ET Science Case

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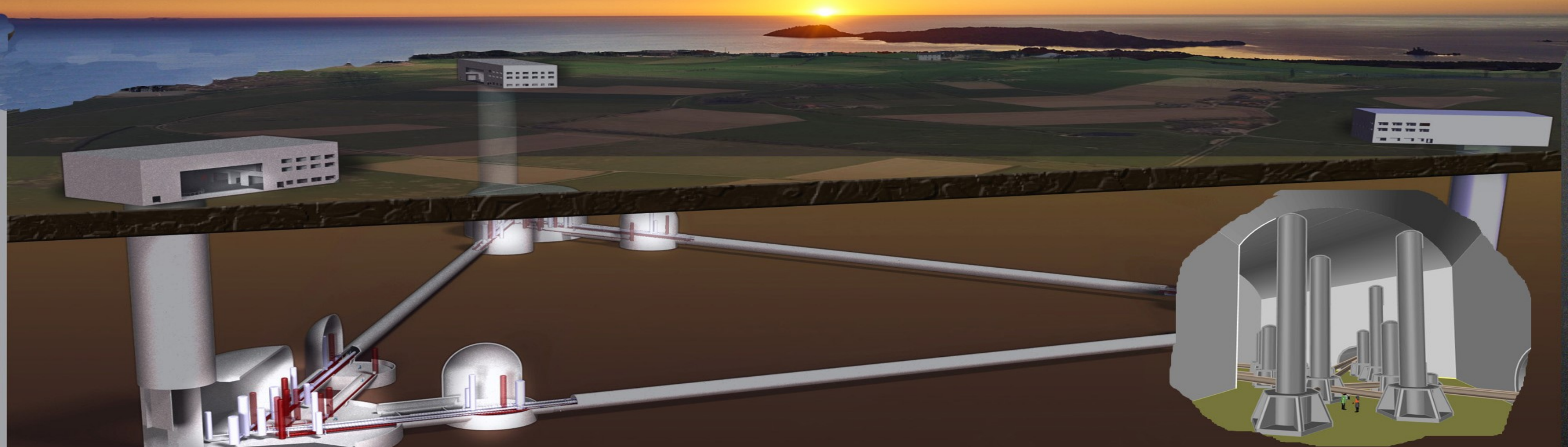


10th ET Symposium – Orosei, April 11-12th 2019

Introduction

We have been asked to write the science case for the new ET TDS:

- Short amount of time available: light document, leveraging on the 3G-GWIC Science Case document
- Emphasis on what can be done with GW alone
- Emphasis on what ET could do alone

Organization

Three (+1) main sections (of course the physics arguments often partially overlap):

- Fundamental physics
- Astrophysics of compact objects
- Cosmology & cosmography
- Computing requirements:

A parallel development in source modeling, data analysis and computing is of paramount importance in order to exploit detector potentialities.

Key points

A sensitivity gain of ~10 (w.r.t. Adv. detectors) over a wide frequency band will enable, at least in principle:

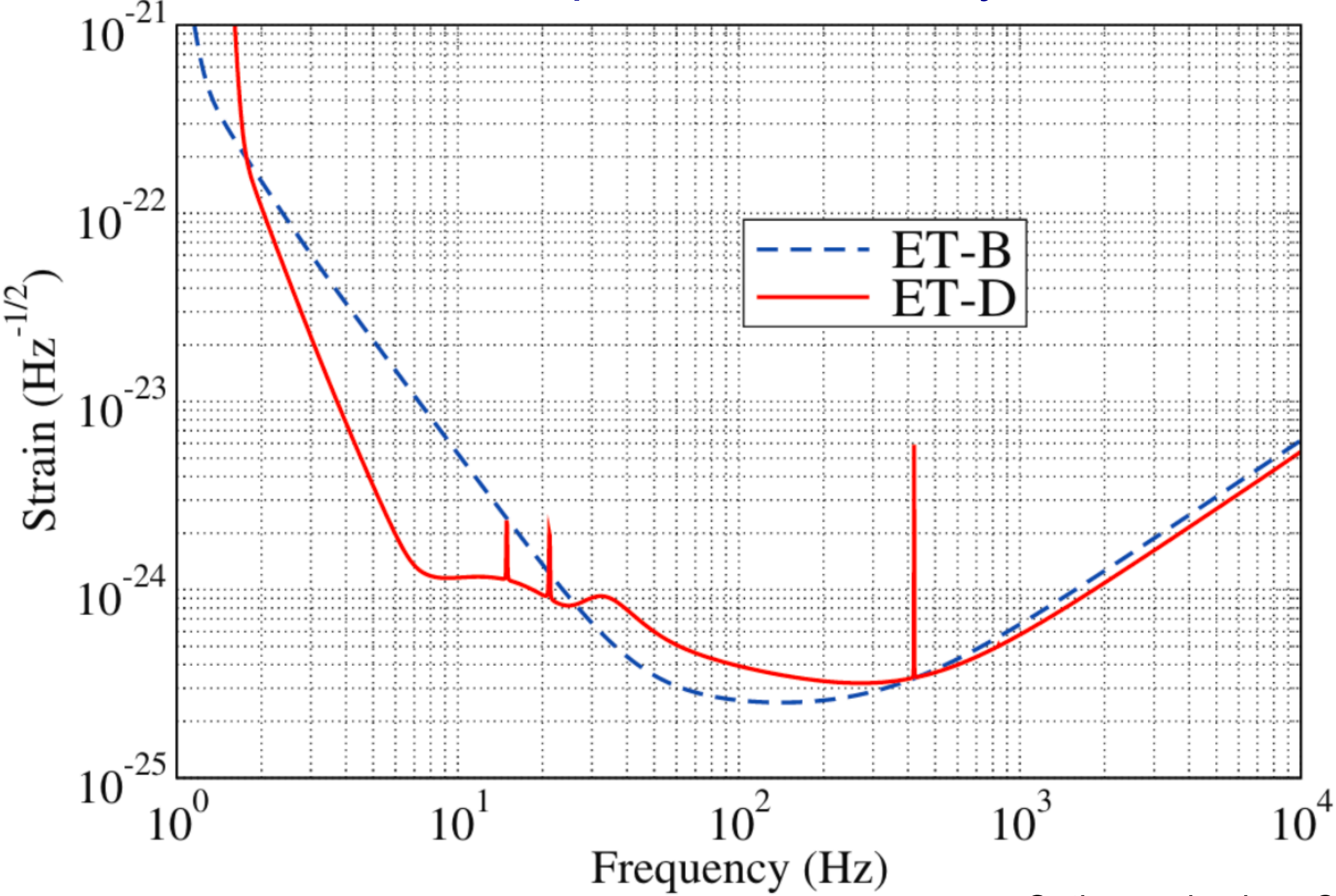
- New/better science with known sources
- Detection (and science) of new sources

For some science goals GWs are a unique probe.

For others GWs are complementary to other tools.

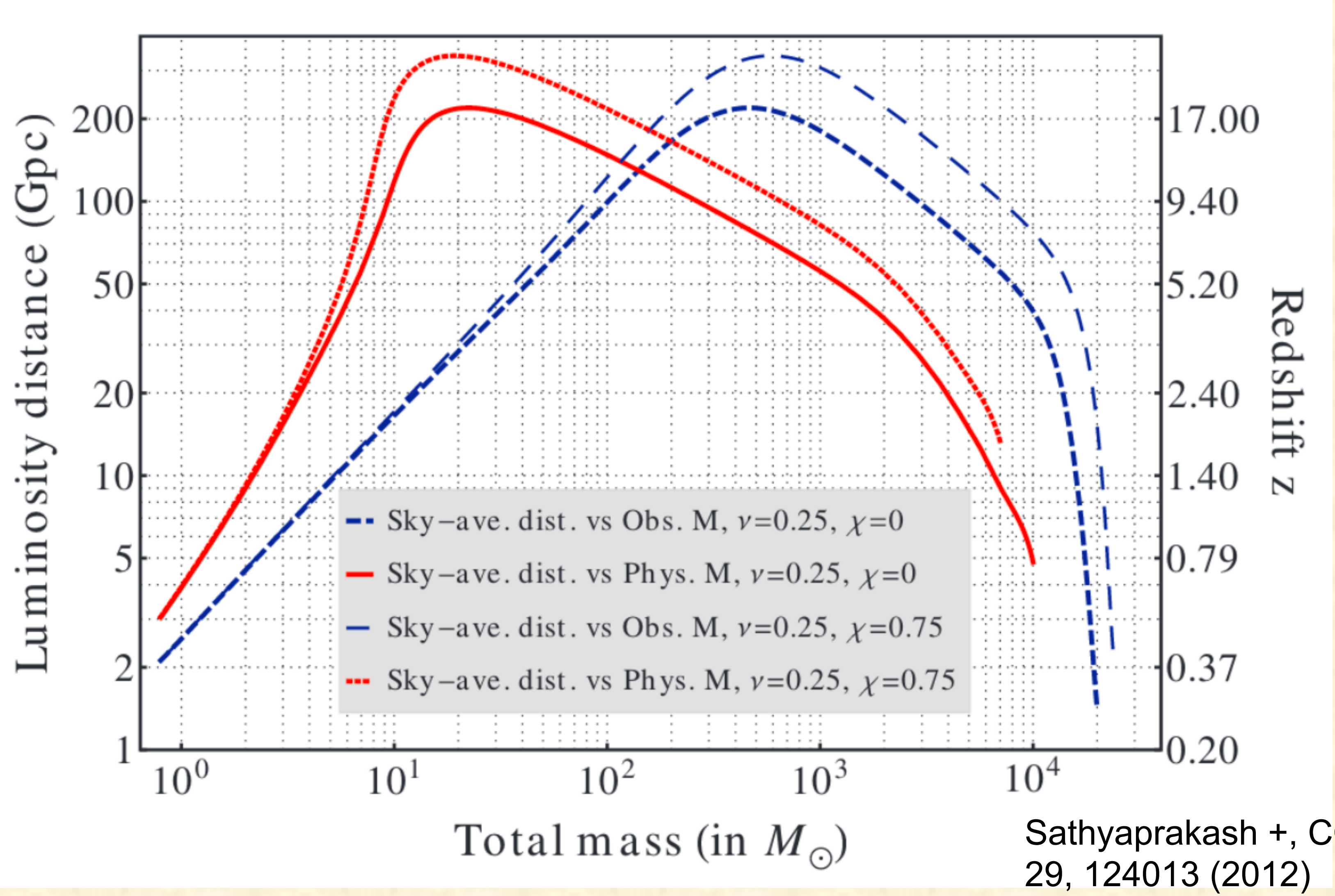
Need to identify which frequency bands are mandatory for each science target (special case of the low frequency band provided by underground facility).

