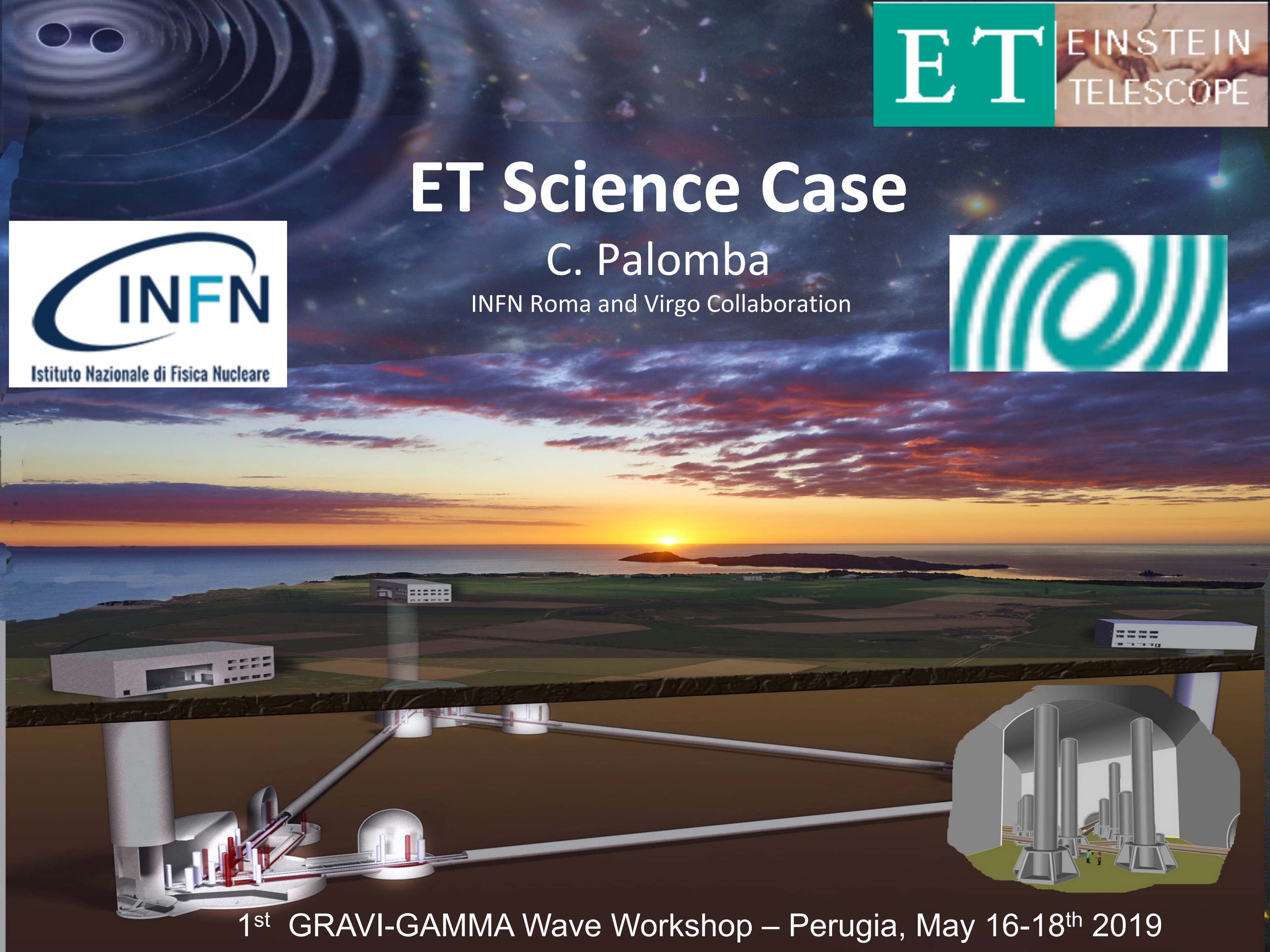


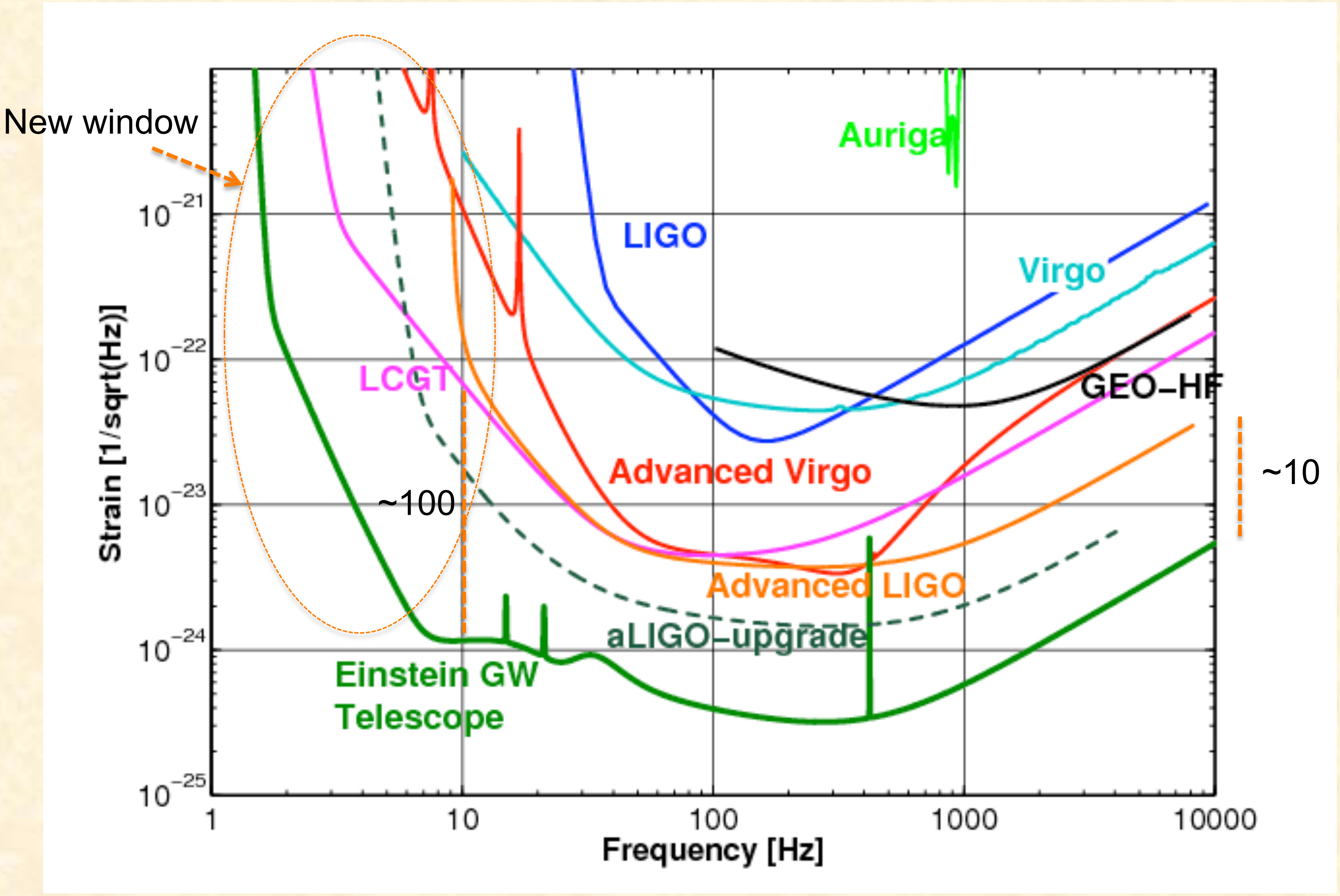
ET Science Case

C. Palomba

INFN Roma and Virgo Collaboration

1st GRAVI-GAMMA Wave Workshop – Perugia, May 16-18th 2019

Planned ET sensitivity



Benefits of 3G detectors

- **Deeper***: observe more distant sources (population studies, cosmological effects,…)

- **Wider***: increase accessible parameter space (new sources, wider study of known sources,…)

- **Sharper***: detect more subtle effects (new sources, test of models,…)

- For some science goals GWs are a unique probe.
- For others a multi-messenger approach is the key.

*: from the BBH chapter of the GWIC 3G white paper

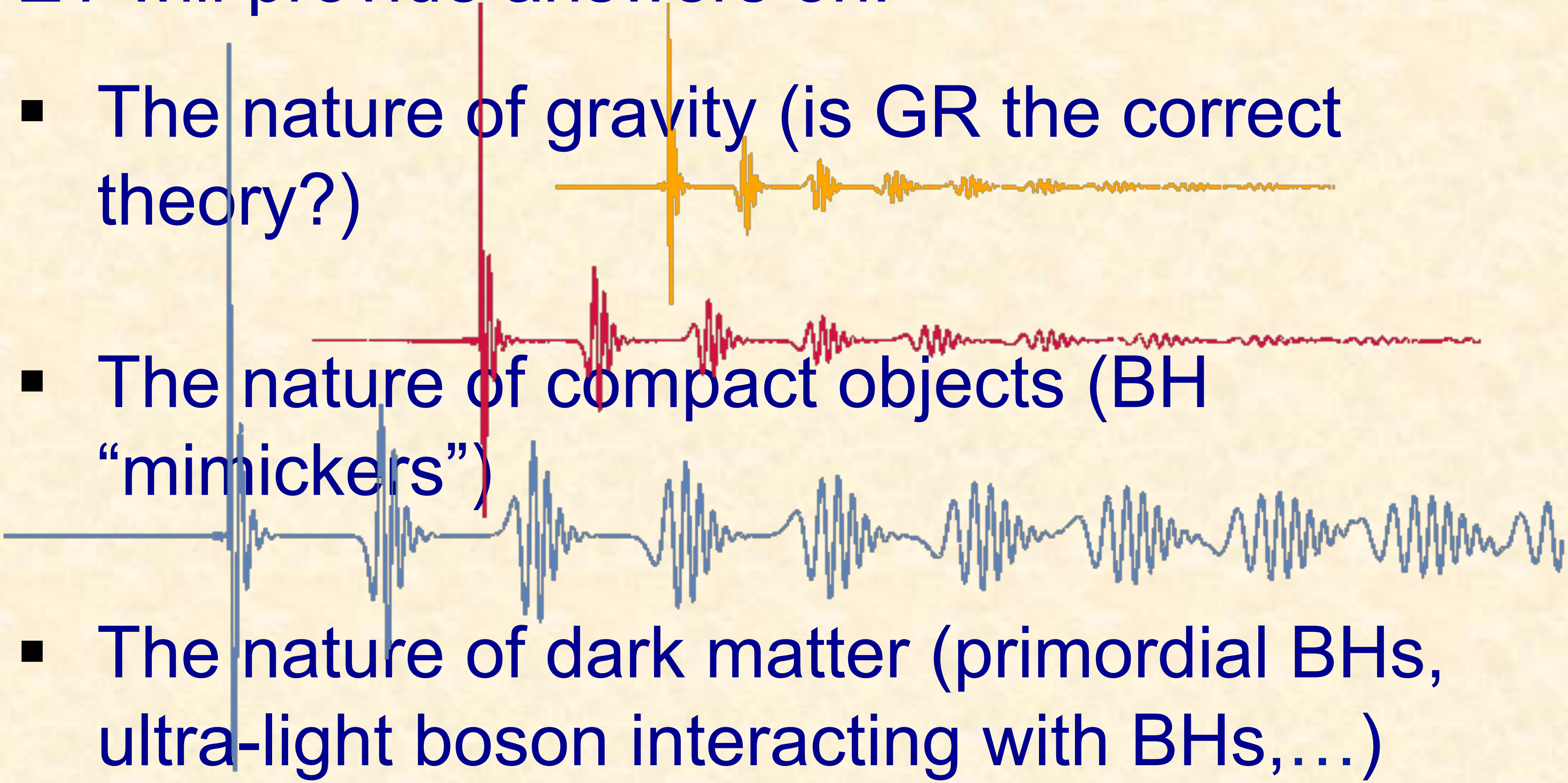
Science case topics (partially overlapped)

- **Fundamental physics**
- **Physics and Astrophysics of compact objects**
- **Cosmology & cosmography**

