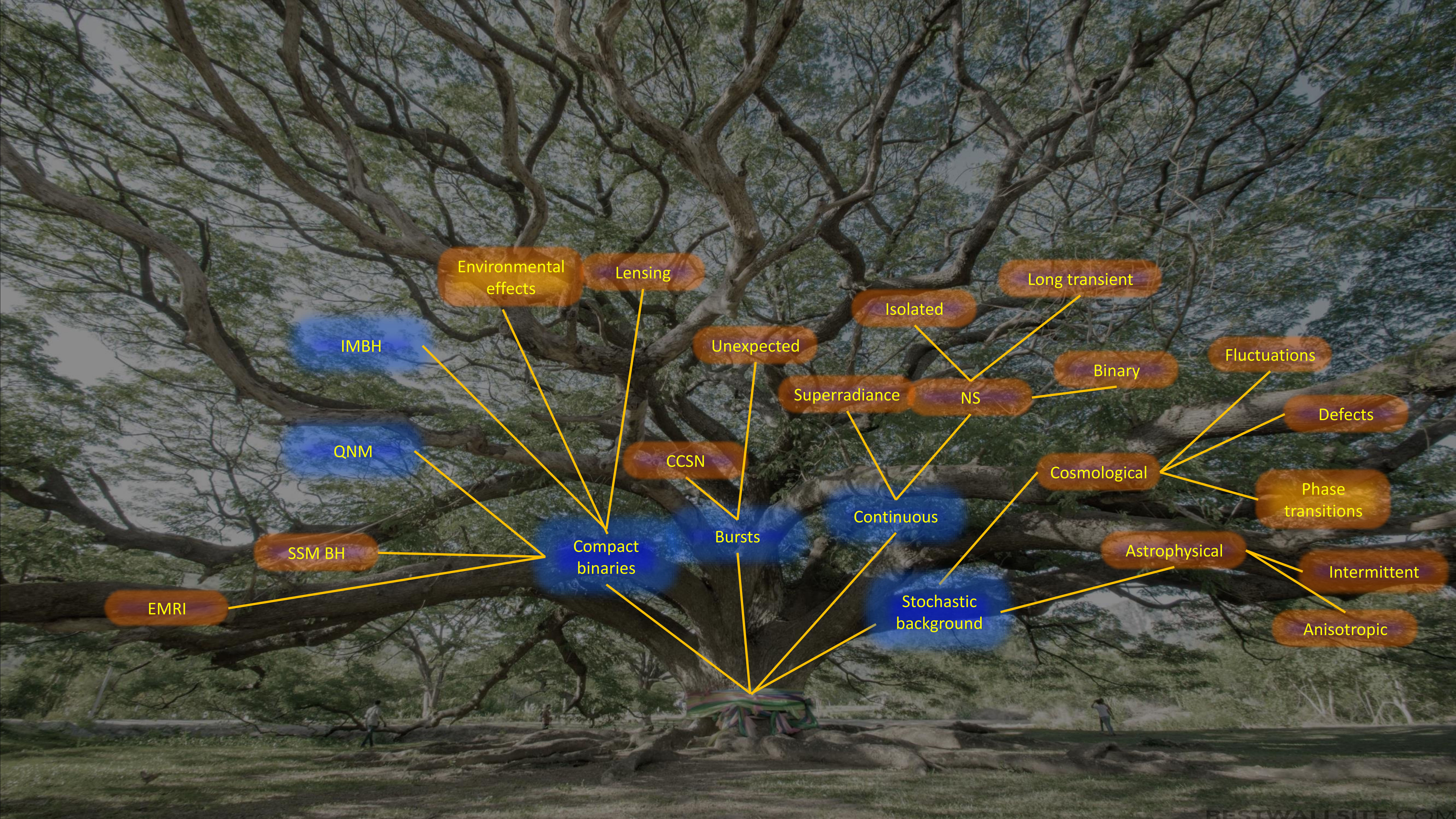
INFN Istituto Nazionale di Fisica Nucleare

Latest (no CBC) News from LIGO/Virgo

Giancarlo Cella

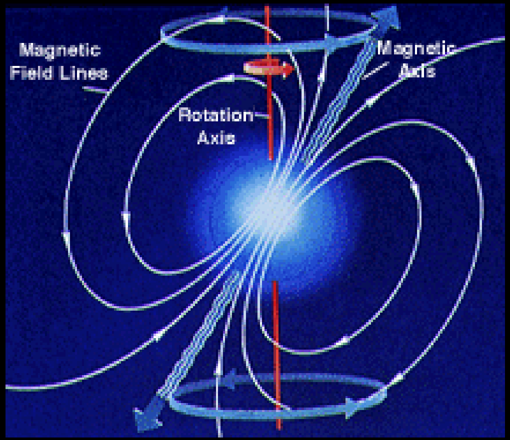
1st MaNiTou Summer School on Gravitational waves

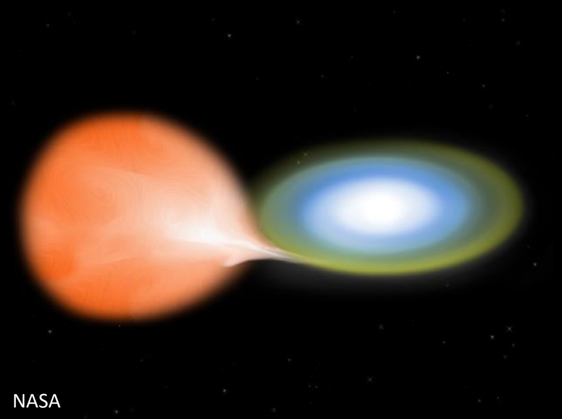
4-8 July 2022


Environmental effects
Lensing
Long transient
Isolated
IMBH
Unexpected
Binary
Fluctuations
Superradiance
NS
Defects
QNM
CCSN
Cosmological
Phase transitions
Continuous
Compact binaries
Bursts
SSM BH
Astrophysical
Intermittent
Stochastic background
EMRI
Anisotropic

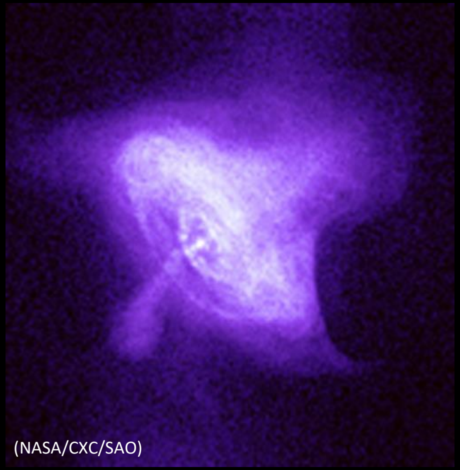
Rotating neutron stars

- Neutron stars can form from the remnant of stellar collapse
- Typical size of 10km, and are about 1.4 solar masses
- Some of these stars are observed as pulsars
- Gravitational waves from neutron stars could tell us about the equation of state of dense nuclear matter
- Our galaxy might contain ~10^9 NS, of which ~10^3 have been identified
    - search for observed neutron stars
    - all sky search (computing challenge)



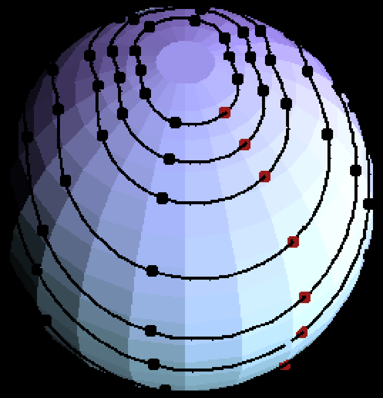


NASA

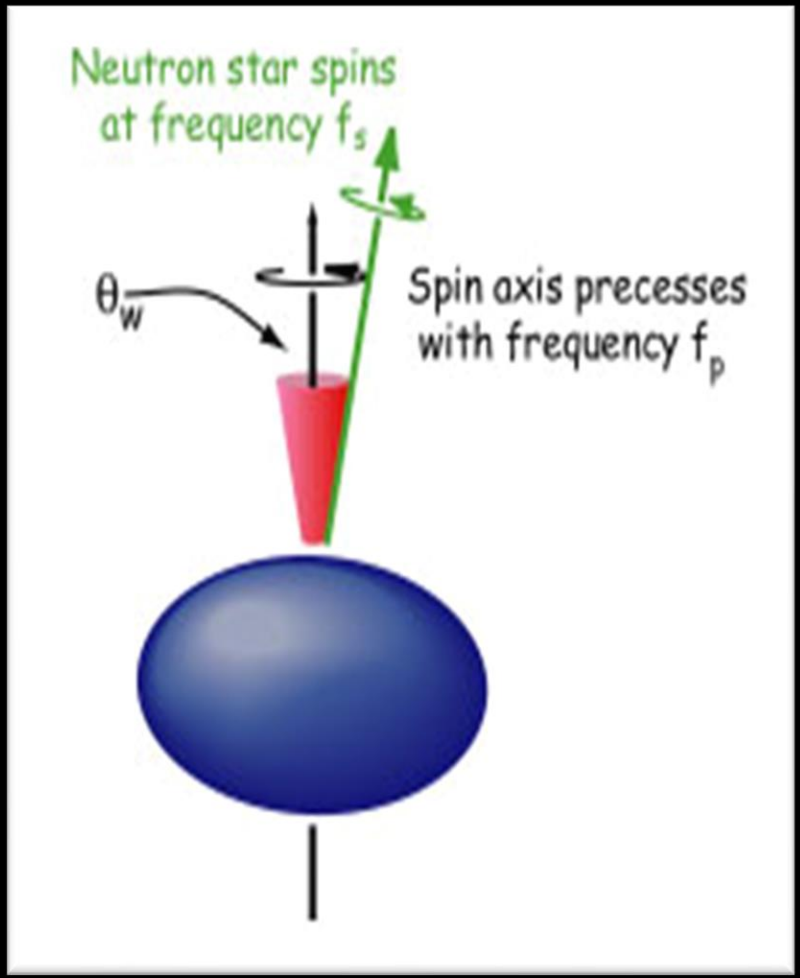


The signal from a NS

- General case: free rigid body rotation.
  - The rotation can be described in term of Elliptic functions
  - Two periodicities: discrete spectrum
- Small deviations from axisymmetry:
  - Deviation from axisymmetry: $2\Omega_{rot}$
  - Precession: $\Omega_{rot} + \Omega_{prec} \simeq \Omega_{rot}$
  - excited oscillatory modes such as the r-mode $\frac{4}{3}\Omega_{rot}$



R-modes in accreting stars



The expected signal at the detector

Jaranowski et al. 1998

A gravitational wave signal we detect from a NS will be:

- Frequency modulated by relative motion of detector and source
- Amplitude modulated by the motion of the non-uniform antenna sensitivity pattern of the detector

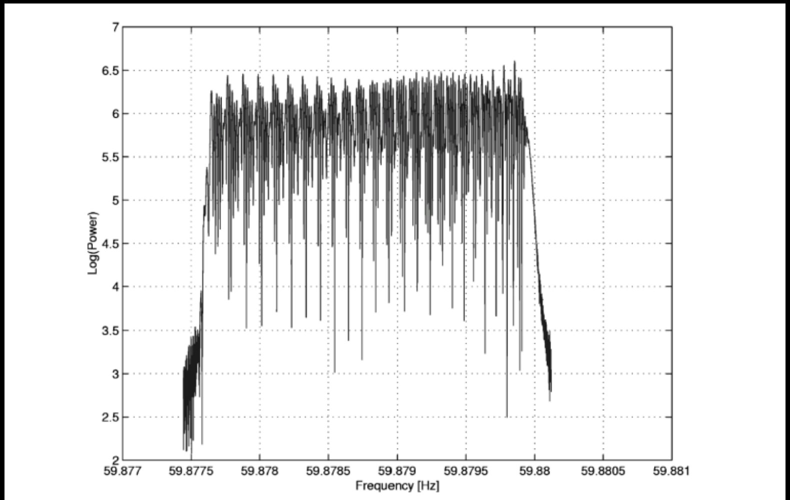
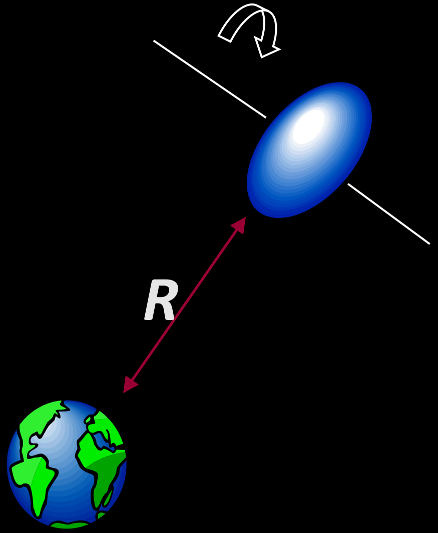
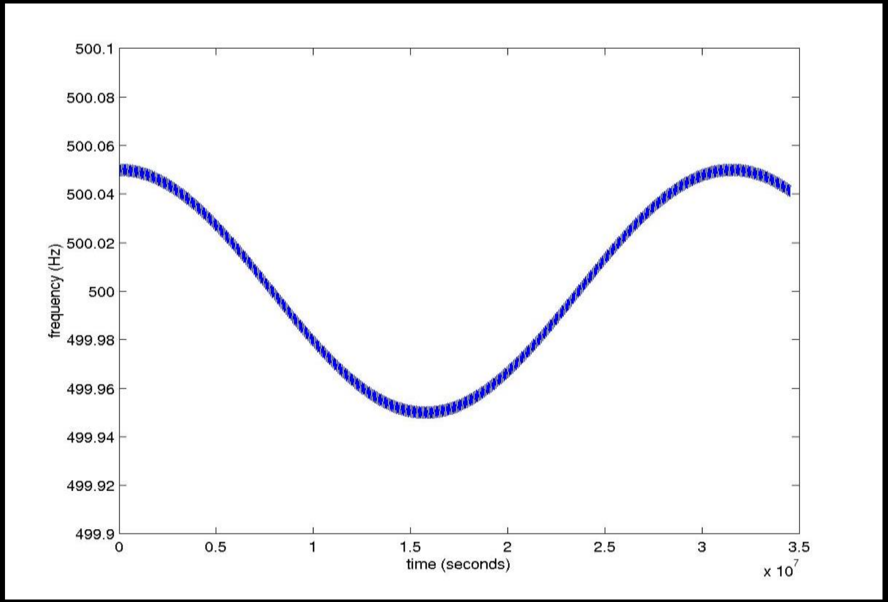
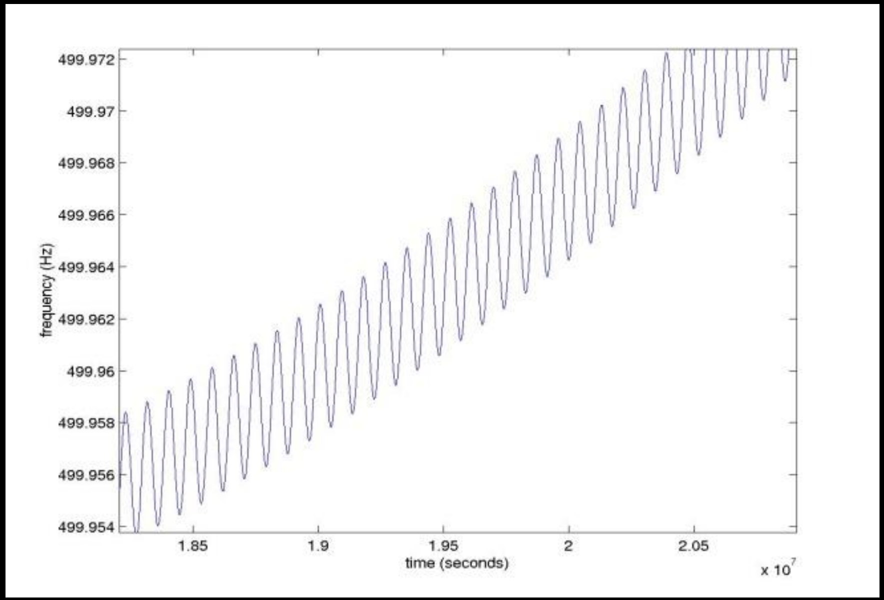


FIG. 1. Power spectrum of the noise-free response of an interferometer located near Hannover to gravitational-wave signal from the Crab