ET planned sensitivity



Sathyaprakash +, CQG 29, 124013 (2012)

ET-B distance reach for coalescing binaries



Sathyaprakash +, CQG 29, 124013 (2012)

- ET will see all the BBH in the Universe

- A single ET detector would of course have reduced sky localization capabilities (**for transient sources**), with an impact on the science reach and multi-messenger astronomy.
- Impact especially for cosmological sources (problem of the measure of the redshift).
- Limited accuracy in the measure of the luminosity distance

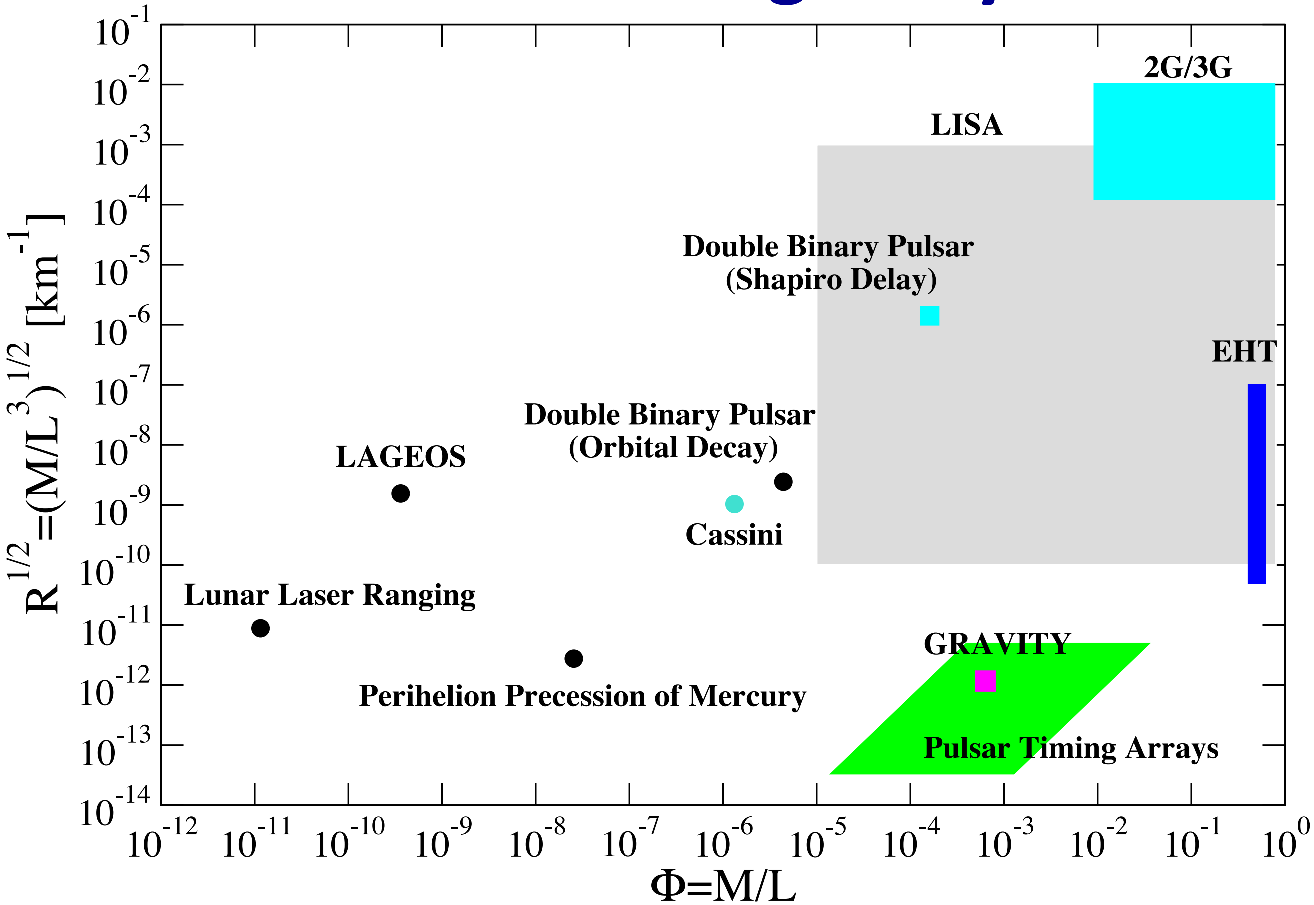
Fundamental physics

Three main subjects:

- The nature of gravity
- The nature of compact objects
- The nature of dark matter

Background picture from https://www.darkgra.org/gw-echo-catalogue.html

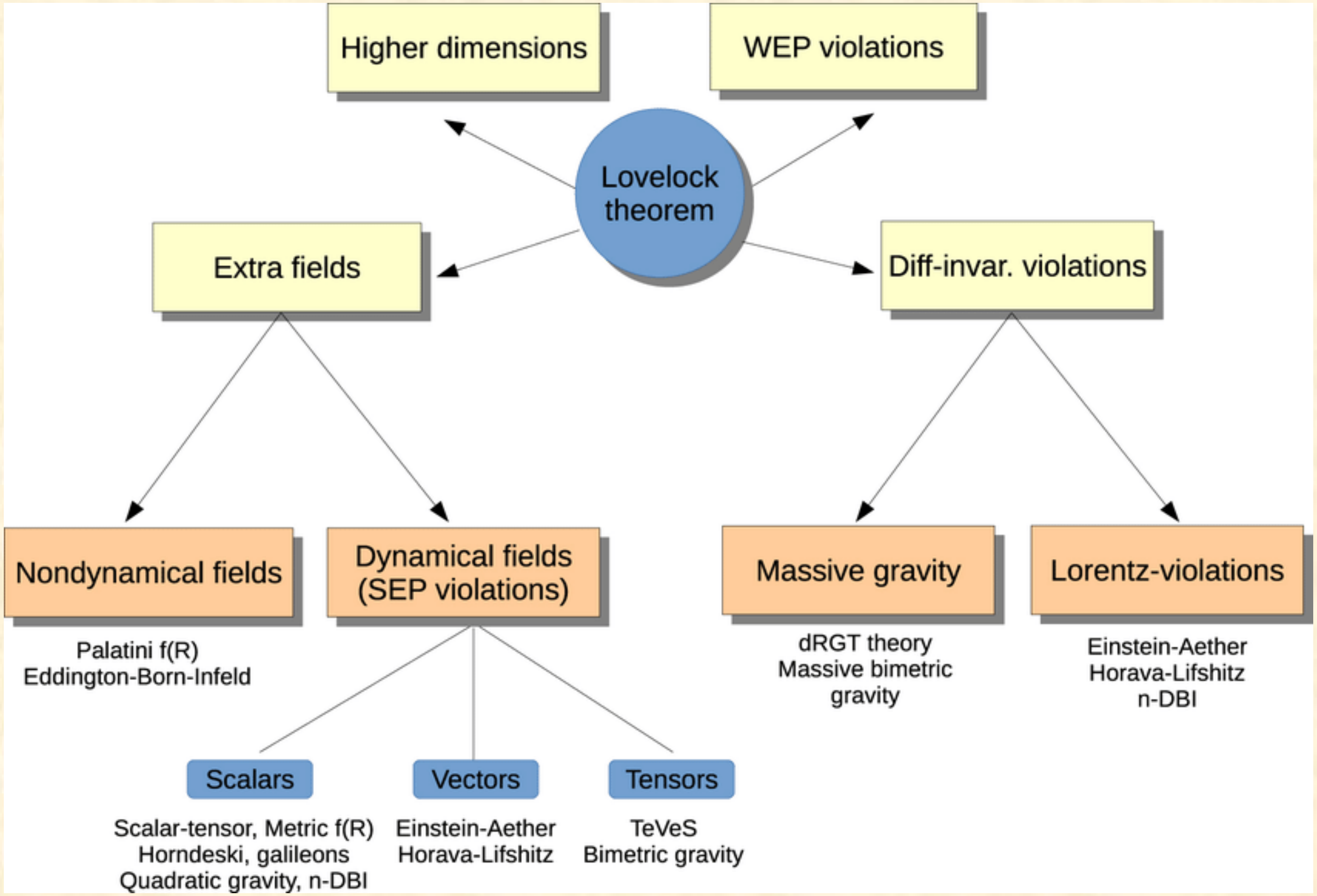
The nature of gravity



3G-GWIC Extreme Gravity Group

- *M*, *L* characteristic mass and size of a system
- In the case of binaries: $M/L \propto v^2/c^2$
- **Accessing strong-curvature *and* highly dynamical regime**

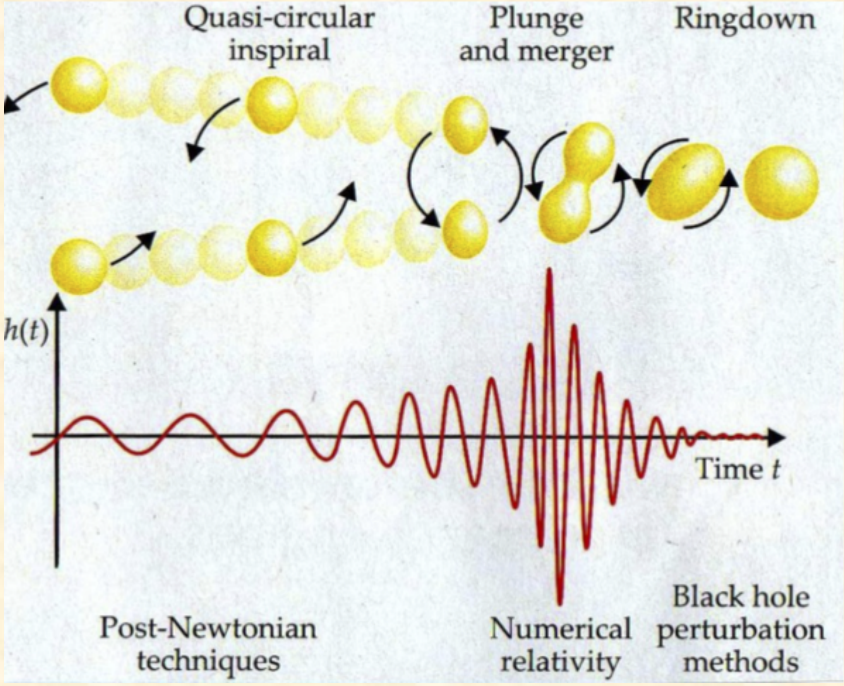
- Lovelock's theorem implies that departures from GR that preserve locality will generically require extra degrees of freedom: e.g. new fields or higher dimensions

