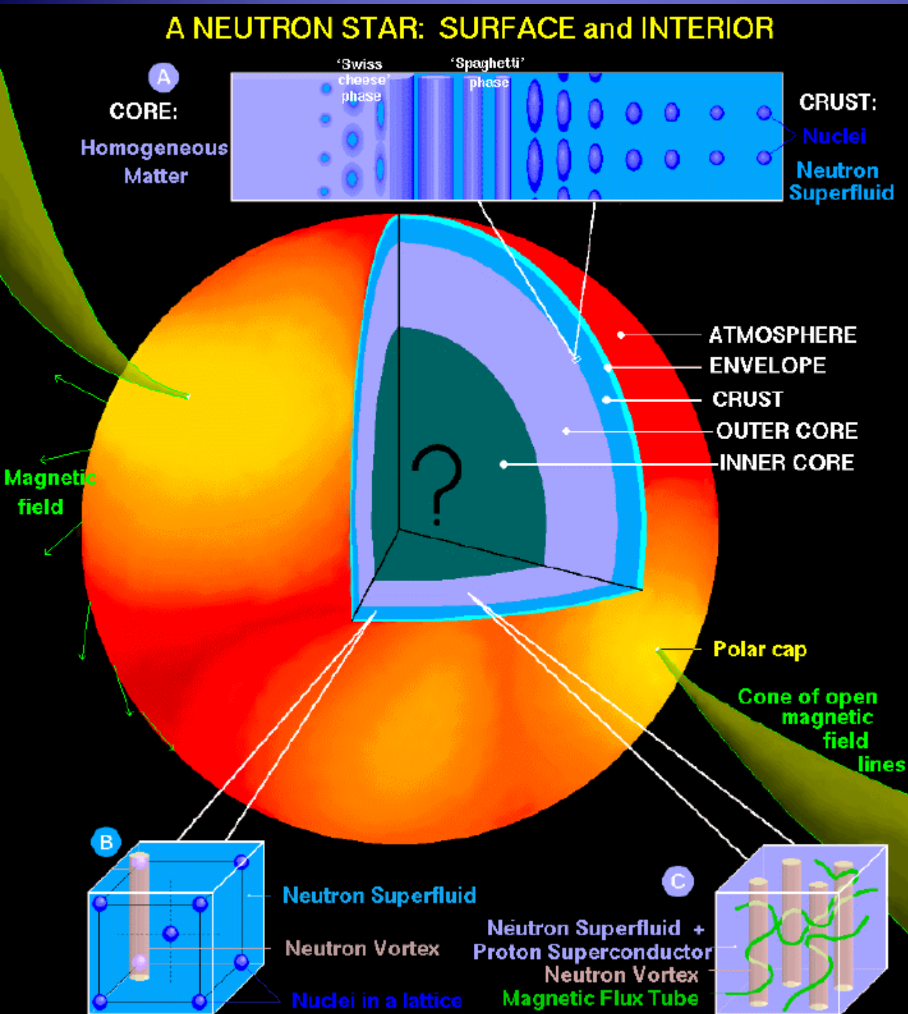
Credits: Bruno Giacomazzo (ILIAS meeting)

Red – NR waveform
Black – PN 3.5 waveform
Green – phenomenological template

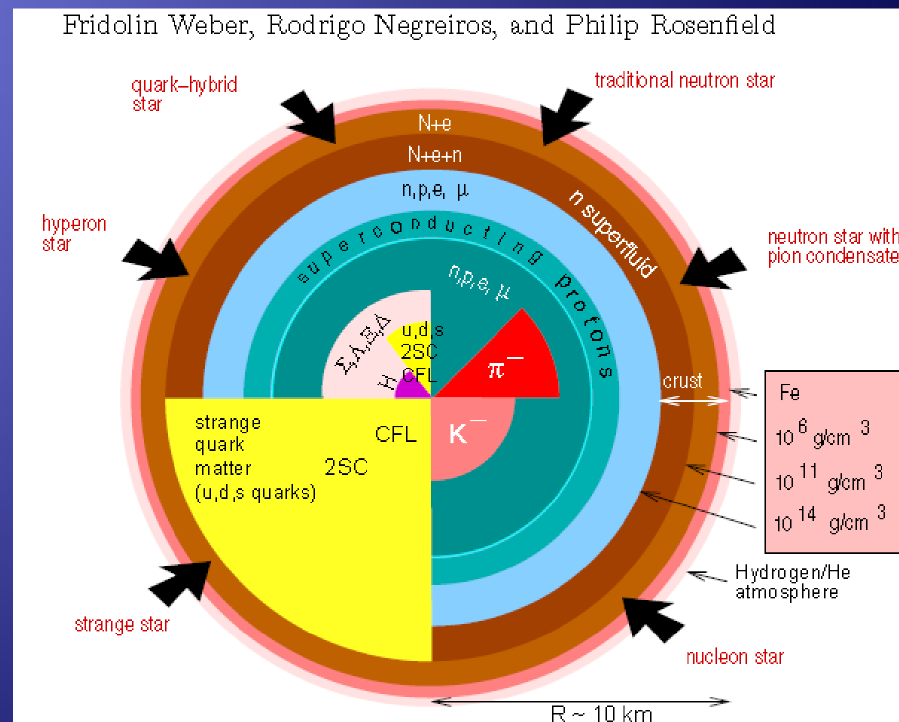
… Learning more from the coalescence

- The late coalescence and the merging phase contain information about the GR models
  - Test it through ET will permit to verify the NR modeling
- This is true also for the NS-NS coalescence where the merging phase contains tidal deformation modeling and could constrain, through numerical simulations, of the Equation Of State (EOS)

Neutron Stars



- EOS of the NS is still unknown
  - Why it pulses?
  - Is it really a NS or the core is made by strange matter?
- Like in the "ordinary" stars, asteroseismology could help to understand the composition of the NS

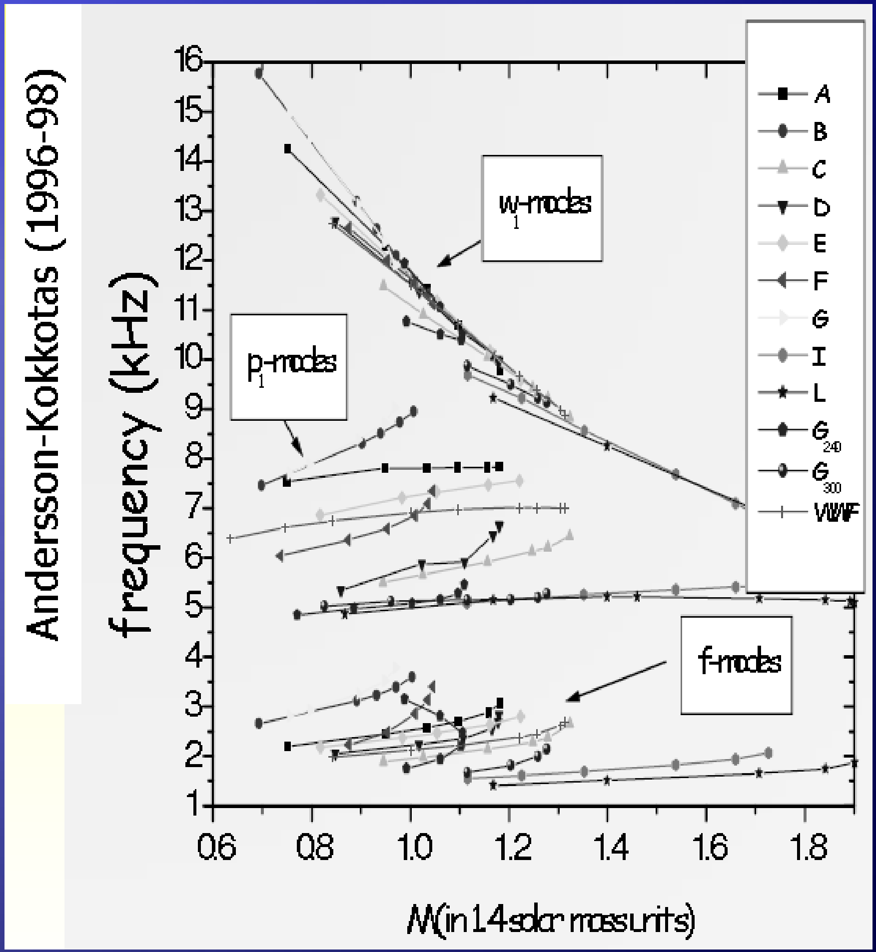


Credits: B.Schutz

Stellar Modes Zoology

Stellar modes are characterized by the different restoring forces:

- g-modes or gravity-modes: buoyancy is the main restoring force
- p-modes or pressure-modes: pressure
- f-mode or fundamental-mode: (surface waves) has an intermediate character of p- and g-mode
- w-modes: pure space-time modes (only in GR, space-time curvature is the restoring agent)
- Inertial modes (r-mode) : Coriolis force
- Superfluid modes: Deviation from chemical equilibrium provides the main restoring agent

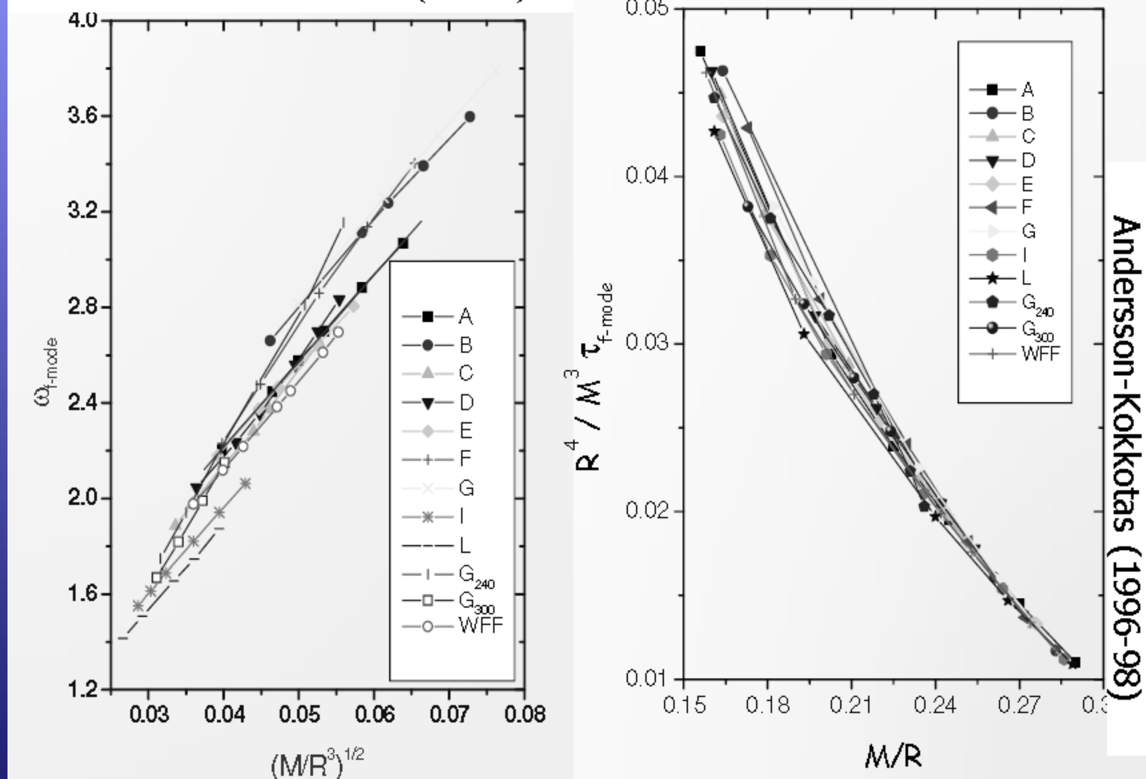


Credits: Schutz

Asteroseismology

- **Measuring the frequency and the decay time of the stellar mode it is possible to reconstruct the Mass and the Radius of the NS**
- **Knowing the Mass and the Radius it is possible to constrain the equation of state (EOS)**

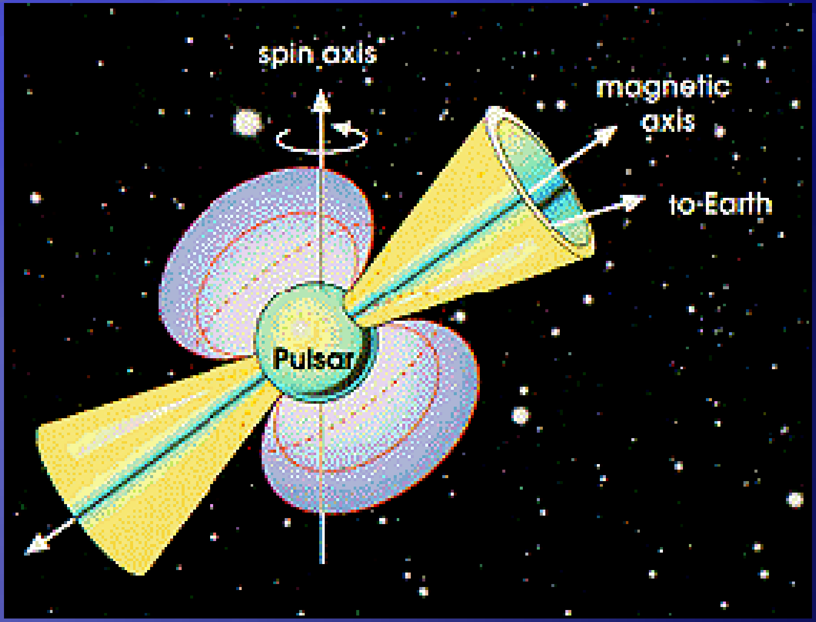
$$\omega_f\,(kHz) \approx 0.78 + 1.637\left(\frac{M_{1.4}}{R_{10}^3}\right)^{1/2} \qquad \frac{1}{\tau_f}(\mathrm{sec}) \approx \frac{M_{1.4}^3}{R_{10}^4}\left[22.85 - 14.65\frac{M_{1.4}}{R_{10}}\right]$$



Credits: B.Schutz

Continuous Waves

- A fraction of the NS emits e.m. waves:
  - Pulsars
- These stars could emit also GW (at twice of the spinning rotation) if a quadrupolar moment is present in the star:
  - ellipticity
- The amount of ellipticity that a NS could support is related to the EOS through the composition of the star:
  - i.e. high ellipticity ⇔ solid quark star?
  - Crust could sustain only $\varepsilon \leq 10^{-7}$
  - Solid cores sustains $\varepsilon \sim 10^{-3}$
  - Role of the magnetic field?