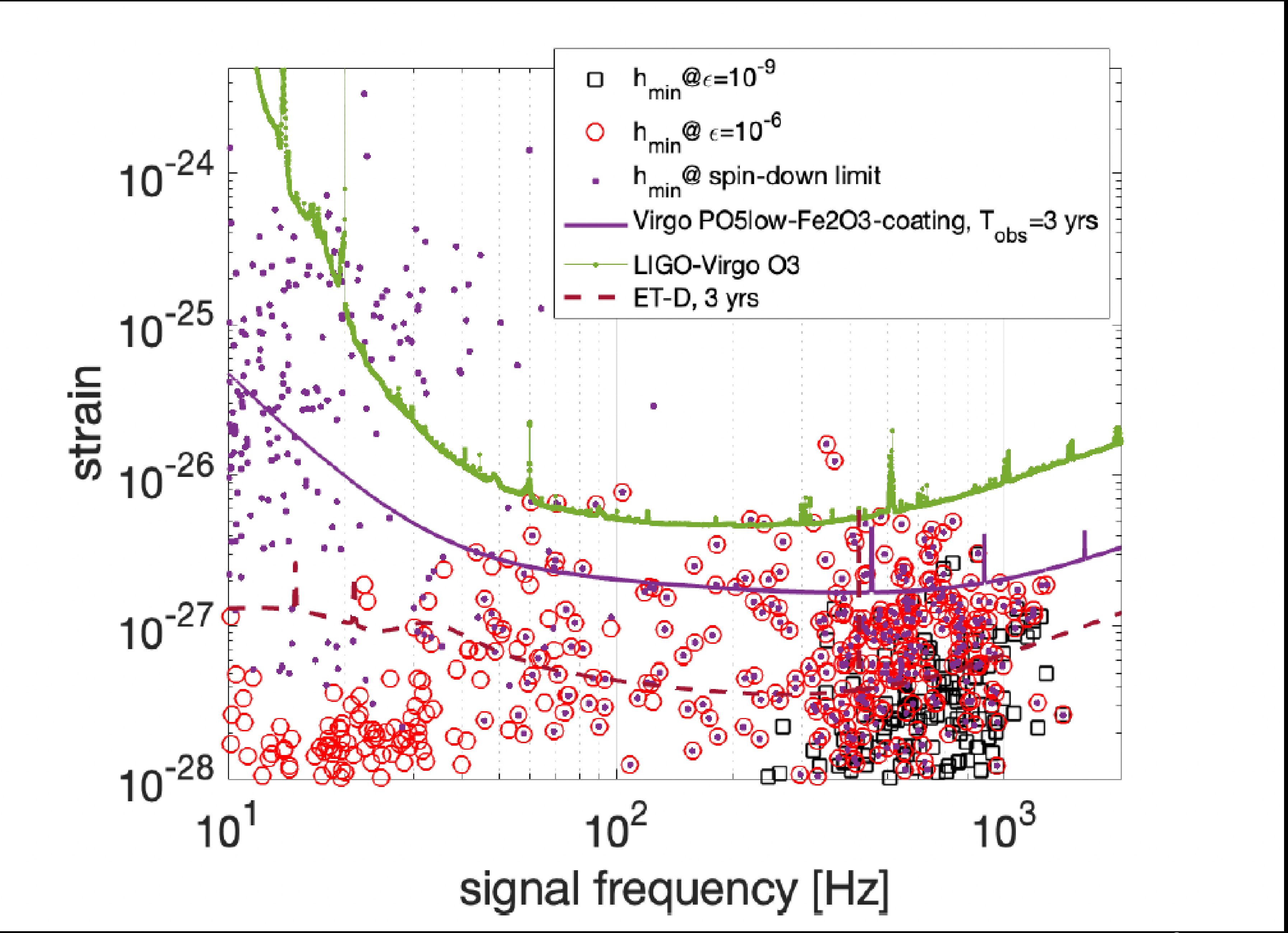






CW searches

- Weak and persistent signal.
  - Targeted (particular source)
  - All sky (unknown sources)
- Not really monocromatic
  - Modulations
  - Spin down, environment effects, glitches



Untargeted search in the galactic center

https://arxiv.org/abs/2204.04523

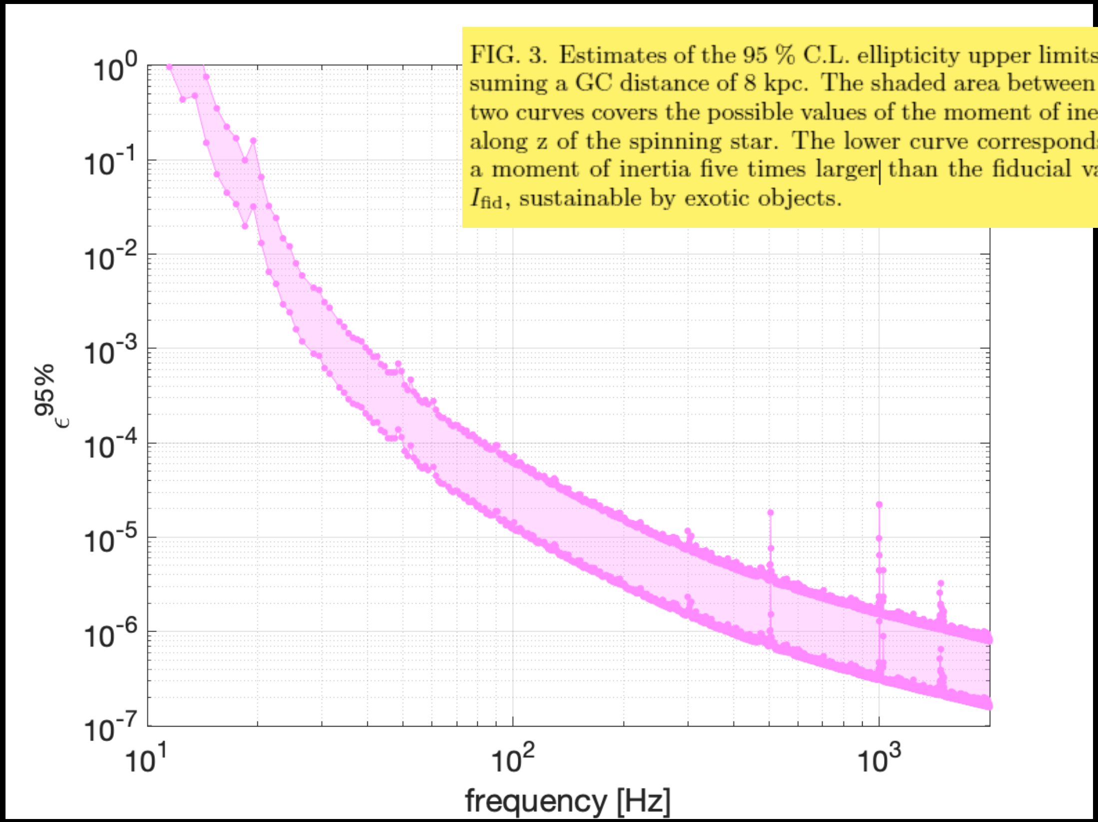


FIG. 3. Estimates of the 95 % C.L. ellipticity upper limits assuming a GC distance of 8 kpc. The shaded area between the two curves covers the possible values of the moment of inertia along z of the spinning star. The lower curve corresponds to a moment of inertia five times larger than the fiducial value $I_{\rm fid}$, sustainable by exotic objects.

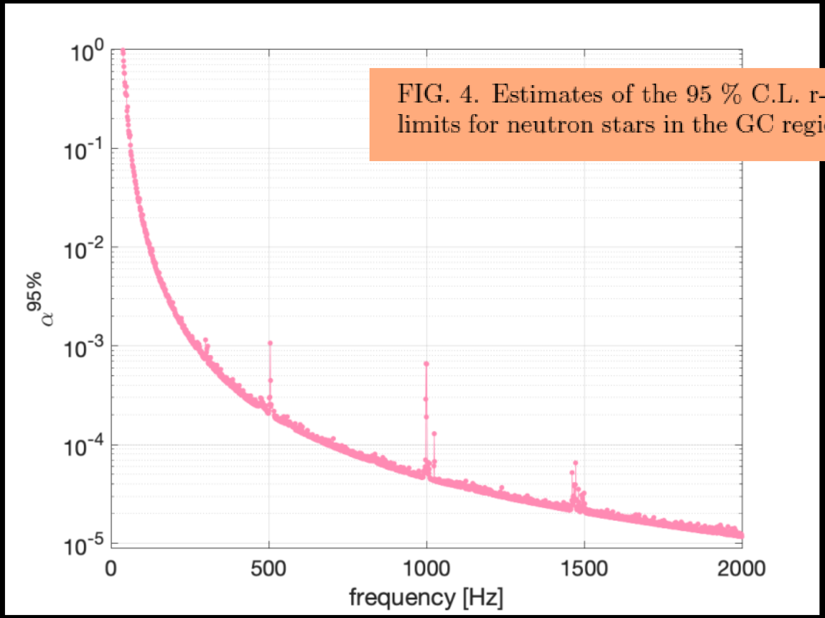


FIG. 4. Estimates of the 95 % C.L. r-mode amplitude upper limits for neutron stars in the GC region assuming $d = 8$ kpc.

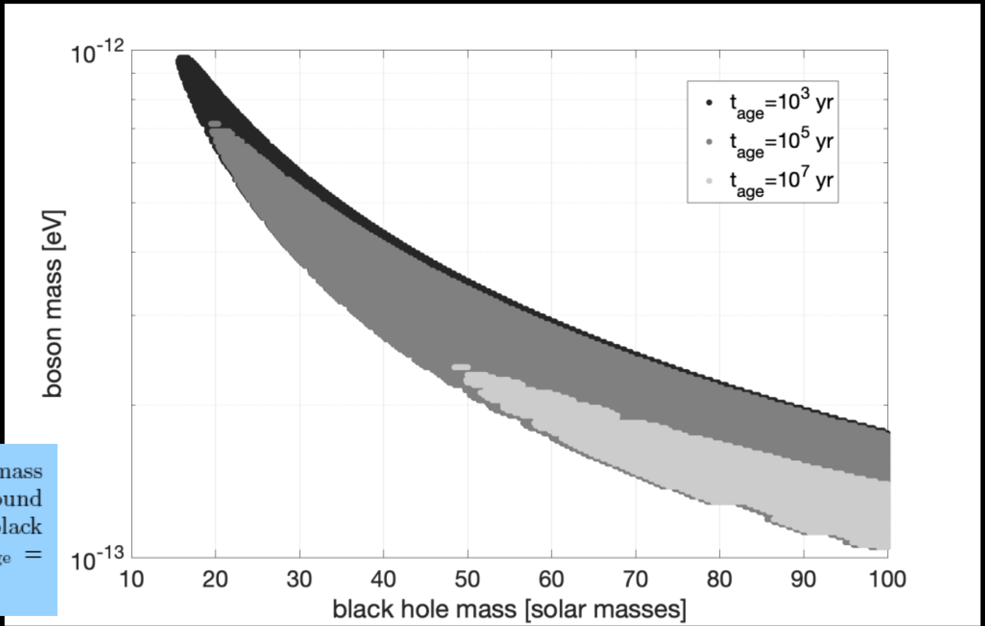
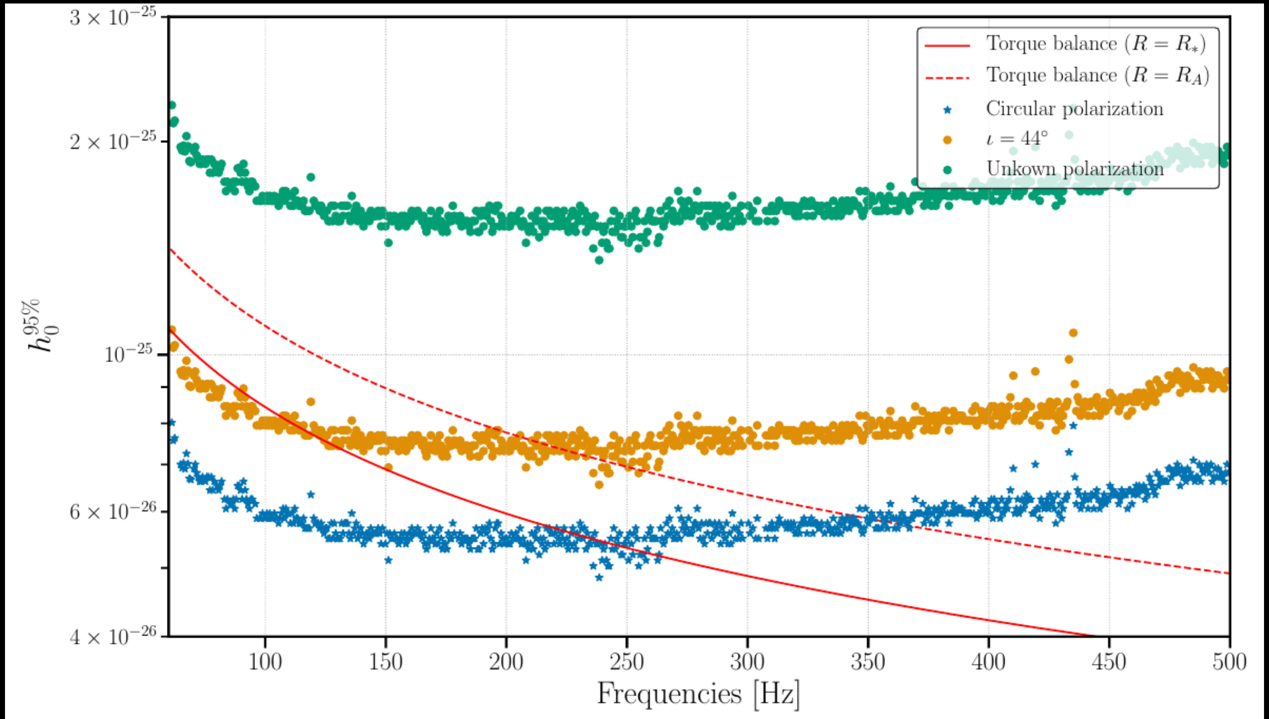


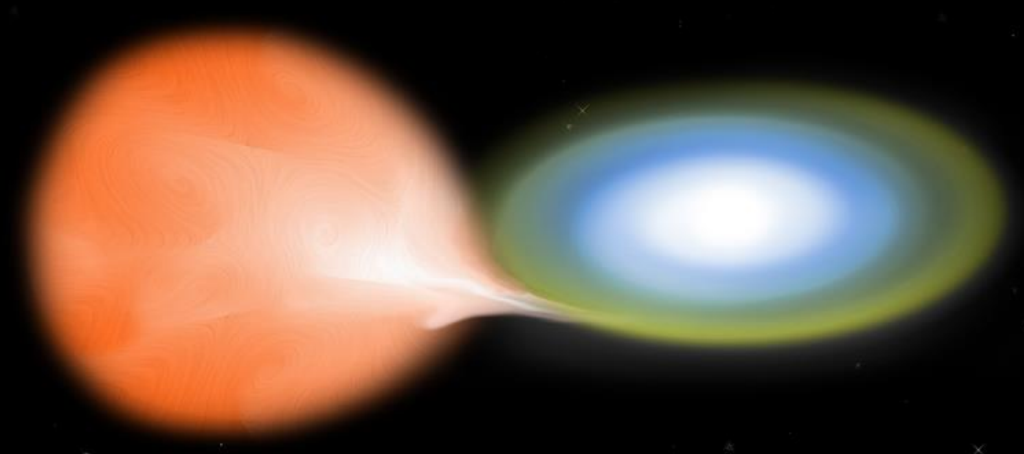
FIG. 5. Constraints on the black hole mass – boson mass plane, assuming CW emission from boson clouds around spinning black holes located in the GC. An initial black hole dimensionless spin $\chi_i = 0.5$ and cloud ages of $t_{\rm age} = 10^3$, 10^5, 10^7 years are considered.

Relaxing assumptions for CW signals

https://arxiv.org/abs/2201.10104



- Gravitational waves are emitted at harmonics (multiples) of the star spin frequency
- No measurements of the spinning frequency of the neutron star in Scorpius X-1.
- The chaotic nature of accretion implies that the spin frequency of the neutron star can change in an unpredictable way over time. *(spin wandering)*
- *Analysis based on Hidden Markov Model*



Artist's impression of the Scorpius X-1 LMXB system.

DM candidates searchable with gravitational waves

- **Environmental effects on compact objects**
  - The **compact object structure** can be changed: accretion disk, spin down effects, formation of a DM core
  - The GW **production mechanism** can be changed
  - **Inpact on propagation** of generated GW and EM waves

  Signature: *Unusual waveform*

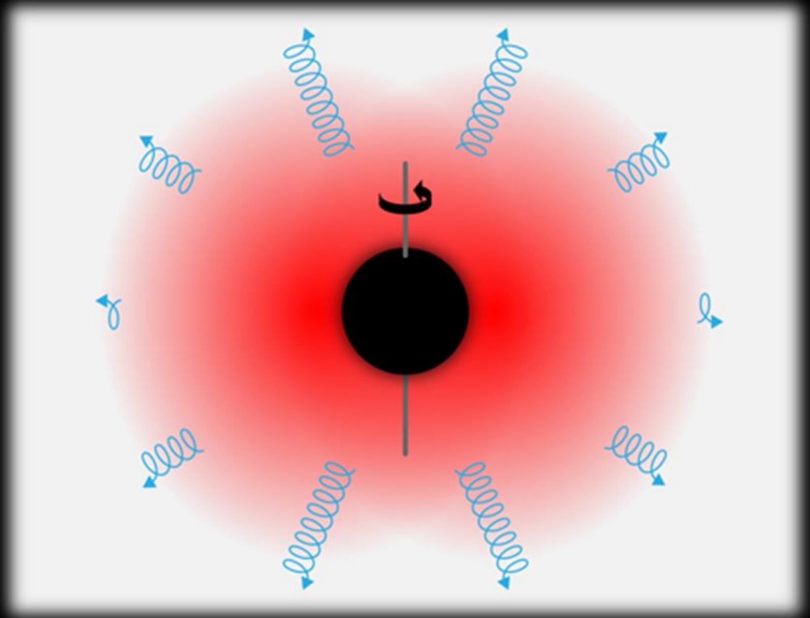
- **Primordial black holes**
  - Microlensing data seems to exclude that ALL DM can be explained in this way.
  - Not completely uncontroversial, some assumptions can be weakened;
  - Could be responsible for a fraction of DM;

  Signature: *Subsolar mass BH evidence*

- **Exotic objects**
  - GW190521 is compatible with a merger between two complex vector boson star, with $m_b \sim 8.7 \times 10^{-13}$ eV (head on collision)

  See Phys. Rev. Lett. **126**, 081101

- **Superradiance effects**
  - A Kerr BH can transfer efficiently its energy to a cloud of ultra-light bosons, (scalar or vector) when $\lambda_c \sim R_s$ (which means $10^{-21} eV < m_b < 10^{-11} eV$)
  - The cloud can emit a nearly-periodic, long duration GW signal potentially detectable by LIGO-Virgo-KAGRA if $10^{-13} eV < m_b < 10^{-11} eV$



From: https://physics.aps.org/articles/v10/83

PRL 123, 171101 (2019)
PRD 101, 063020 (2020)
PRD 99, 084042 (2019)
PRD 98, 103017 (2018)