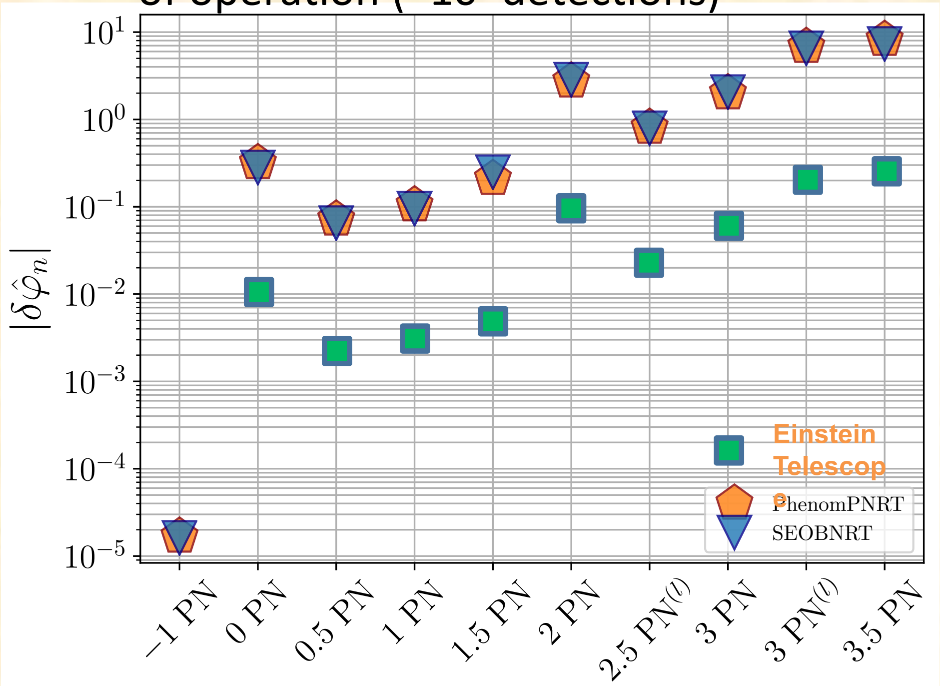


- New fields, for example:
  - Scalar-tensor theories
    - Binary components get "dressed" with scalar charge *(benefit from ET's high-frequency sensitivity)*
  - Gravitational parity violation
    - Modifications in binary dynamics
    - GW birefringence, building up over distance *(benefit from ET'S large distance reach)*
- Massive graviton, and local Lorentz invariance violations
  - Cause dispersion of GWs: accumulates over distance
  - Current bound $m_g < 5 \times 10^{-23}$ eV/c^2 will be improved upon by 2 orders of magnitude
- Variability of G, and local position invariance violation
  - Constraints better by 8 orders of magnitude over 2G *(benefit from ET's large distance reach)*
- Additional fields often lead to extra polarizations

- Any anomaly showing up in GW waveform:
  - Benefit from loud sources (ET's precision)
  - Benefit of faraway sources (effects on GW propagation)
  - Combine information from all detections to place tighter bounds

Orange, blue: GW170817
Green: Einstein Telescope after few years of operation (~10^5 detections)



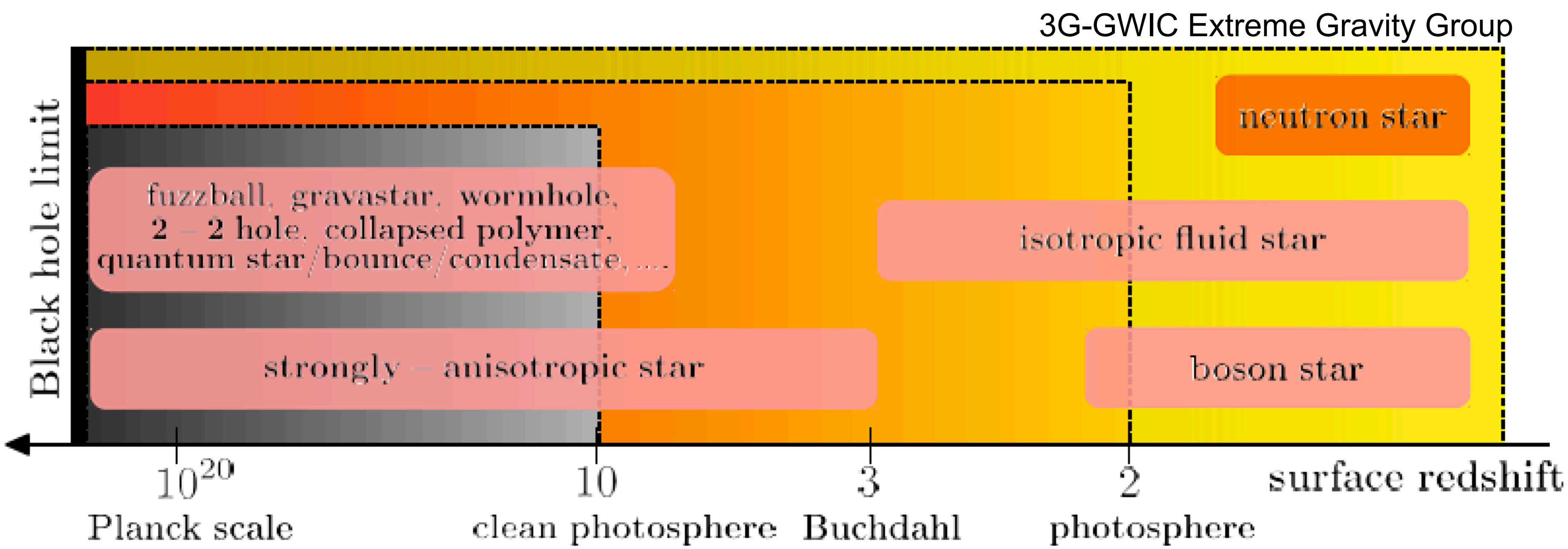


$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^{2} + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}}\log\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^{5} + \ldots + \varphi_{3.5\mathrm{PN}}\left(\frac{v}{c}\right)^{7}\right]$$

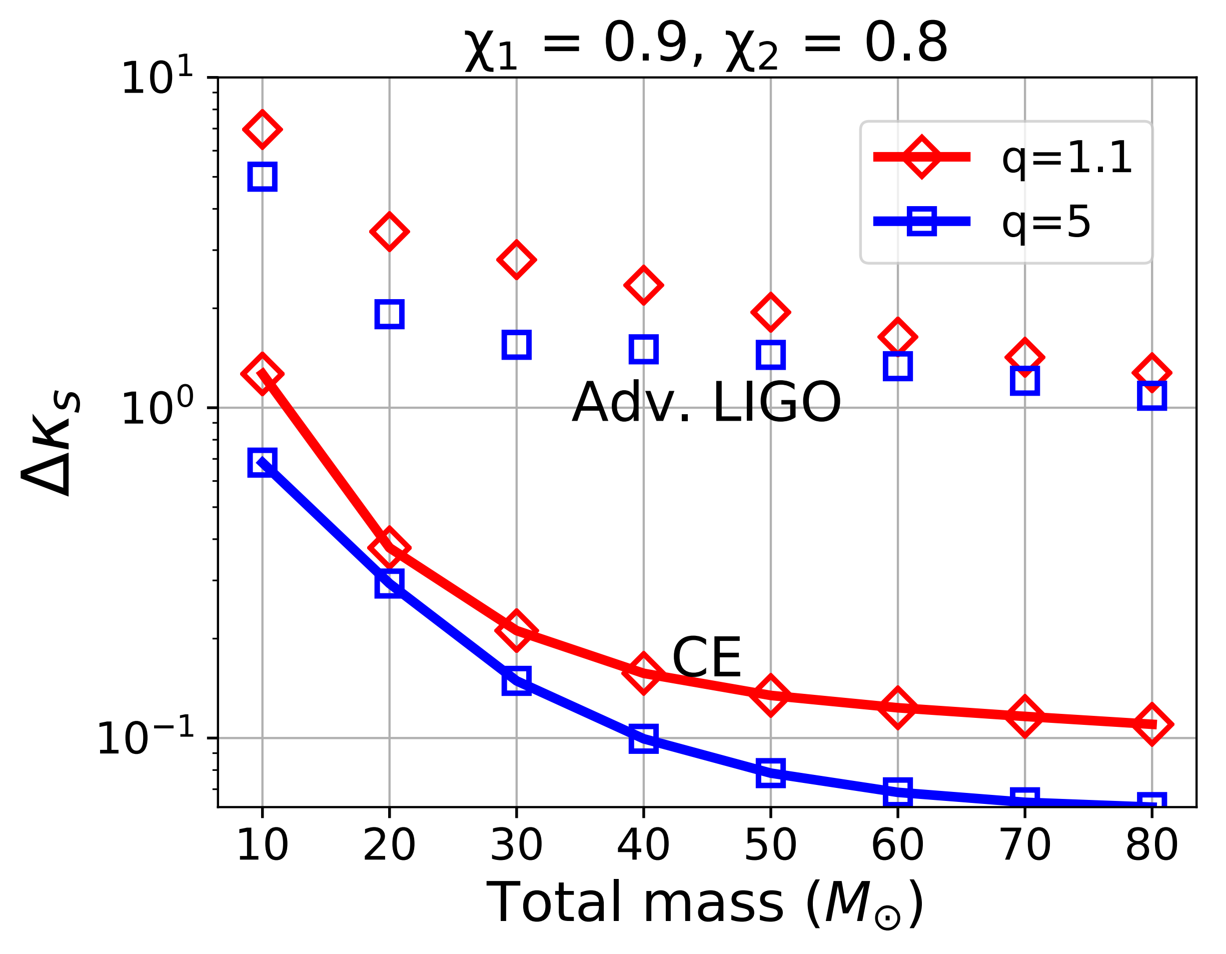
The nature of compact objects

How certain are we that the massive compact objects we are observing are the “standard” black holes of general relativity?

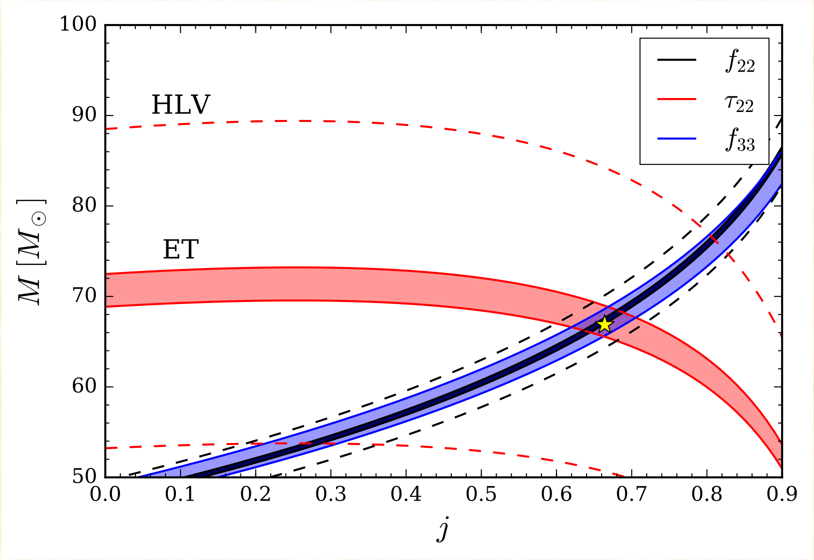
→ “Black hole mimickers”