Imagine.gsfc.nasa.gov

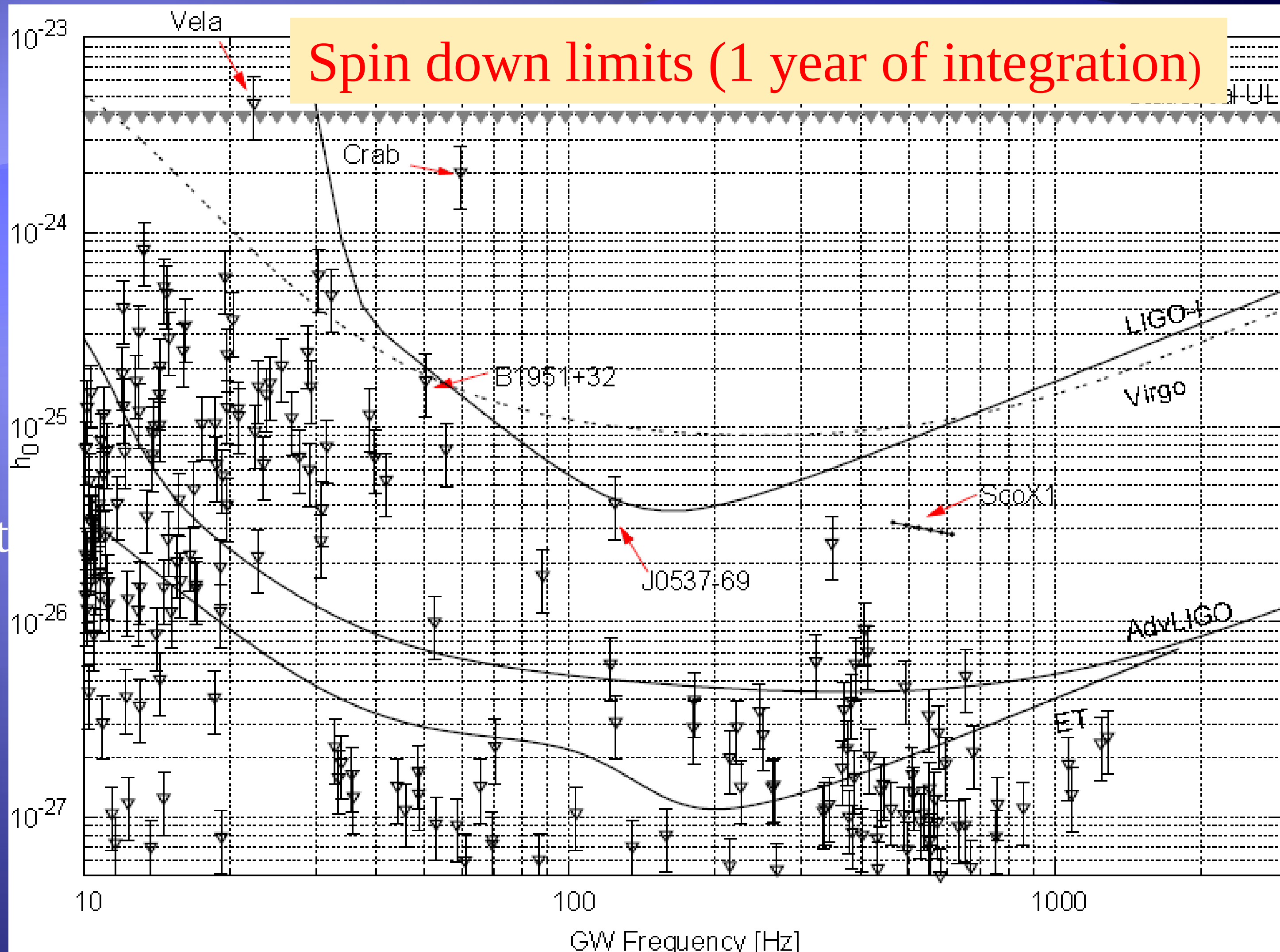
$$\dot{E} = I\Omega\dot{\Omega} = I\Omega\left(\dot{\Omega}_{GW} + \dot{\Omega}_{em}\right)$$

$$\dot{E}_{GW} = I\Omega\dot{\Omega}_{GW} = \frac{32}{5}\frac{G}{c^5} I^2 \epsilon^2 \Omega^6$$

$$h \approx \left(\frac{G}{\pi^2 c^3}\right)^{1/2} \frac{\dot{E}^{1/2}}{rf}$$

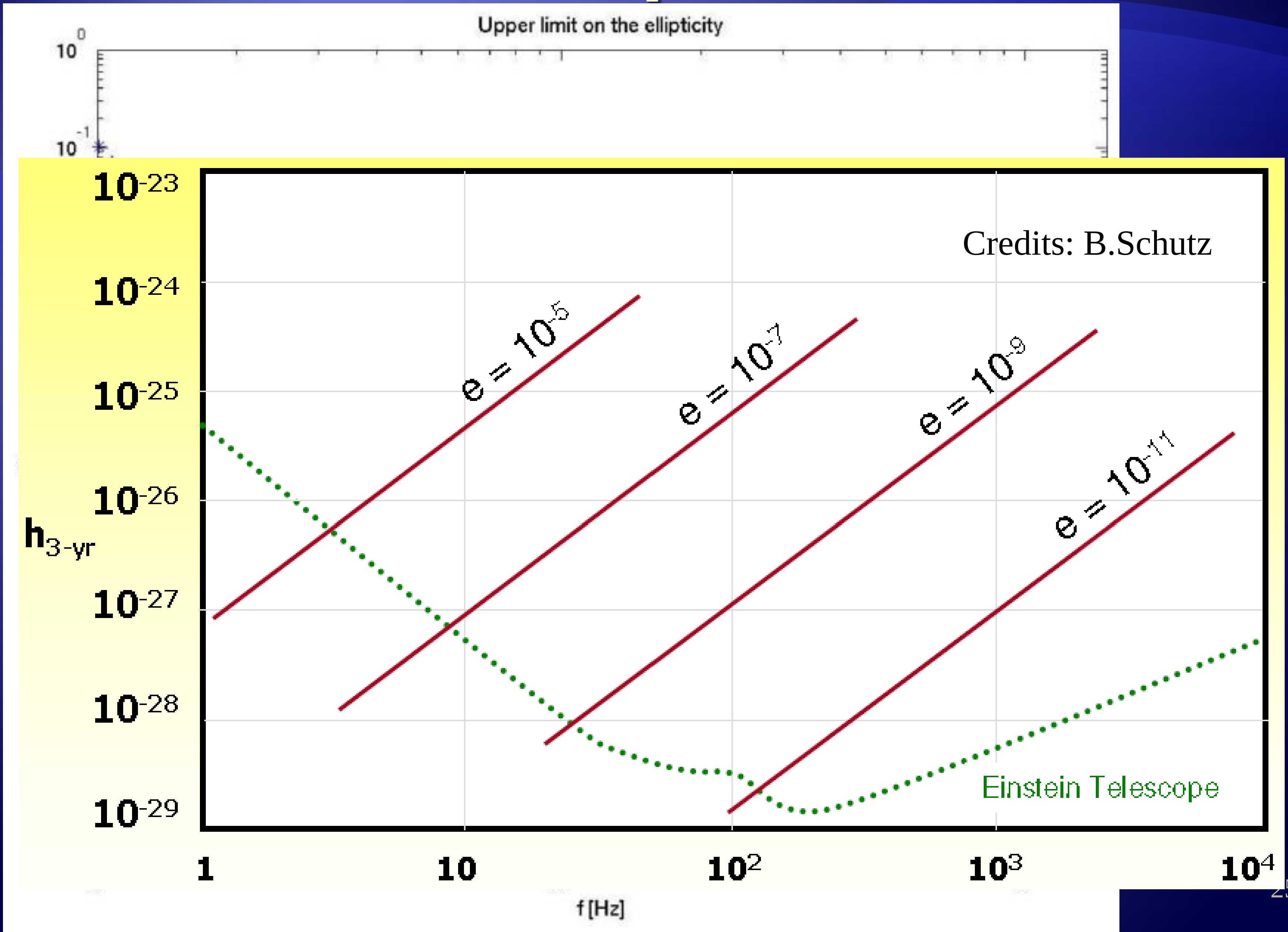
CW: Current Status

- LIGO limited the fraction of energy emitted by the Crab pulsar through GW to ~6% ($\varepsilon<1.8\times10^{-4}$)
- Virgo, at the start of the next science run could in few weeks set the upper limit for the Vela.