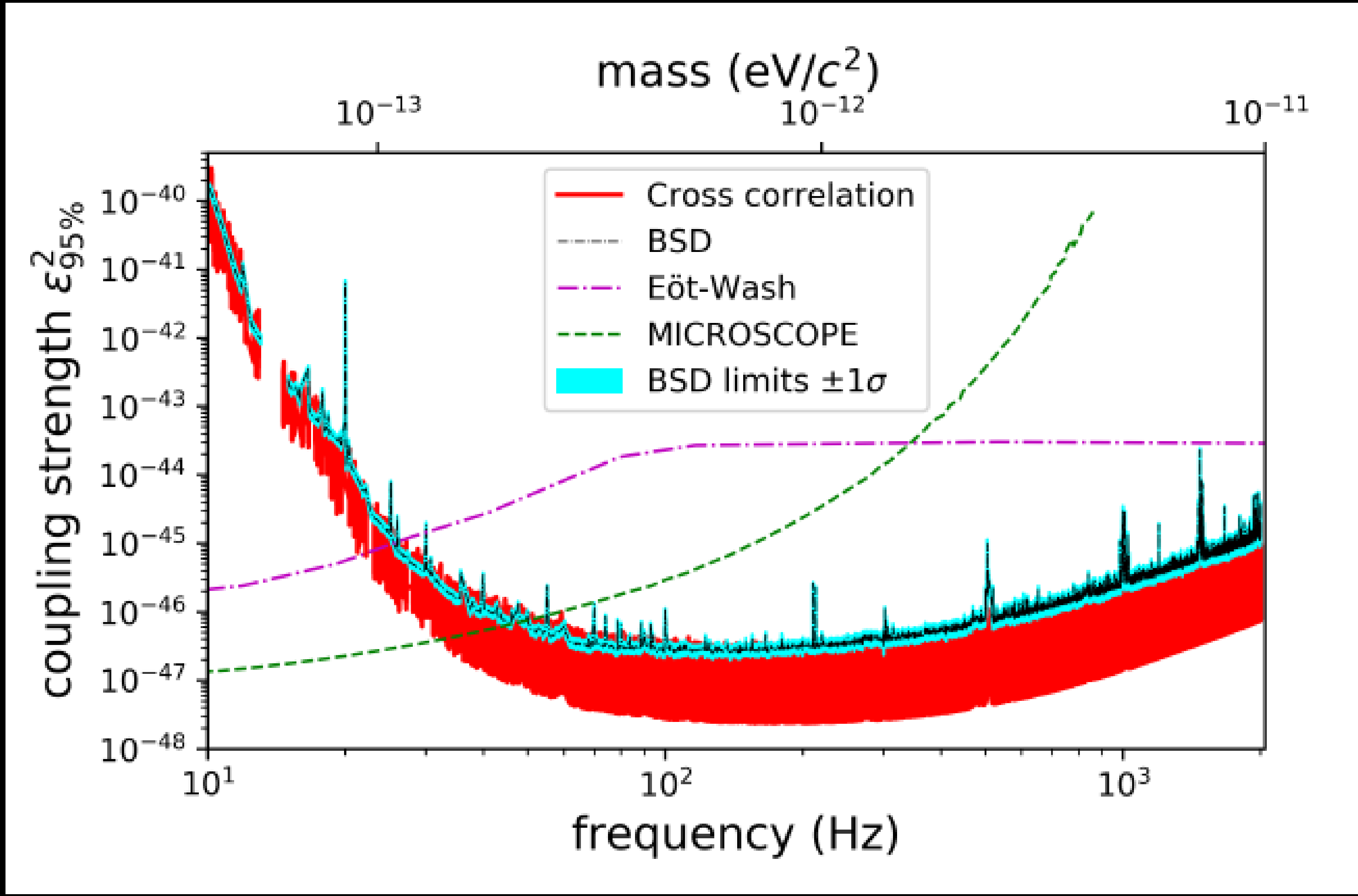
DM direct coupling

- DM can DIRECTLY (no GW) couple to the detector, in a way which depends on the candidate
  - Dilaton (fundamental constant modulation)
  - Axion (IF beam phase modulation)
  - dark photon (direct coupling to mirrors)
  - tensor,
  - ….
- Ultra-light DM: bosonic field with huge occupation numbers

  Signature: *Quasi-monochromatic (Maxwell-Boltzmann broadened) signal correlated between different detectors*

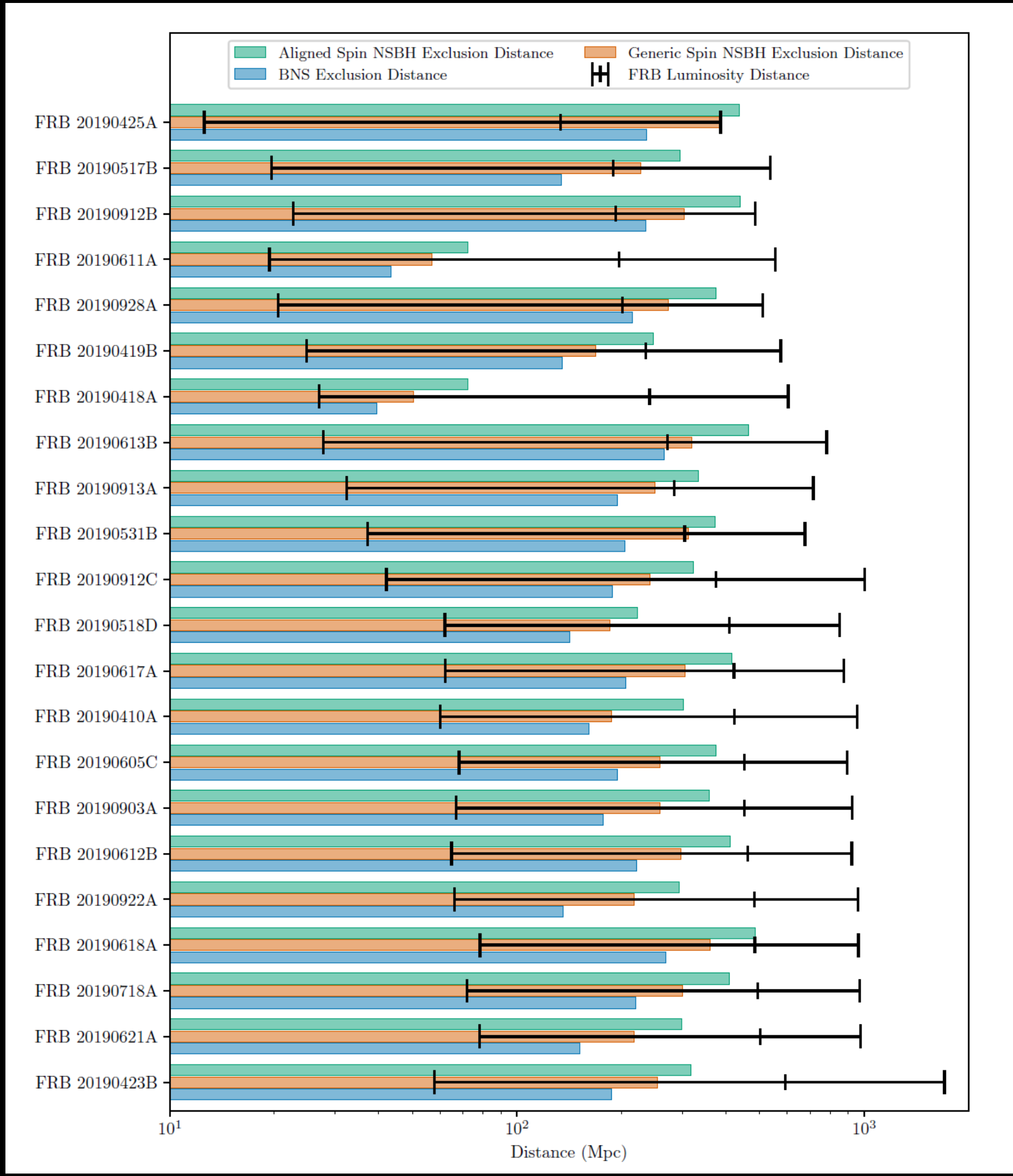
  Frequency is determined by the mass

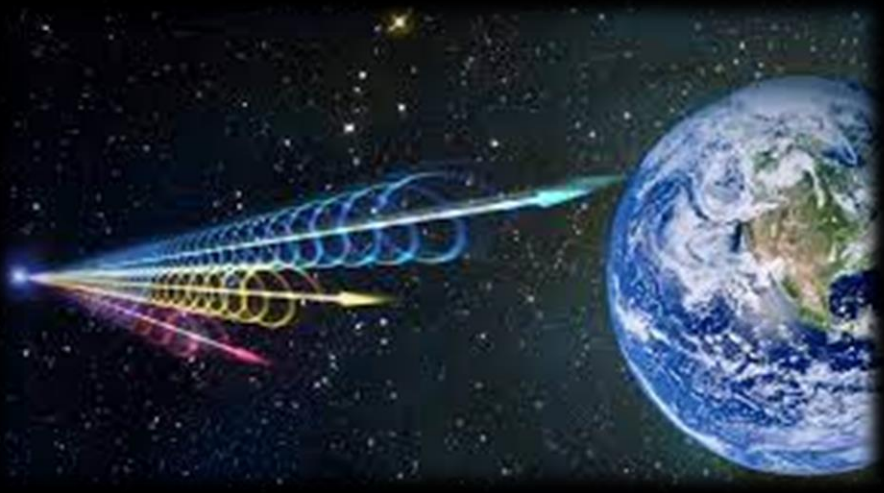
  Broadening contains information about DM distribution



https://arxiv.org/abs/2105.13085

GW associated to Fast Radio Burst https://arxiv.org/abs/2203.12038





- Lower limits on the 90% confidence level exclusion distances for BNS (lower bar), generic spin NSBH (middle bar), and aligned spin NSBH (upper bar) progenitor systems are shown as found by the modelled search. These are compared to the 90% credible intervals (whisker plot) on the DL posterior determined by the MCMC method for the FRBs considered in this study.

Stochastic backgrounds

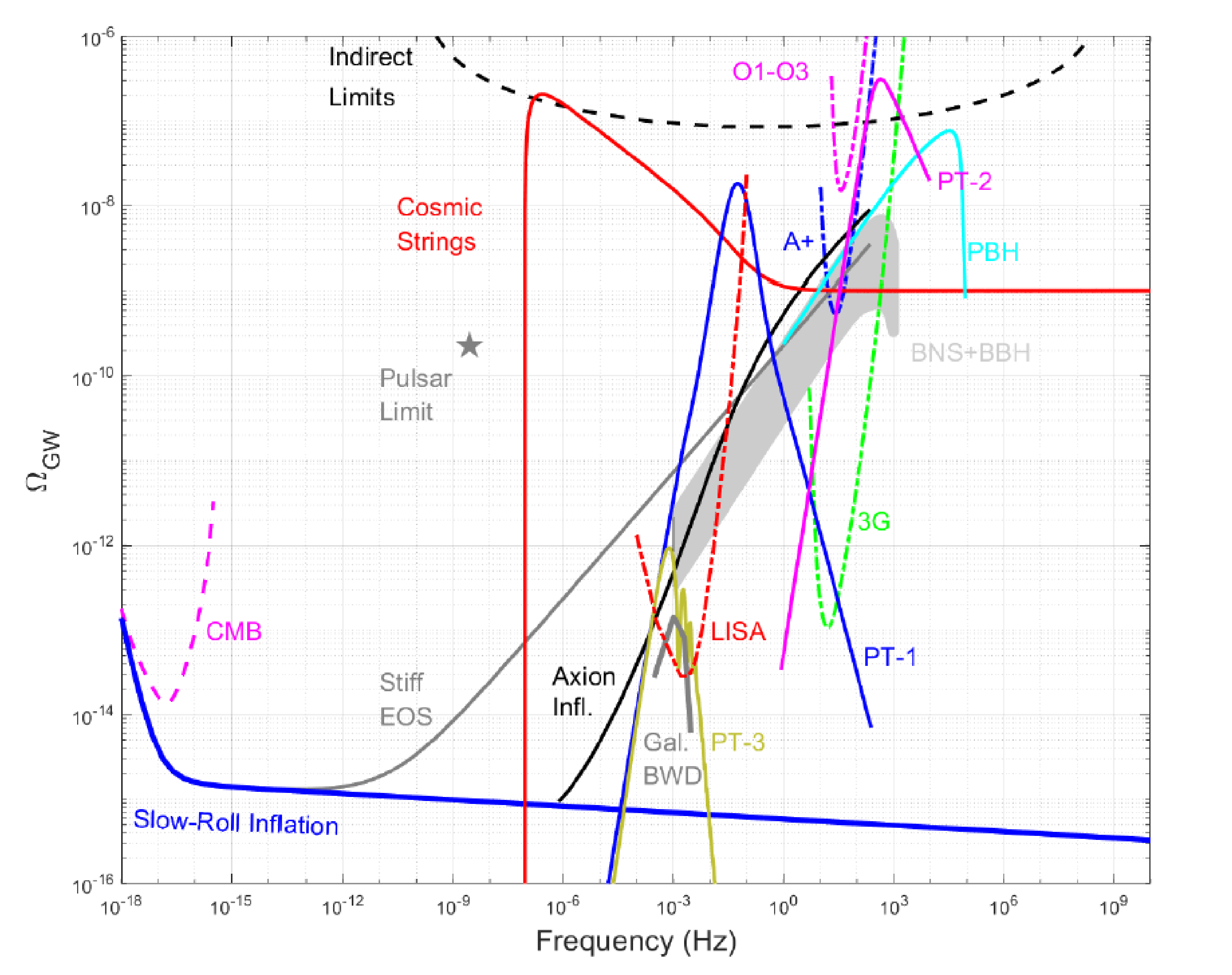
2203.07972

A stochastic background can be seen as

- a GW field which evolves from an initially random configuration
- the result of a superposition of many uncorrelated and unresolved sources

Two different kinds:

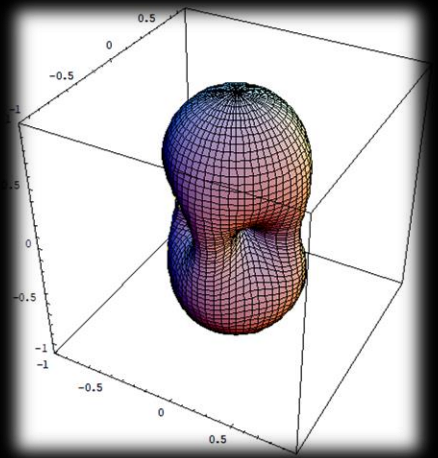
- Cosmological:
  - signature of the early Universe
  - inflation, cosmic strings, phase transitions…
- Astrophysical:
  - sources since the beginning of stellar activity
  - compact binaries, supernovae, rotating NSs, core-collapse to NSs or BHs, supermassive BHs…



Description (simplest model)

1. Strain: sum over modes

$$h_{ij}(t,\vec{r}) = \sum_{P=+,\times} \int_{S^2} d\hat{\Omega}\, \varepsilon^{P}_{ij}(\hat{\Omega}) \int_{-\infty}^{\infty} df\, \tilde{h}_P(f,\hat{\Omega}) e^{i2\pi f(t-\hat{\Omega}\cdot\vec{r})}$$



2. Signal at the detector: projection on the detector’s tensor

$$h(t,r) = D^{ij} h^{ij}(t,r)$$

3. Correlation between GW modes

$$< h^{\star}_{A}(f,\hat{\Omega},\psi) h_B(f',\hat{\Omega}',\psi') >= \delta_{AB}\delta(f-f')\frac{\delta^2(\hat{\Omega},\hat{\Omega}')}{4\pi}\frac{\delta(\psi-\psi')}{2\pi}\frac{1}{2}S_h(f)$$

4. Connection with GW energy density

$$h_0^2\Omega_{gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{gw}}{d\log f} = \frac{4\pi^2 h_0^2}{3H_0^2} f^3 S_h(f)$$

How it is possible to (directly) detect it

- We have a vector-valued Gaussian stochastic process

$$\underline{x}_i = \left(x_i^{\mathrm{Virgo}}, x_i^{\mathrm{Hanford}}, \cdots\right) \qquad dP = \mathcal{N} \prod_f \exp\left(-\frac{1}{2}\underline{\tilde{x}}_f^{+} C^{-1}(f)\, \underline{\tilde{x}}_f\right) d\underline{\tilde{x}}_f$$

$$\underline{x}_i = \underline{h}_i + \underline{n}_i \qquad \left\langle \underline{n}_i \otimes \underline{n}_j \right\rangle = I c_{ij}$$

- We must discriminate between two hypothesis:

$\mathcal{H}_0$

$$C = C_N = \begin{pmatrix} S_N^{\mathrm{Virgo}} & 0 & \cdots & 0 \\ 0 & S_N^{\mathrm{Hanford}} & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & S_N^{\mathrm{Kagra}} \end{pmatrix}$$

$\mathcal{H}_1$

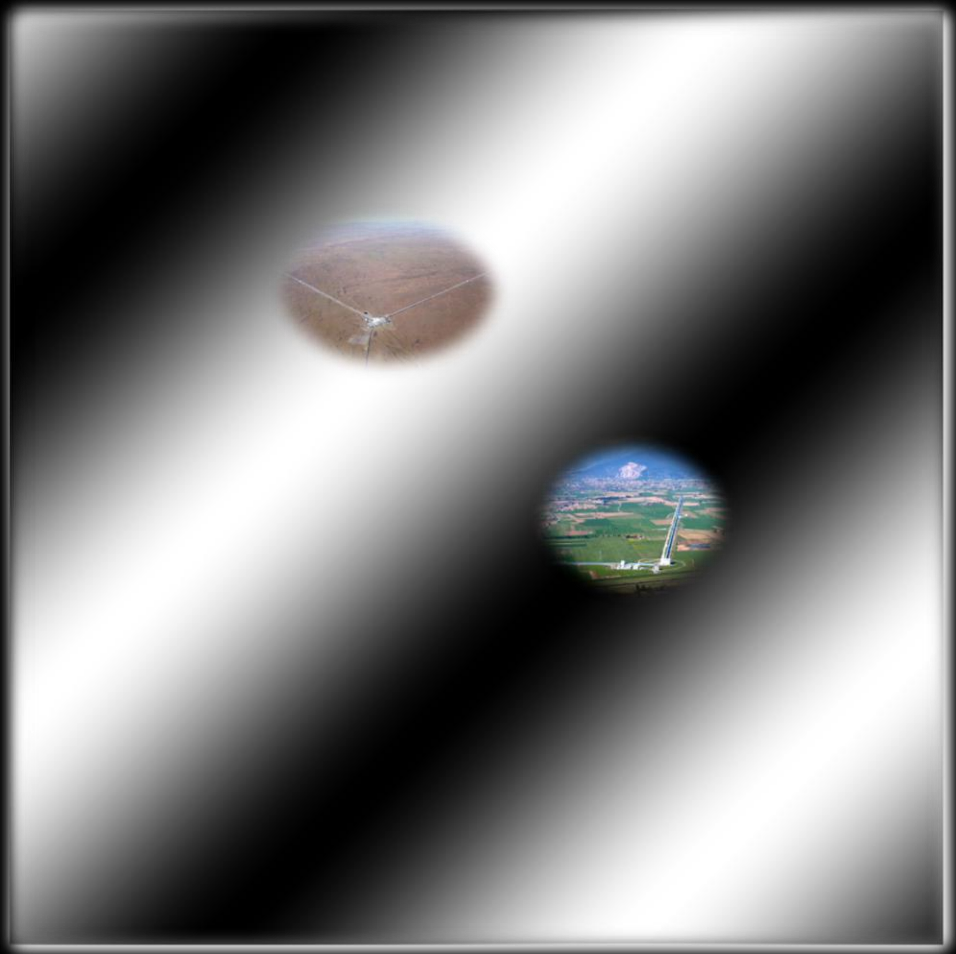
$$C = C_N + S_h \begin{pmatrix} \gamma_{V,V} & \gamma_{V,H} & \cdots & \gamma_{V,K} \\ \gamma_{V,H} & \gamma_{H,H} & \cdots & \gamma_{H,K} \\ \vdots & \vdots & \ddots & \cdots \\ \gamma_{V,K} & \gamma_{H,K} & \cdots & \gamma_{K,K} \end{pmatrix}$$