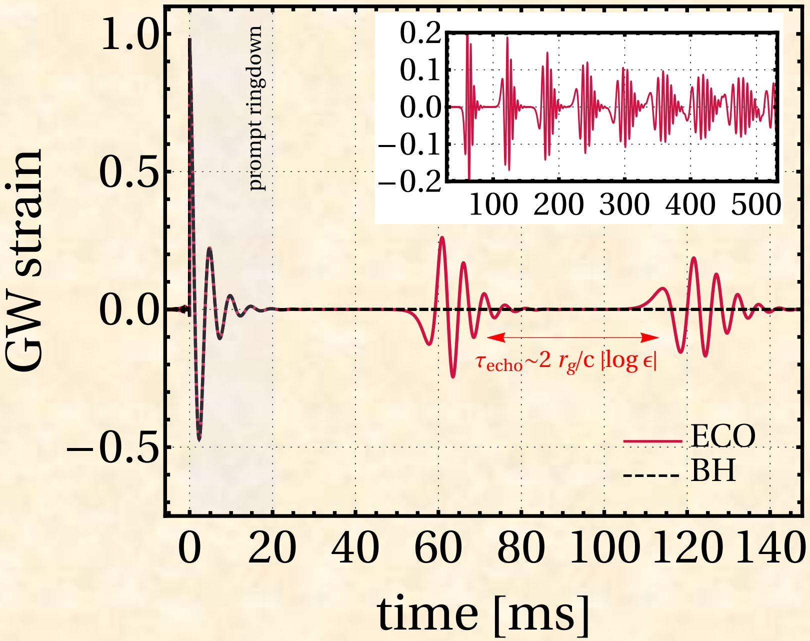


Departures from "standard" GR objects



- Spin-induced quadrupole moment during inspiral
  - κ_s = 1 for ordinary BHs, but not for BH mimickers
  - Not accessible with 2G, while 3G measurements to few percent

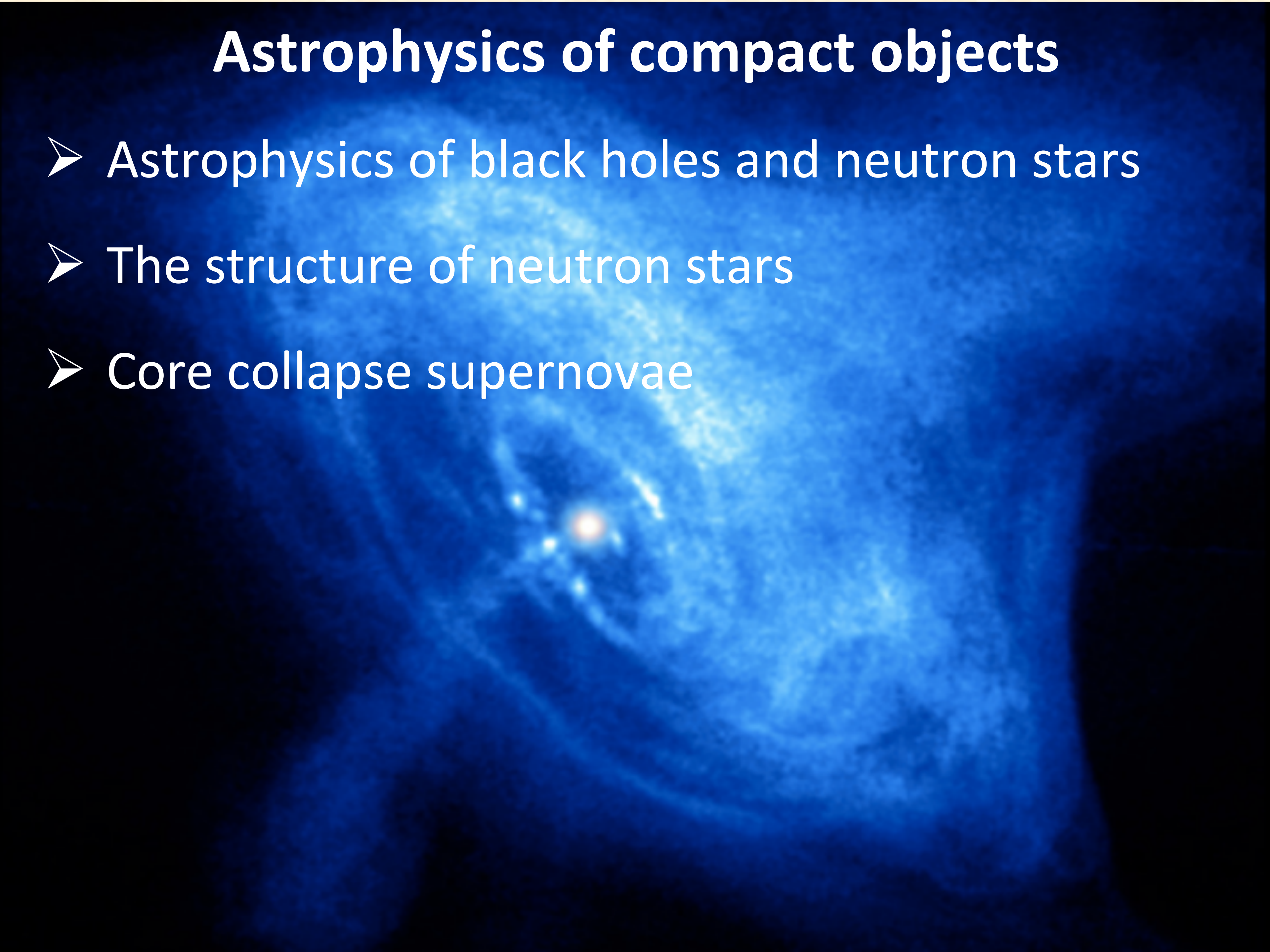




- Black hole "no hair" conjecture: Stationary, vacuum black hole completely determined by mass and spin
  - Qualitative advantage of ET: able to distinguish the various QNM, perform consistency check
- GW echoes
  - If horizon modified: periodic bursts of GW after ringdown has ended
  - Possibility to access macroscopic quantum effects: firewalls, fuzzballs

Astrophysics of compact objects

- Astrophysics of black holes and neutron stars
- The structure of neutron stars
- Core collapse supernovae



Neutron star and black hole astrophysics -1

- Merger rate as a function of z (relation with star formation rate, metallicity dependence, merger time delay) → better with 3G network
- Accurate mass, mass ratio and spin distributions (BH mass gap, natal kicks,…)→ better with 3G network
- Residual eccentricity, IMBH: low frequency
- Multi-band GW observations