Credit: B. Krishnan

CW: Next developments



ET and Cosmology

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- Improving the sensitivity of the advanced detectors by an order of magnitude will permit to access, for the BNS observation, cosmological distances in the universe
- BNS are considered "standard sirens" because, the amplitude depends only on the Chirp Mass and Effective distance
  - Effective distance depends on the Luminosity Distance, Source Location (pointing!!) and polarization
- The amplitude of a BNS signal is:

$$h_{+} = 2M^{\frac{5}{3}}\left[\pi \cdot f(t)\right]^{\frac{2}{3}} \frac{1+\left(\hat{L} \bullet \hat{n}\right)^{2}}{D_L} \cos\left[\Phi(t)\right]$$

$$h_{\times} = 4M^{\frac{5}{3}}\left[\pi \cdot f(t)\right]^{\frac{2}{3}} \frac{\hat{L} \bullet \hat{n}}{D_L} \sin\left[\Phi(t)\right]$$

where the chirp mass is:

$$M = \frac{\left(m_1 \cdot m_2\right)^{\frac{3}{5}}}{\left(m_1 + m_2\right)^{\frac{1}{5}}}$$

- The Redshift is entangled with the binary's evolution:
  - The coalescing evolution has timescales (Gm_i/c^3) and these timescales redshift
    - Since also D_L scales with (1+z), a coalescing binary with masses $[m_1, m_2]$ at redshift z is indistinguishable from a local binary with masses $[(1+z)m_1, (1+z)m_2]$

Credits: D. E. Holz, S.A.Hughes

Credits: B.Schutz

… ET and Cosmology

- Hence, GW are able to measure the luminosity distance D_L through red-shifted BNS, but need an e.m. counterpart to measure the Redshift z.
  - i.e. Short GRB are currently considered to be generated by coalescing BNS
  - Coupling GW and e.m. measurements it is possible to determine the origin of GRB
- Knowning (1+z) and D_L it is possible to test the cosmological model and parameters that relate these two quantities:

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\left[\Omega_M (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}\right]^{1/2}}$$

Ω_M: total mass density
Ω_Λ: Dark energy density
H_0: Hubble parameter
w: Dark energy equation of state parameter

- Preliminary results, by B.Sathyprakash and co. show that it is possible to determine some of the cosmological parameters with few percent of error
  - See WP4 meeting: https://workarea.et-gw.eu/et/WG4-Astrophysics/meetings/cardiff-090325/

Stochastic Background

- Many cosmological mechanisms could be adopted to generate a Stochastic Gravitational-Wave Background (SGWB)
  - Amplification of the quantum vacuum fluctuation during the inflation epoch, cosmic strings, pre-big-bang, …
  - The extremely week interaction of the GW with the matter preserved the information carried by the wave about the generation mechanism
  - Very early universe snapshot could be extracted from the detection (or missed detection) of the SGWB

Characterization of the SGWB

- The SGWB is characterized by the adimensional energy density $\Omega_{GW}(f)$:

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

Where ρ_{GW} is the energy density of the SGWB and ρ_c is the critical energy density for closing the universe

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

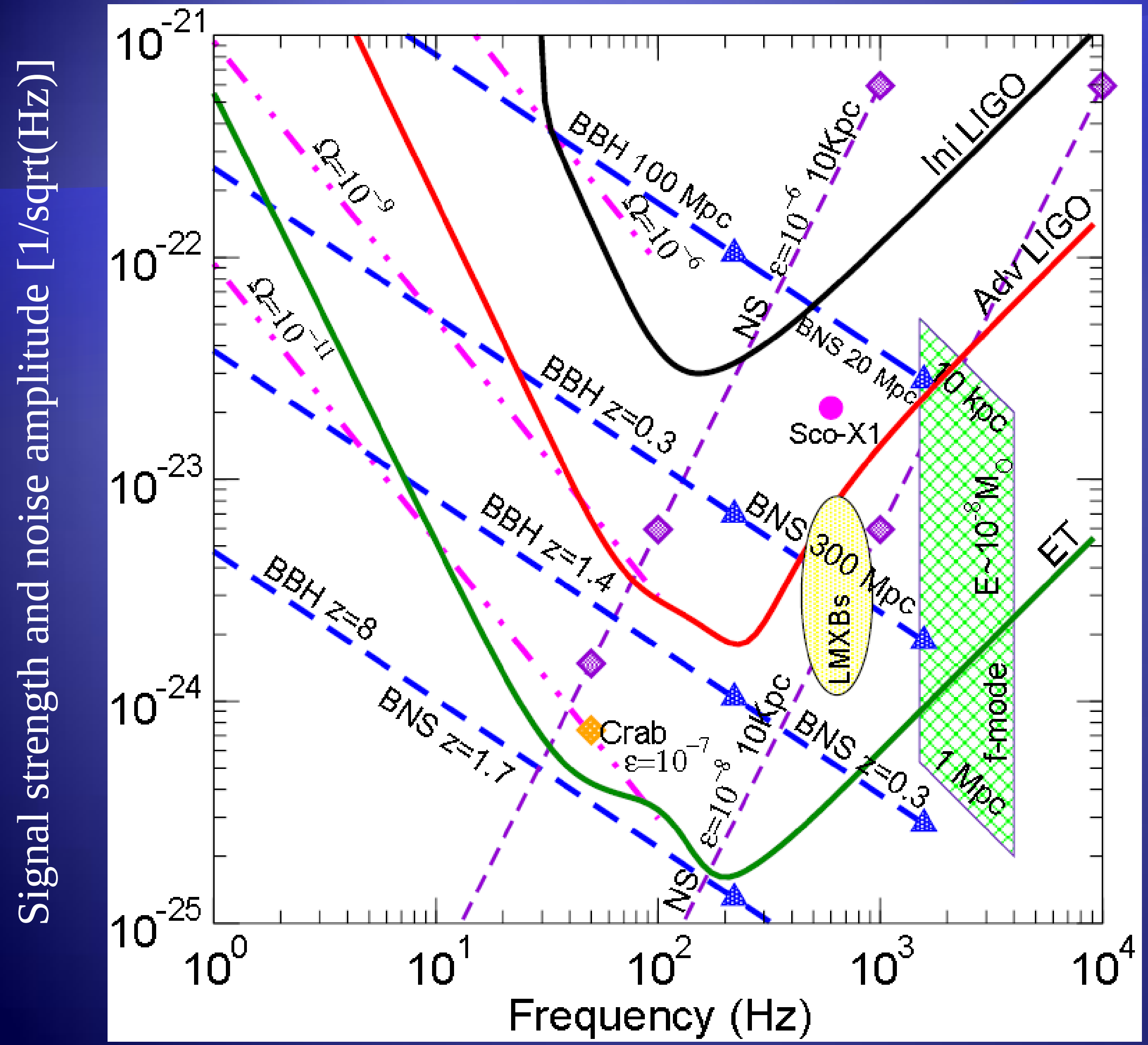
- The SGWB generation models generally foresee a behavior for $\Omega_{GW}(f)$:

$$\Omega_{GW}(f) = \Omega_{f_0}\left(\frac{f}{f_0}\right)^n$$

n=0 for standard inflationary theory
n>1 for other theories (strings,..)