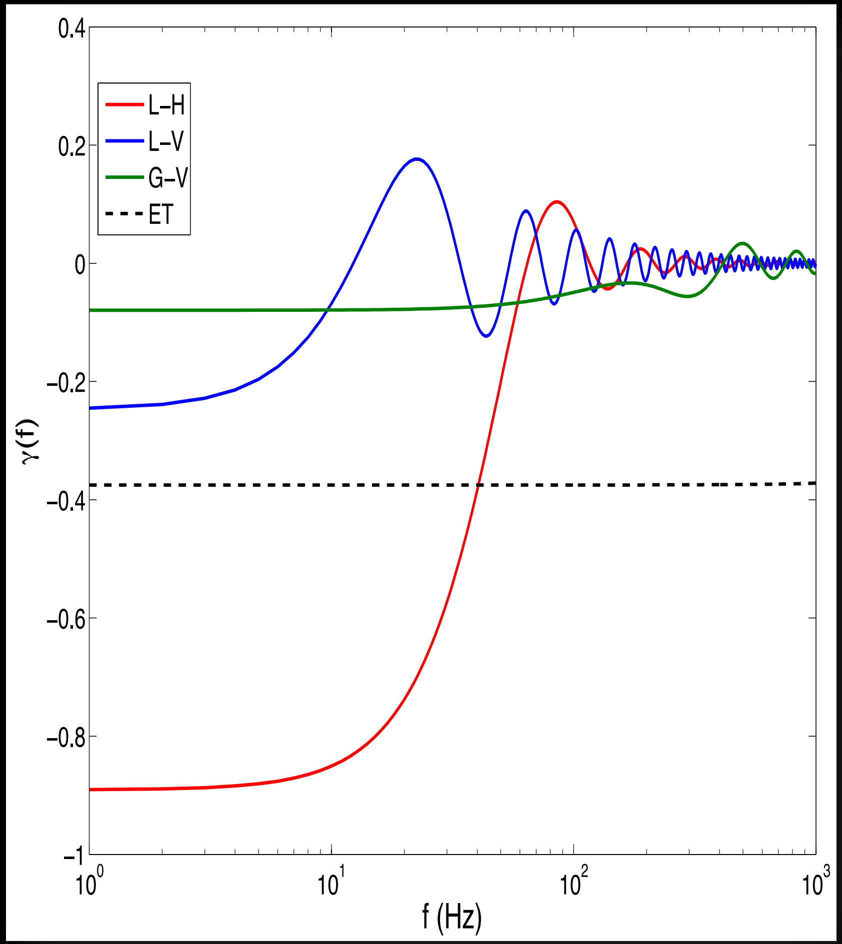
- Optimal statistic (two detectors):

$$Y = \lambda \int df \frac{\tilde{x}_1^{\star}(f)\tilde{x}_2(f)\gamma_{12}(f)S_h(f)}{S_{n,1}(f)S_{n,2}(f)}$$

Overlap reduction function (a.k.a. coherence)

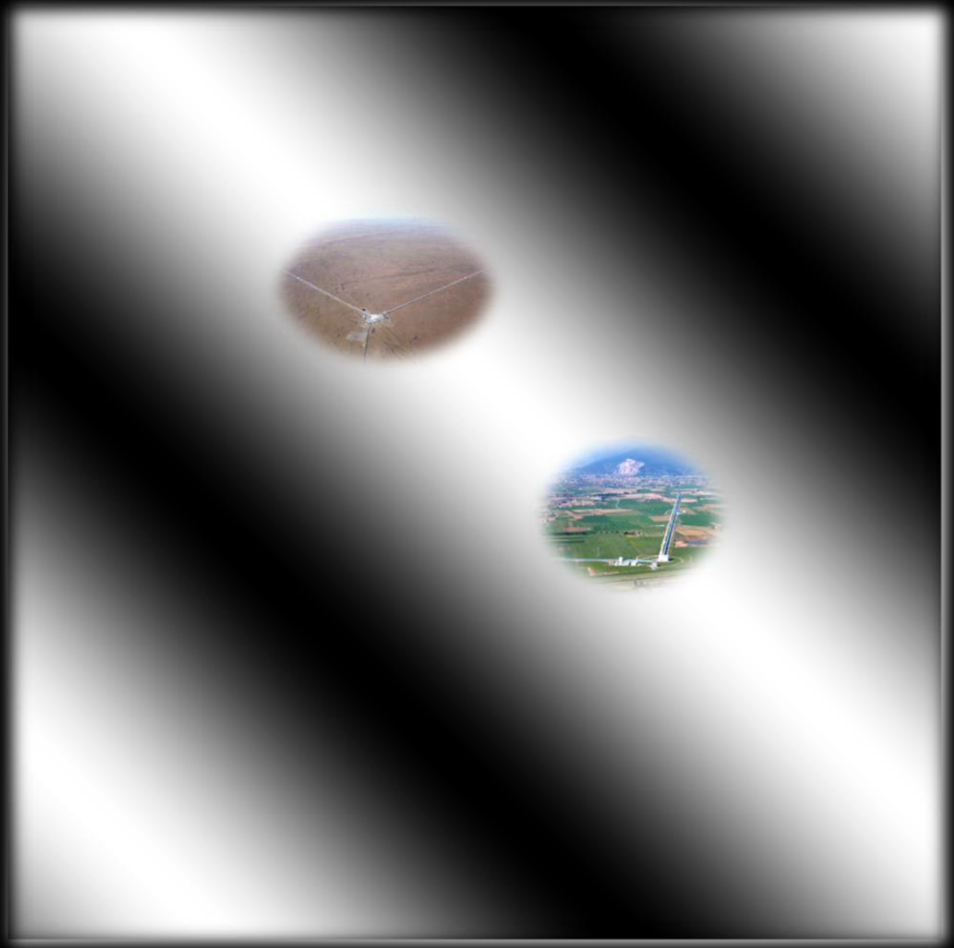
$$\mathrm{SNR}_Y^2 := \frac{\mu_Y^2}{\sigma_Y^2} = 2T\int_0^\infty S_h^2(f)\frac{\gamma_{12}^2(f)}{S_{n,1}(f)S_{n,2}(f)}\,df$$

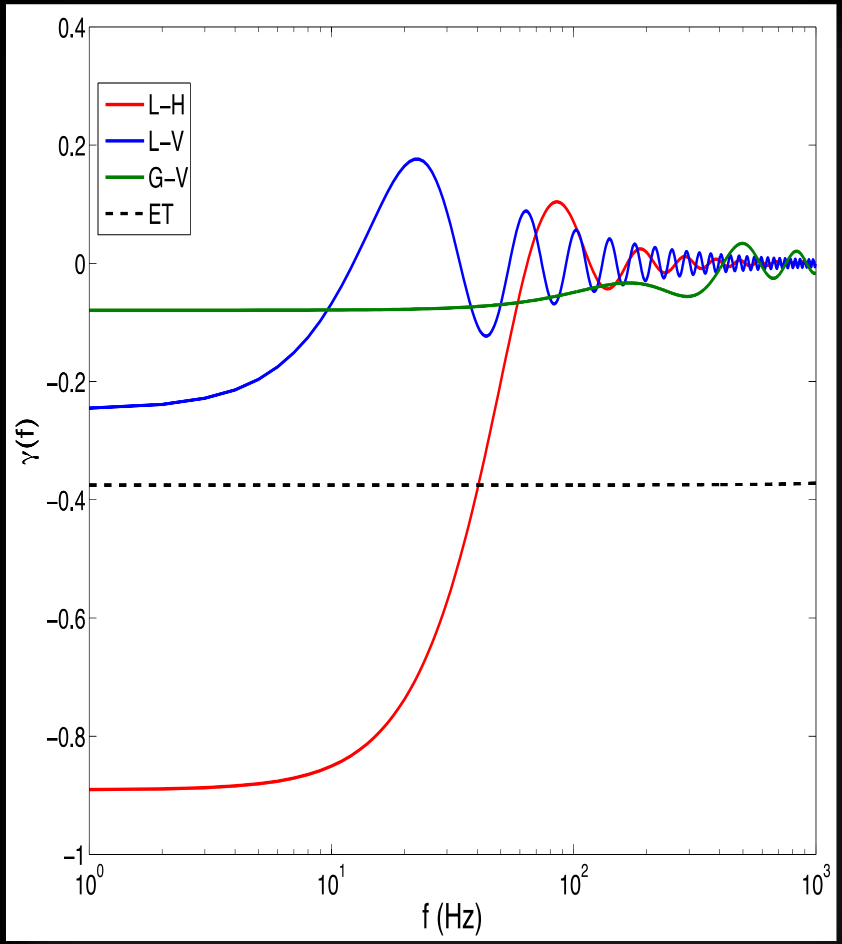




Overlap reduction function (a.k.a. coherence)

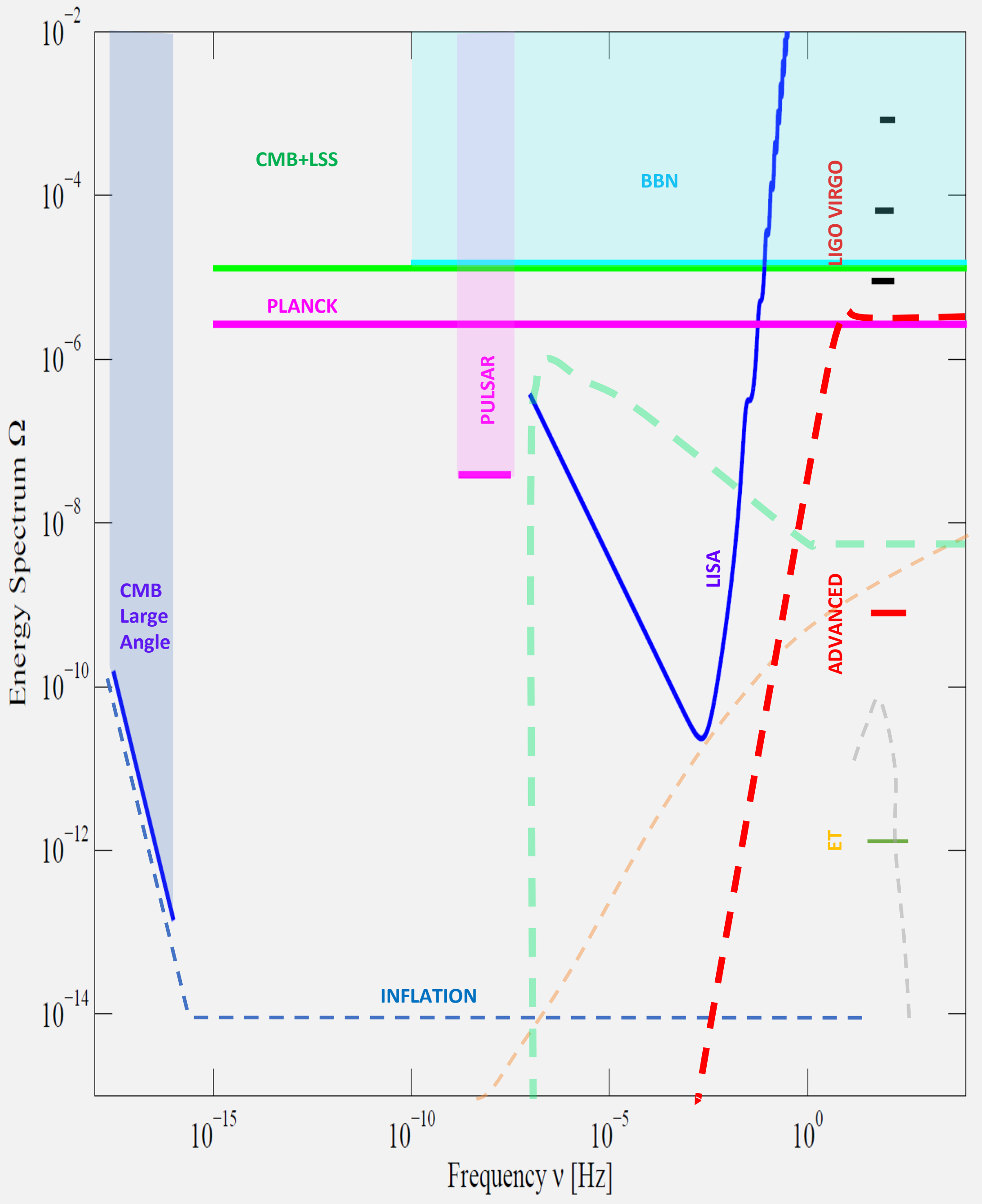
$$\text{SNR}_Y^2 := \frac{\mu_Y^2}{\sigma_Y^2} = 2T \int_0^\infty S_h^2(f) \frac{\gamma_{12}^2(f)}{S_{n,1}(f) S_{n,2}(f)} df$$





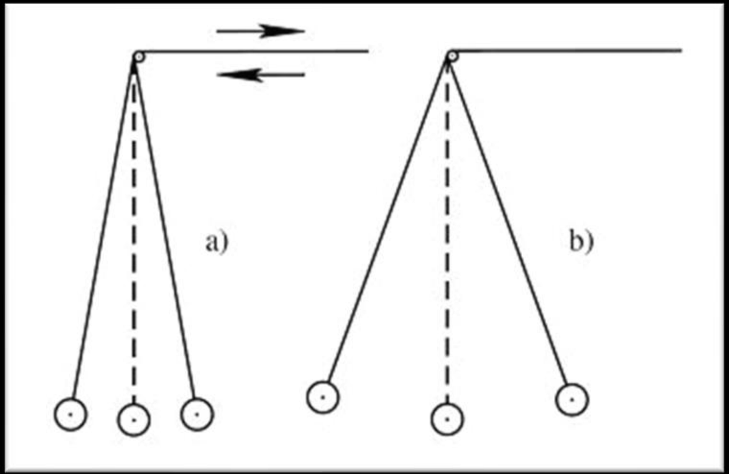
Upper limits & expected sensitivities

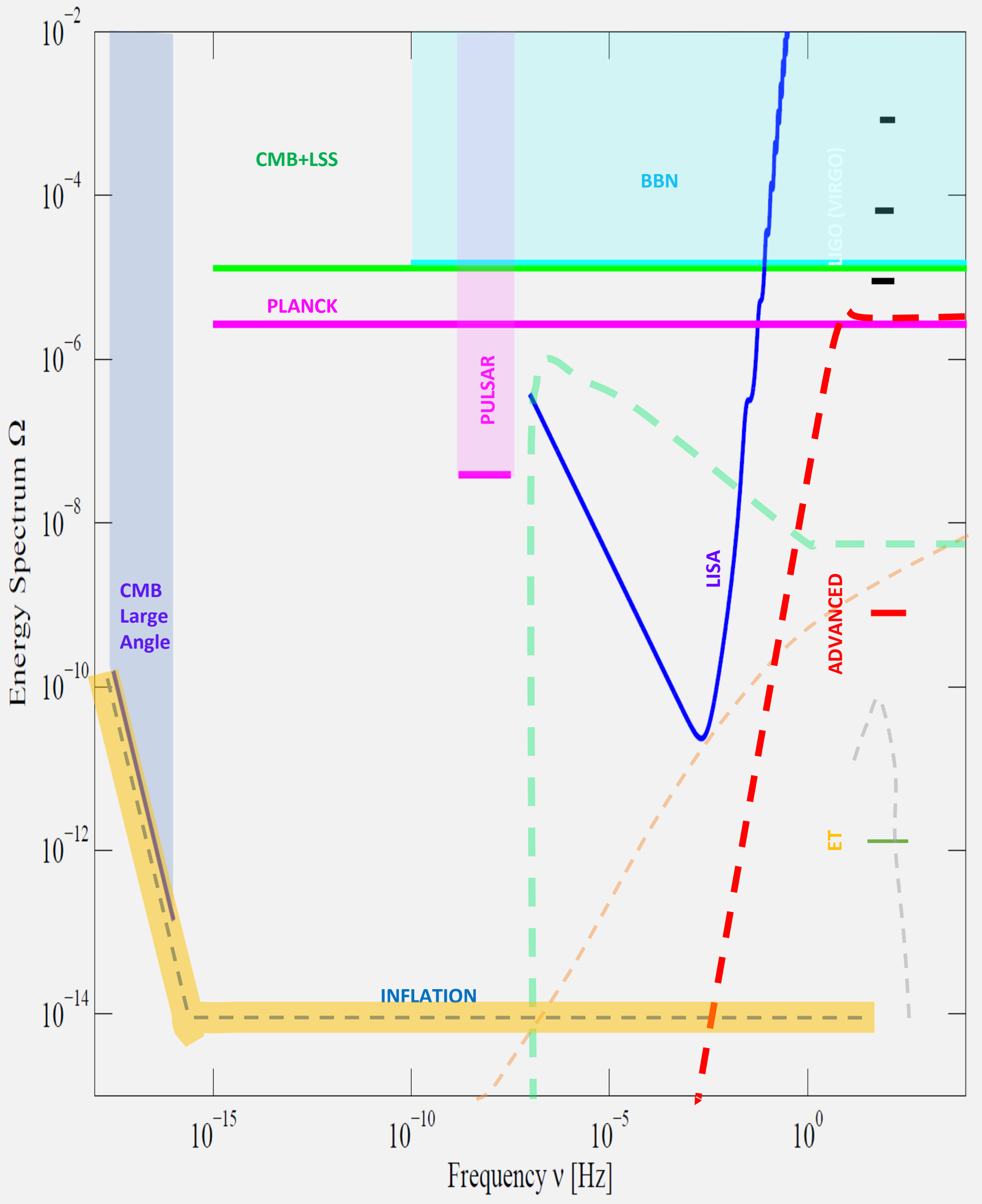
- **Big-Bang Nucleosynthesis model and observations** constrain the total GW energy at the time of BBN (integral bound)
- Similar bound from **CMB observations**
- Too much GW gives too much **large angle anisotropy** by the Sachs Wolfe effect
- Signal from **millisecond pulsars** works as a (big) interferometer:



Inflation

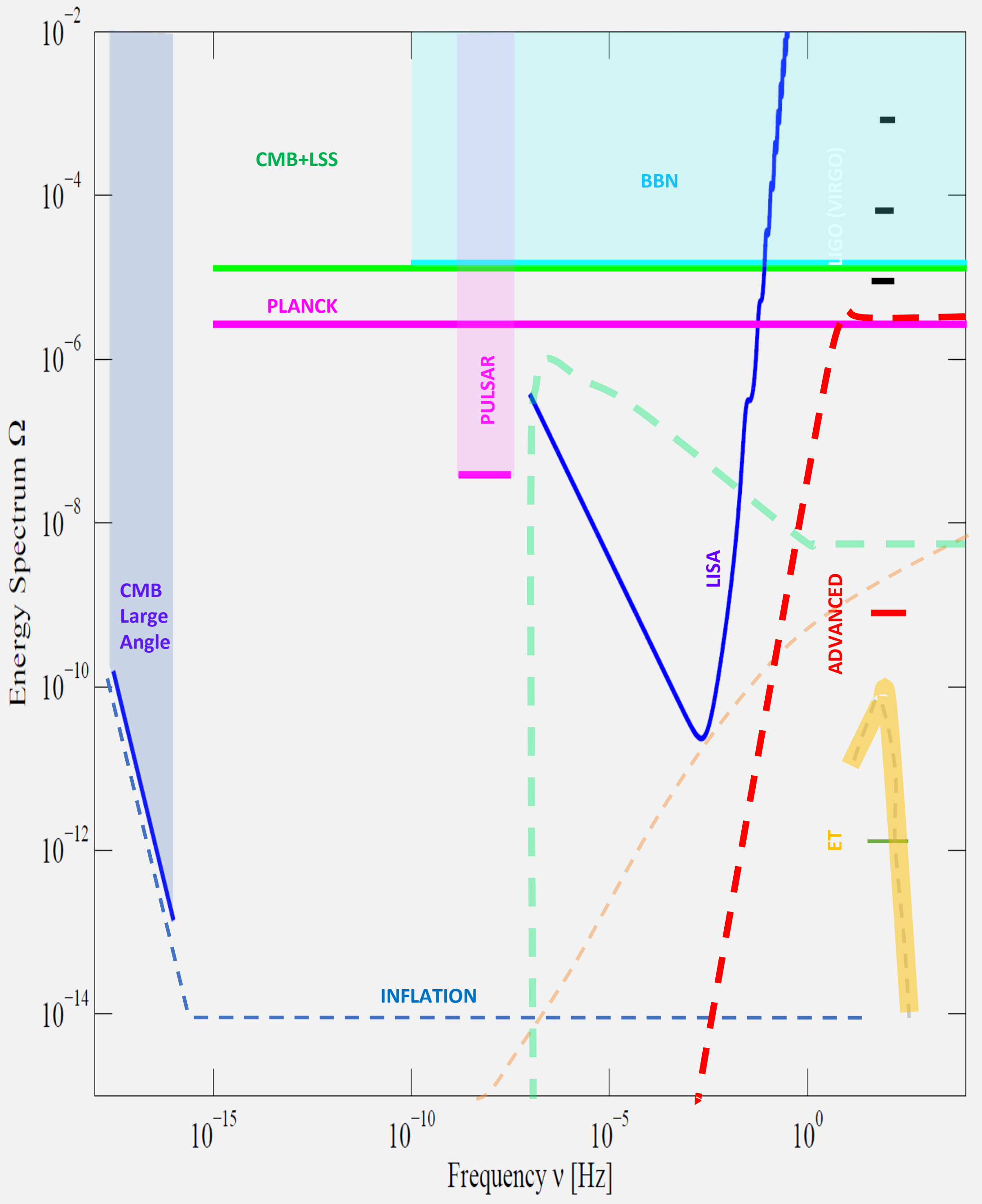
- Parametric amplification of vacuum quantum fluctuations
- Standard inflationary models are weakly dependent on frequency
- Tight bound: CMB large angle anisotropy
- Out of reach of advanced detectors by 5 orders of magnitude





Resonant preheating

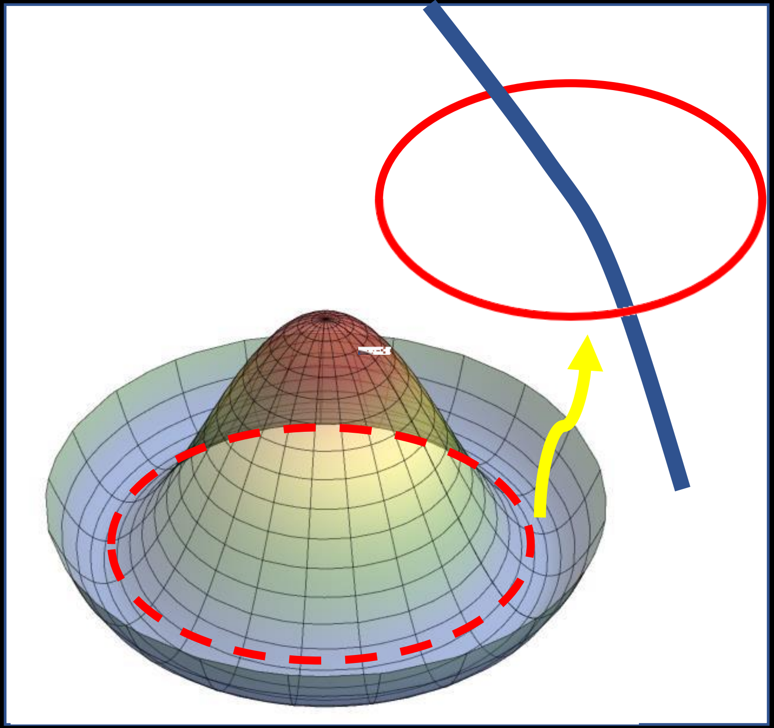
- During a resonant preheating phase at the end of the inflation, inflaton energy can be transferred efficiently to other particles
- Can produce a significant GW background
- Spectrum peak depends on energy scale (here 10 GeV, higher frequencies for a larger scale)



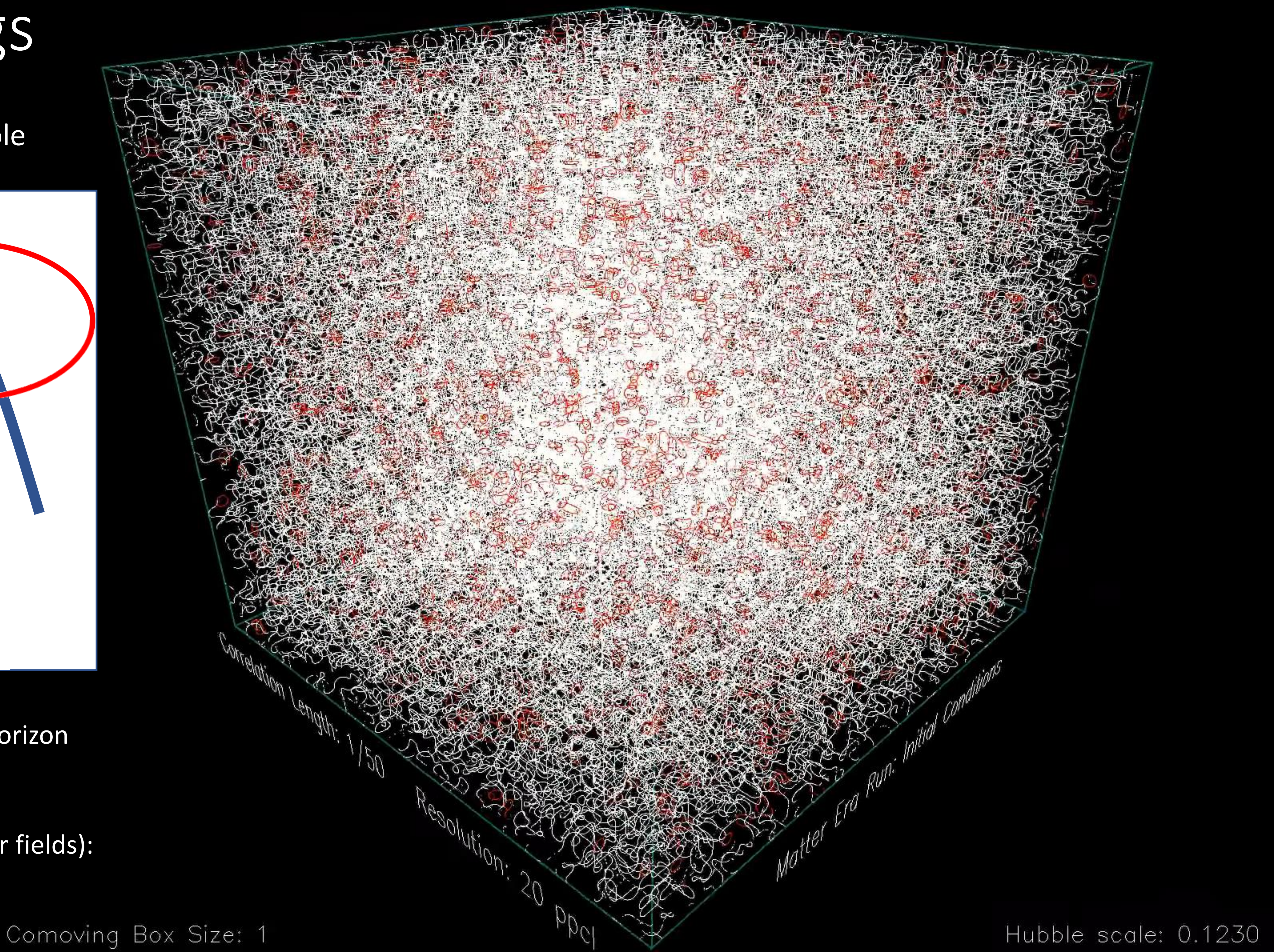
Easther & Lim, JCAP 0604, 010 (2006)
Easther et al., PLR 99, 221301 (2007)
Easther, Nucl. Phys. Proc. Suppl. 194, 33 (2009)

Cosmic strings

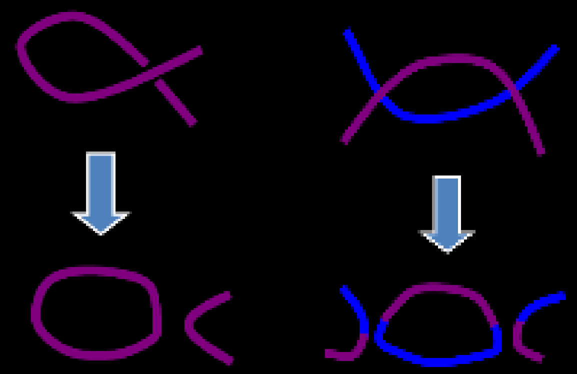
- Topological defects, possible result of SSB

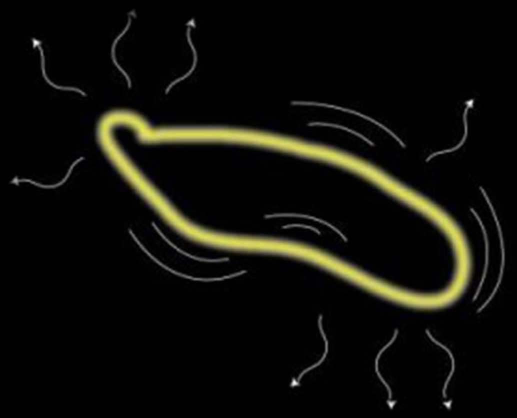


- Dynamical network:
    - Strings entering in the horizon
    - Interconnection: loops generation
    - Radiation (GW and other fields): loop destruction