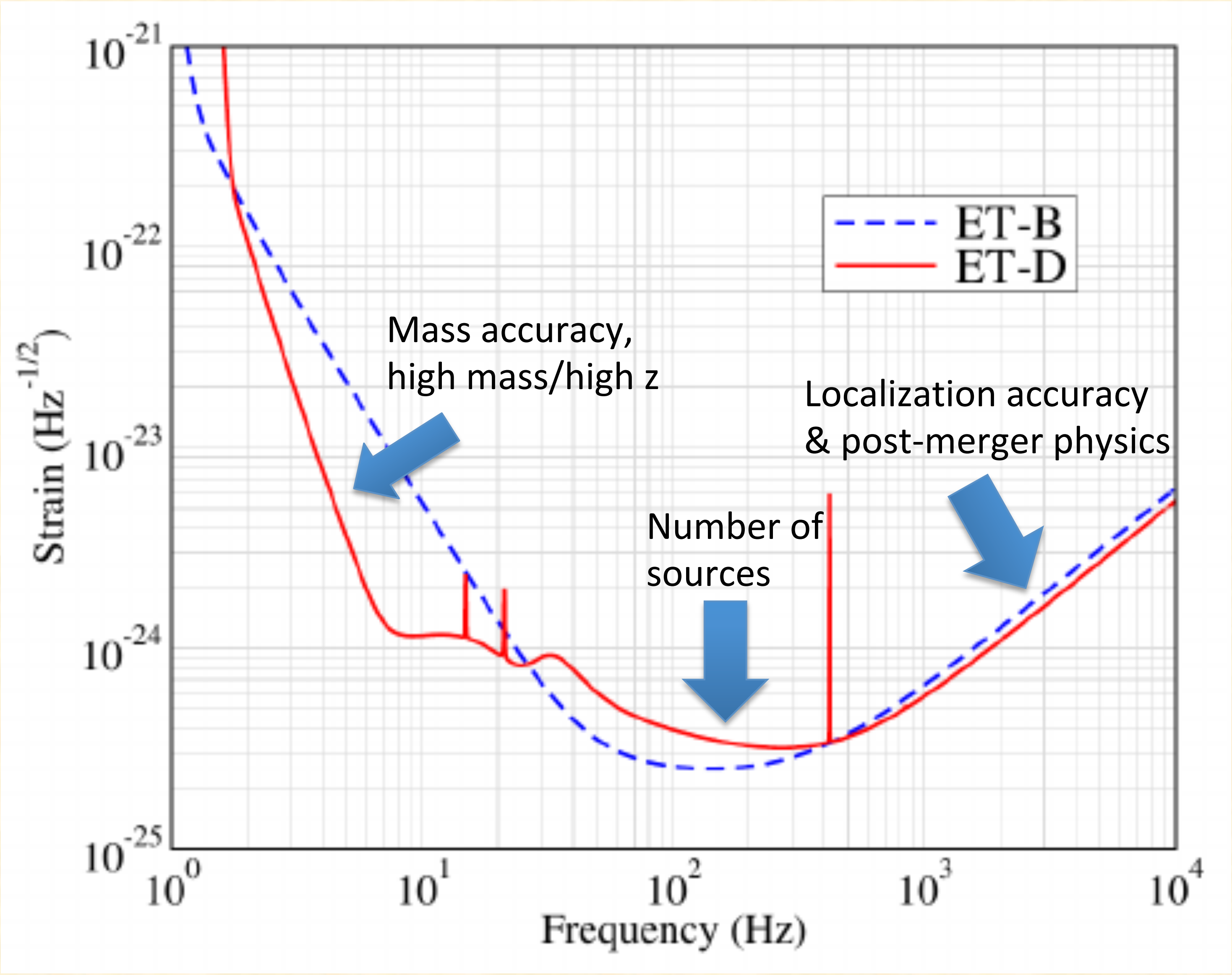
A. Ballone and M. Colpi's talks

Compact binaries formation channels

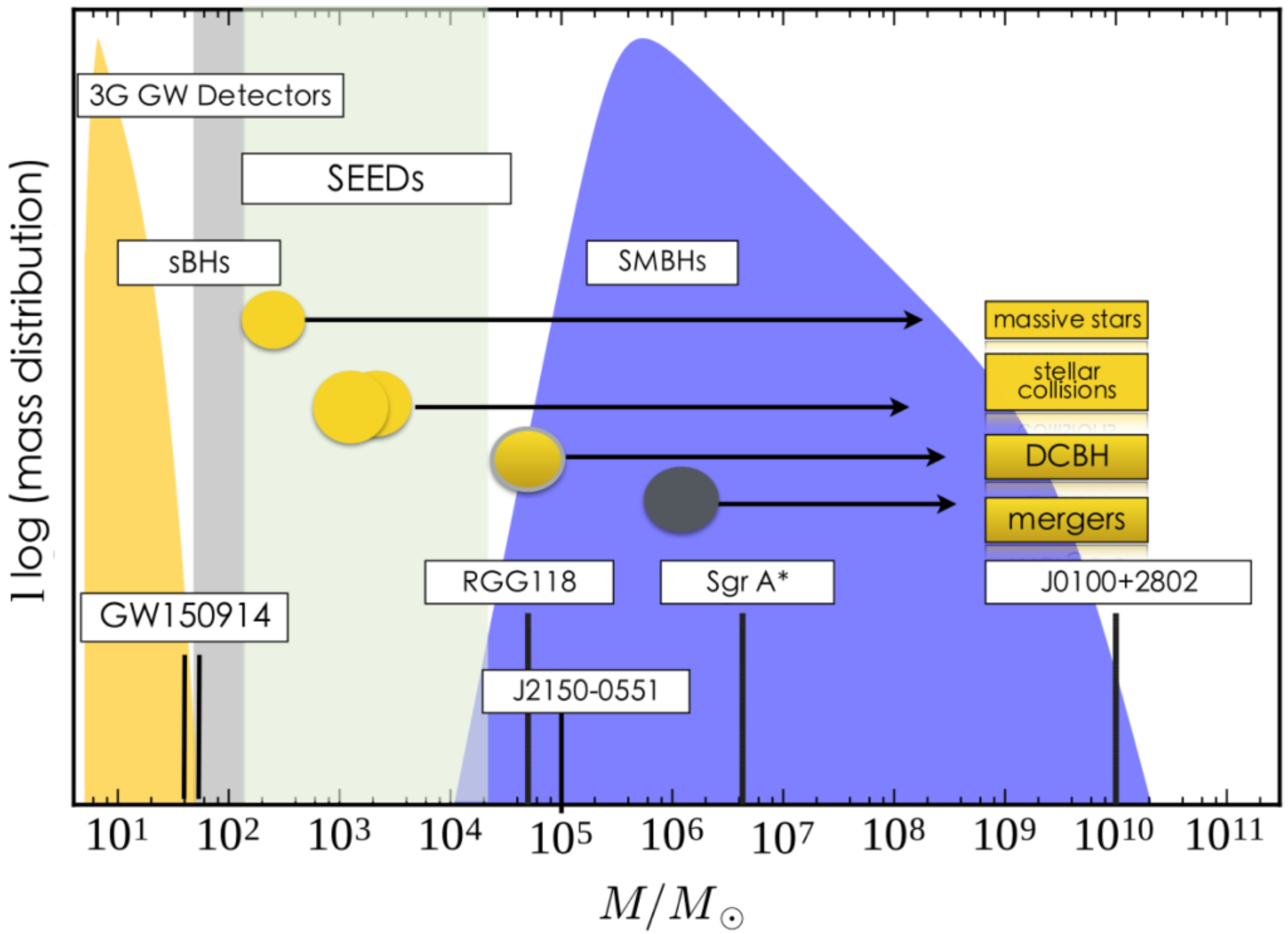
IMBH existence and connection with SMBH

Properties of first stars

ET configuration impact for mergers



Origin of SMBH



Low frequency is crucial for light seed BHs (100-1000 M_{sun})

Neutron star and black hole astrophysics - 2

- Formation of heavy elements
- Host galaxy identification
- Connection to Galactic double NS binaries
- Gamma-ray bursts engine

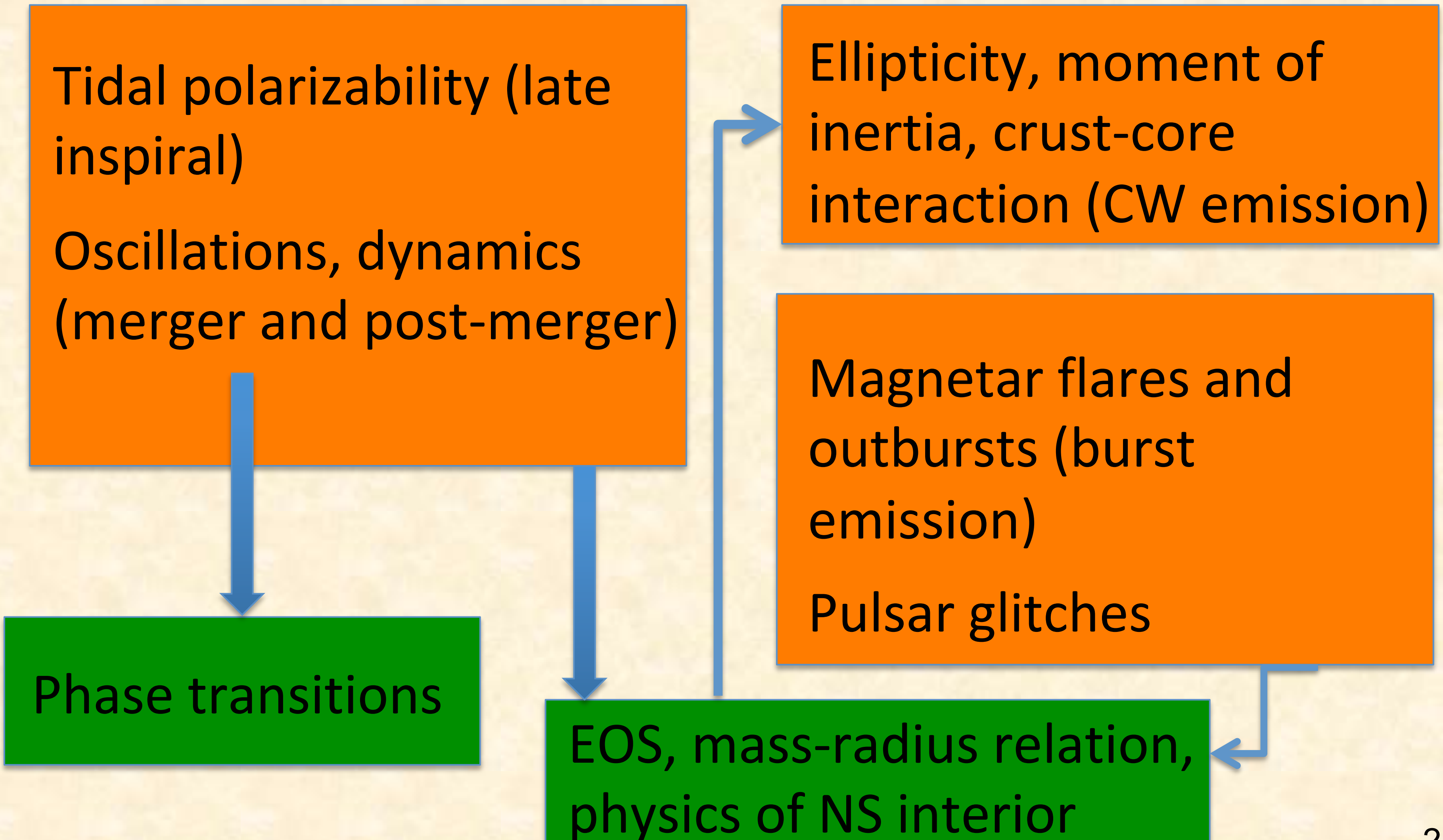
BNS and NSBH demography

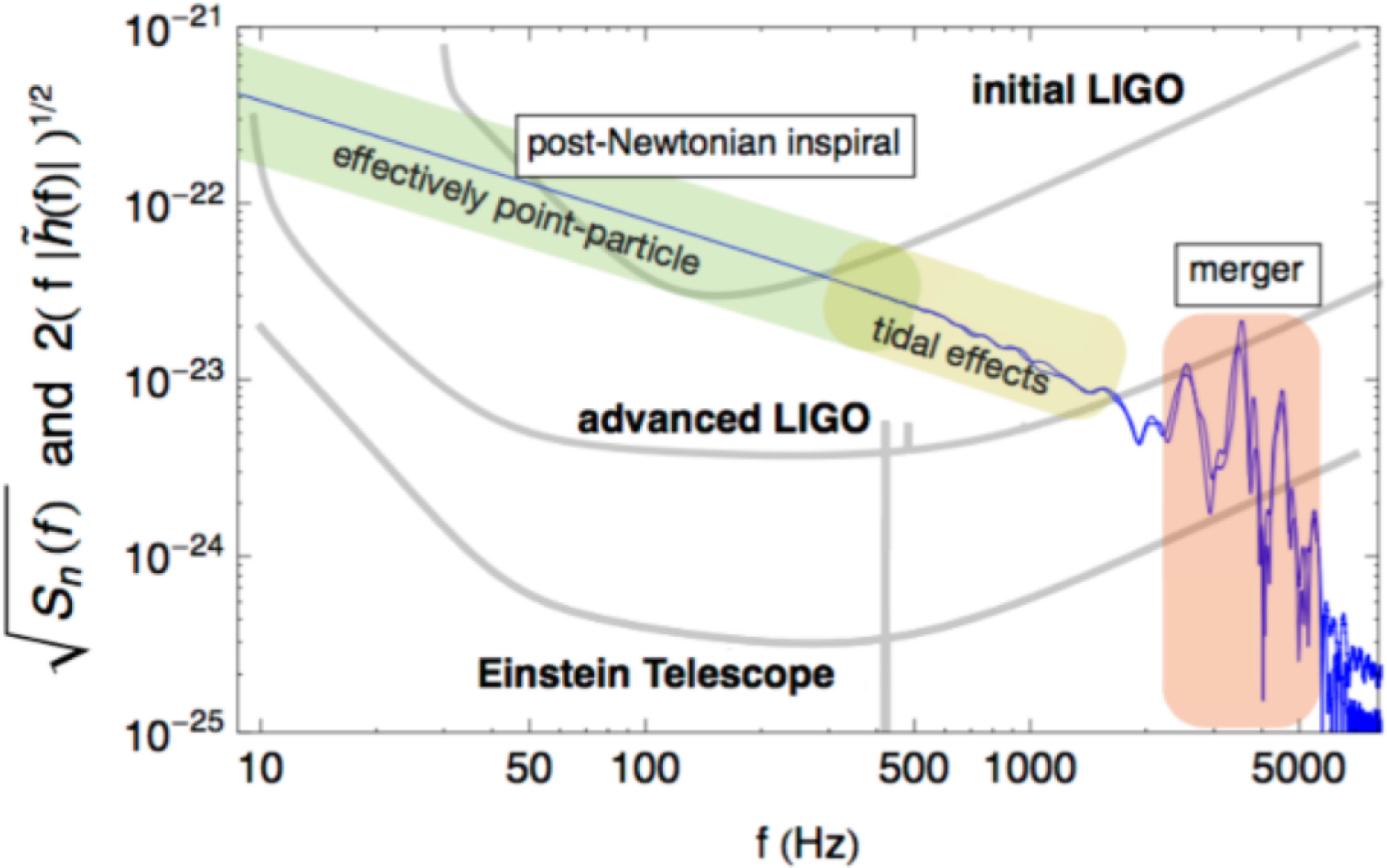
Nucleosynthesis

Jet physics

L. Amati's talk

Neutron star structure





10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
$\sqrt{S_n(f)}$ and $2(\,f\,|\tilde{h}(f)|\,)^{1/2}$
initial LIGO
post-Newtonian inspiral
effectively point-particle
merger
tidal effects
advanced LIGO
Einstein Telescope
10
50
100
500
1000
5000
f (Hz)