- In principle, co-located ITF could measure the correlation needed to detect the SGWB, but local (low frequency) noises spoil the measurement
- Let consider 2 ET 'like' detectors, 5000km apart

Sensitivity to stochastic background

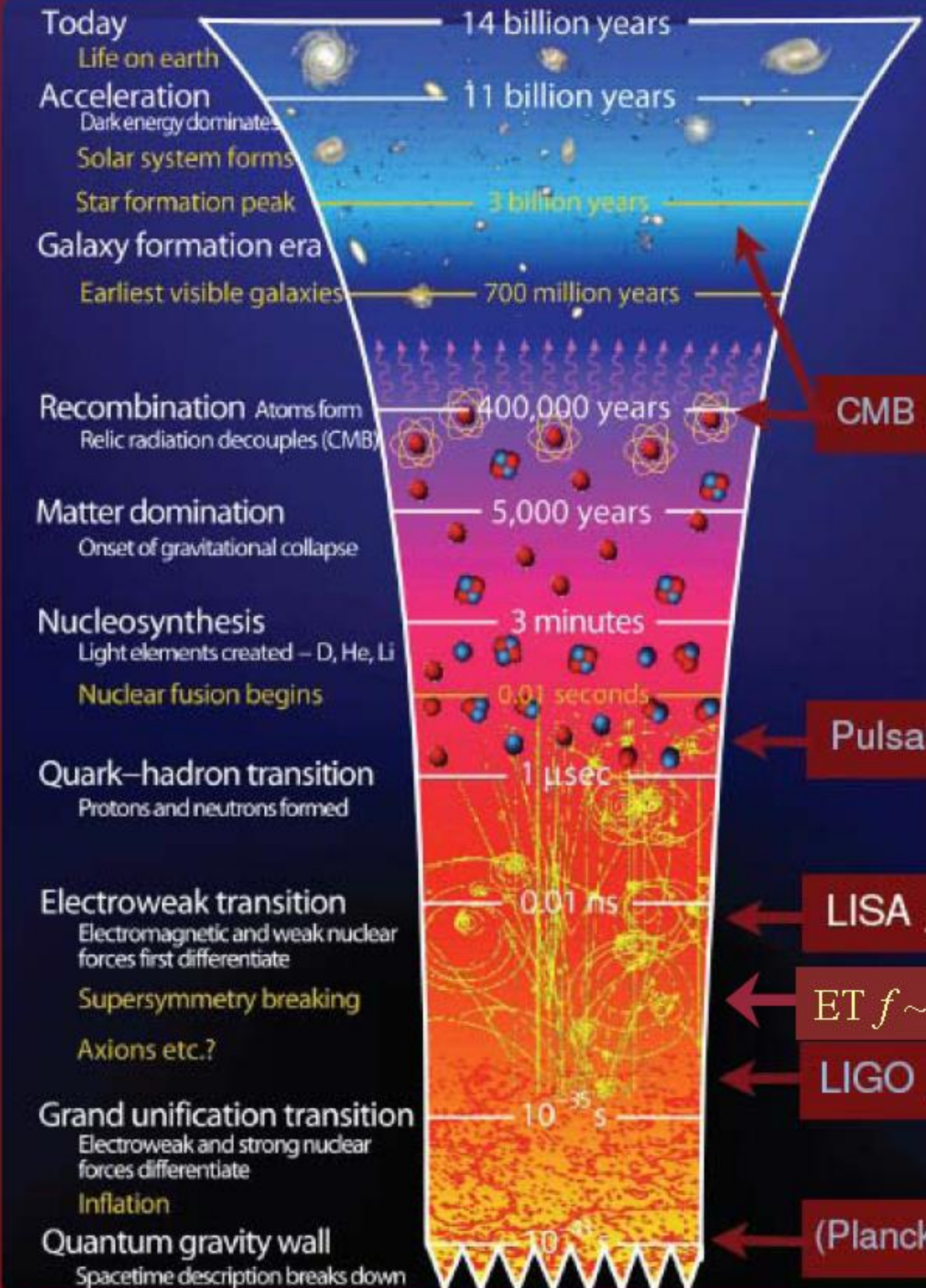


If n=0, the Big-Bang-Nucleosynthesis limit is $\Omega_0 < 1.1 \times 10^{-5}$.

Credits: B.Sathyaprakash

Slide by: P 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)

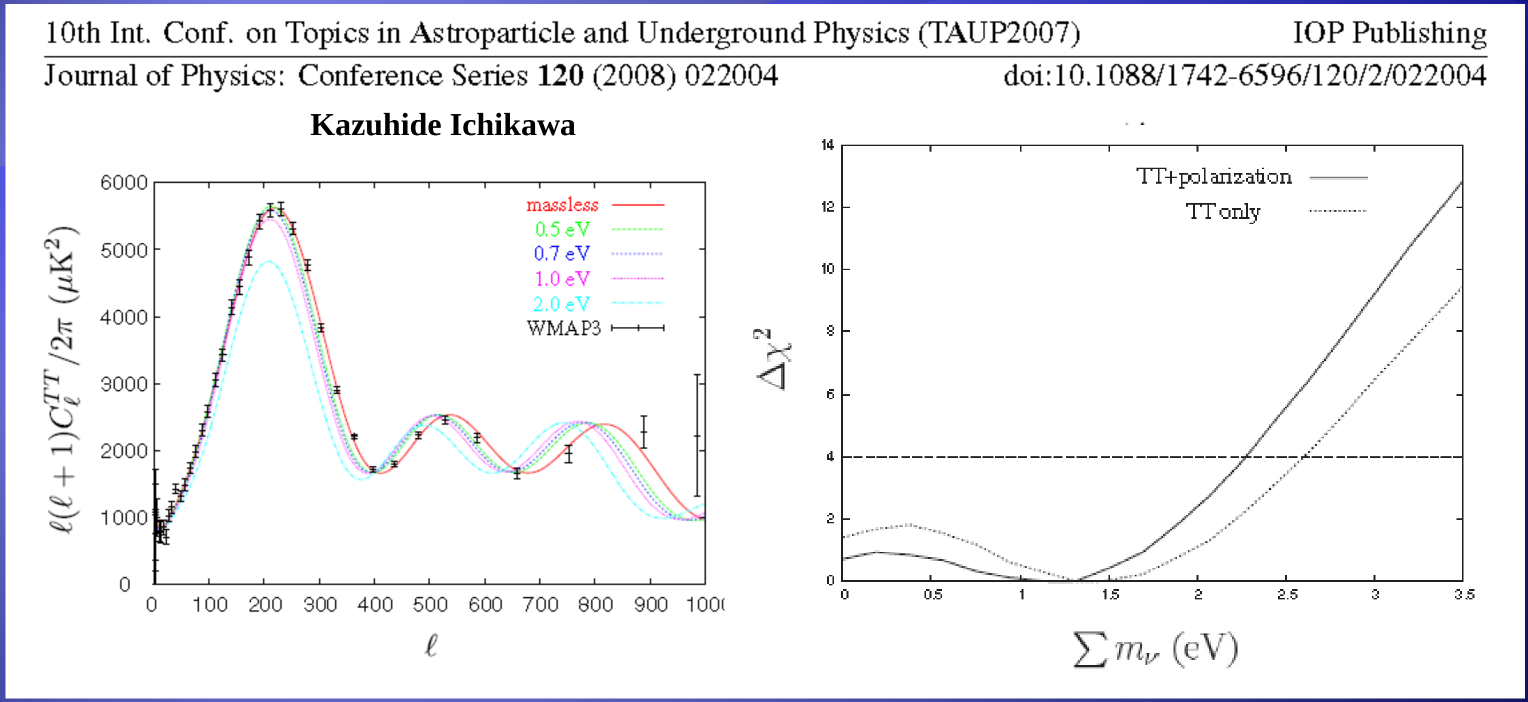
(Planck scale $f \sim 10^{11}$Hz has $t_e \sim 10^{-43}$s ($T \sim 10^{19}$GeV)

Neutrino mass

- Neutrino flavor mixing measurement at Super-Kamiokande demonstrated the non-null mass of the neutrinos
  - Mixing measurement are sensitive only to the difference in the squares of the masses of mass eigenstates (Δm_{ij})
    - It is possible to argue that one of the two neutrino mass eigenstate has non-null mass m>0.04eV
  - Direct measurement through nuclear beta decay or neutrinoless double beta decay
  - Indirect measurement through cosmological consideration

WMAP and neutrino mass

- Using the CMB anisotropy measurement made by WMAP:



- Power spectrum of the cosmic microwave background radiation temperature anisotropy in terms of the angular scale (or multipole moment).
- The χ^2 minimization over the 6 cosmological parameteres of a ΛCDM model gives a m_ν<0.63eV limit
  - The actual minimum of χ^2 occurs at a nonzero neutrino mass Σ m=1.3 eV, but χ^2 relative to the vanishing neutrino mass is less than one, meaning that the preference of a finite neutrino mass is insignificant
  - Estimation depends on the cosmological parameters

GW and Neutrino in SN

EINSTEIN TELESCOPE

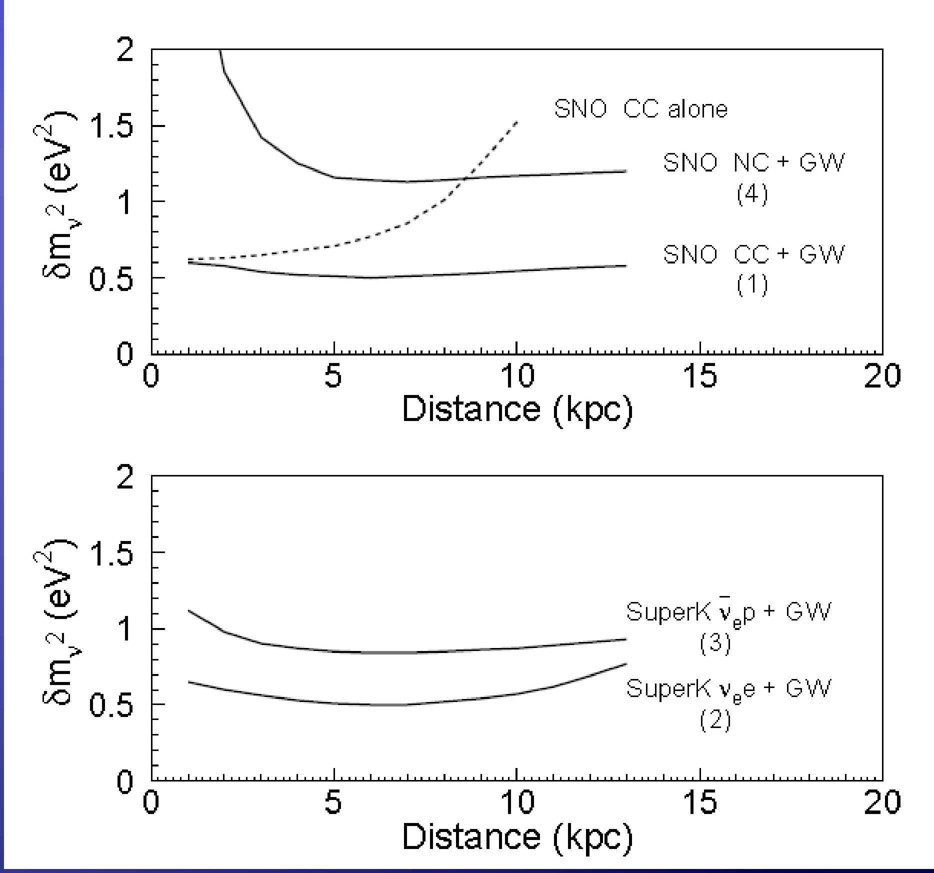
- Supernova Explosions generates visible light, huge neutrino emission and GW emission
- Large Δt between light arrival and neutrino arrival times, due to the interaction of the light in the outer layer of the collapsing star
  - 3 hours according to the SNEWS (SuperNova Early Warning System) in the SN1987A
- Small Δt expected for GW detectors: $\Delta t = \Delta t_{SN} + \Delta t_{prop} + \Delta t_{\det}$
- Where Δt_{SN} depends on the different models adopted to describe the neutrinos and GW emission ($\delta_{\Delta t_{SN}}$ <1ms)
- Δt_{det} depends on the detectors reciprocal distance and on the source direction
- Δt_{prop} depends only on the mass of the neutrino and on the distance L of the source:

$$\Delta t_{prop} = \frac{L}{2c}\left(\frac{m_\nu c^2}{E_\nu}\right)^2 = 5.15ms\left(\frac{L}{10kpc}\right)\left(\frac{m_\nu c^2}{1eV}\right)^2\left(\frac{10MeV}{E_\nu}\right)^2$$

N.Arnaud et al, Phys.Rev.D65:033010,2002

Neutrino mass and GW

N.Arnaud et al, Phys.Rev.D65:033010,2002



- Neutrino mass determination still depends on the model but the incertitude is "competitive": $\delta m_\nu < 1$eV
- Time accuracy (and then neutrino mass accuracy) is improved by GW SNR
  - In favor of ET
- But the event rate is a crucial issue

SNe event rate 1/2

- Current SNe models estimates about $10^{-8}M_{\odot}$ emitted in GW; in the past $10^{-2}M_{\odot}$ were expected
  - 1st generation were limited to our galaxy:
    - Event rate 1evt every 20 years
- To reach an acceptable event rate (1evt/year) a sight sphere of 3-5Mpc should be considered (Christian D Ott, 2008)
  - Events, optically detected, from 1/1/2002, to 31/8/2008 < 5MPc:

SN	Host Galaxy	Date	Type	Distance
2008bk	NGC 7793	20080325 [230]	II-P	$\sim$ 3.9 [231]
2005af	NGC 4945	20050208 [232]	II-P	$\sim$ 3.6 [231]
2004dj	NGC 2403	20040731 [233]	II-P	$\sim$ 3.3 [231]
2004am	M 82	20040305 [234]	II-P	$\sim$ 3.5 [235]
2002kg	NGC 2403	20021026 [236]	IIn	$\sim$ 3.3 [231]

arXiv:0809.0695v1 [astro-ph] 3 Sep 2008

SNe event rate 2/2

- Upper limit SNR estimated

advLIGO

Process	Model	LIGO 2 4 km	LIGO L1/H1 4 km	LIGO H2 2 km	GEO600 600 m	VIRGO 3 km
Rotating Collapse	s11A2O13	0.124	0.008	0.005	0.001	0.009
& Bounce	s20A2O09	0.130	0.008	0.006	< 0.001	0.010
[99]	s40A3O12	0.214	0.024	0.013	< 0.001	0.018
Rotational Instability	s20A2B4	0.319	0.021	0.014	0.003	0.022
[42, 104, 105]	s20A2B4 ($\times 5$)	0.713	0.047	0.031	0.007	0.049
PNS g-modes	s11.2	0.147	0.006	0.005	0.002	0.009
[22, 23]	s15.0	0.454	0.021	0.015	0.006	0.027
and section 6.1	s25.0	0.612	0.029	0.020	0.007	0.037
	s25.0 ($\times 2$)	0.866	0.041	0.029	0.009	0.052
	s25WW	5.331	0.217	0.151	0.057	0.328