Science is beautiful but you need appropriate tools to make it

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

Fundamental physics

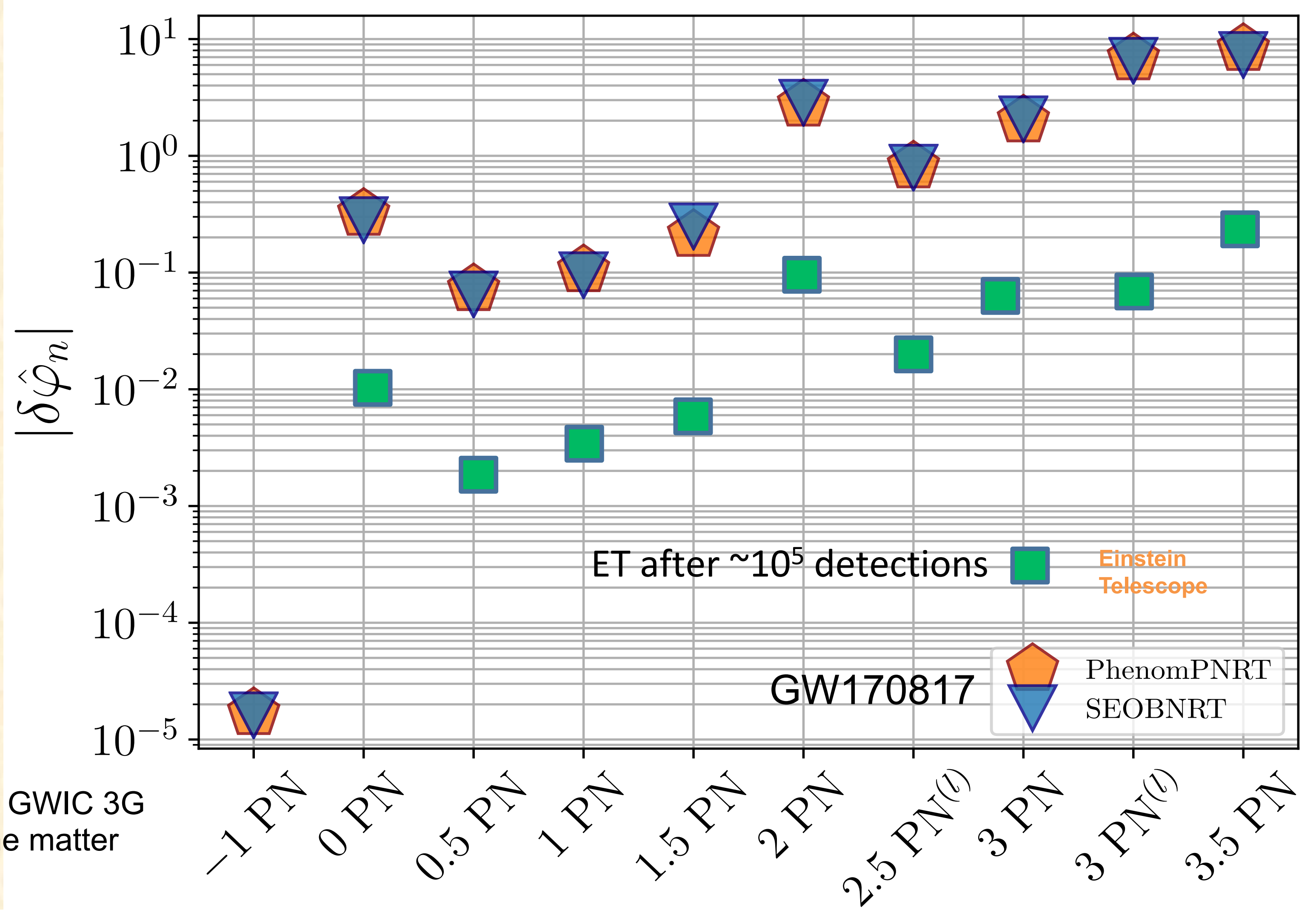


ET will provide answers on:

- The nature of gravity (is GR the correct theory?)
- The nature of compact objects (BH “mimickers”)
- The nature of dark matter (primordial BHs, ultra-light boson interacting with BHs,…)

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

Deviations from GR show up in GW waveform

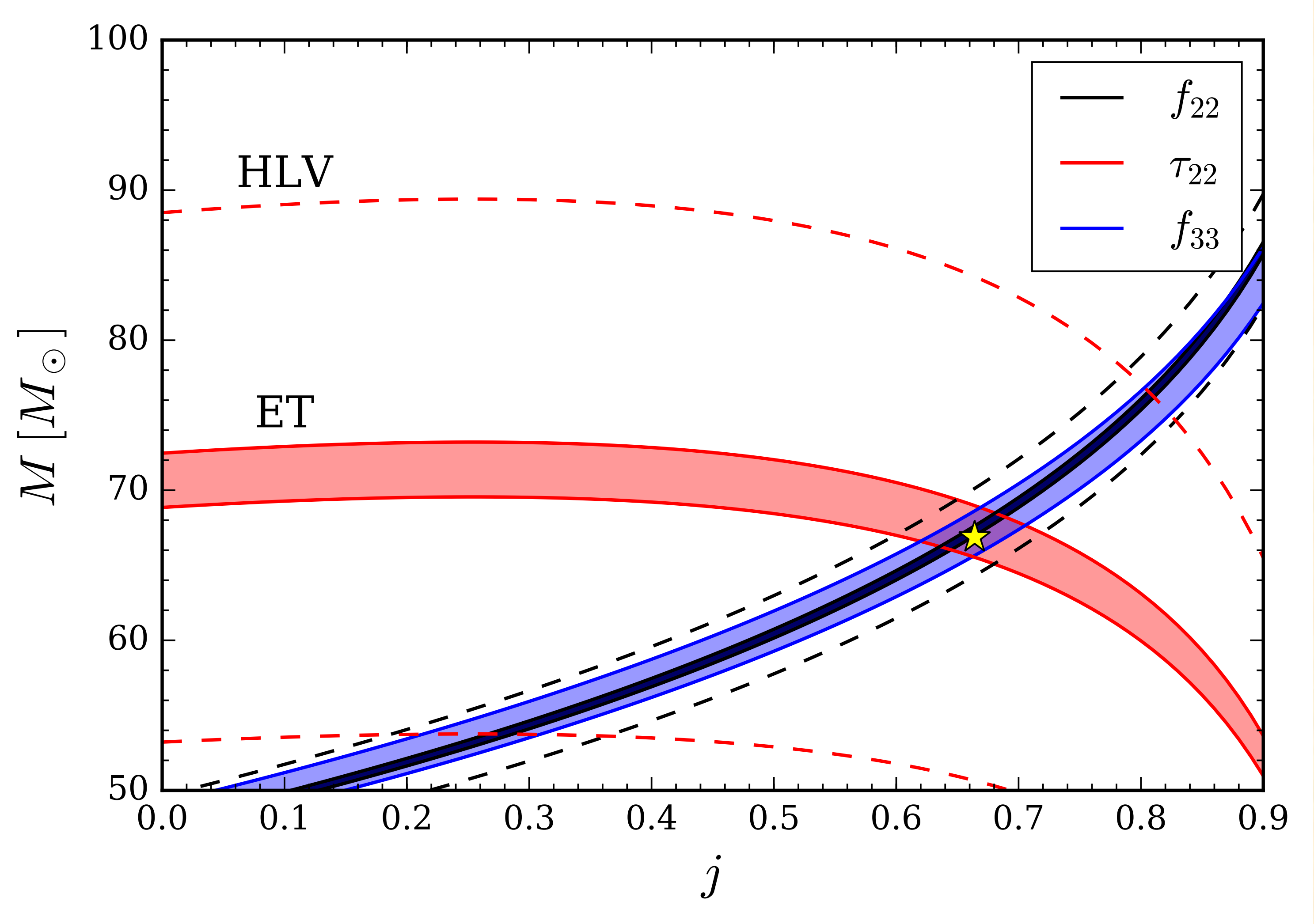


90% upper bounds on GR-violating parameters

Credit: GWIC 3G extreme matter group

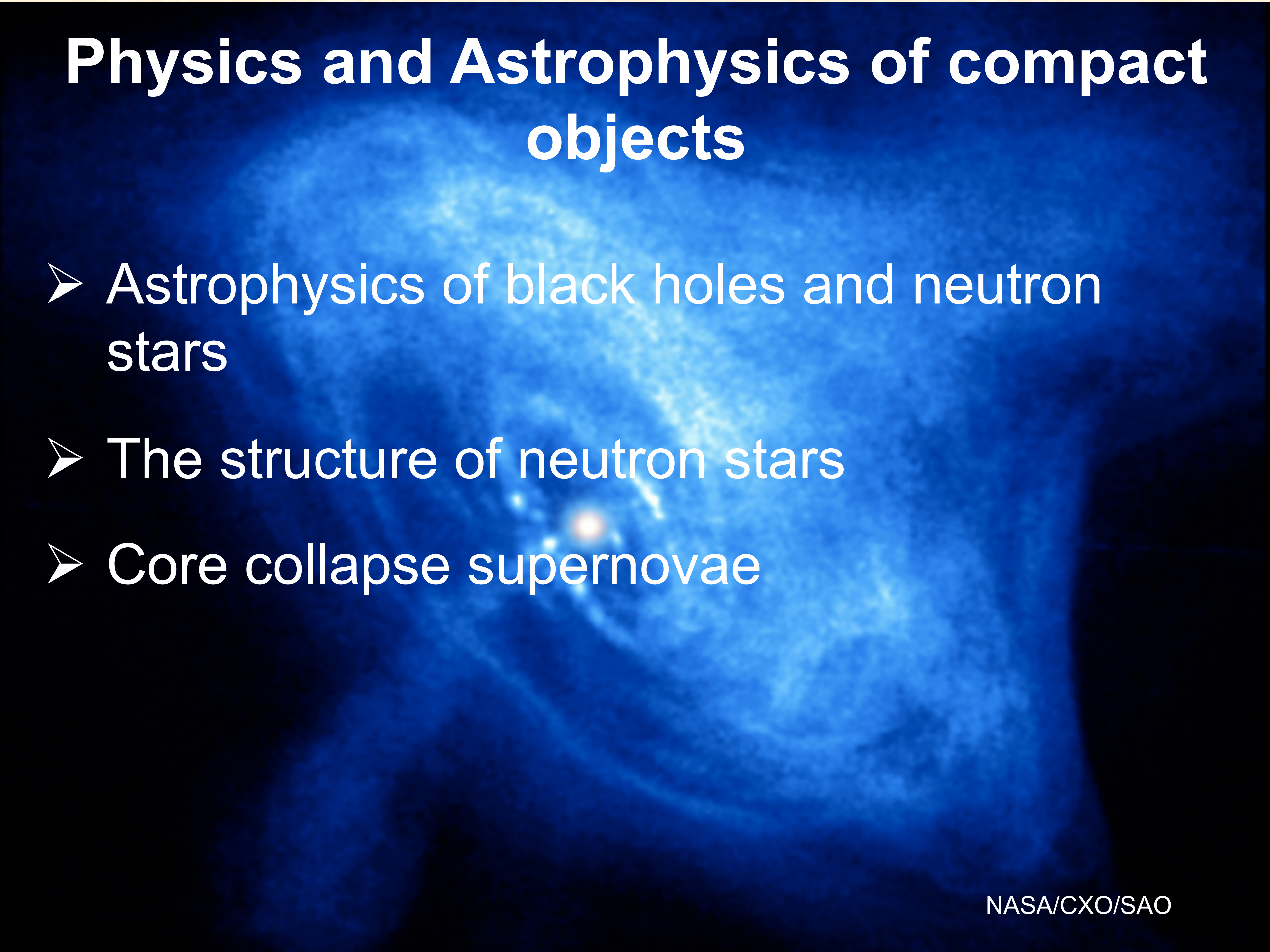
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^{2} + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}}\log\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^{5} + \ldots + \varphi_{3.5\mathrm{PN}}\left(\frac{v}{c}\right)^{7}\right]$$

- Test the 'no-hair' conjecture by measuring frequency and decay times of at least two BH quasi-normal modes



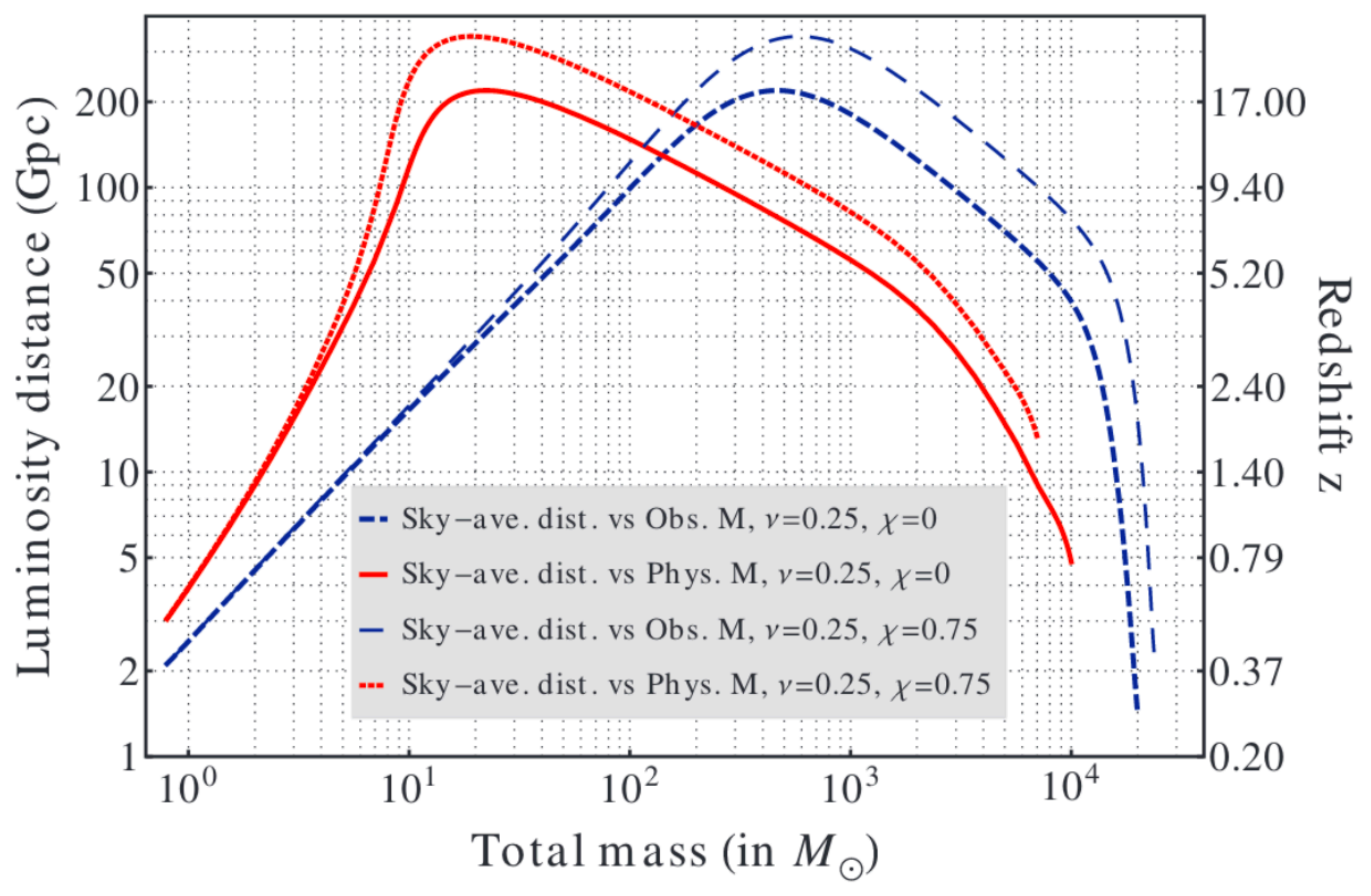
Physics and Astrophysics of compact objects