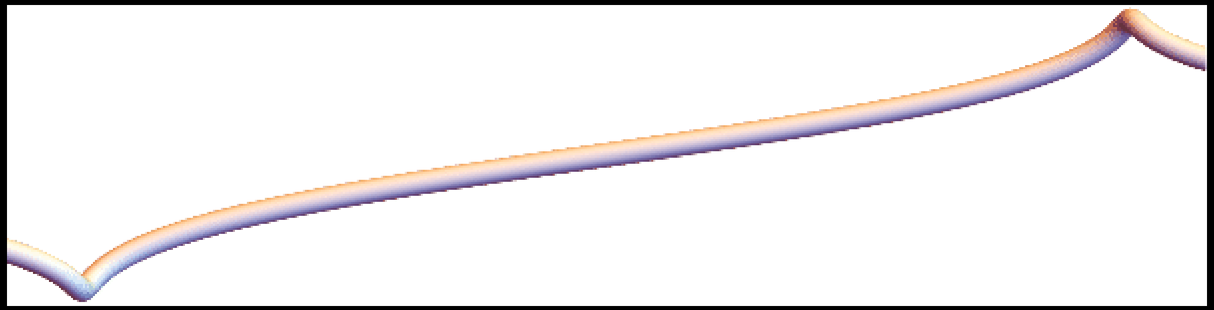


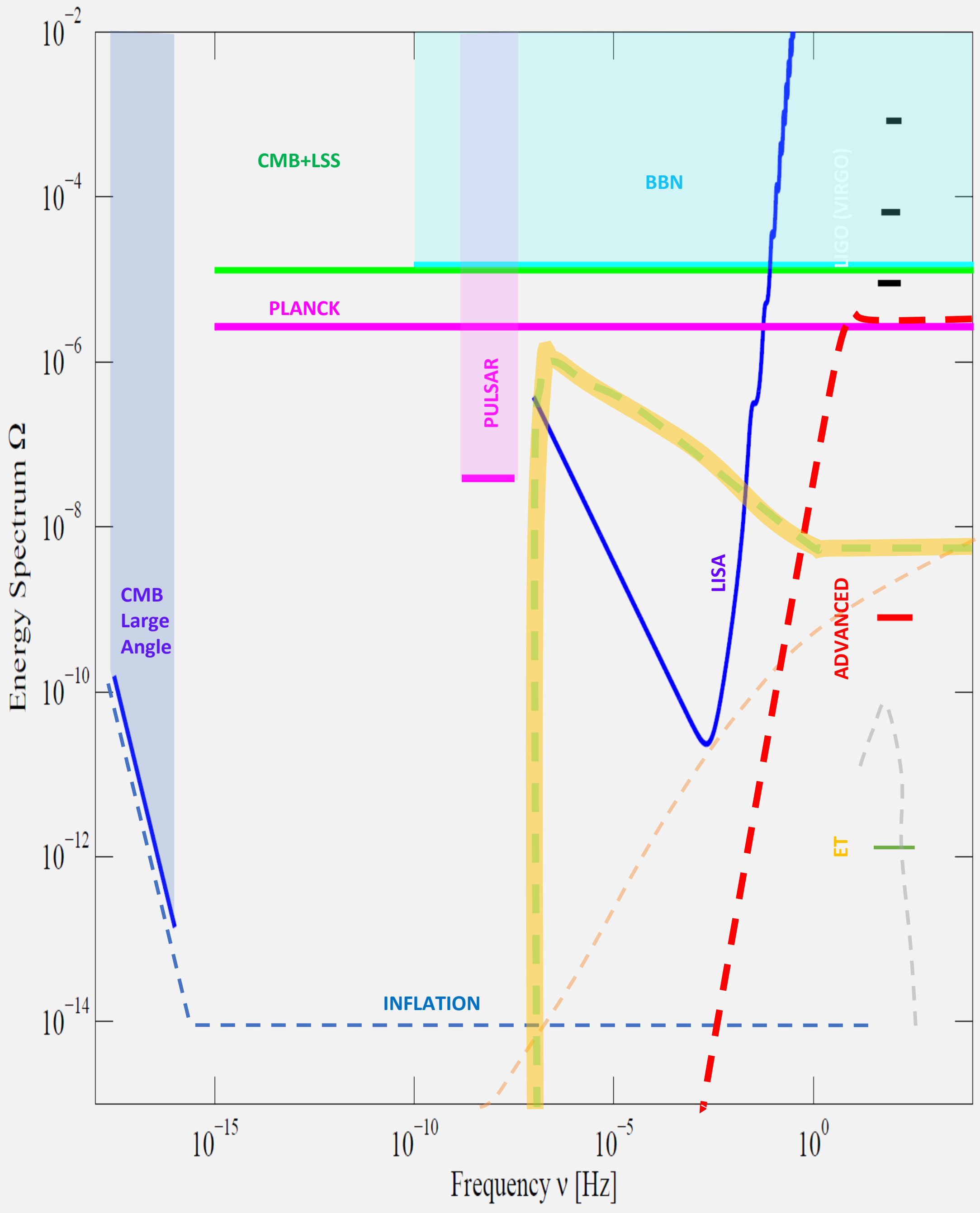
Cosmic string models





- Most efficient emission mechanisms: cusps and kinks



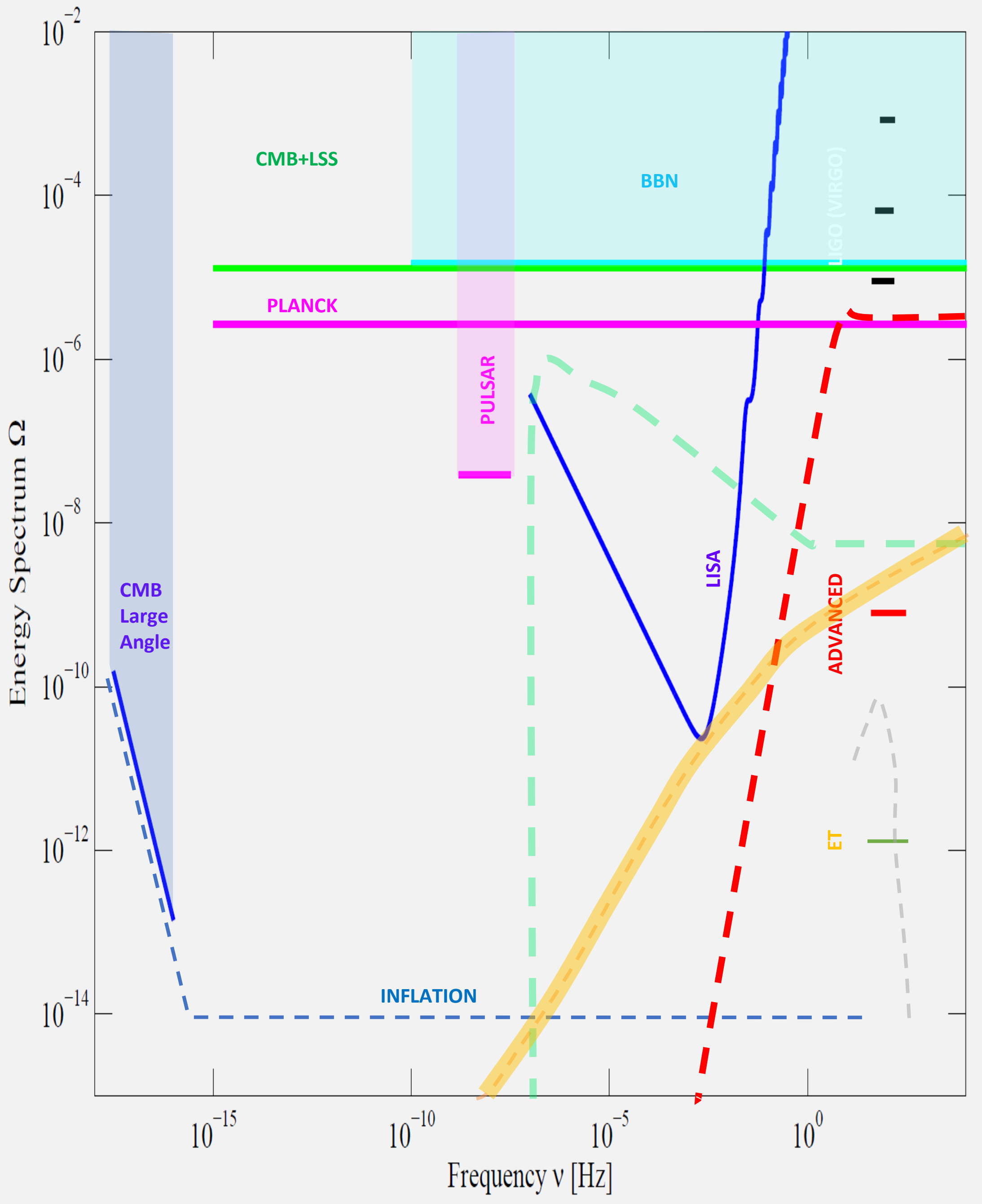


Damour & Vilenkin, PRL 85, 3761 (2000)
Siemens et al., PRL 98, 111101 (2007)
Olmez et al., PRD 81, 104028 (2010)

Axion-based inflation models

- Models include axion-gauge couplings
- Gauge backreaction on the inflaton extends inflation
- The late inflationary phase increases GW production at high frequencies

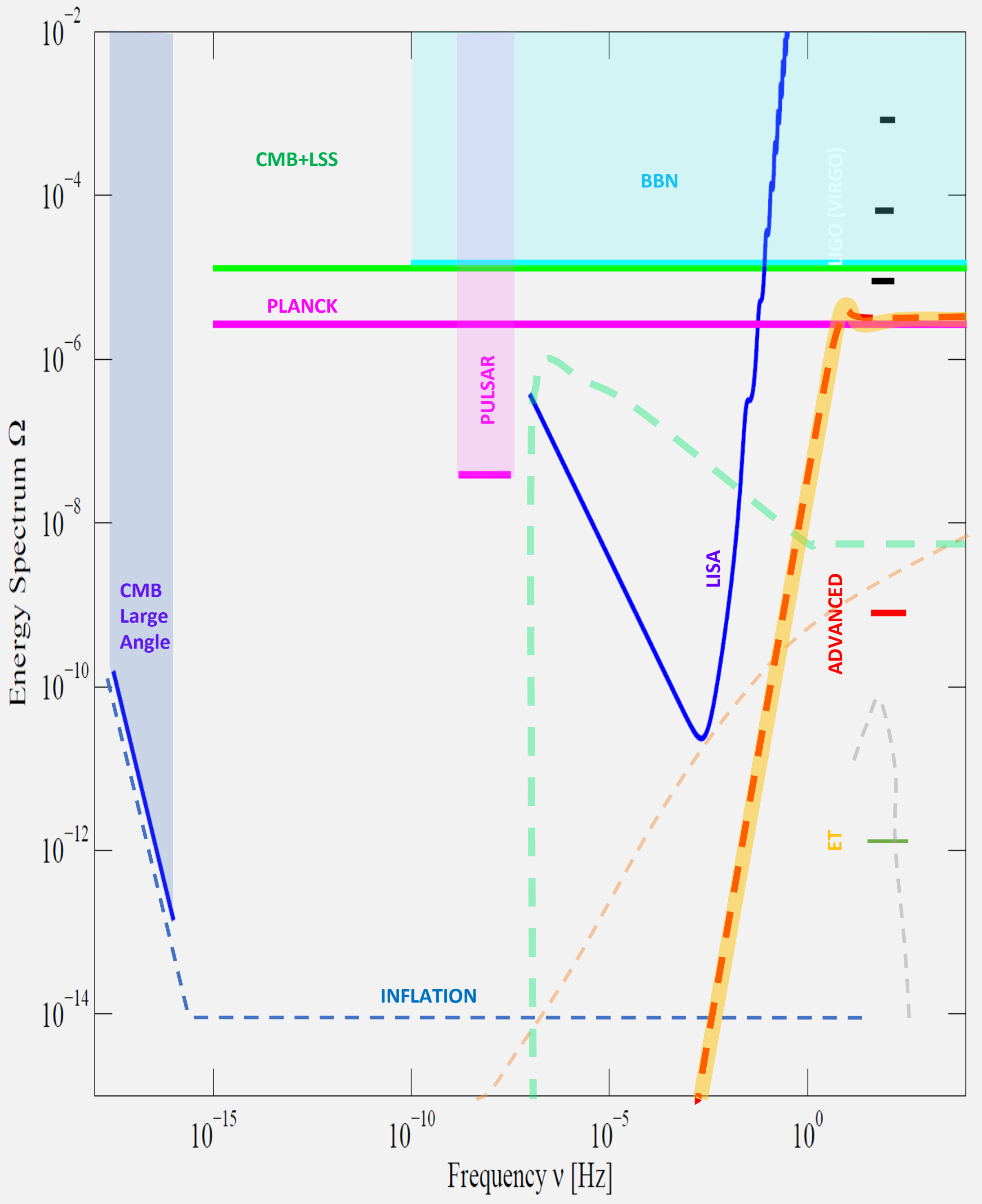
Barnaby, Pajer and Peloso - Phys. Rev. D 85, 023525



Pre-BB models

- Alternative cosmologies
- Evade the CMB large angle anisotropy bound
- Evade the BBN-CMB integral bound
- Could be significant at Virgo/LIGO frequencies

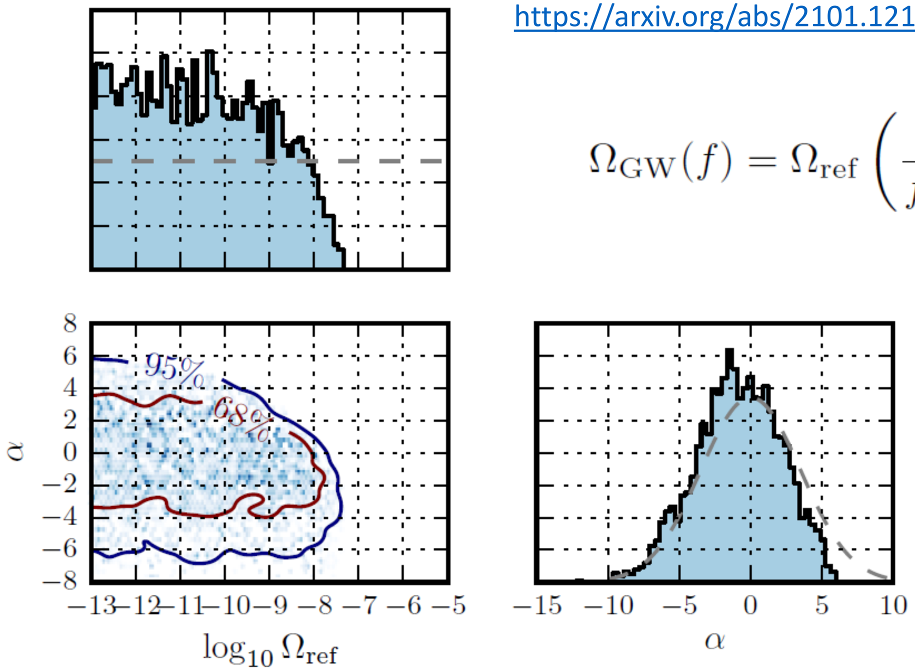
Gasperini & Veneziano, Phys. Rep. 373, 1 (2003)
Buonanno et al., PRD 55, 3330 (1997)



Stochastic background searches

Upper Limits on the Isotropic Gravitational-Wave Background from Advanced LIGO's and Advanced Virgo's Third Observing Run

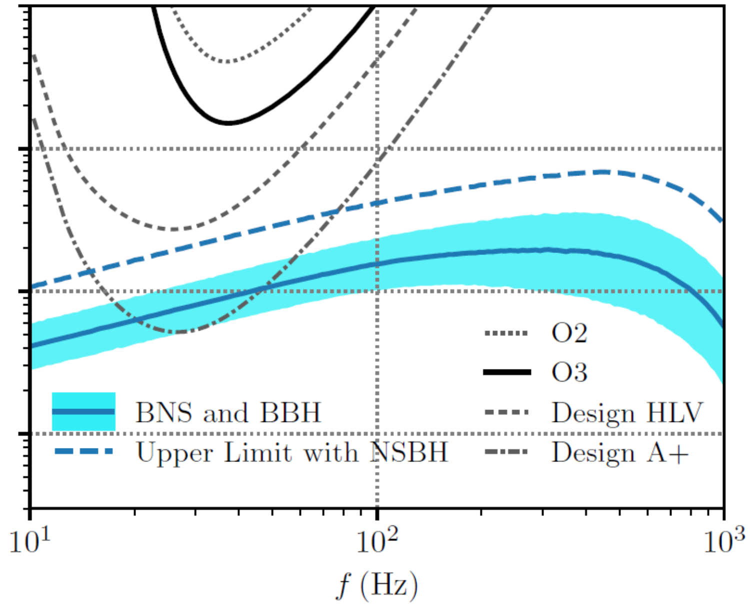
https://arxiv.org/abs/2101.12130



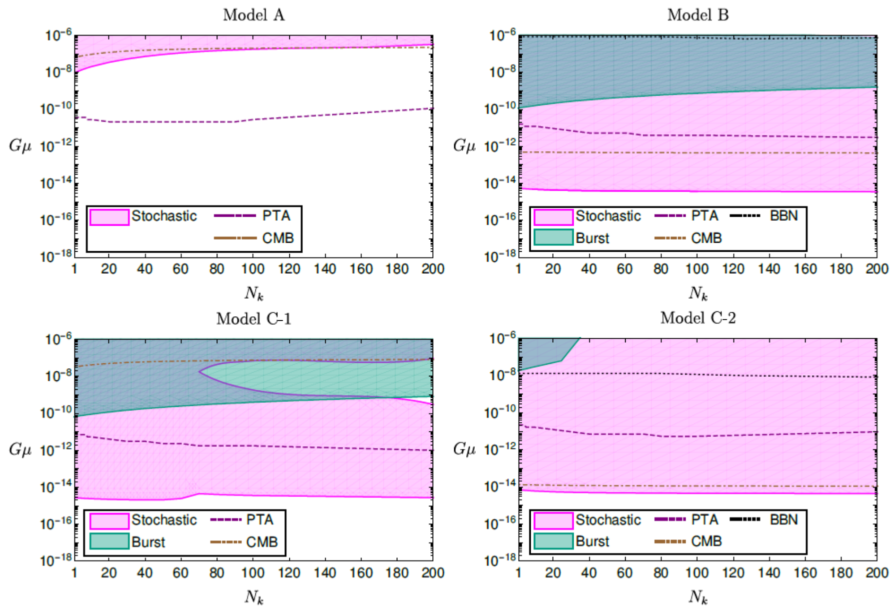
$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{\alpha}$$

	Uniform prior			Log-uniform prior		
α	O3	O2 [43]	Improvement	O3	O2 [43]	Improvement
0	1.7×10^{-8}	6.0×10^{-8}	3.6	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	1.2×10^{-8}	4.8×10^{-8}	4.0	3.4×10^{-9}	3.0×10^{-8}	8.8
3	1.3×10^{-9}	7.9×10^{-9}	5.9	3.9×10^{-10}	5.1×10^{-9}	13.1
Marg.	2.7×10^{-8}	1.1×10^{-7}	4.1	6.6×10^{-9}	3.4×10^{-8}	5.1

Polarization	O3	O2 [43]	Improvement
Tensor	6.4×10^{-9}	3.2×10^{-8}	5.0
Vector	7.9×10^{-9}	2.9×10^{-8}	3.7
Scalar	2.1×10^{-8}	6.1×10^{-8}	2.9

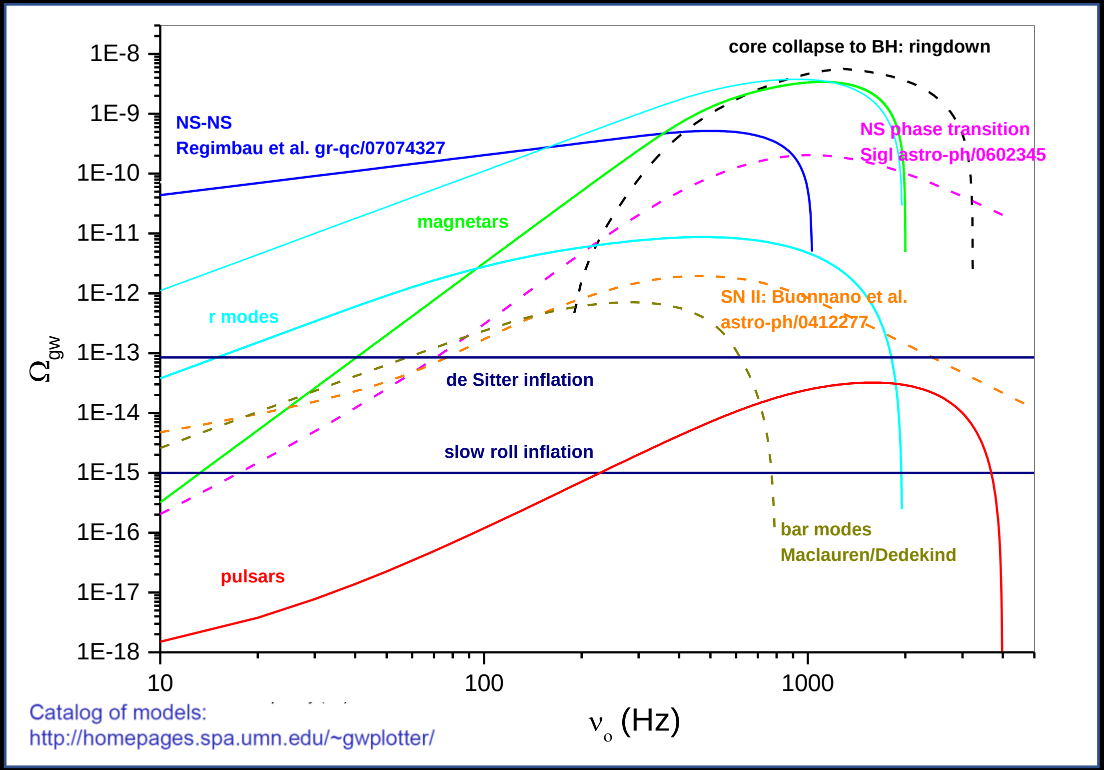


Constraints on cosmic strings using data from the third Advanced LIGO–Virgo observing run https://arxiv.org/abs/2101.12248



Astrophysical Stochastic Background

- **Core collapse supernovae**
  - **Neutron star formation:** *Blair & Ju 1996, Coward et al. 2001-02, Howell et al. 2004, Buonanno et al. 2005*
  - **Stellar Black Hole formation:** *Ferrari et al. 1999, de Araujo et al. 2000-04*
- **Neutron stars**
  - **tri-axial emission:** *Regimbau & de F. Pacheco 2001-06*
  - **bar or r-modes:** *Owen et al. 1998, Ferrari et al. 1999, Regimbau 2001*
  - **phase transitions:** *Sigl 2006*



- **Stellar Compact Binaries**
  - **near coalescence (NS, BH):** *Regimbau et al. 2006-07 , Coward et al. 2005 (BNS), Howell et al. 2007 (BBH)*
  - **low frequency inspiral phase:** *Ferrari et al. 2002, Farmer & Phinney 2002, Cooray 2004 (WD-NS)*
- **Capture of compact objects by SMBHs** *: Barack & Cutler 2004*

$$\Omega_{gw}(f) = \int P(\underline{\theta})\Omega_{gw}(f,\underline{\theta})d\underline{\theta}$$