arXiv:0809.0695v1 [astro-ph] 3 Sep 2008

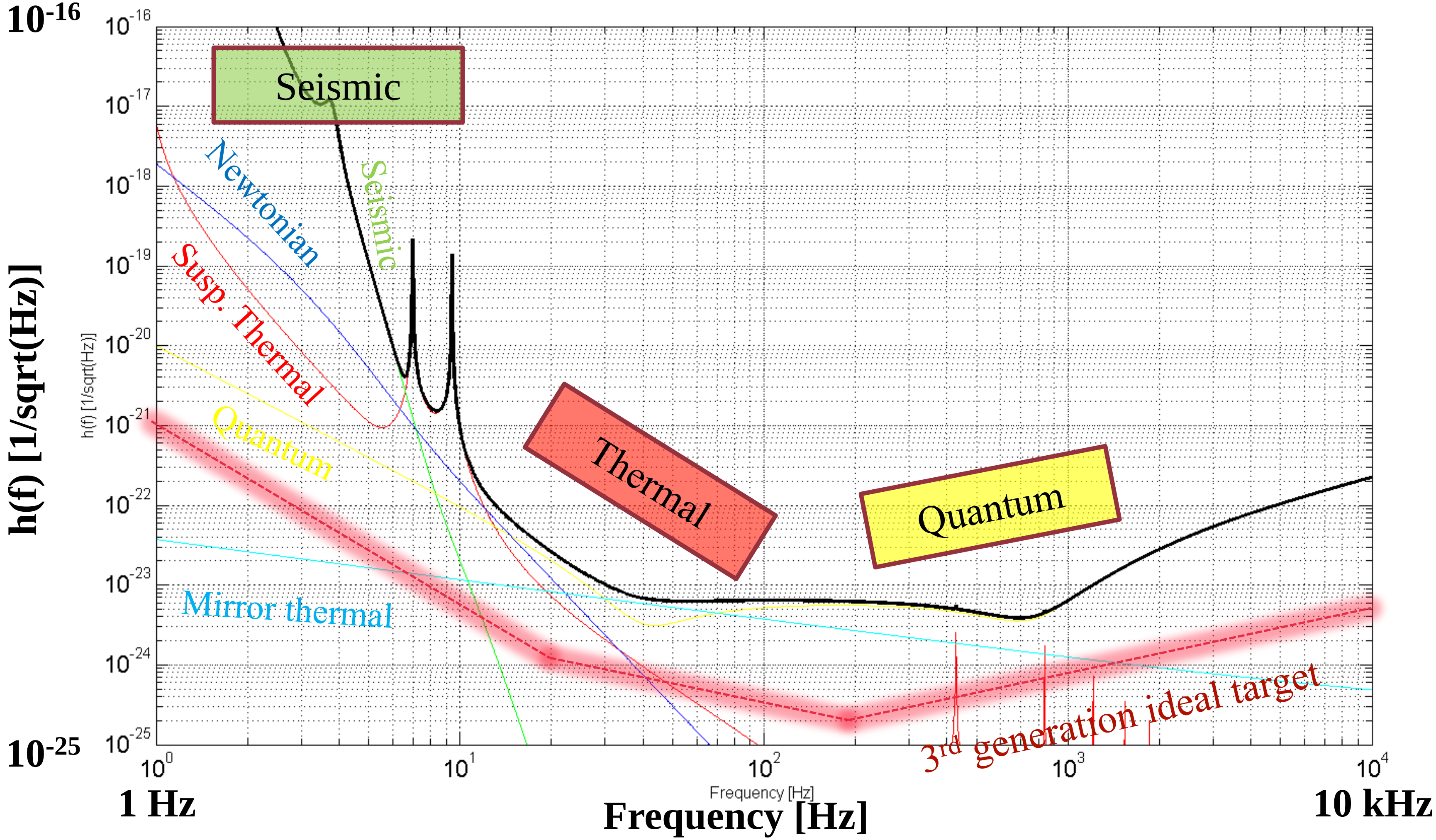
ET: $\sim \times 10$

EINSTEIN TELESCOPE

2^{nd} generation GW detectors

- 2^{nd} generation GW detectors are under design and realization
  - Technological steps already introduced within current detectors
  - Mainly developing and (difficult) tuning of available technology
- But what are the main limitations of the advanced detectors?

2nd generation noise limitations

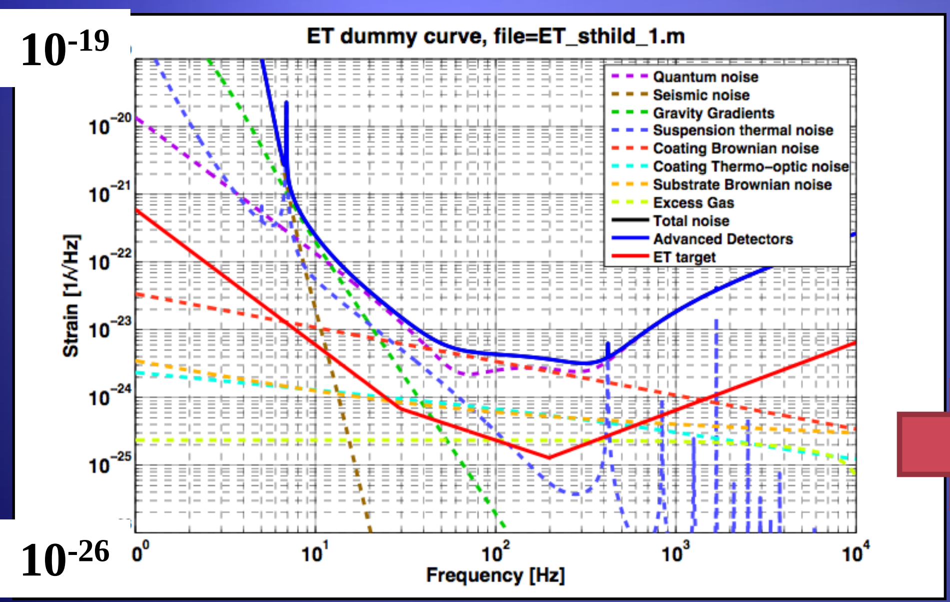


Noise reduction steps

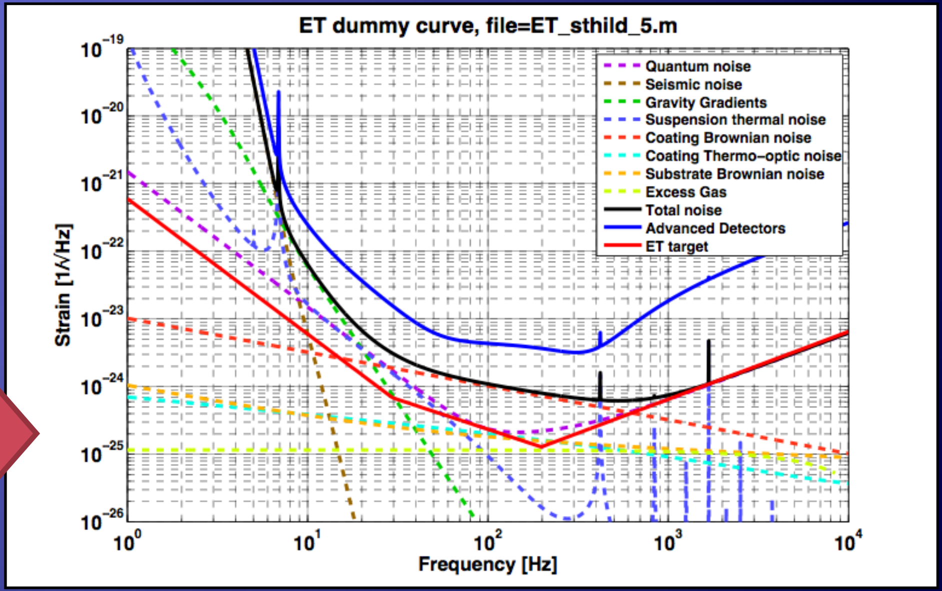
- Step 1: increase of the arm length:
  - $h = \Delta L / L_0$: 10 km arm, reduction factor 3.3 respect to Virgo
    - New infrastructure!!
- Step 2: reduction and optimization of the quantum noise:
  - Increase of the laser power from 125W to 500W
  - Optimization of the optical parameters (signal recycling factor)
  - Introduction of a 10dB squeezing