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



NASA/CXO/SAO

Maximum distance of detectable binary systems



- **ET will see all the BBH in the Universe and BNS systems up to z~2**

→ Accurate measure of spins, masses, natal kicks, orbital eccentricity,…

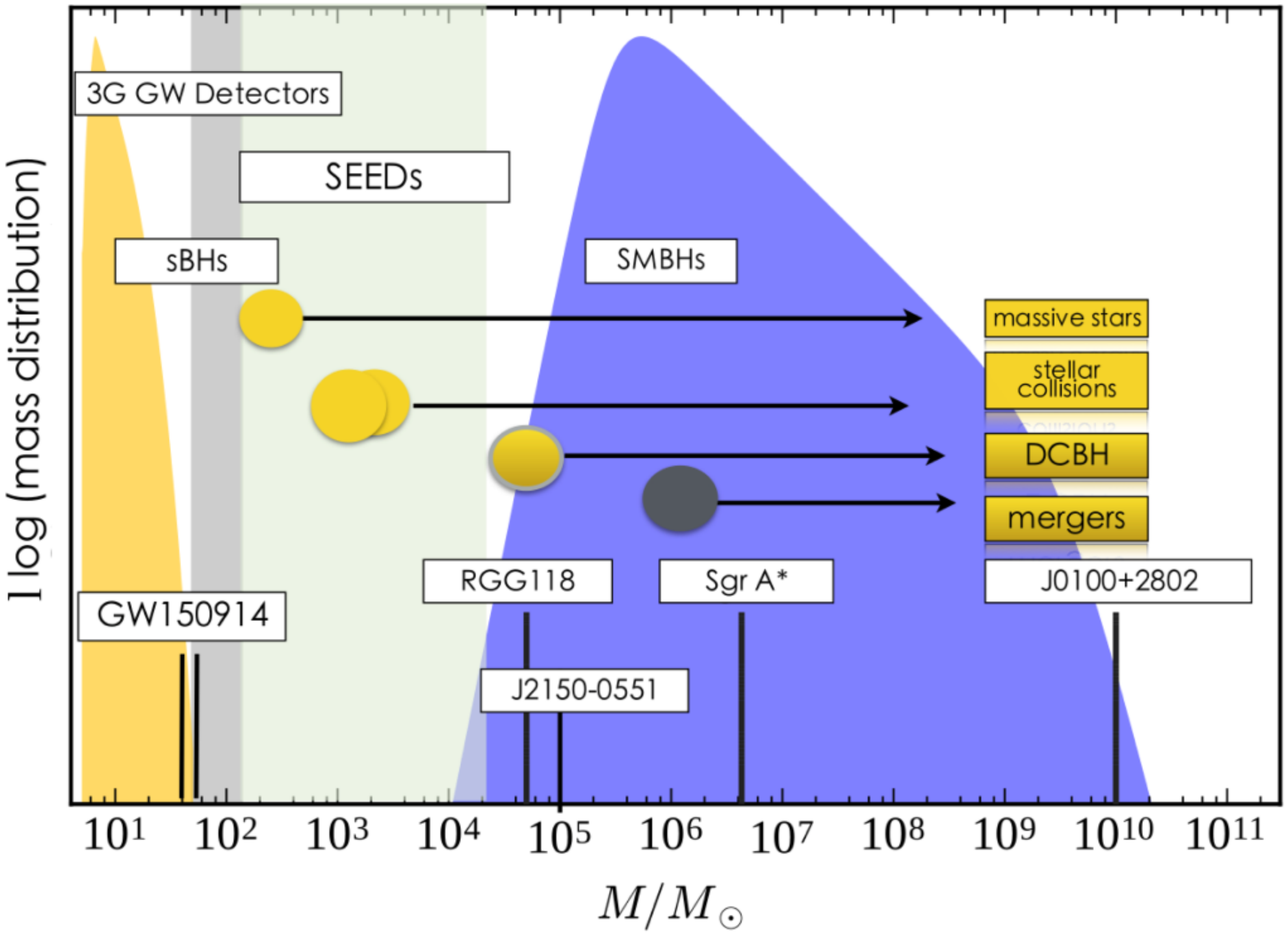
→ Merger rate vs redshift

Compact binaries formation channels

Properties of first stars

IMBH existence and connection with SMBH

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



- In conjunction with EM observations (e.g. of kilonovae and GRBs)

Nucleosynthesis (formation of heavy elements)

Jet physics (GRB engine)

Host galaxy identification

- Identification of kilonovae beyond z~0.5 needs 8-m class facilities (e.g. LSST) in absence of a GRB pointing toward us
- At z<0.5 thousand host galaxy will be identified through kilonova emission

- In c njunction with EM observations (e.g. of ki and GRBs)

N (for heavy elen

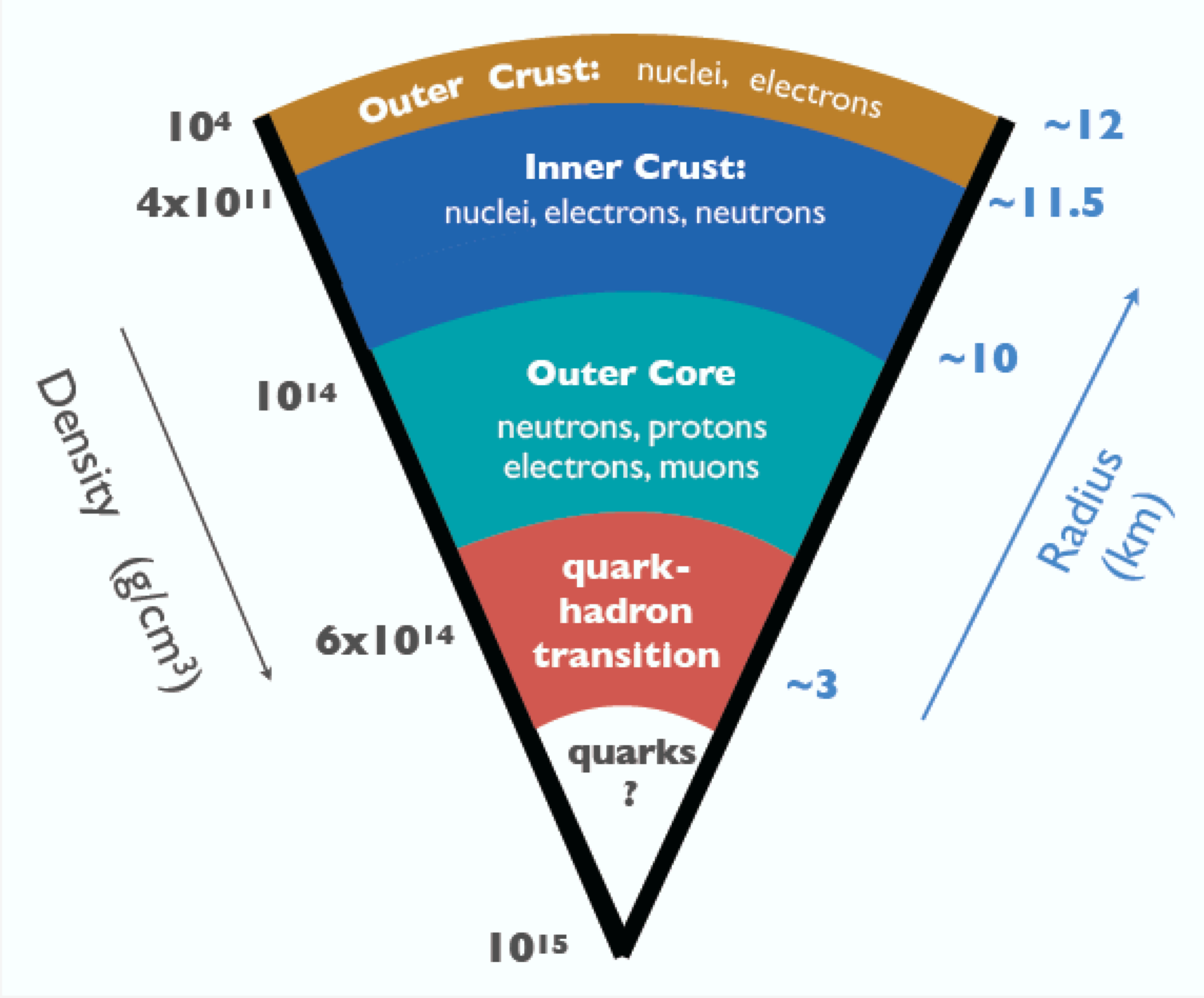
ics)

Host galaxy identification

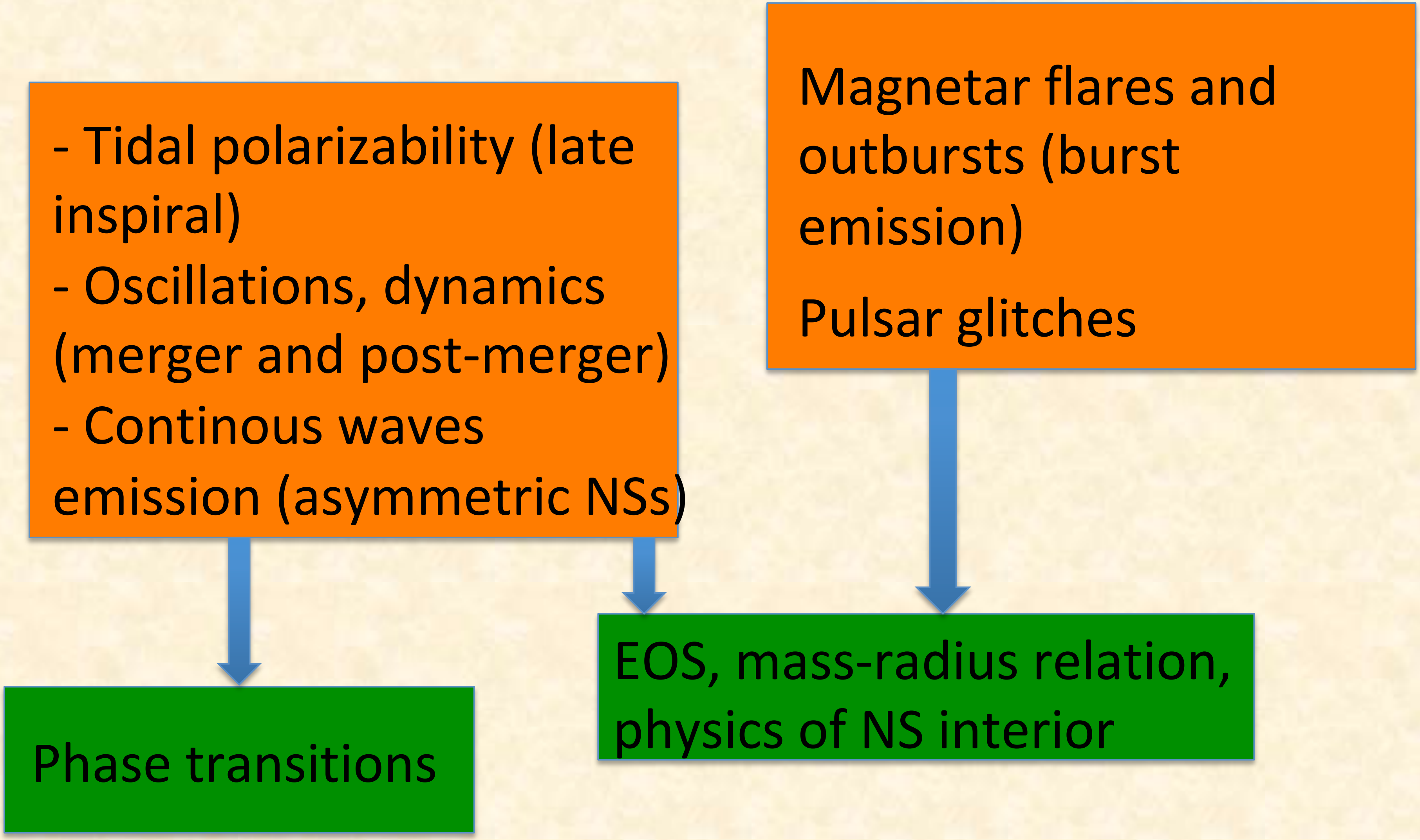
Much more in M. Branchesi's seminar tomorrow

- Identification o 0.5 needs 8-m class facilities (e of a GRB pointing toward us
- At z<0.5 thousand host galaxy tified through kilonova emission

Neutron star structure



Neutron star structure



- Tidal polarizability (late inspiral)
- Oscillations, dynamics (merger and post-merger)
- Continous waves emission (asymmetric NSs)

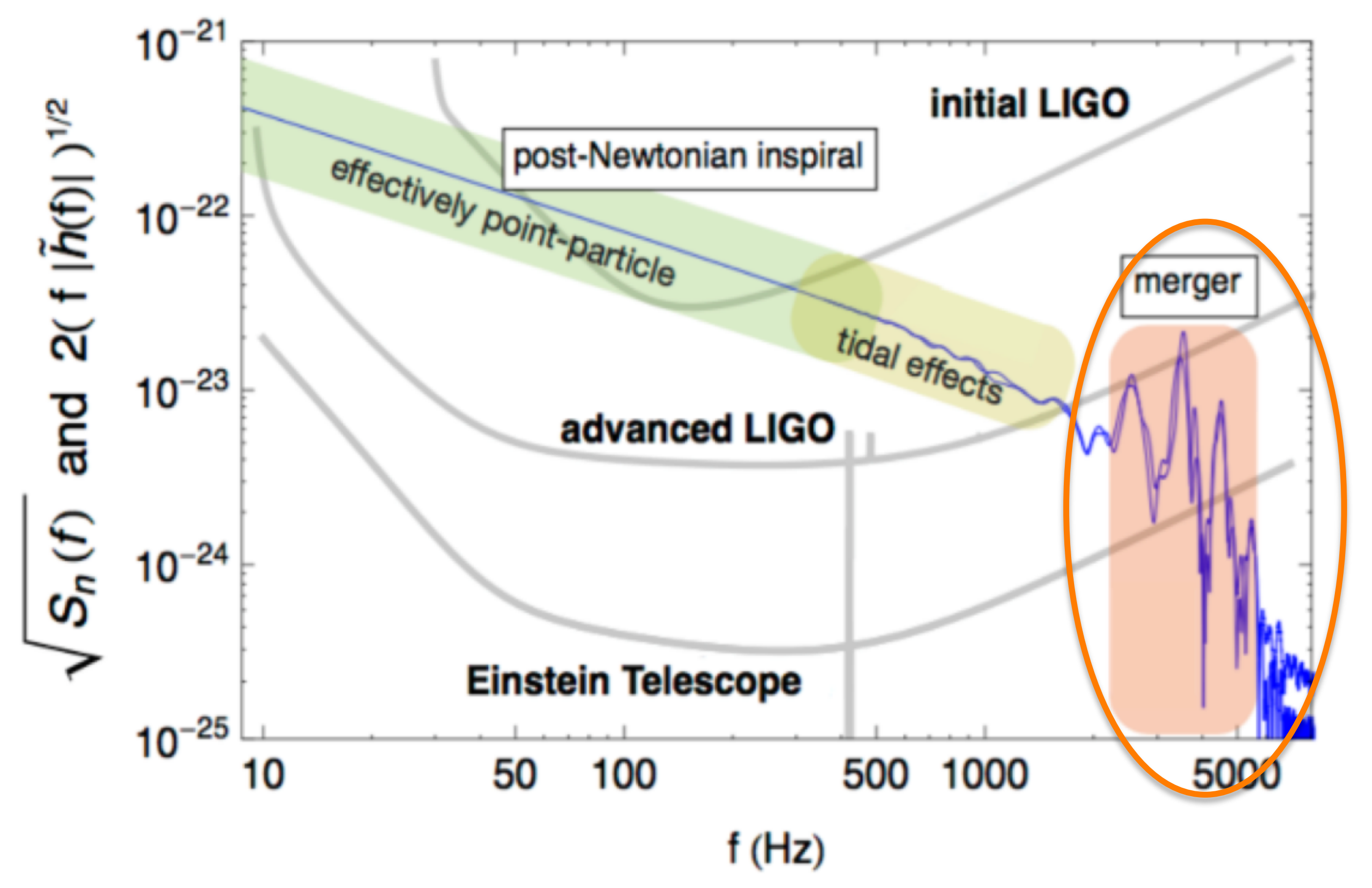
Magnetar flares and outbursts (burst emission)

Pulsar glitches

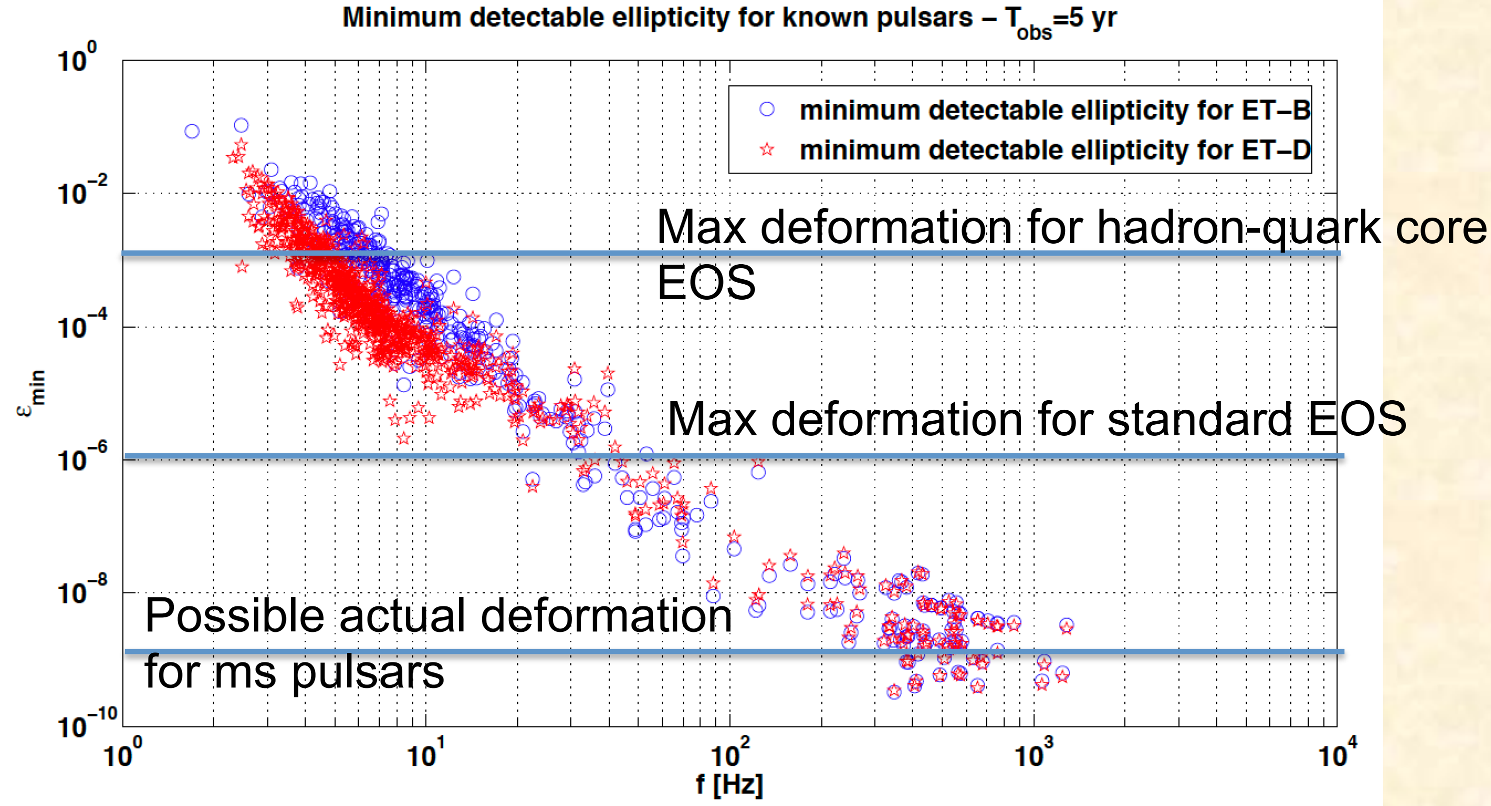
Phase transitions

EOS, mass-radius relation, physics of NS interior

Inspiral and merger signal amplitude spectrum



ET constraints on NS ellipticity



Some indication exists that millisecond pulsars could have ellipticity ~10^{-9}: testable by ET [Woan+, ApJ 863, L40 (2018)]

→ True astrophysics and nuclear physics laboratory to study NS properties

Cosmology and cosmography

SGWB of cosmological origin

Inflation

1st order phase transitions

Cosmic strings

Not guaranteed

SGWB of astrophysicsal origin

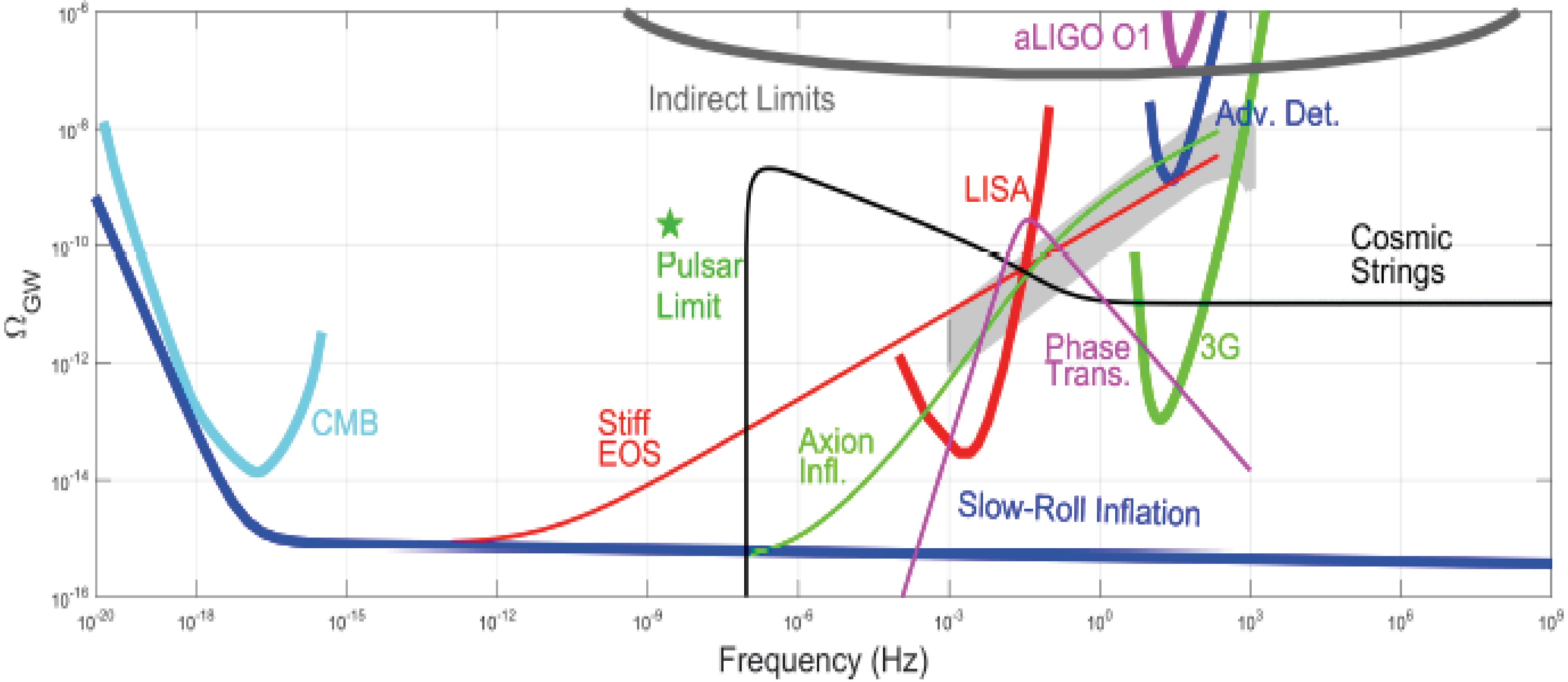
BBH background noise

Distorted NS

Core collapses

Almost guaranteed

SGWB landscape plot



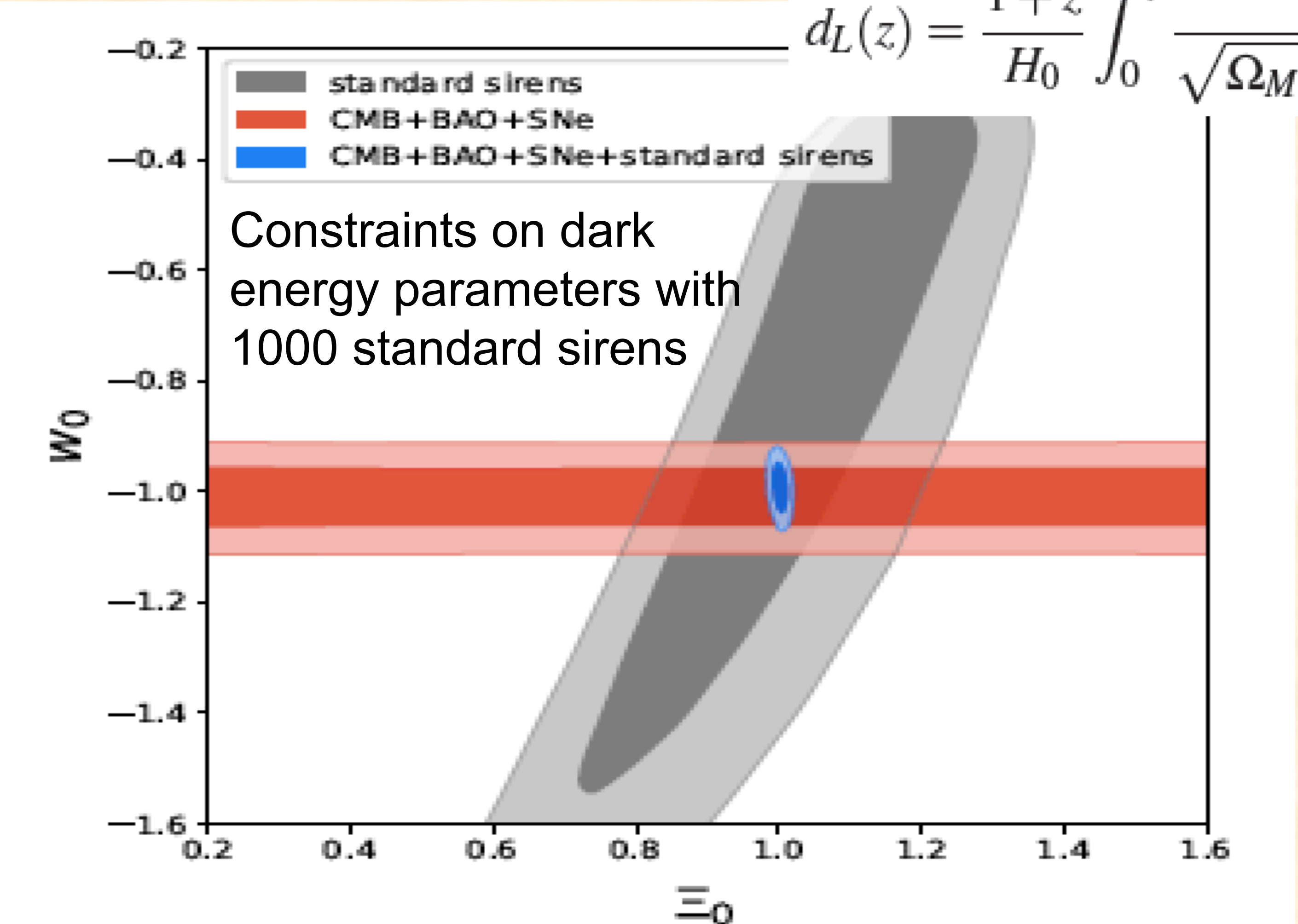
$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df}$: normalized energy spectrum $\rho_c = 3H_0^2c^2/(8\pi G)$

Need to subtract all individual BBH mergers throughout the Universe

➢ ET will measure cosmological parameters with high accuracy (~1% after few years)

→ through standard candles

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



Constraints on dark energy parameters with 1000 standard sirens

The present and the future of GW astronomy


Saturn as viewed by
G. Galilei in 1610

The present and the future of GW astronomy

Saturn as viewed by
G. Galilei in 1610

Advanced detectors

The present and the future of GW astronomy

Advanced detectors


Saturn as viewed by G. Galilei in 1610

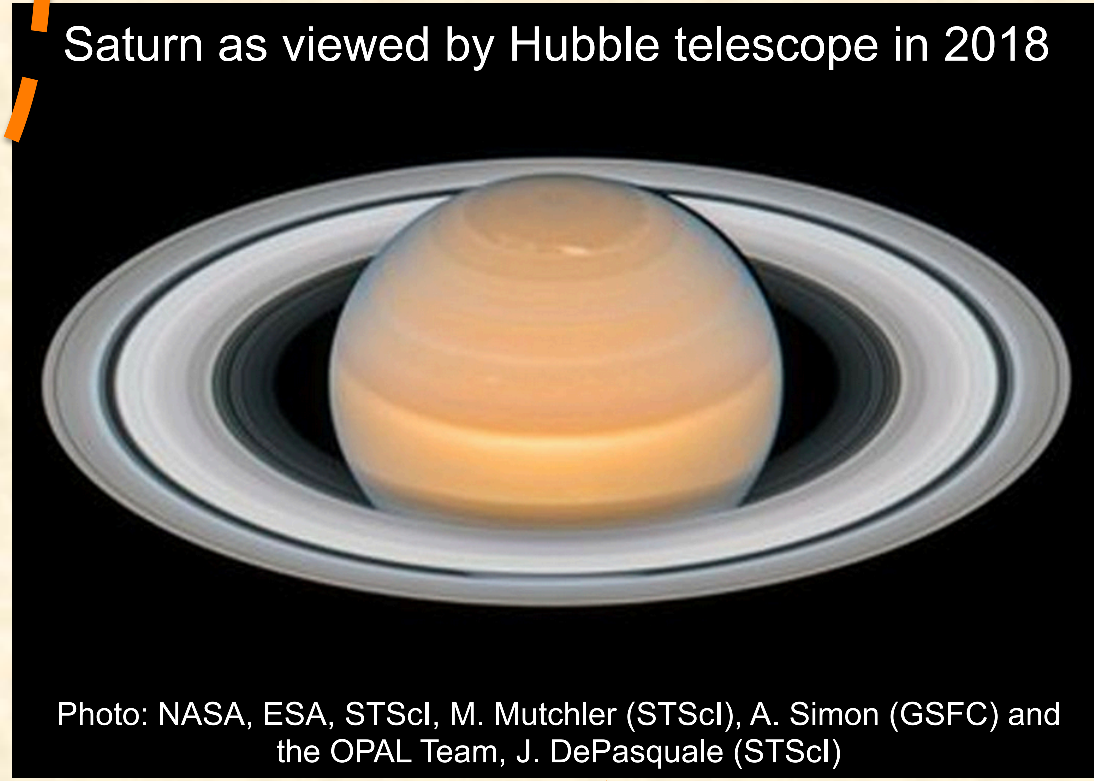

Saturn as viewed by G. Cassini in 1675

arXiv:1309.1711

The present and the future of GW astronomy

Saturn as viewed by G. Galilei in 1610

Advanced detectors



Saturn as viewed by Hubble telescope in 2018

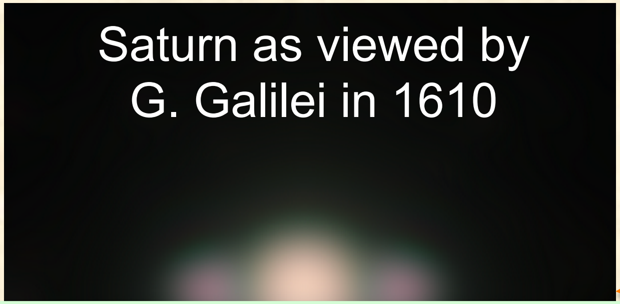
Photo: NASA, ESA, STScI, M. Mutchler (STScI), A. Simon (GSFC) and the OPAL Team, J. DePasquale (STScI)

Saturn as viewed by G. Cassini in 1675

arXiv:1309.1711

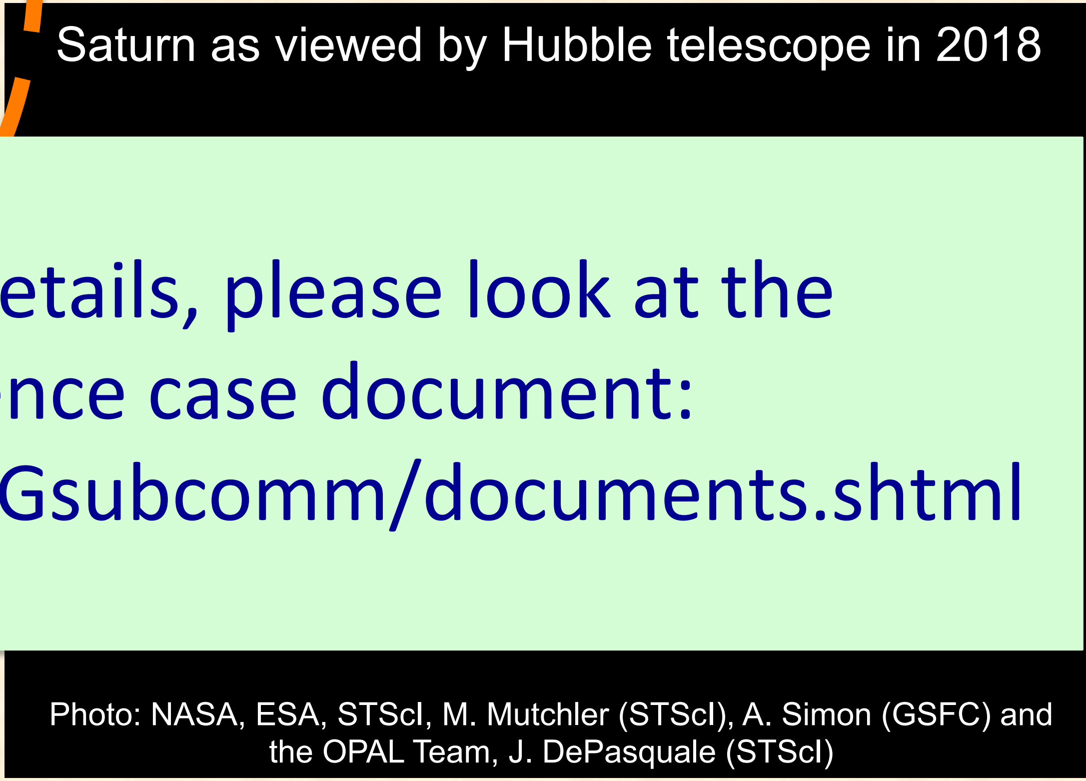
Einstein Telescope

The present and the future of GW astronomy



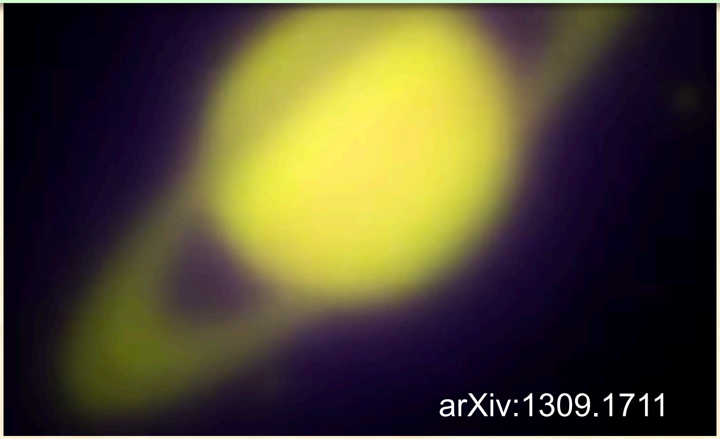
Saturn as viewed by G. Galilei in 1610

Advanced detectors



Saturn as viewed by Hubble telescope in 2018

For much more details, please look at the GWIC 3G science case document:
https://gwic.ligo.org/3Gsubcomm/documents.shtml