ET constraints for CW from spinning NSs

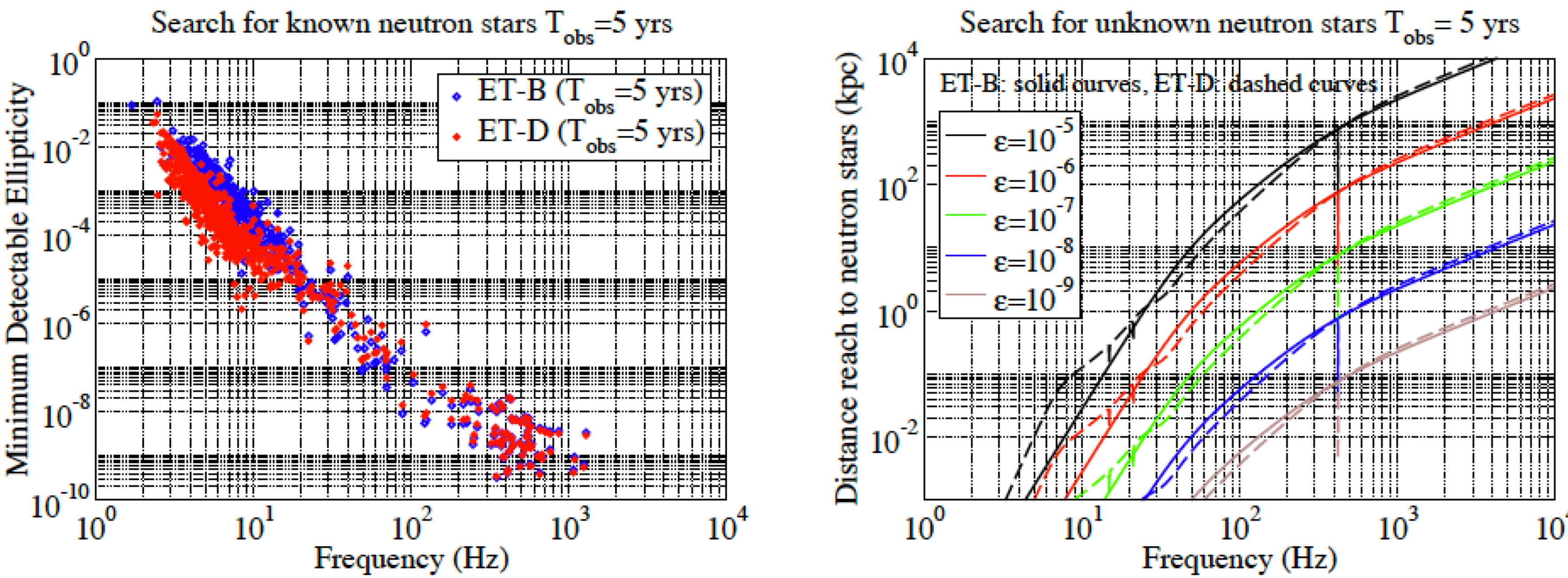


Figure 20: Left: Minimum detectable ellipticity for known pulsars for ET-B and ET-D sensitivities. The search parameters are the same as for Fig. 19. Right: Maximum distance of an unknown source in order to be selected among the candidates of an all-sky search with ET-B and ET-D sensitivities. Search parameters are given in the text.

Plots from ET CDS

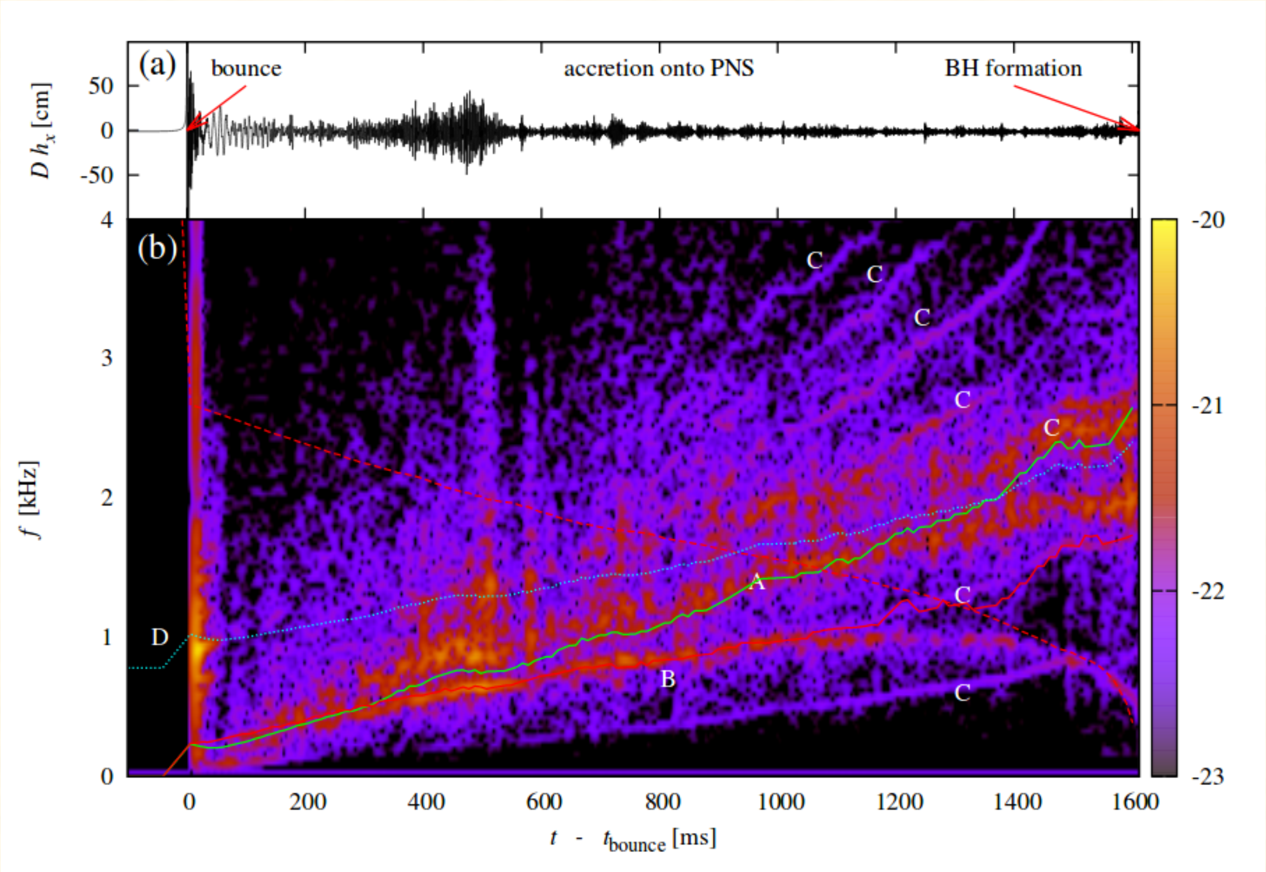
Some indication exists that millisecond pulsars could have ellipticity ~10^{-9}: testable by ET

[Woan+, ApJ 863, L40 (2018)]

Core collapse supernovae

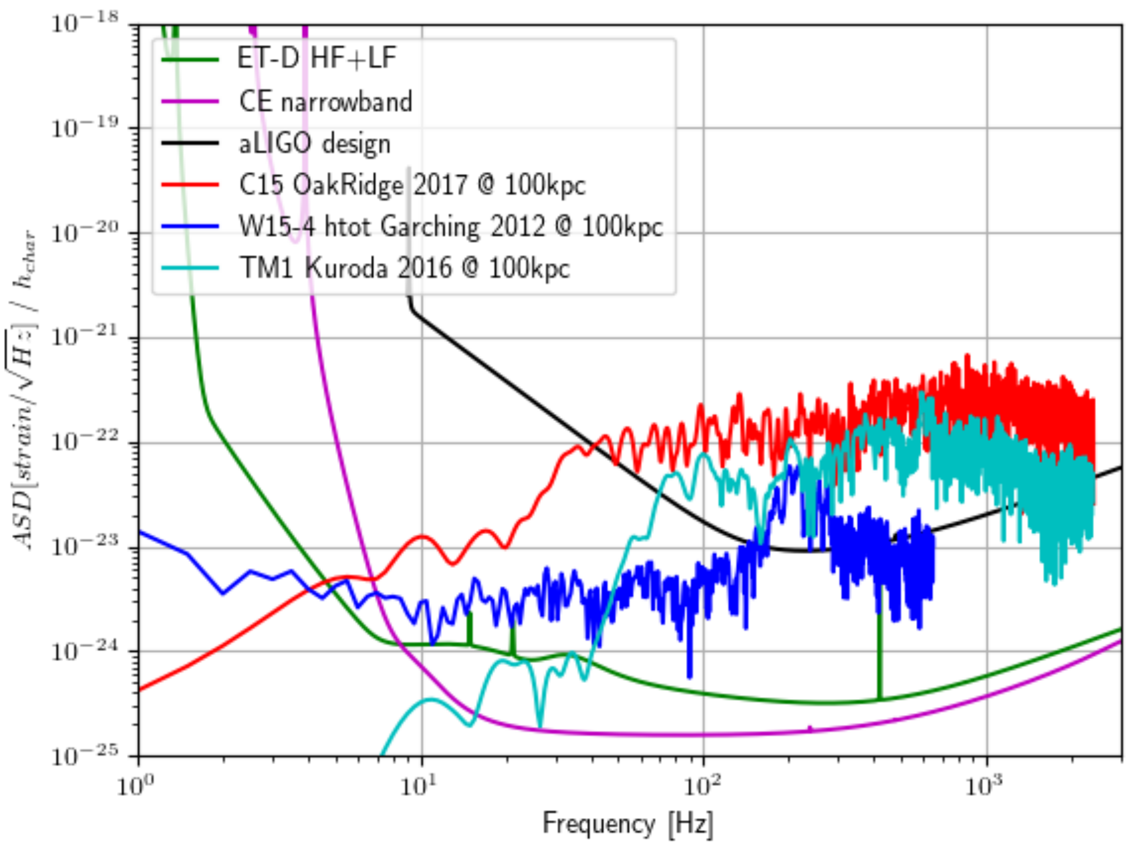
Key questions:

- Understanding the explosion mechanism:
  - Role of neutrinos
  - Role of SASI
  - Role of rotation
  - Role of progenitor mass
  - Mass accretion rate after shock
  - Asymmetry of the explosion
- Time frequency evolution of PNS oscillation modes
- Fate of the collapse (NS or BH?)



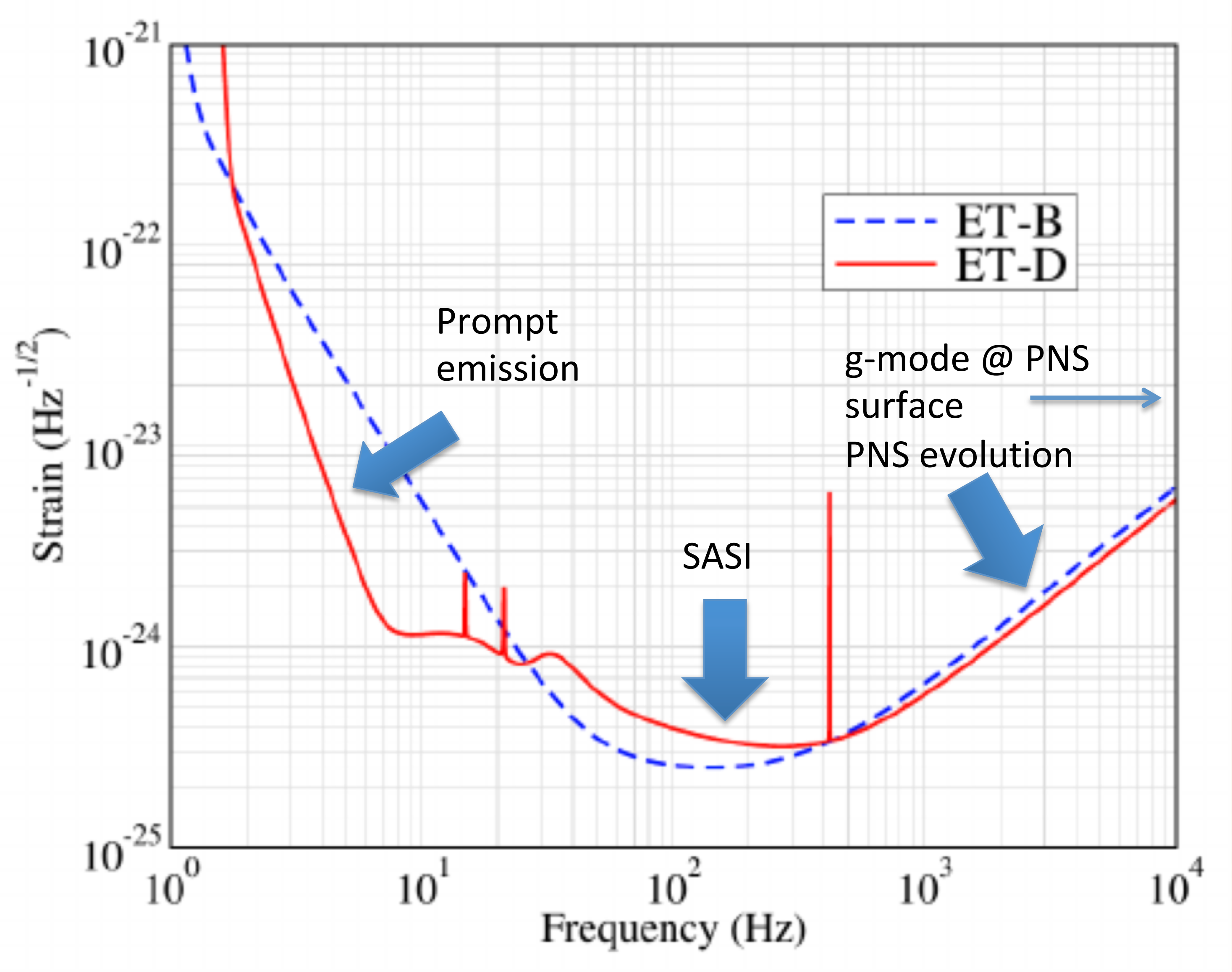
P. Cerda-Duran et al, Astrophys.J. 779 (2013) L18

- Need of (computationally expensive) multi-dimensional, multi-physics simulations.
- Multi-messenger approach (EM, nu) to increase detection efficiency.



	Yakunin 2017	Mueller 2012			Kuroda 2016	
	C15	L15-3	N20-3	W15-1	SFHX	TM1
ET-D	54	12	4	6	24	18
CE	129	26	11	11.5	51	37
aLIGO	5.9	1.3	0.4	0.6	2.7	2.0

Table 4.1: Matched-filter SNRs of six 3D neutrino-driven explosion simulations for a source located at 100 kpc recorded in 1) the Einstein Telescope (ET-D), 2) the Cosmic Explorer (CE), and 3) and advanced LIGO at design sensitivity (aLIGO) are provided here. The matched-filter SNRs do not include a detector's antenna function.



10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain (Hz$^{-1/2}$)
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)
ET-B
ET-D
Prompt emission
SASI
g-mode @ PNS surface
PNS evolution

Cosmology and cosmography - 1

SGWB of cosmological origin

Inflation

1^{st} order phase transitions

Cosmic strings

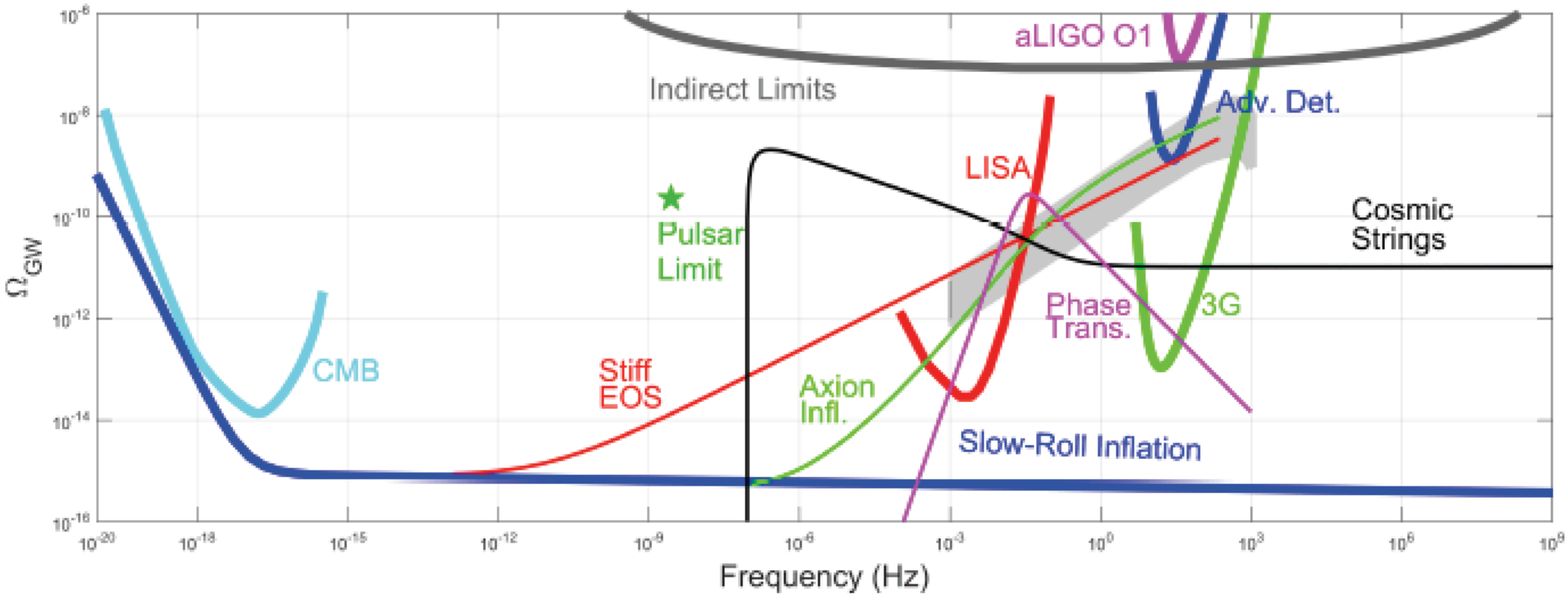
SGWB of astrophysicsal origin

BBH background noise

Distorted NS

Core collapses

SGWB landscape plot



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

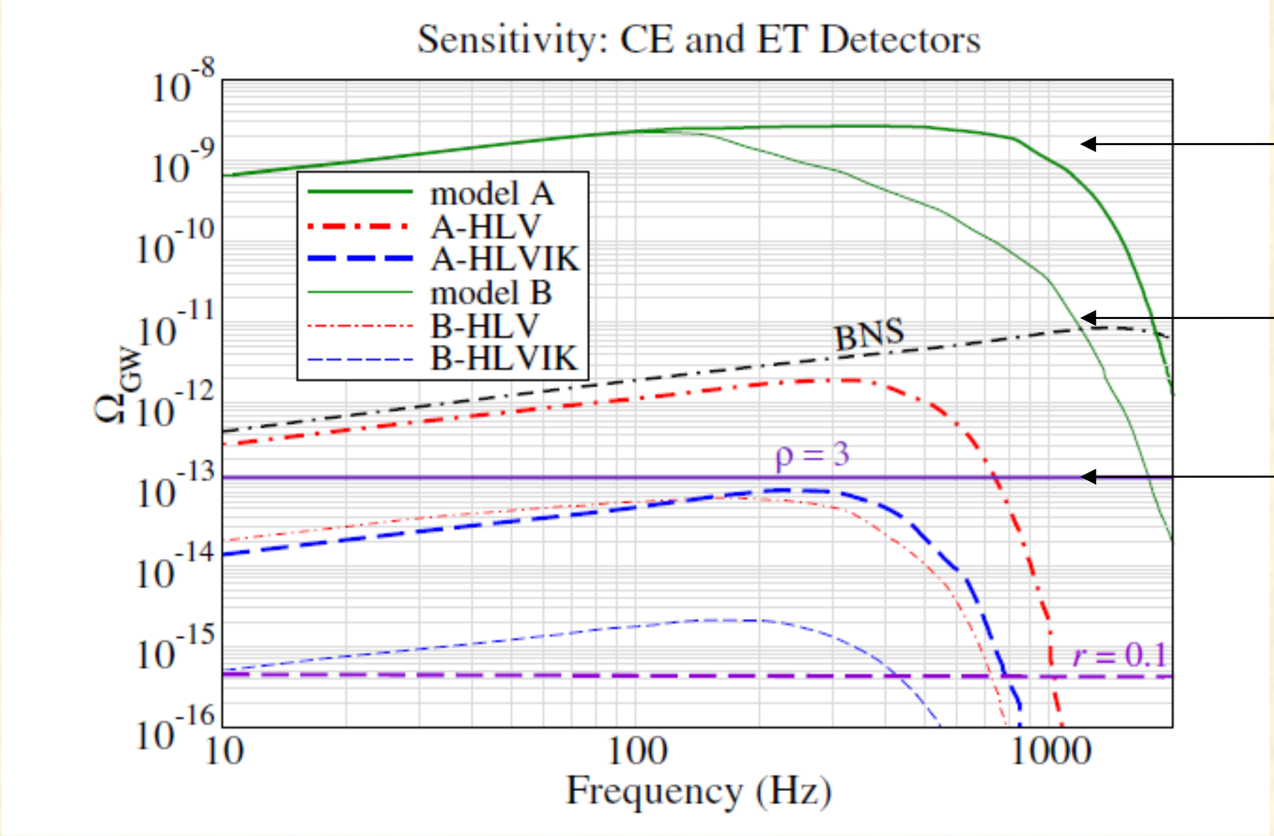
: normalized energy spectrum

$$\rho_c = 3H_0^2c^2/(8\pi G)$$

A. Ricciardone's talk

Observing primordial SGWB below the BBH foreground?

Assuming ET is able to detect individually all BBH mergers throughout the Universe



SGWB from BBH

SGWB from BNS (may remain a background)

Limit on Ω_{GW} reachable if all BBH individual mergers are removed after 5 years: 10^{-13}

Regimbau et al PRL 118, 151105 (2017)

Cosmology and cosmography - 2

Dark matter effects

- Primordial BHs
- Dark photon
- Ultra-light bosons around BHs

Cosmological parameters

- H_0
- dark energy density
- Modified GW propagation

- Use standard sirens to infer cosmological parameters:

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M (1+\tilde{z})^3 + \rho_{\mathrm{DE}}(\tilde{z})/\rho_0}}$$

From a measure of the luminosity distance, we can get H_0, dark energy density,…

M. Maggiore’s talk

This requires the source redshift:

- EM counterpart
- Statistical method
- Tidal polarizability (assuming NS EOS is known)

-> 1% accuracy after ~10^5 events in 3G detectors

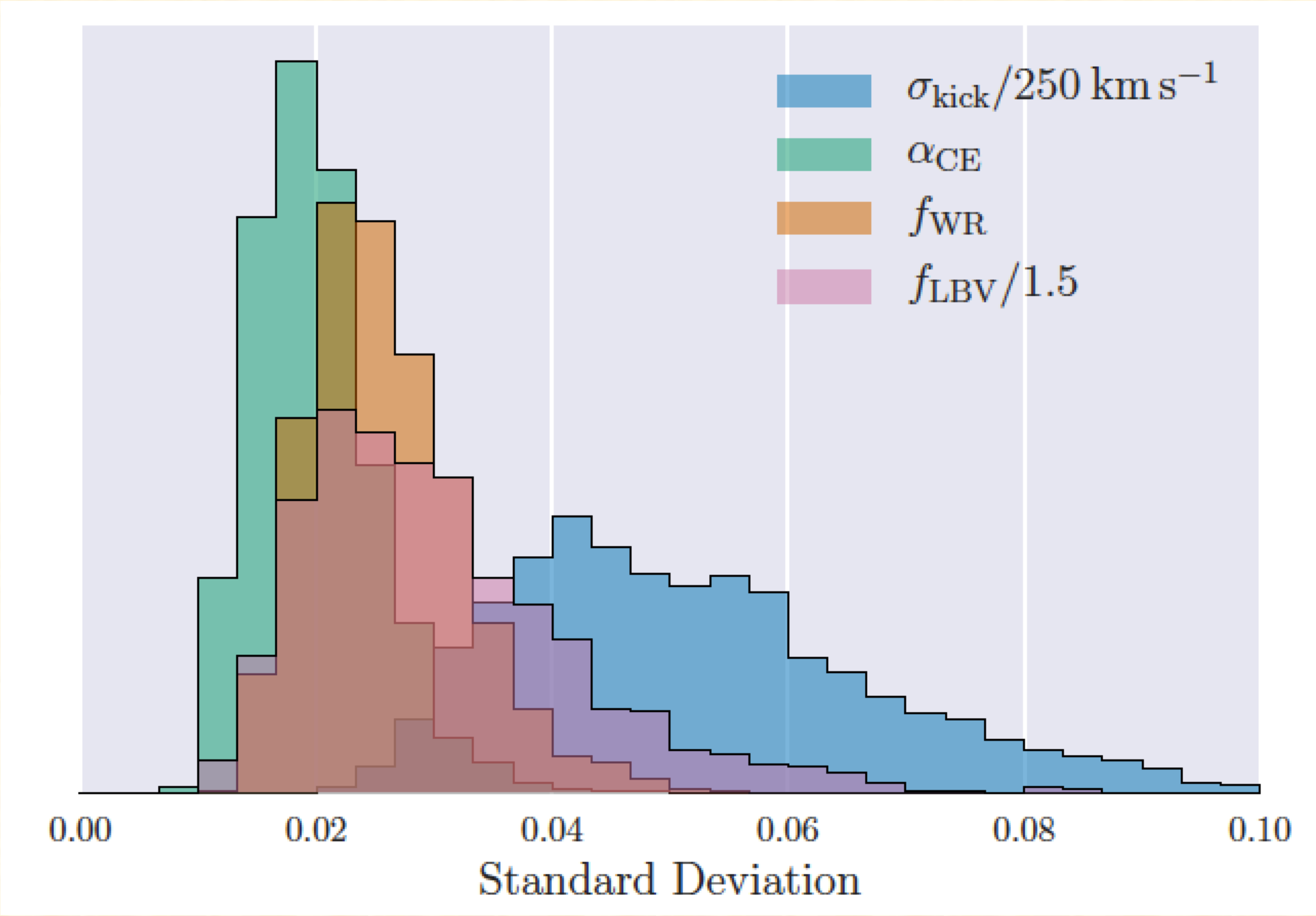
Conclusions

- Timeline: first draft of the science case available in June

- Do we foresee to make a review?

BACKUP SLIDES

Expected distribution of fractional measurement accuracy for various quantities related to BHBH progenitors common-envelope phase



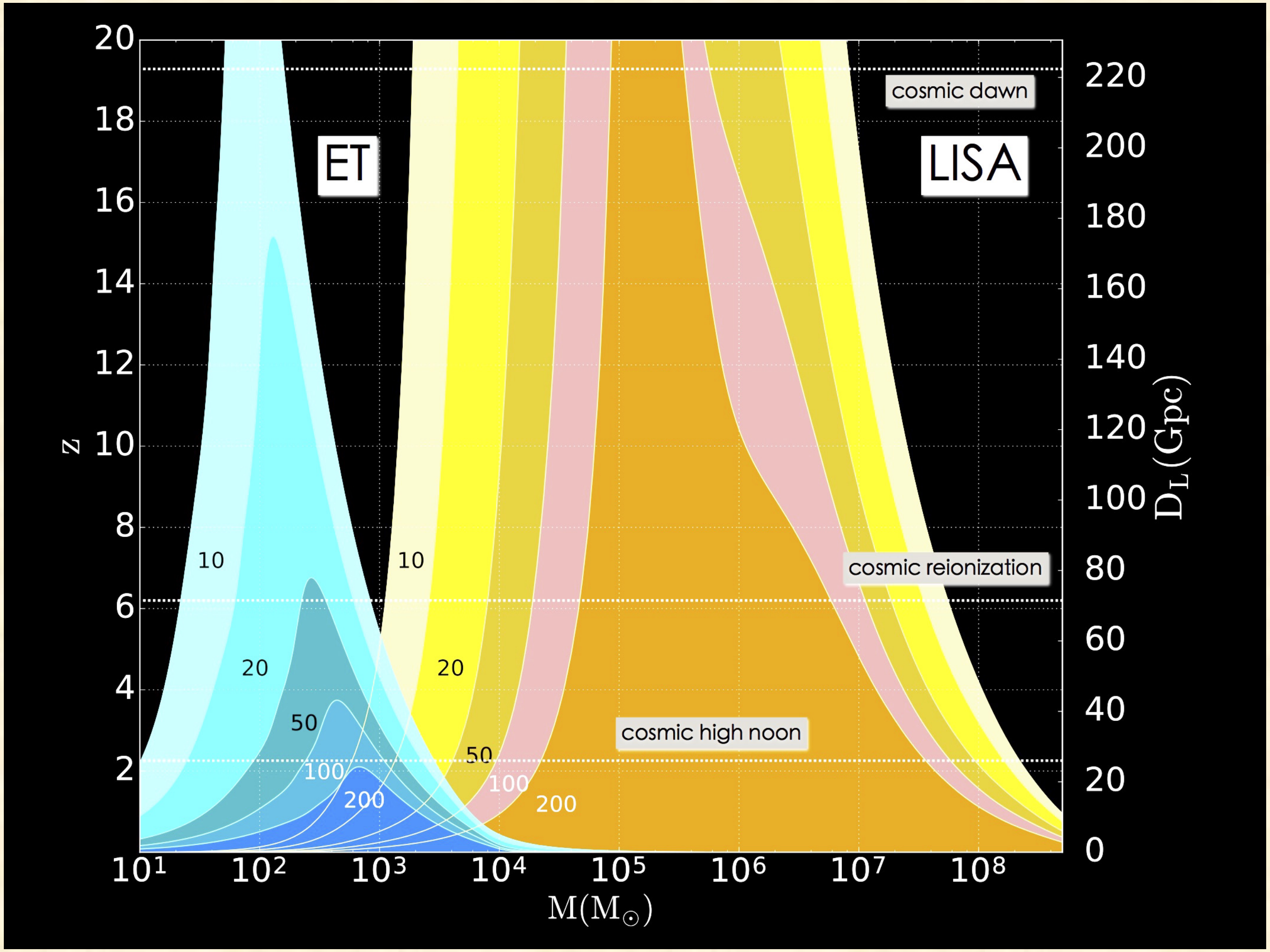
For cosmological sources a knowledge of the redshift is needed to convert from “observed” to “intrinsic” values of the observables. E.g. $M_{\rm obs} = M_{\rm int}(1+z).$

If the host galaxy cannot be determined, the redshift can in principle obtained from a measure of the source luminosity distance, assuming a cosmology:

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M(1+\tilde{z})^3+\rho_{\rm DE}(\tilde{z})/\rho_0}}$$

The luminosity distance, however, is strongly correlated with source’s orientation and polarization (30% error at SNR~10)

Detectability of BBH systems by ET and LISA



Multi-band detection of IMBH

Complementarity in understanding the origin of SMBHs

SGWB from cosmic strings

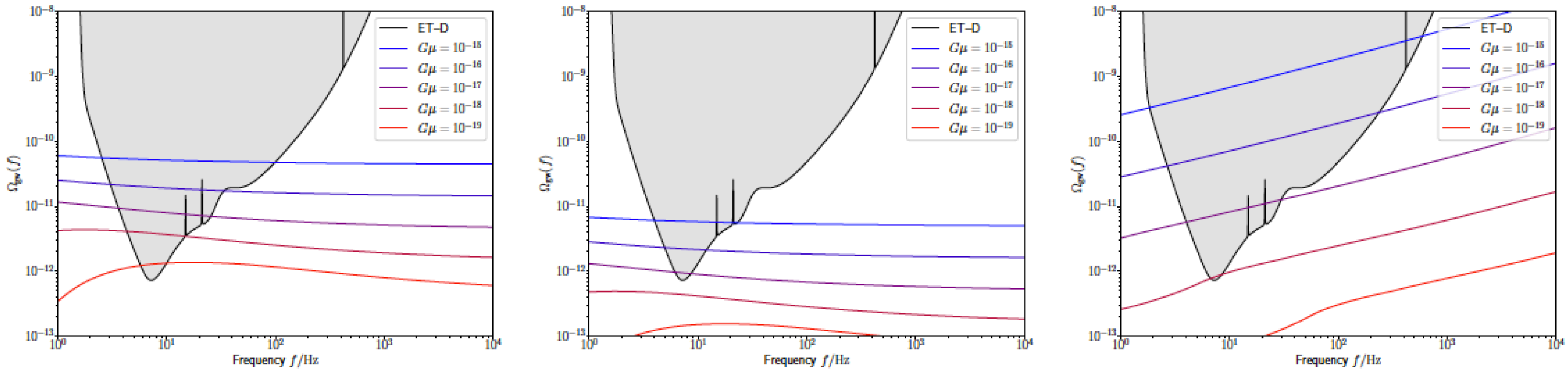


Figure 6.3: Stochastic background intensity from cosmic strings using a particular model of the loop distribution function, with the three different plots corresponding to the three models in Ref. [759, 760]. The shaded area is the 95% confidence detection region of ET-D for stochastic backgrounds, assuming cross-correlation of data between two co-located detectors at the ET site with uncorrelated noise, and one year of observation time (increasing this to N years would bring the curve down by a factor of $\sqrt{N}$).

Reference????

Likelihood contour plots (1000 standard sirens with ET)