Effect on the HF sensitivity

2nd generation



10km+High Frequency

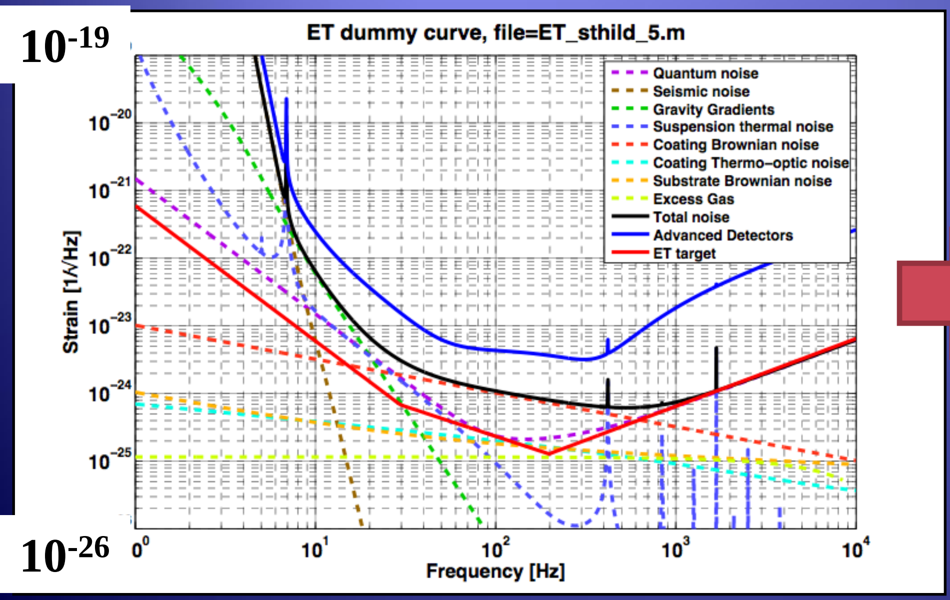


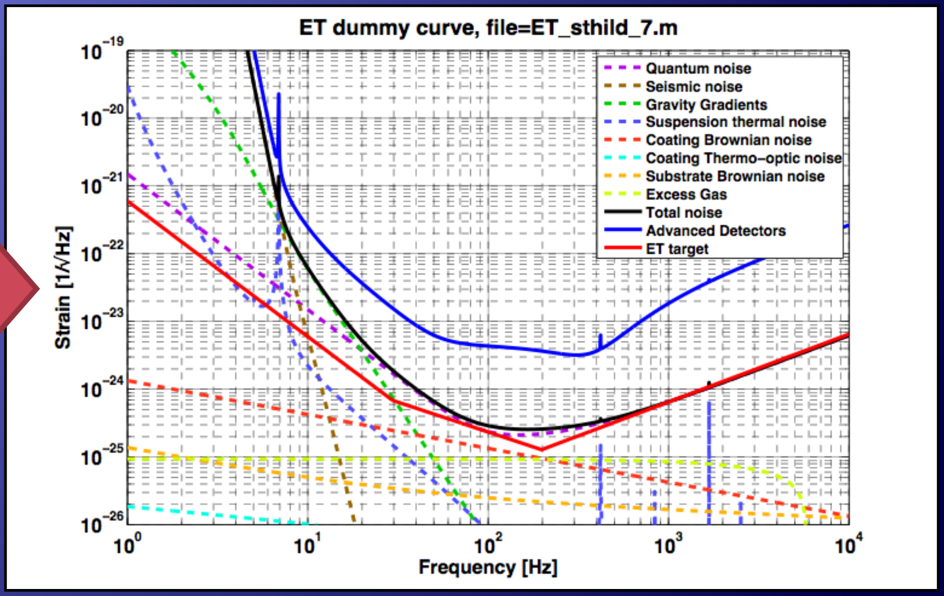
Credits: S.Hild

Reduction of the thermal noise

- The thermal noise reduction could pass through two main steps
  - Enlargement of the laser beam size
  - Cryogenics and new materials
- Other possibilities will be investigated: Higher order modes

Central Frequencies noise reduction

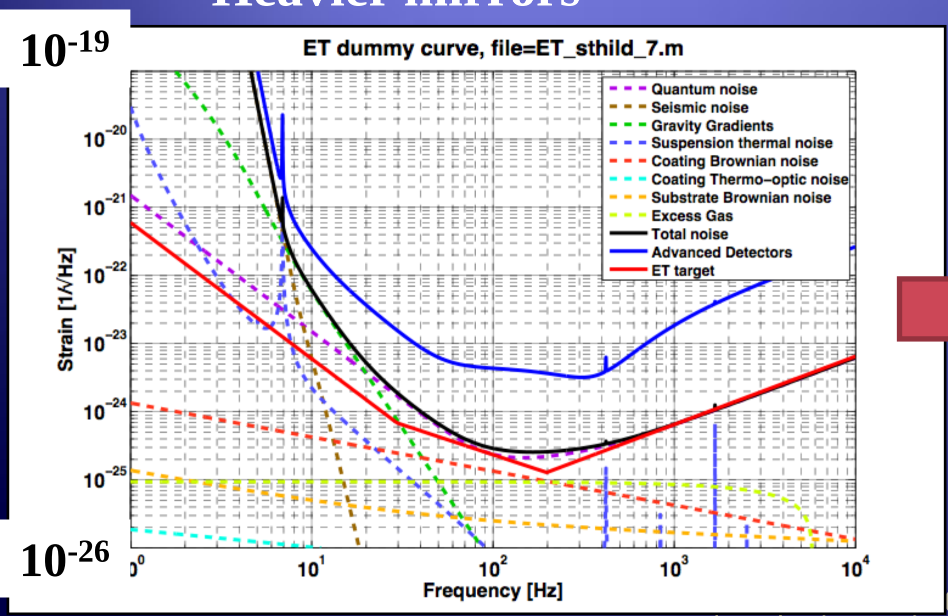


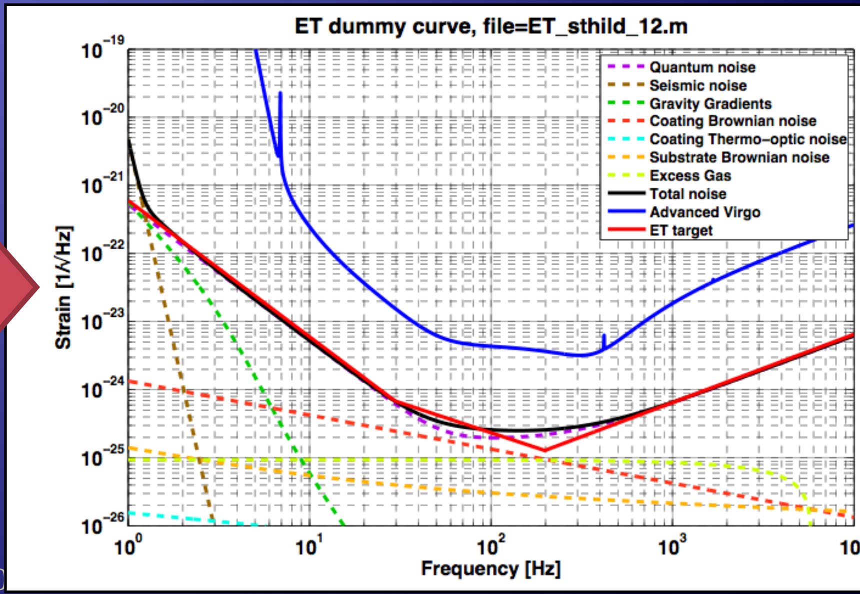


Credits: S.Hild

Low frequency noise reduction

- Reduction of the seismic excitation:
  - New underground facility
  - New multistage and longer (~50m equivalent) super attenuator
- Reduction of the gravity gradient noise (NN)
  - New underground facility
  - Suppression of the NN through correlation measurements?
- Reduction of the radiation pressure noise
  - Heavier mirrors





Credits: S.Hild

Comments

- Many unresolved questions
  - Feasibility of many steps still to be understood
  - Possibility to disentangle some problem splitting the observatory in two co-located interferometers
    - LF and CF+HF detectors (Xylophone strategy)
- ET Working groups dedicated to this subject
  - WP1: infrastructure and site location
  - WP2: Thermal noise and suspensions issues
  - WP3: Topologies and geometries
  - WP4: Astrophysics issues
- Many open questions need additional expertise:
  - An open Science Team is attracting new scientists close to the ET project