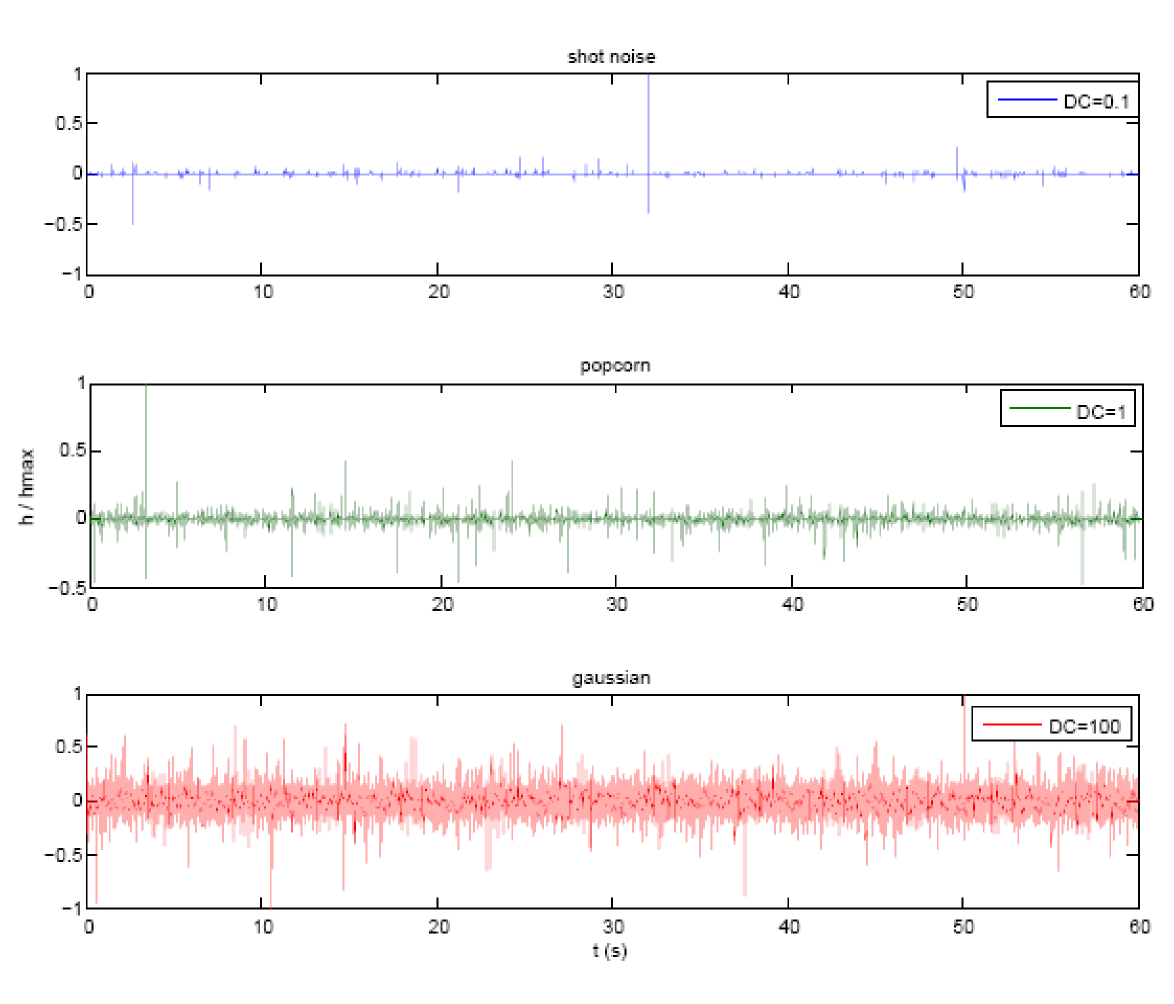
$$\Omega_{gw}(f,\underline{\theta}) = \frac{f}{\rho_c}\int \frac{dR}{dz}(z,\underline{\theta})\,\frac{1}{4\pi r^2(z)}\,\frac{dE_{gw}}{df}(\underline{\theta}, f(1+z))\,dz$$

Astrophysical Stochastic Background

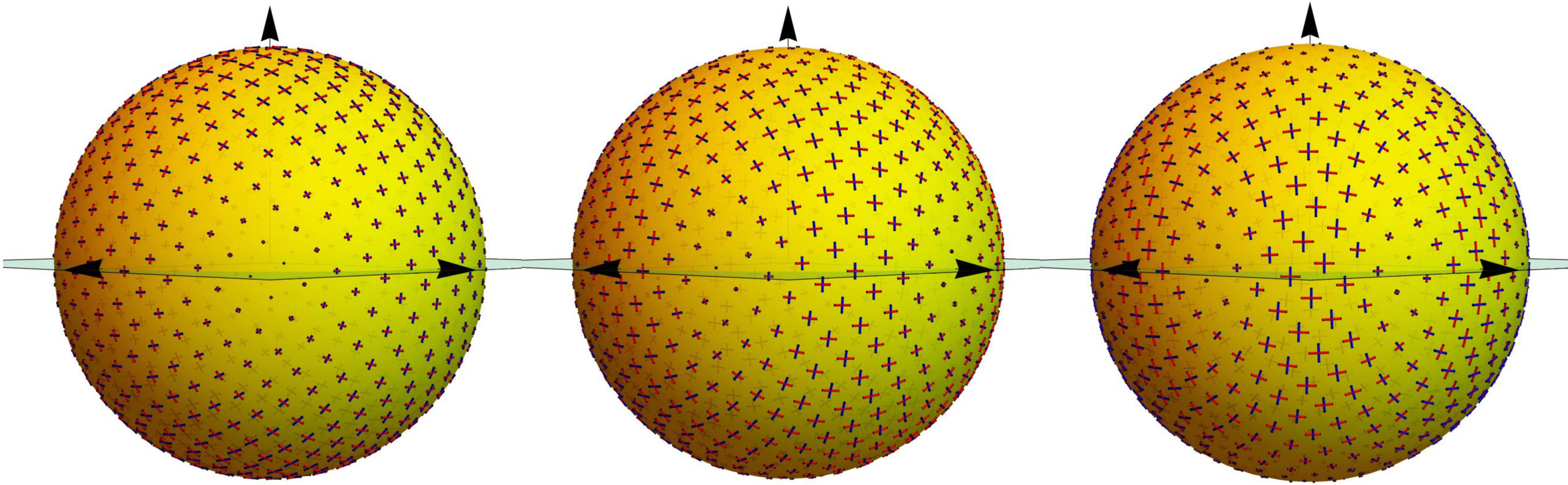
$$D(z) = \int_0^z \tau \, (1+z') \frac{dR}{dz'} dz'$$

Duty cycle: ratio between the observed typical duration of the event and the average time between events.

- $D \ll 1$: resolved sources
  - Burst data analysis, optimal filtering
- $D \simeq 1$: «popcorn noise»
  - Bayesian approach
  - Suboptimal, unmodeled approaches
- $D \gg 1$: Gaussian stochastic background
  - Cross correlation statistic (isotropic/anisotropic)

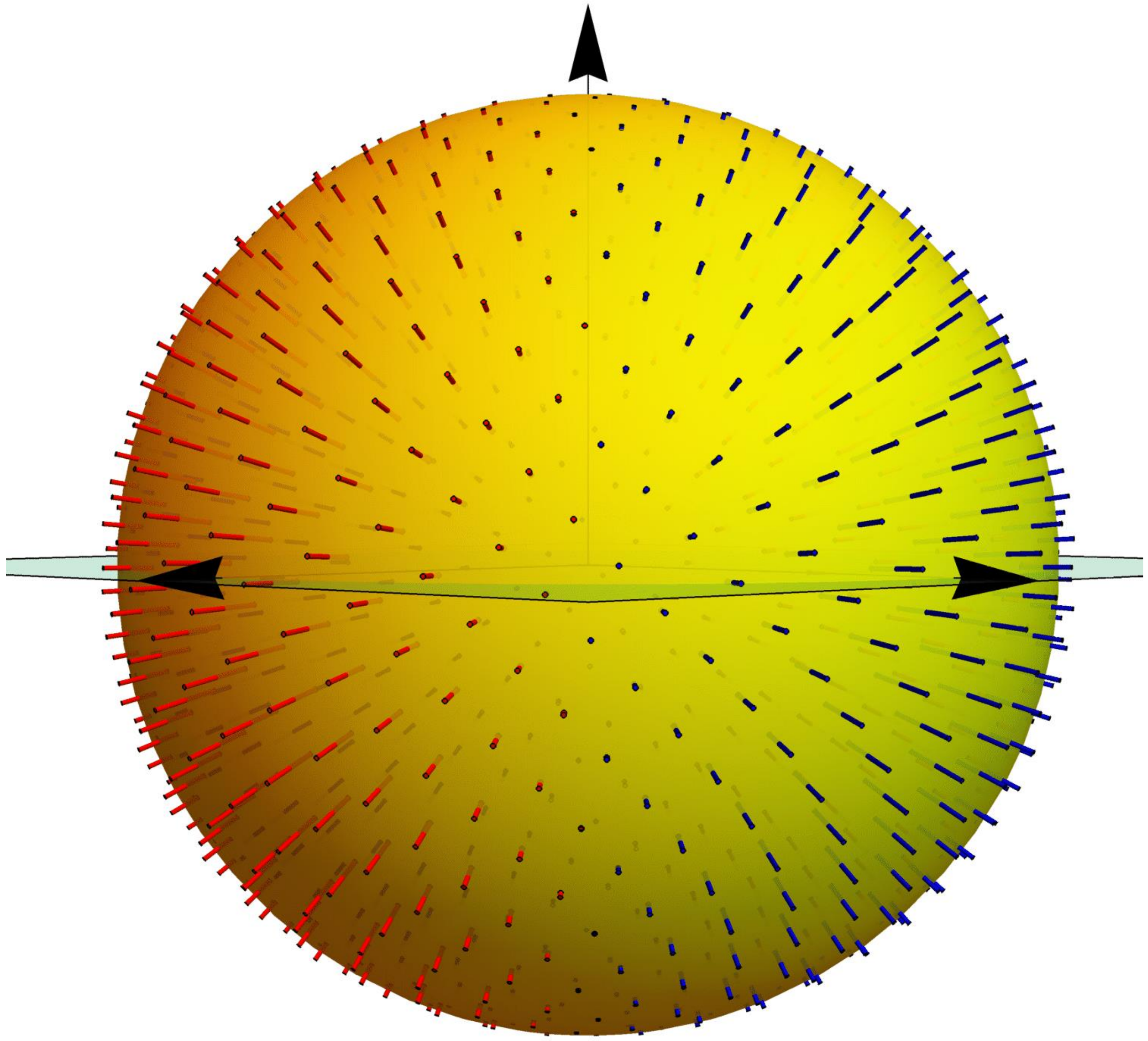


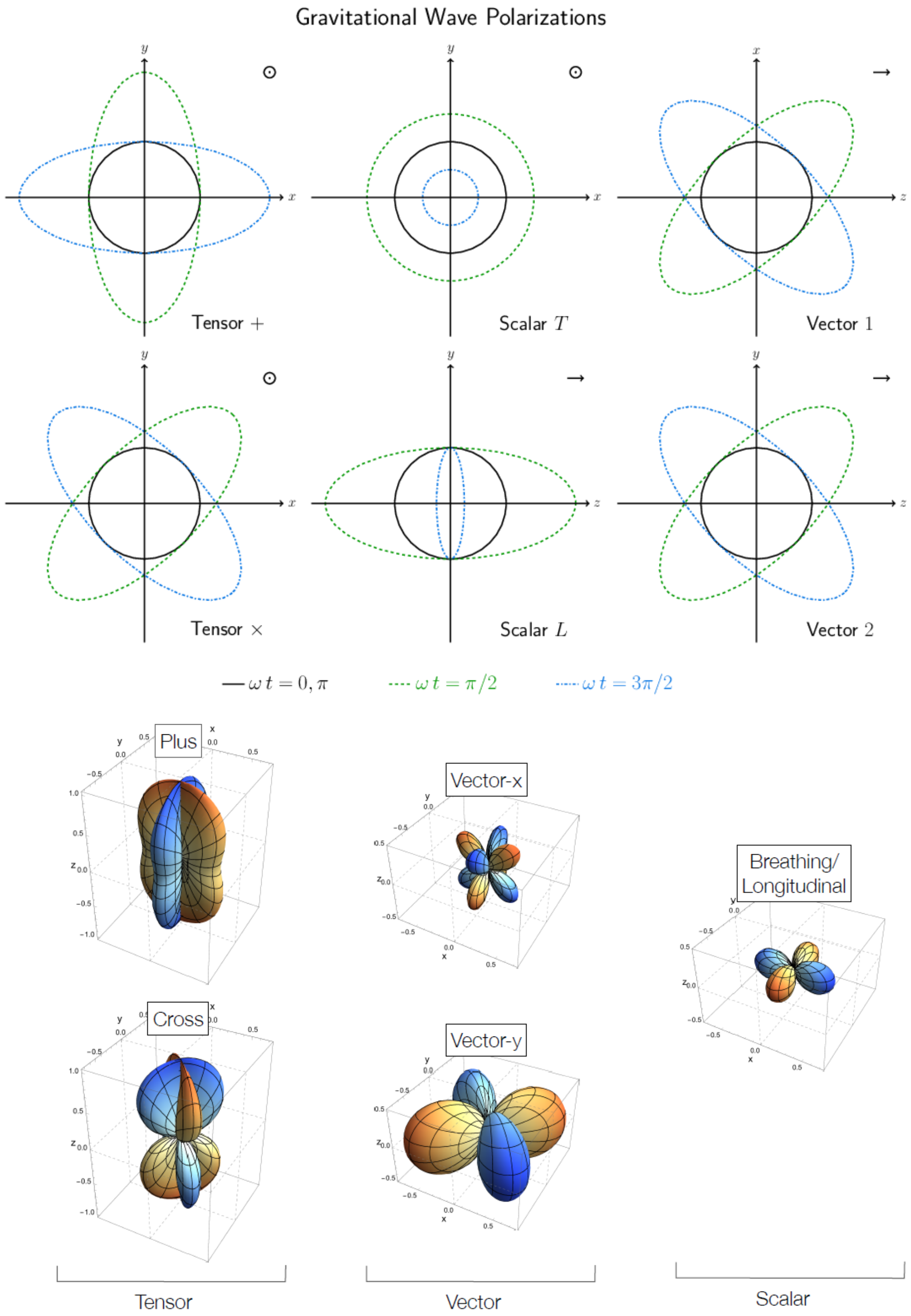
Standard polarizations



$TE_{2,2}$ $\qquad$ $TE_{3,3}$ $\qquad$ $TE_{4,4}$

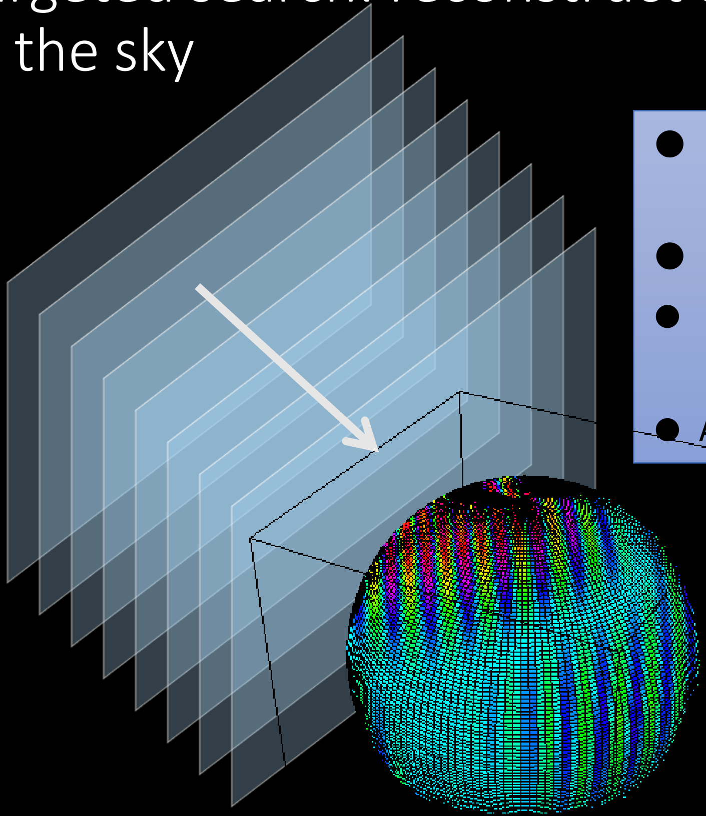
$\omega_{gw} = 2\omega_{orb}$ $\qquad$ $\omega_{gw} = \frac{3}{2}\omega_{orb}$ $\qquad$ $\omega_{gw} = 4\omega_{orb}$



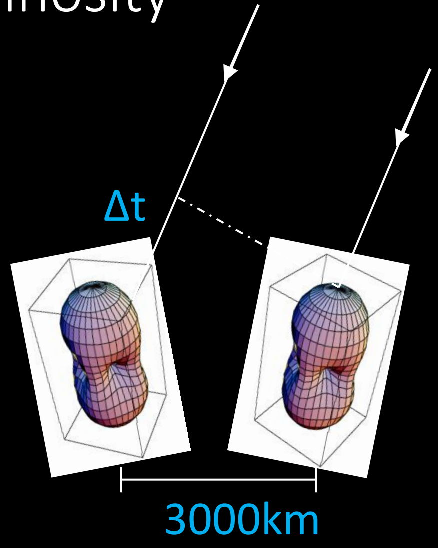


Gravitational Wave Polarizations
Tensor +
Scalar T
Vector 1
Tensor ×
Scalar L
Vector 2
$\omega t = 0, \pi$
$\omega t = \pi/2$
$\omega t = 3\pi/2$
Plus
Cross
Vector-x
Vector-y
Breathing/ Longitudinal
Tensor
Vector
Scalar