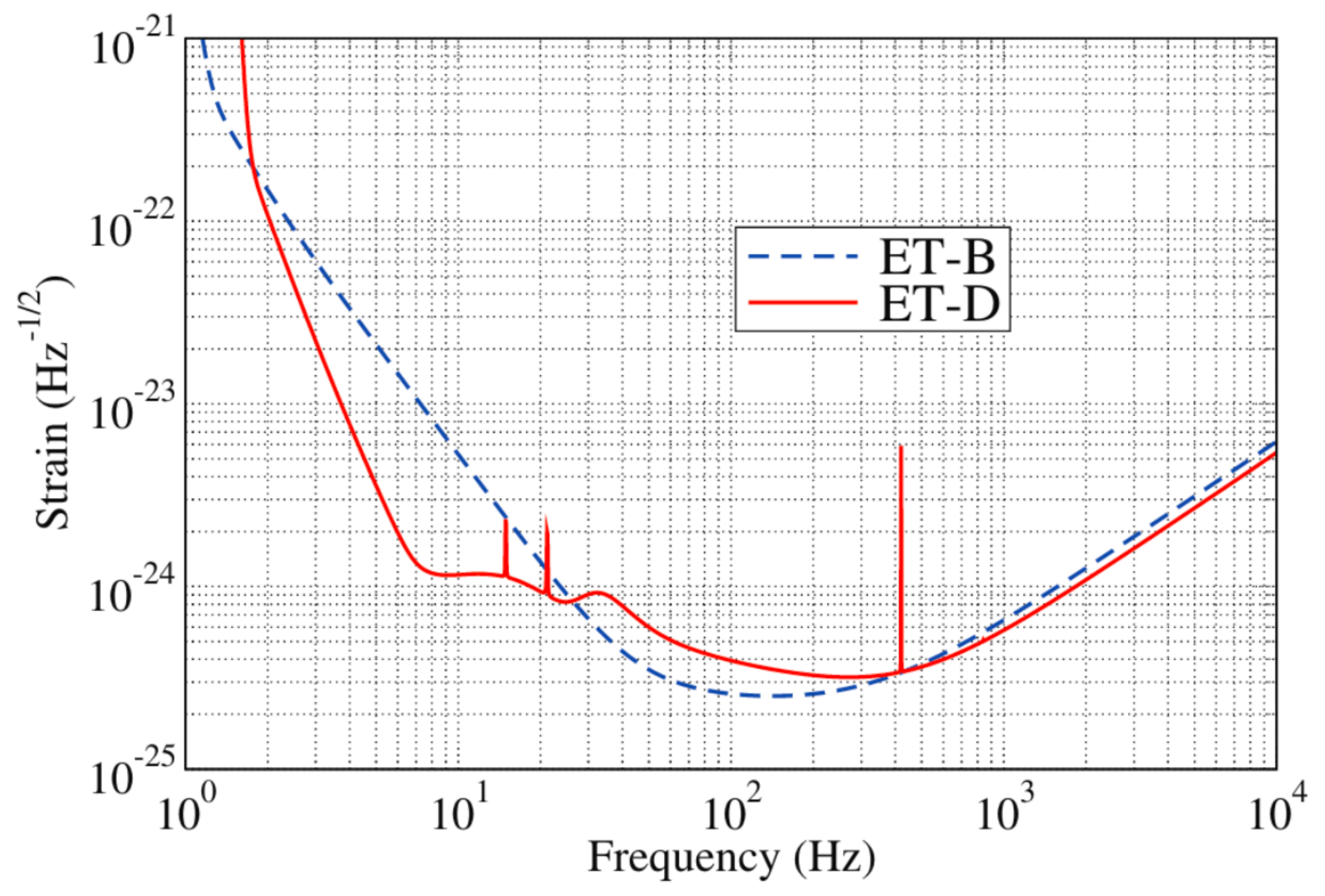


arXiv:1309.1711

Photo: NASA, ESA, STScI, M. Mutchler (STScI), A. Simon (GSFC) and the OPAL Team, J. DePasquale (STScI)

Einstein Telescope

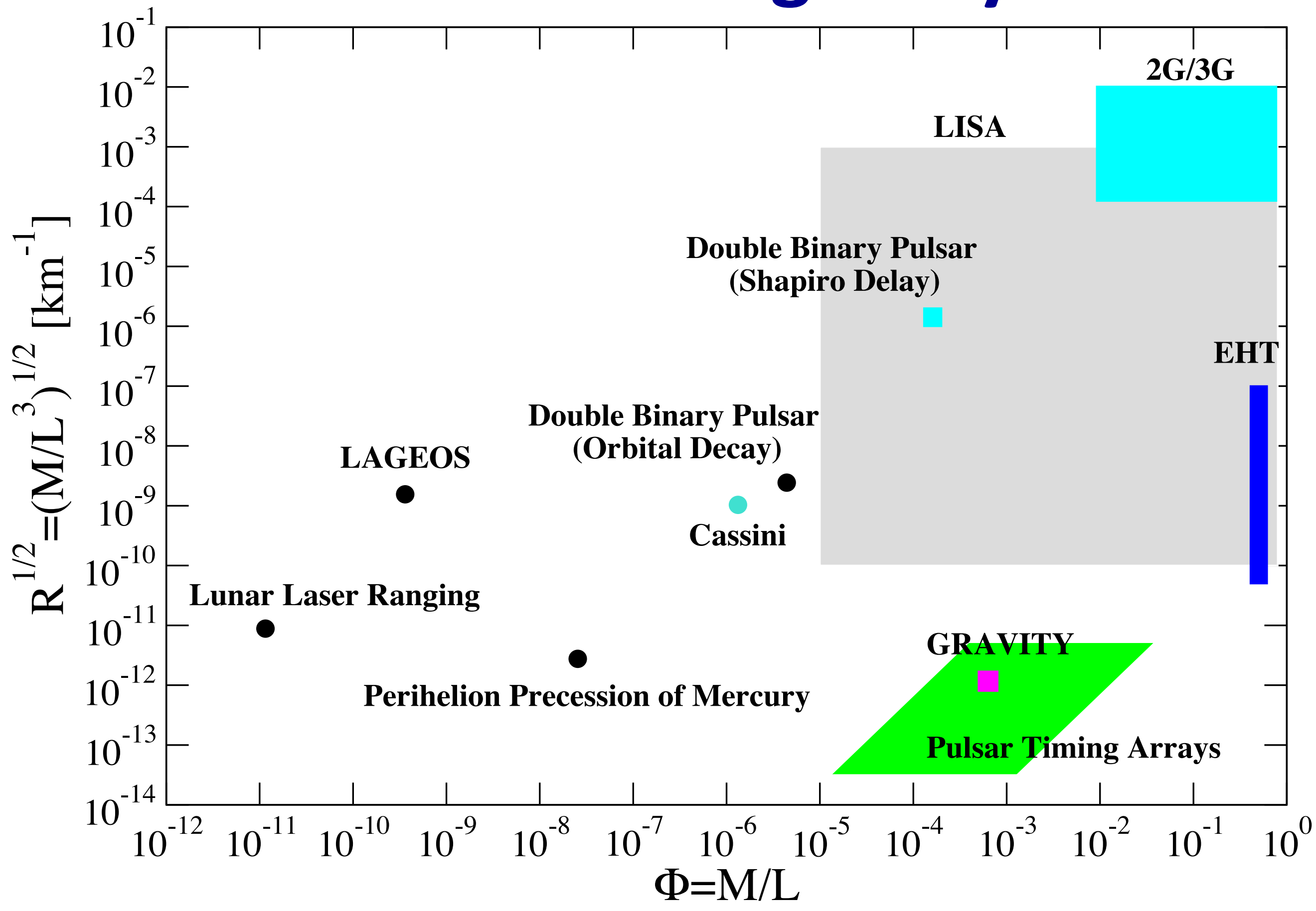
BACKUP SLIDES



Limitations of a single ET observatory

- 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
- Correlated noise

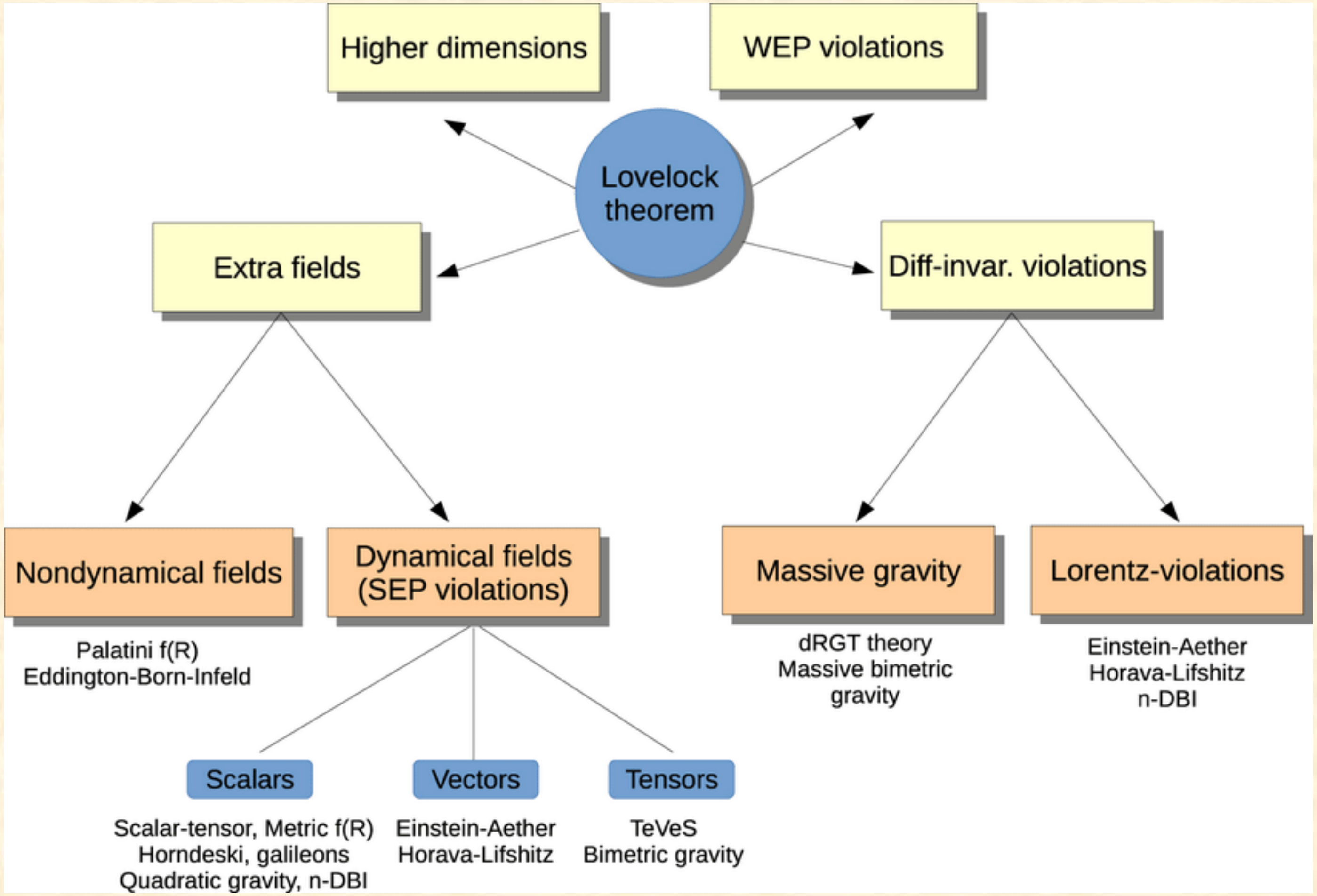
The nature of gravity



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

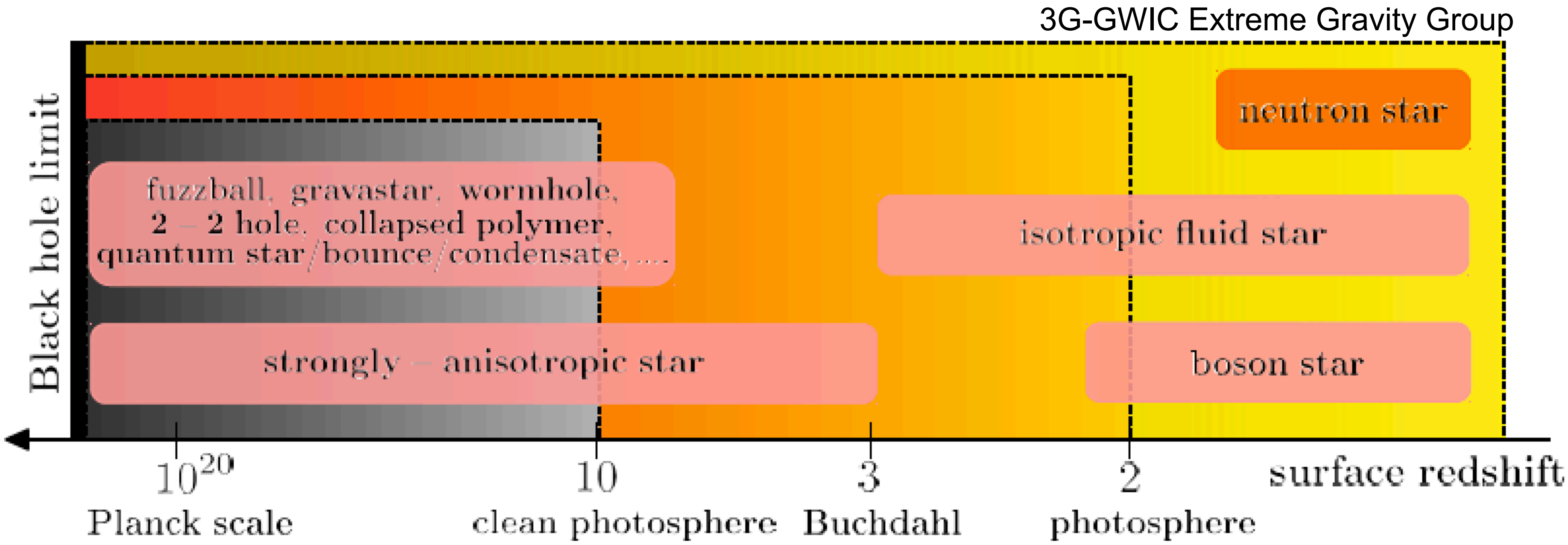


- New fields, for example:
  - Scalar-tensor theories
    - Binary components get “dressed” with scalar charge *(benefit from ET’s high-frequency sensitivity)*
  - Gravitational parity violation
    - Modifications in binary dynamics
    - GW birefringence, building up over distance *(benefit from ET’S 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

The nature of compact objects

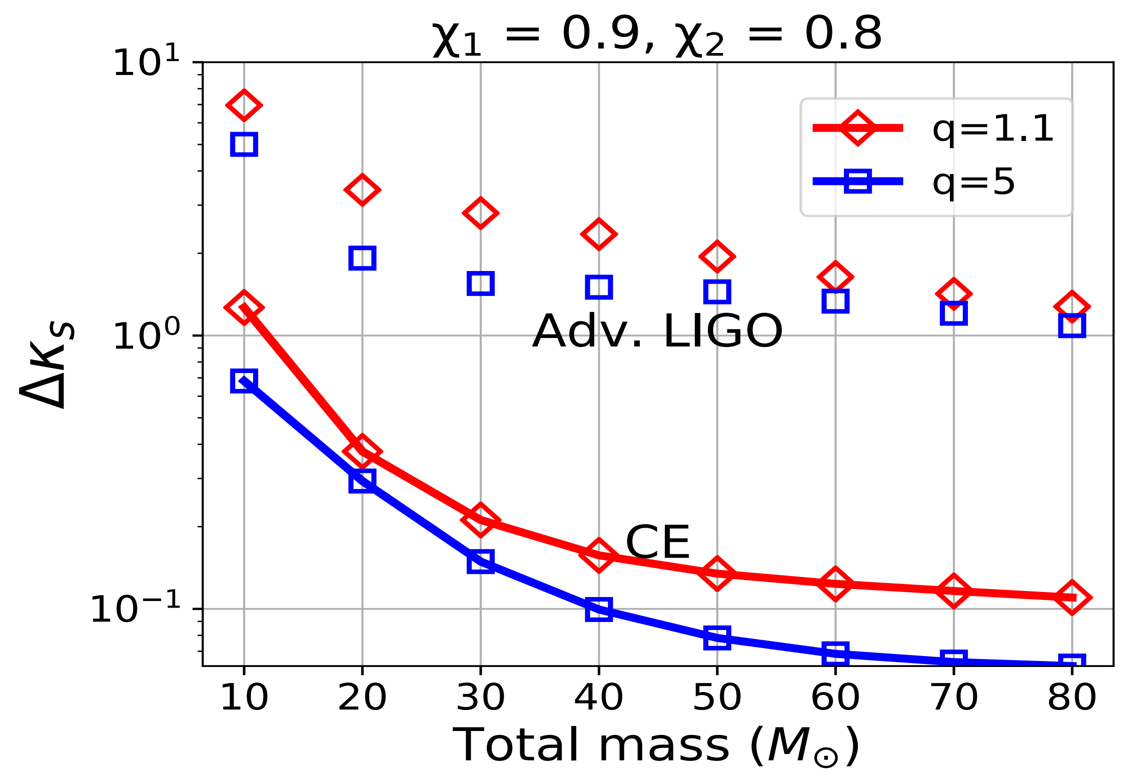
How certain are we that the massive compact objects we are observing are the "standard" black holes of general relativity?

→ "Black hole mimickers"

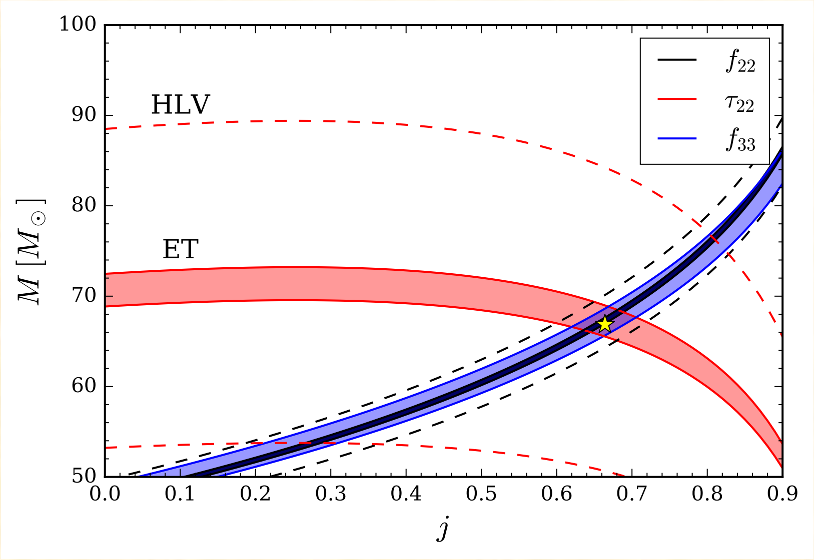


The nature of compact objects (BH “mimickers”)

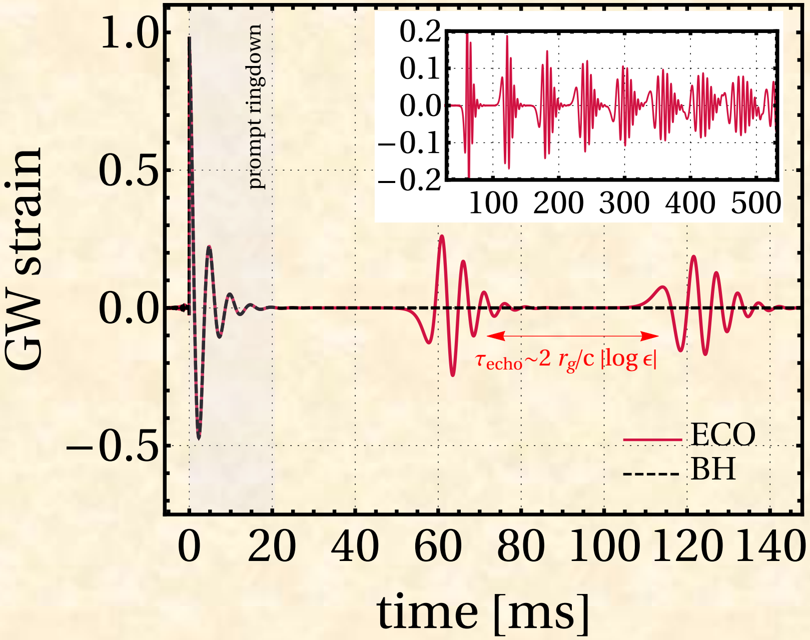
How certain are we that the massive compact objects we are observing are the “standard” black holes of general relativity?



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

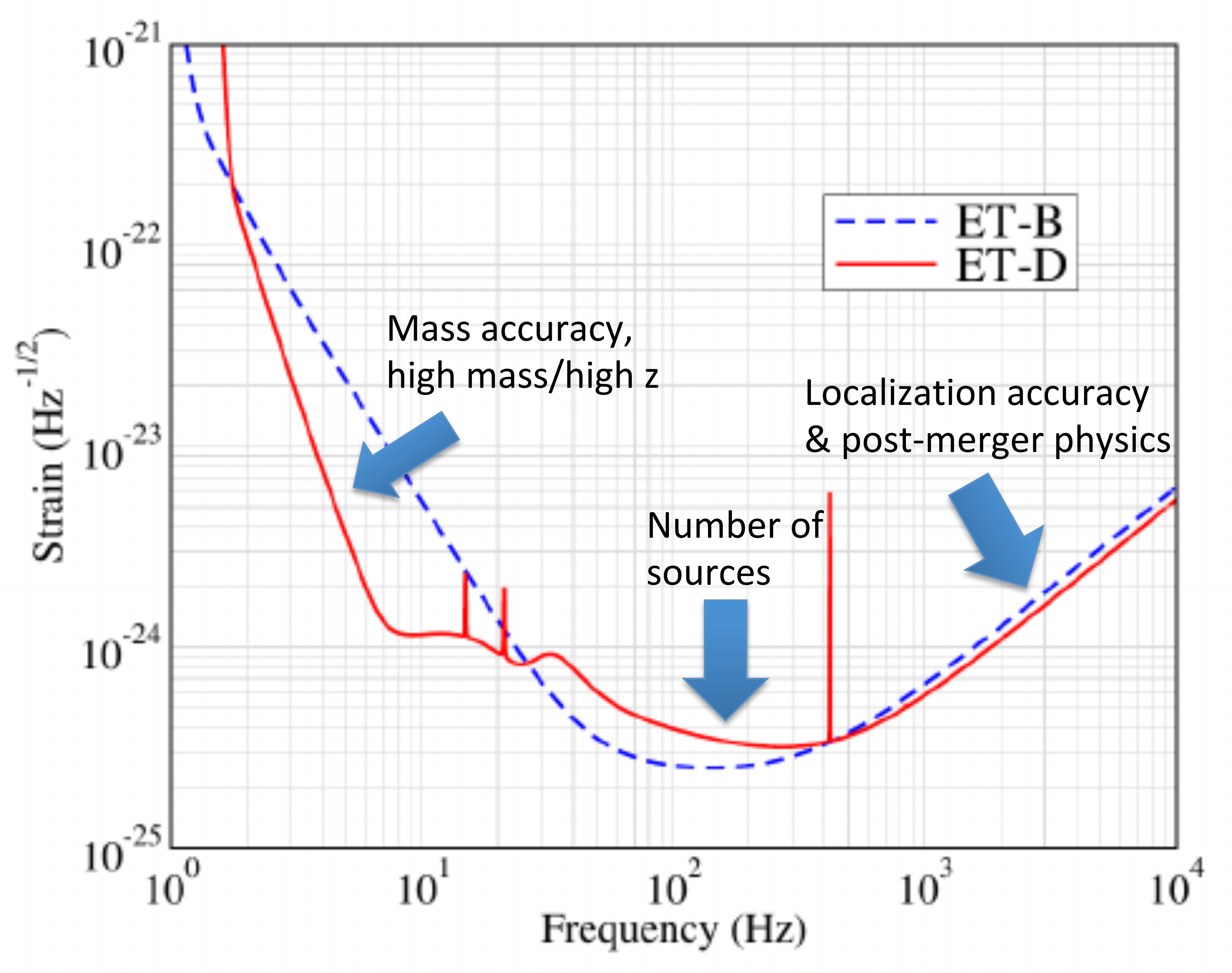


- Black hole "no hair" conjecture: Stationary, vacuum black hole completely determined by mass and spin
  - Qualitative advantage of ET: able to distinguish the various QNM, perform consistency check



- GW echoes
  - If horizon modified: periodic bursts of GW after ringdown has ended
  - Possibility to access macroscopic quantum effects: firewalls, fuzzballs

ET configuration impact for mergers



Mass accuracy,
high mass/high z

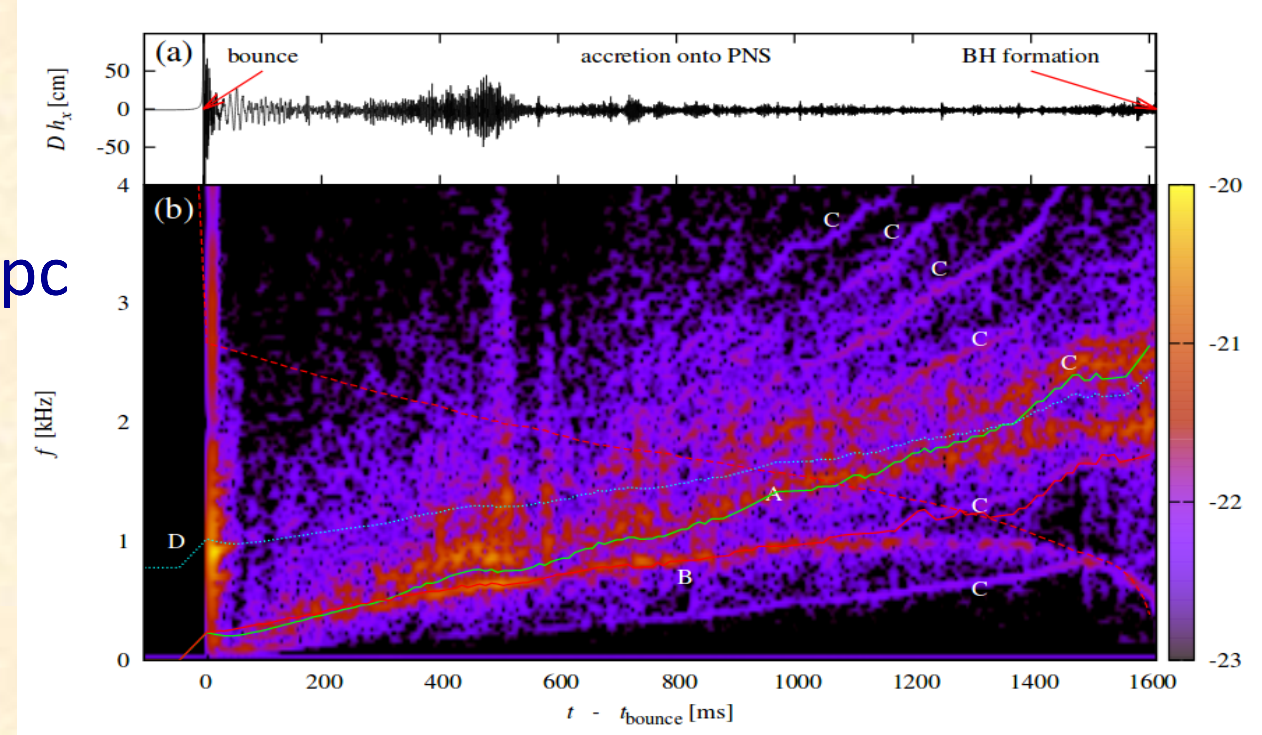
Number of
sources

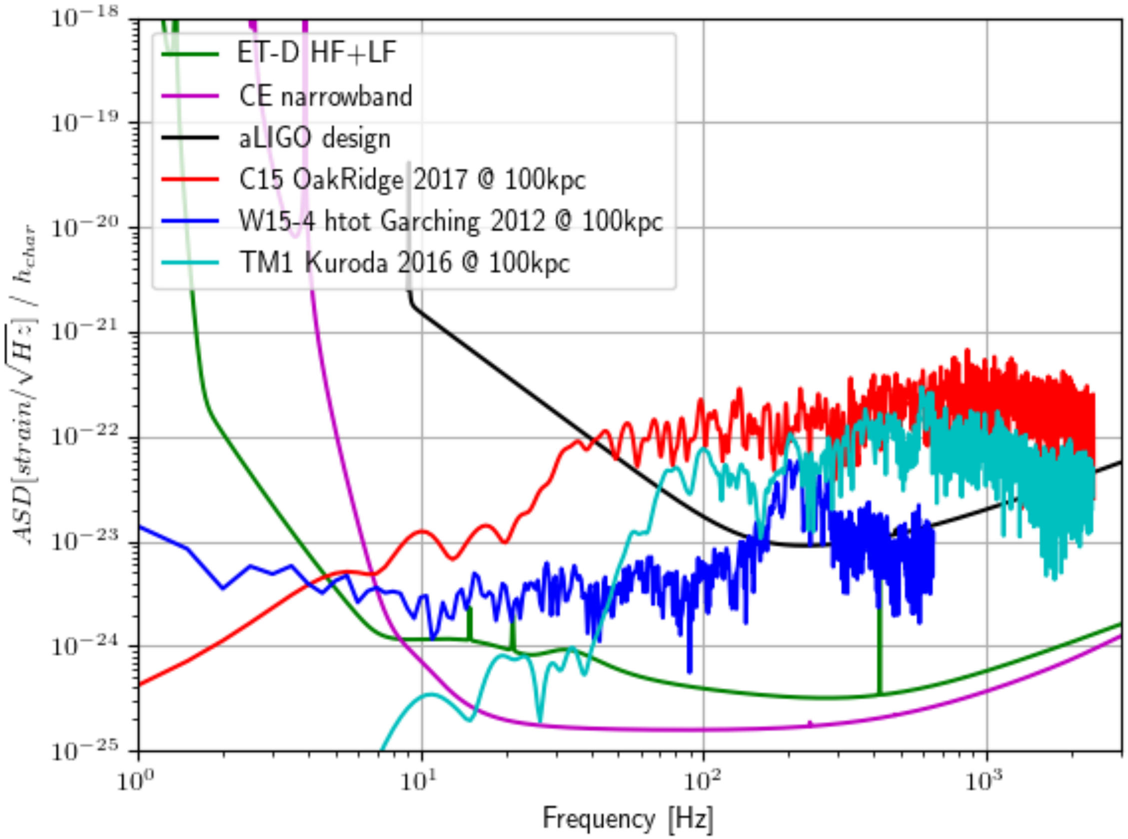
Localization accuracy
& post-merger physics

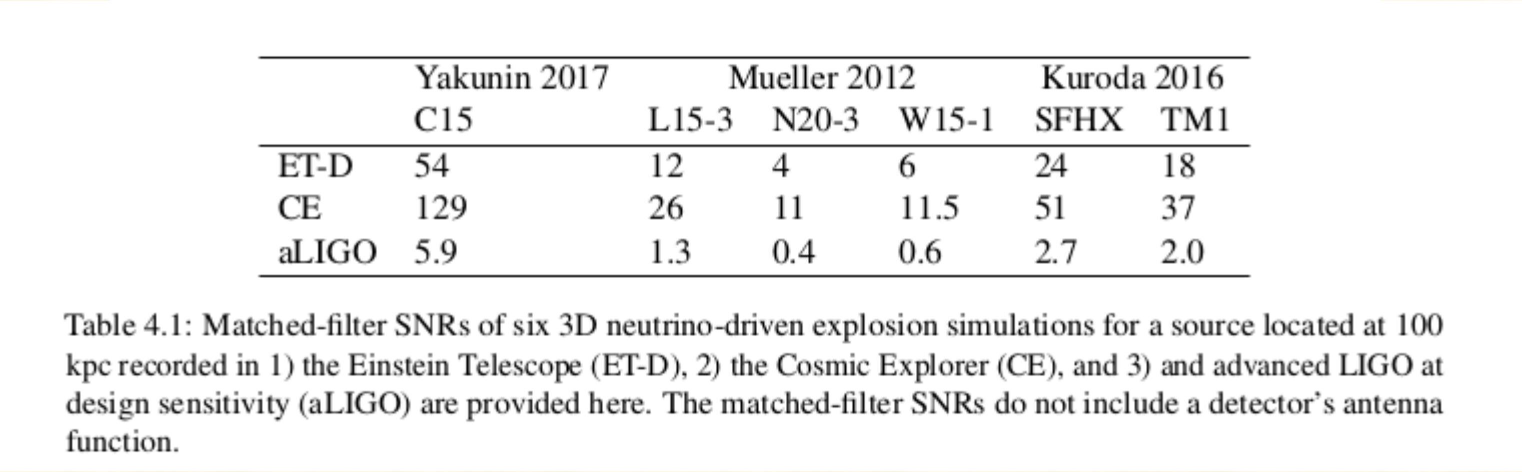
Core collapse supernovae

- Understanding the explosion mechanism (neutrinos, SASI, rotation, etc.)
- Time frequency evolution of PNS oscillations
- Fate of the collapse (NS or BH?)

D_{max}~100 kpc

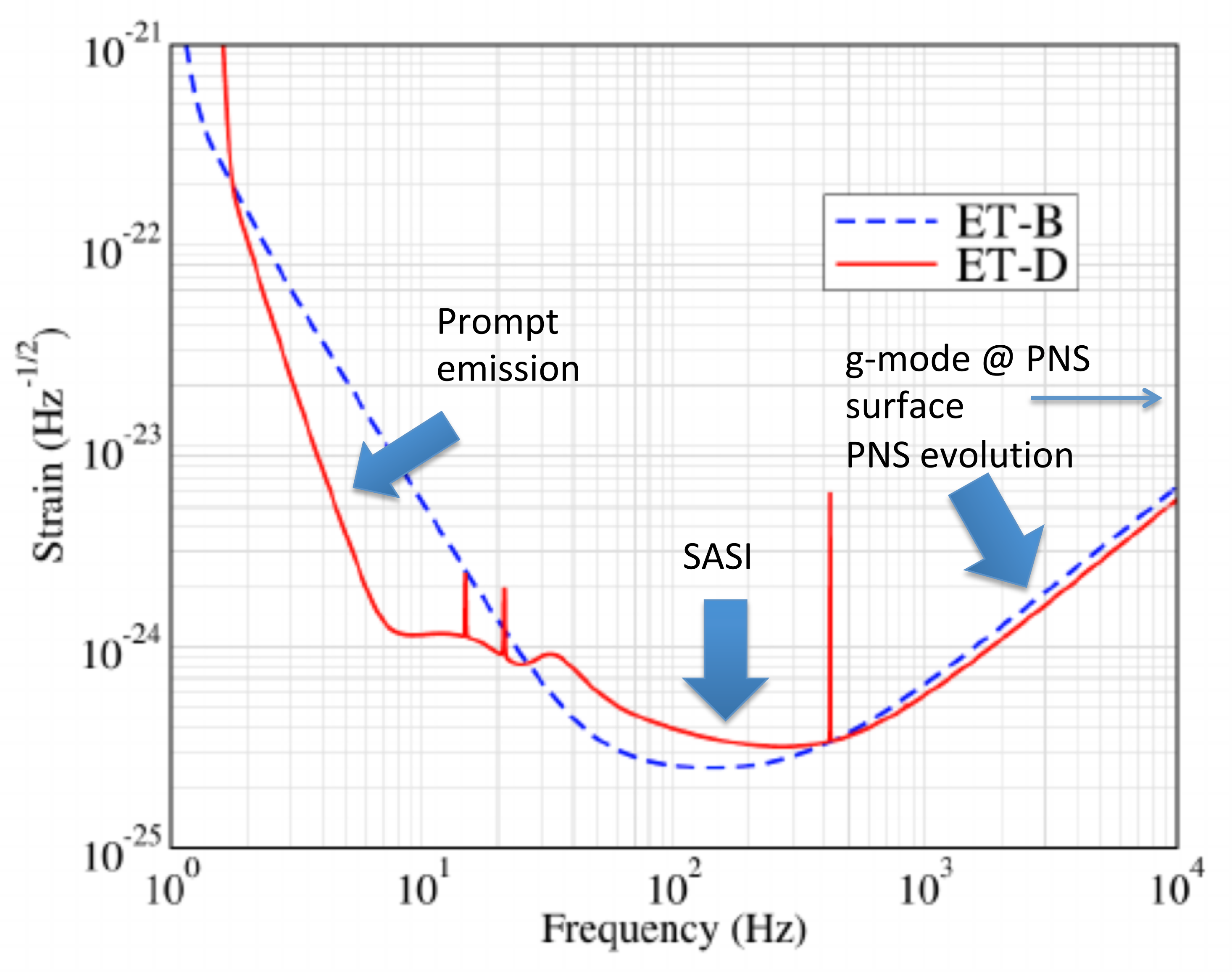






	Yakunin 2017	Mueller 2012			Kuroda 2016	
	C15	L15-3	N20-3	W15-1	SFHX	TM1
ET-D	54	12	4	6	24	18
CE	129	26	11	11.5	51	37
aLIGO	5.9	1.3	0.4	0.6	2.7	2.0

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.



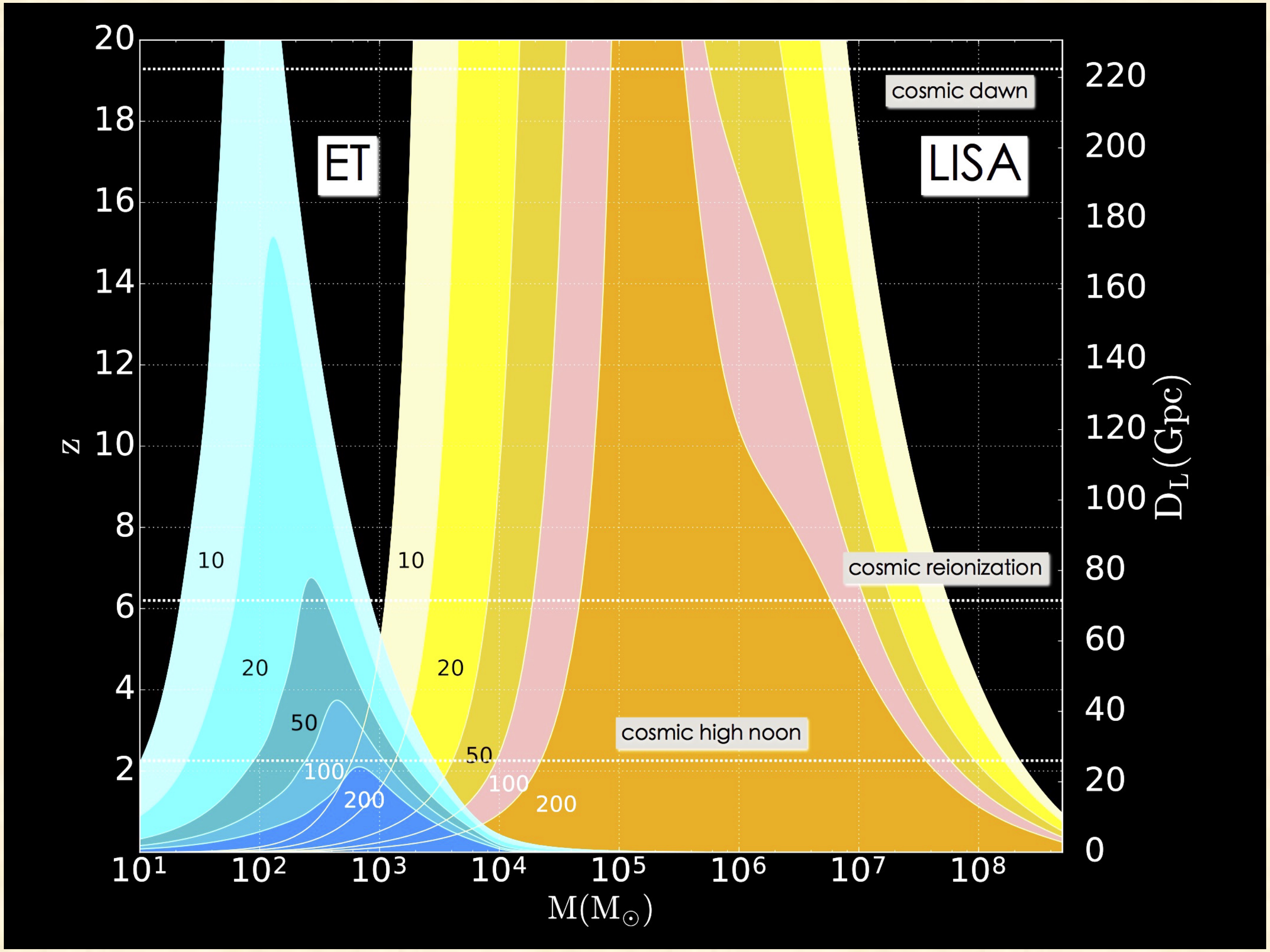
Prompt emission

SASI

g-mode @ PNS surface

PNS evolution

Detectability of BBH systems by ET and LISA



Multi-band detection of IMBH

Complementarity in understanding the origin of SMBHs