Targeted search: reconstruct a map of the gravitational wave luminosity in the sky



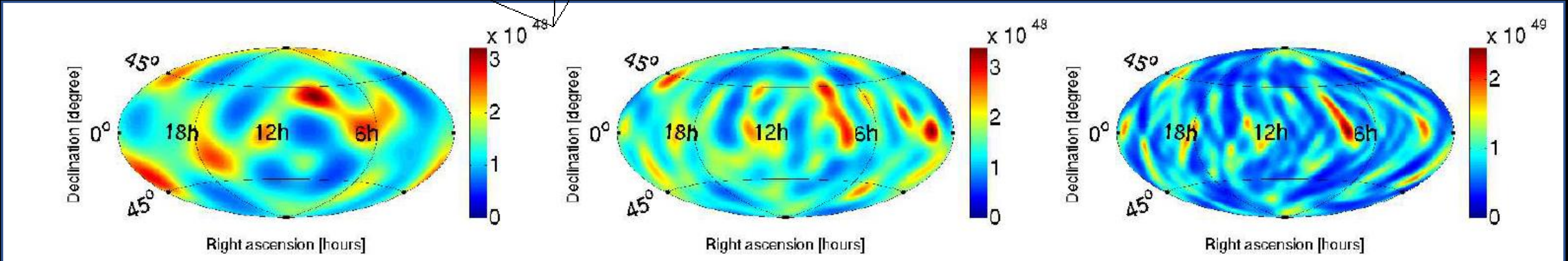
- Correct the direction-dependent modulation
- Cross-Correlate
- At least 3 detectors needed to close the inverse problem.
- Angular resolution limited by λ/D



$$\Omega_{gw}(f) = \frac{2\pi^2}{3H_0^2} f^2 S_h(f) \int_{S^2} d\hat{\Omega}\, \mathcal{P}(\hat{\Omega})$$

$$\mathcal{P}(\vec{\Omega}) \equiv \int \eta(\hat{\Omega}')\delta^2(\hat{\Omega}, \hat{\Omega}')d\hat{\Omega}'$$ «radiometer» search

$$\mathcal{P}(\vec{\Omega}) \equiv \sum_{\ell,m} c_{\ell m} Y_{\ell m}(\hat{\Omega})$$ «SA» search

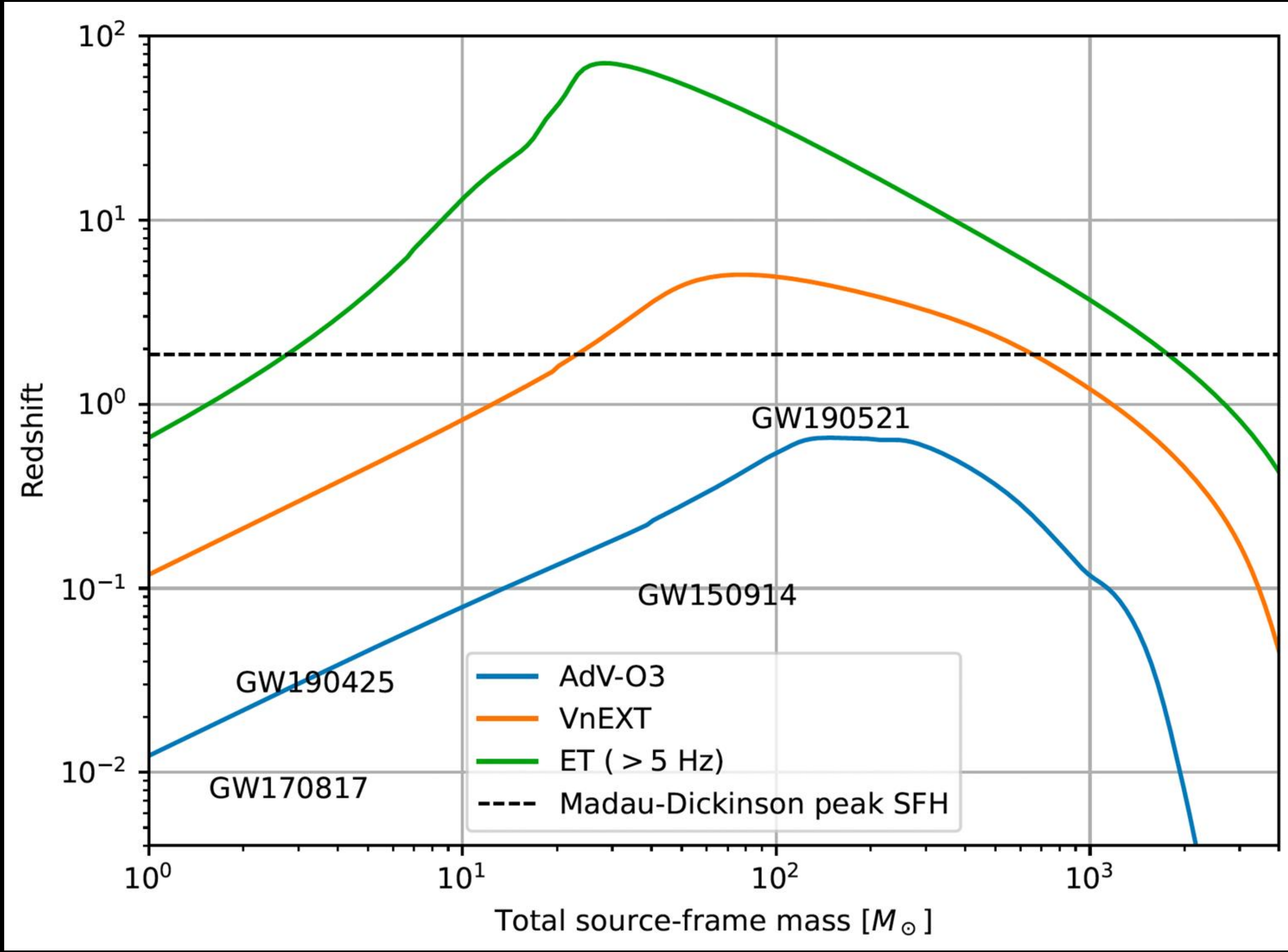


Virgo+WA 200 Hz

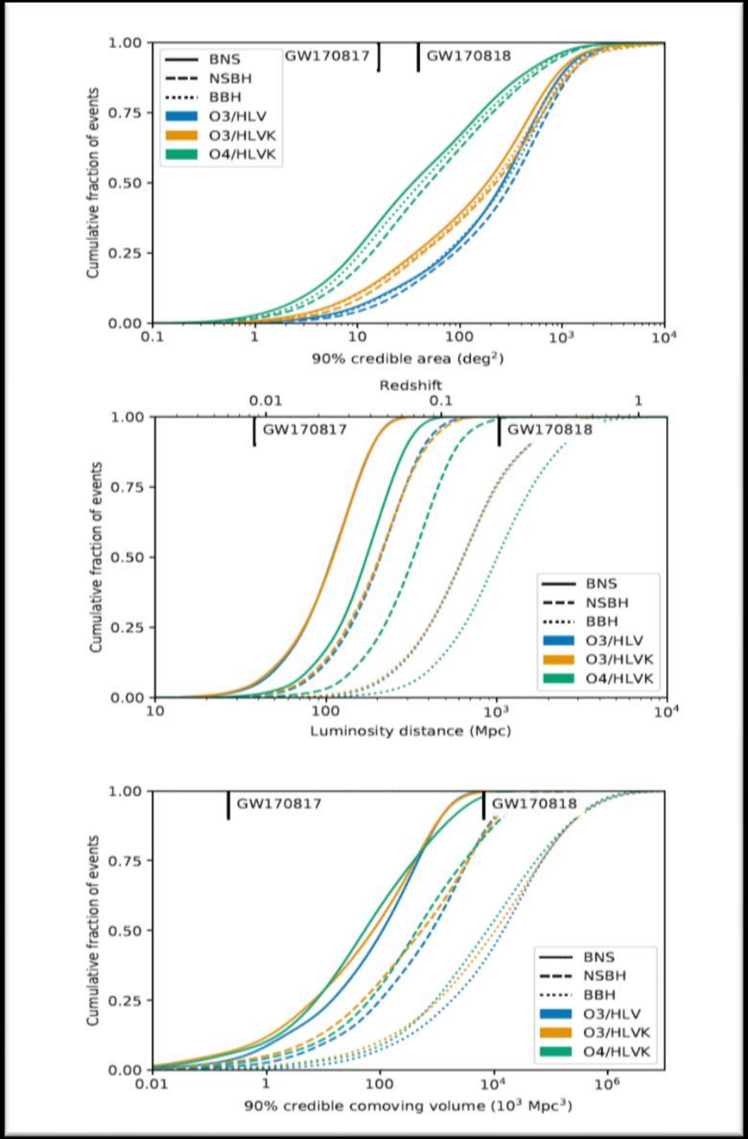
PRD76, 082003, 2007

Phys. Rev. Lett. 107, 271102

Some future perspectives



O4: what we expect



		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
$1.4M_\odot + 30M_\odot$	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
$30M_\odot + 30M_\odot$	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
$1.4M_\odot + 10M_\odot$	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
$[E_{GW} = 10^{-2} M_\odot c^2]$	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc)	aLIGO	15	20	25 – 30	35 – 40	70
$[E_{GW} = 10^{-9} M_\odot c^2]$	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

SNR = 8 on each detector

Living Rev Relativ **23,** 3 (2020). https://doi.org/10.1007/s41114-020-00026-9

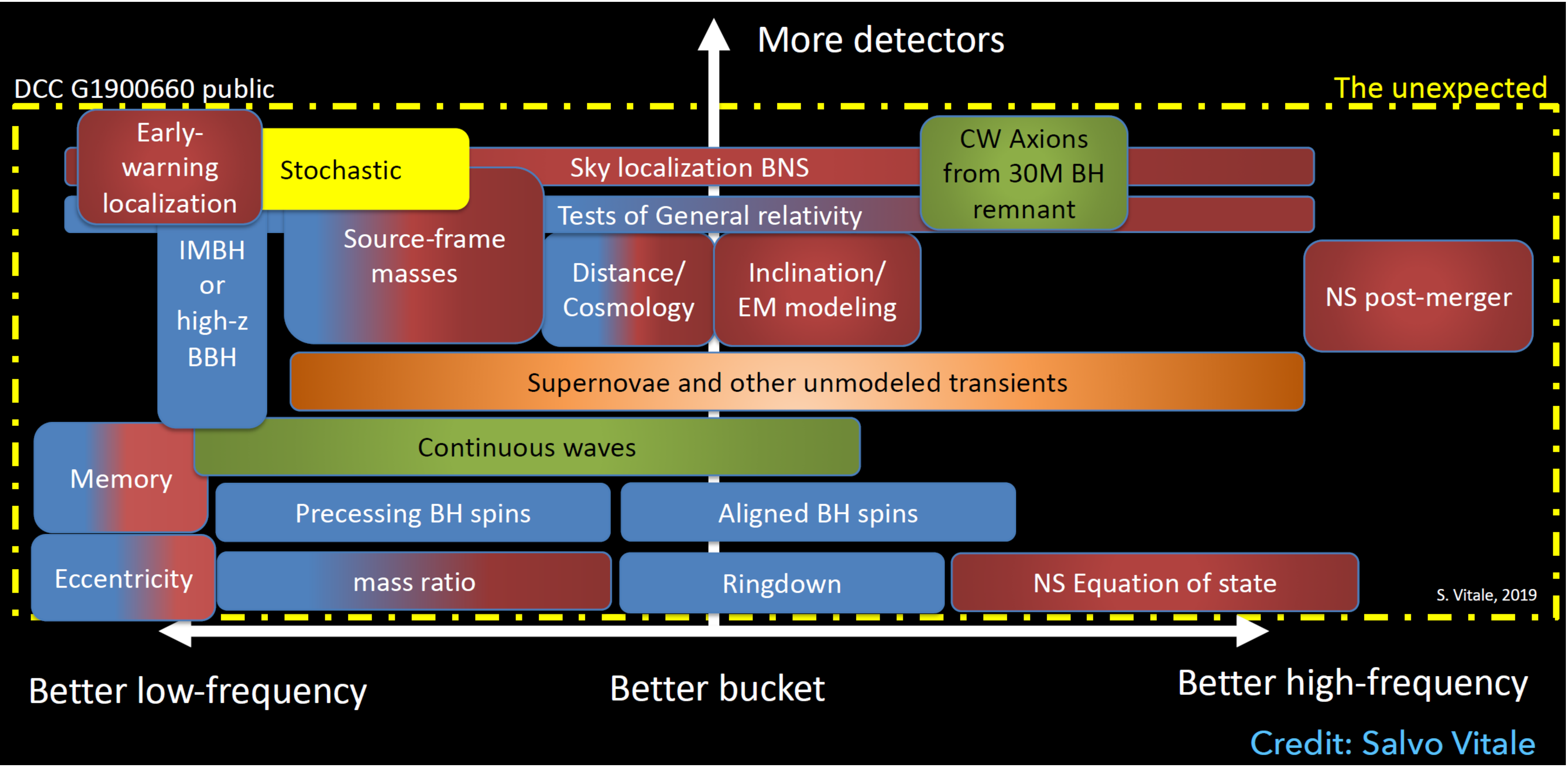
O4: what we expect

Table 5 Expected BNS, BBH and NSBH detections and localization accuracy for the O3 and O4 observing runs

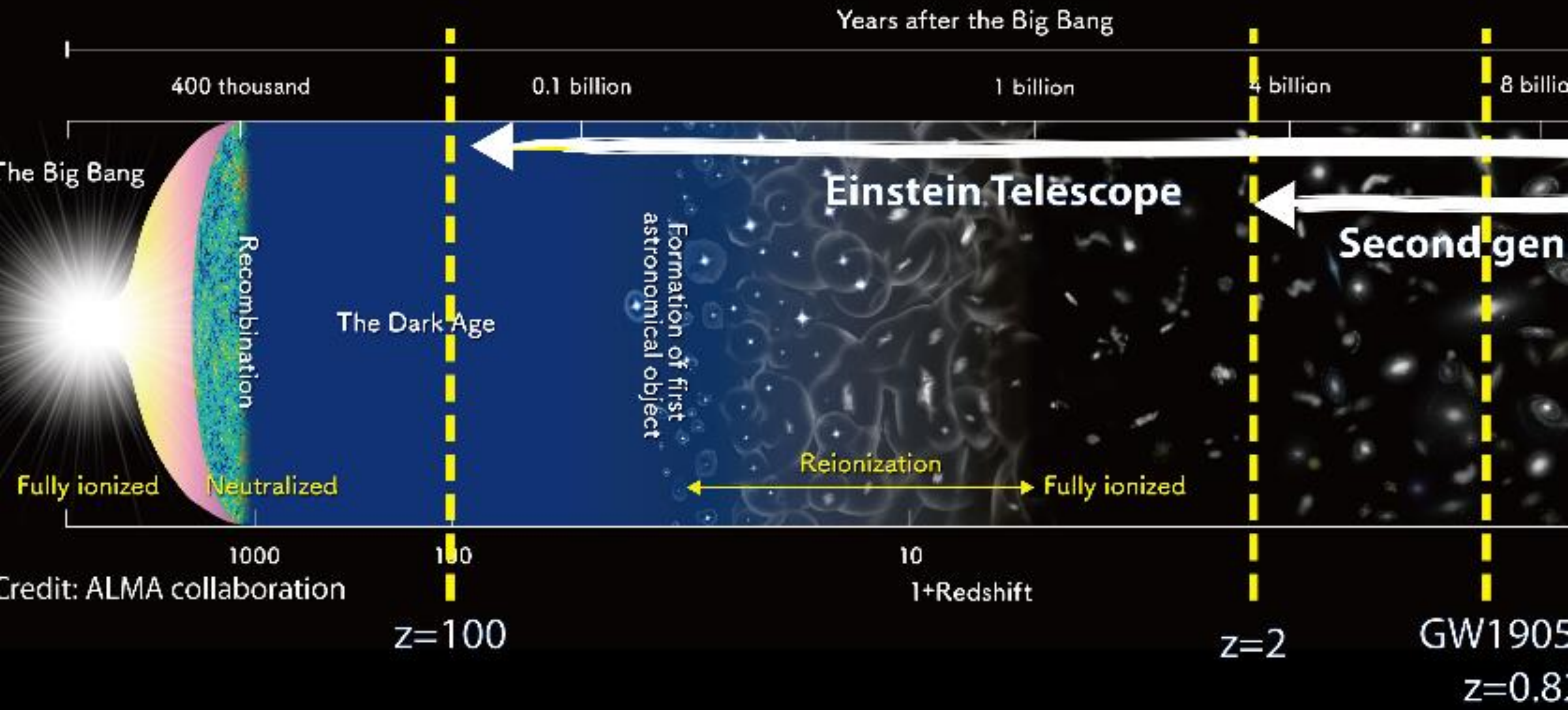
Observation run	Network	Expected BNS detections	Expected NSBH detections	Expected BBH detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}
		Comoving volume (10^3 Mpc^3) 90% c.r.	Comoving volume (10^3 Mpc^3) 90% c.r.	Comoving volume (10^3 Mpc^3) 90% c.r.
O3	HLV	120^{+19}_{-24}	860^{+150}_{-150}	16000^{+2200}_{-2500}
O4	HLVK	52^{+10}_{-9}	430^{+100}_{-78}	7700^{+1500}_{-920}

One year data taking period

Living Rev Relativ **23,** 3 (2020). https://doi.org/10.1007/s41114-020-00026-9


More detectors
DCC G1900660 public
The unexpected
Early-warning localization
Stochastic
Sky localization BNS
CW Axions from 30M BH remnant
Tests of General relativity
IMBH or high-z BBH
Source-frame masses
Distance/ Cosmology
Inclination/ EM modeling
NS post-merger
Supernovae and other unmodeled transients
Memory
Continuous waves
Precessing BH spins
Aligned BH spins
Eccentricity
mass ratio
Ringdown
NS Equation of state
S. Vitale, 2019
Better low-frequency
Better bucket
Better high-frequency
Credit: Salvo Vitale

Detection horizon for black-hole binaries



Summary: present and future GW science

ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings