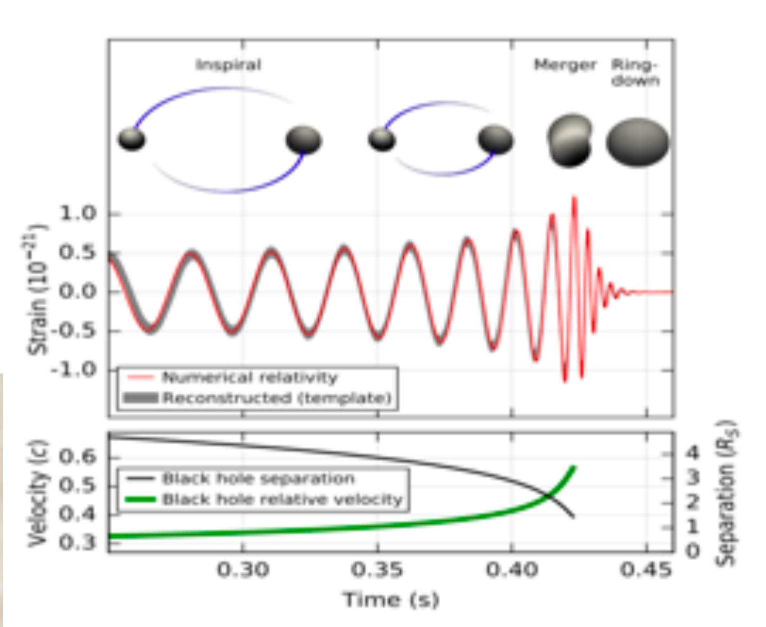
INAF after GW150914



MONTE MARIO – 11 APRIL 2016

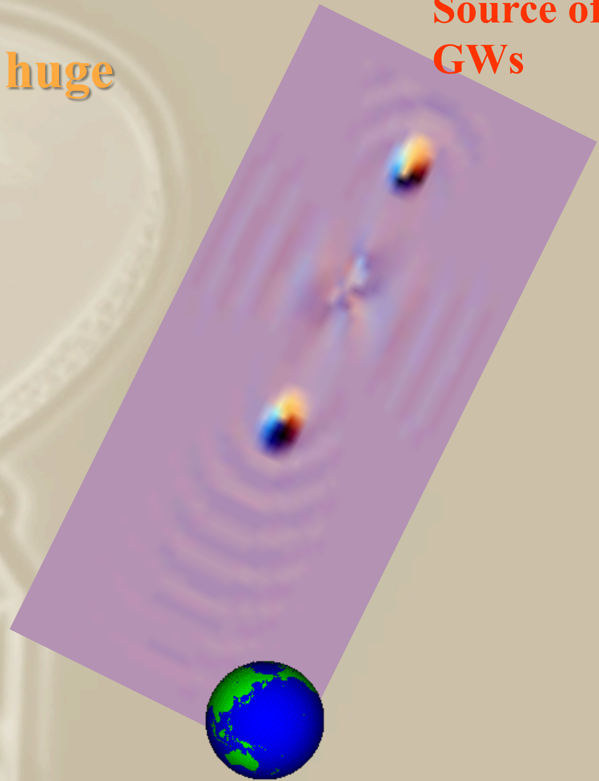
The European Pulsar Timing Array
et other activities in the radio band

ANDREA POSSENTI

INAF · OAC Osservatorio Astronomico di Cagliari

Pulsars as GW detectors

The Pulsar-Earth path can be used as the arm of a huge cosmic gravitational wave detector



Perturbation in space-time can be detected in timing residuals over a suitable long observation time span

Radio Pulsar

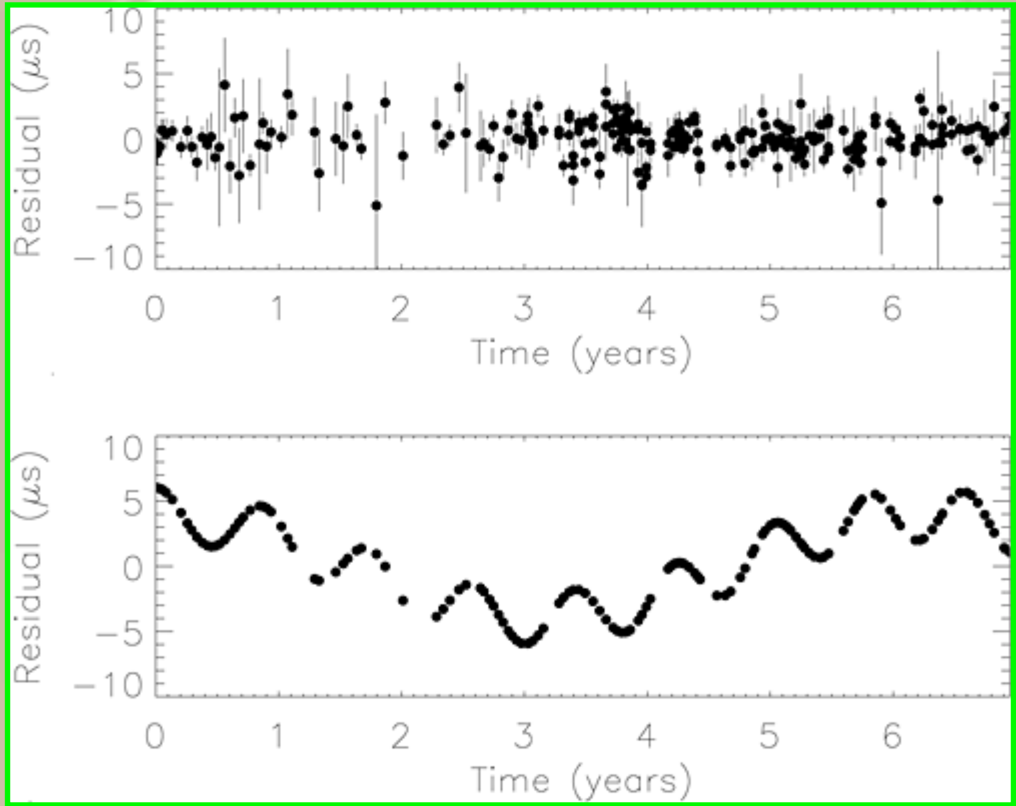
Sensitivity (rule of thumb, **with few caveats**):

$$h_c(f) \sim \frac{\sigma_{TOA}}{T}$$

where
$h_c(f)$ is the dimensionless strain at freq f
σ_{TOA} is the rms uncertainty in Time of Arrival
T is the duration of the dataspan

An instructive application

The radio galaxy 3C66 (at z = 0.02) was claimed to harbour a double SMBH with a total mass of $5.4 \cdot 10^{10}\ M_{sun}$ and an orbital period of order ~yr [Sudou et al 2003]



[Jenet et al 2004]

Timing residuals from PSR B1855+09 exclude such a massive double BH at 95 c.l.

The GW background from Massive BH binaries

The current paradigm is that [e.g. Ferrarese & Merrit 2000]

- mergers are an essential part in galaxy formation and evolution
- nuclei of most (all?) large galaxies host Massive BH(s) (MBH: i.e. mass larger than 10^6 M_{sun})

There should be plenty of SMBH binaries in the early universe, sinking to the their galaxy center (due to dynamical friction?)

When reaching orbital separation less than about 1 pc, GW emission become the dominant term in energy loss, making the MBH binary to shrink faster and faster

The frequency of GW emitted by these systems is typically

$$f \sim 3\text{nHz} \left[\frac{M}{10^9 M_{sun}}\right]^{1/2} \left[\frac{a}{0.01\text{pc}}\right]^{-3/2}$$

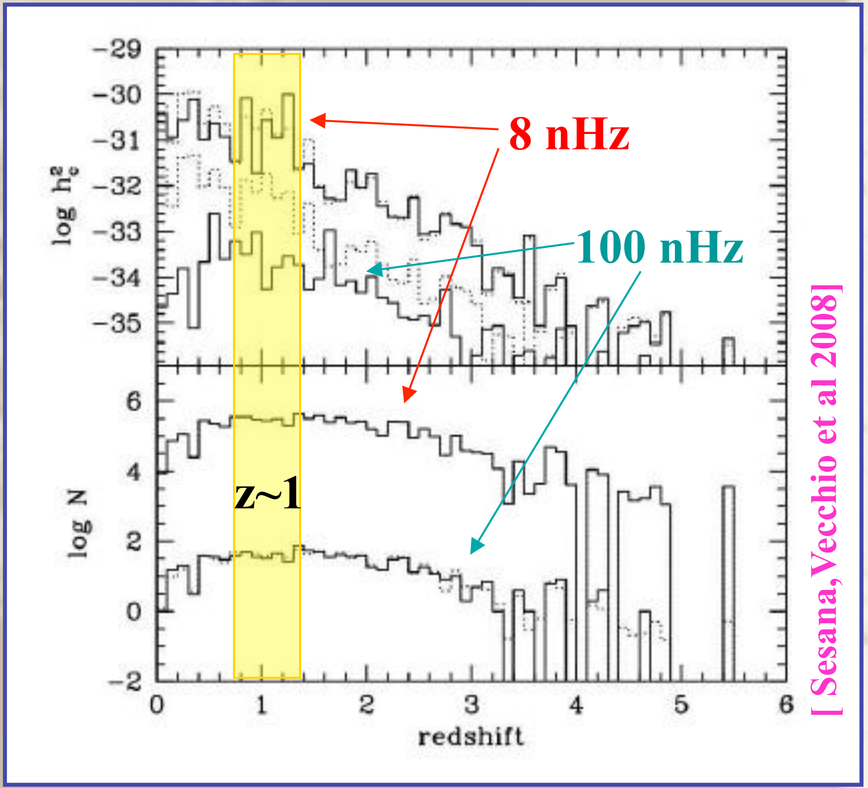
The GW background of massive BH binaries

The expected amplitude spectrum from the ensemble of these MBH binaries is [e.g. Phinney 2001; Jaffe & Backer 2003]

$$h_c(f) \sim f^{-\alpha}; \alpha = 2/3$$

with a strain amplitude theoretically expected in the range
[e.g. Jaffe & Backer 2003, Sesana,Vecchio et al 2008]

$h_c \approx 10^{-16} \rightarrow 10^{-15}$ **(but...)**
around frequency $f_{GWB} = 1\ yr^{-1}$



Introducing Ω_{GW}**, the expected spectrum of the GWB goes as**

$$h_{0,H}^2 \Omega_{GW}(f) \propto f^{2/3}$$

The "best" cases for upper limits to the GWB from small samples

Remembering the approx formula $h_c(f) \sim \frac{\sigma_{TOA}}{T}$

one can estimate that for detecting the expected GW background from merging of SMBHs (strain amplitude $h_c \sim 10^{-16}$-10^{-15}) one would require at least a timing stability σ_{TOA} < 10-100 ns over few years

Until recently, the best result using a single source was from 8-yr timing of PSR B1855+09 at Arecibo implying limit for f~7 nHz [Kaspi et al 94]

$h_c <\sim 10^{-13}$

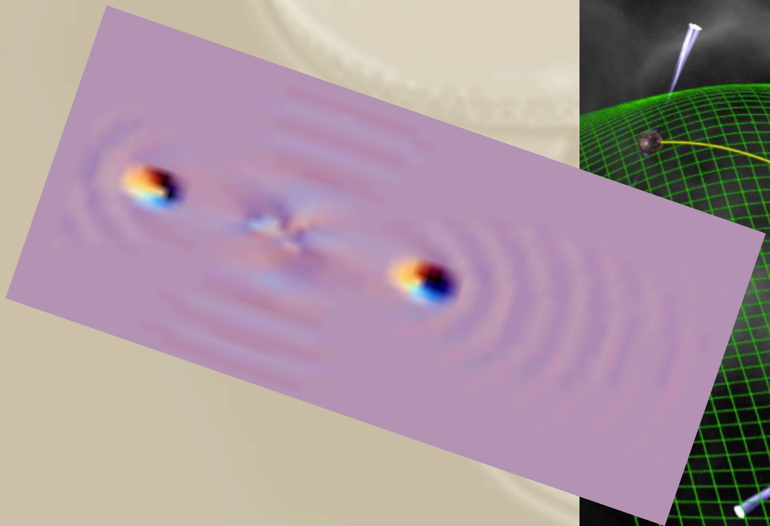
On 2015, using only four sources (dominated by PSR J1909-3744) from 11-yr timing at Parkes it was derived for f~2.8 nHz [Shannon et al 15]

$h_c <\sim 10^{-15}$

When using only 1 or a handful of pulsars, it is very hard to control spurious effects: many pulsars needed for detection of a GWB!

A pulsar timing array (PTA)

Using a number of pulsars distributed across the sky it is possible to separate the various "noise" contribution from each pulsar from the signature of the GW background, which manifests (at Earth) as a local distortion in the times of arrival of the pulses which is common to the signal from all pulsars



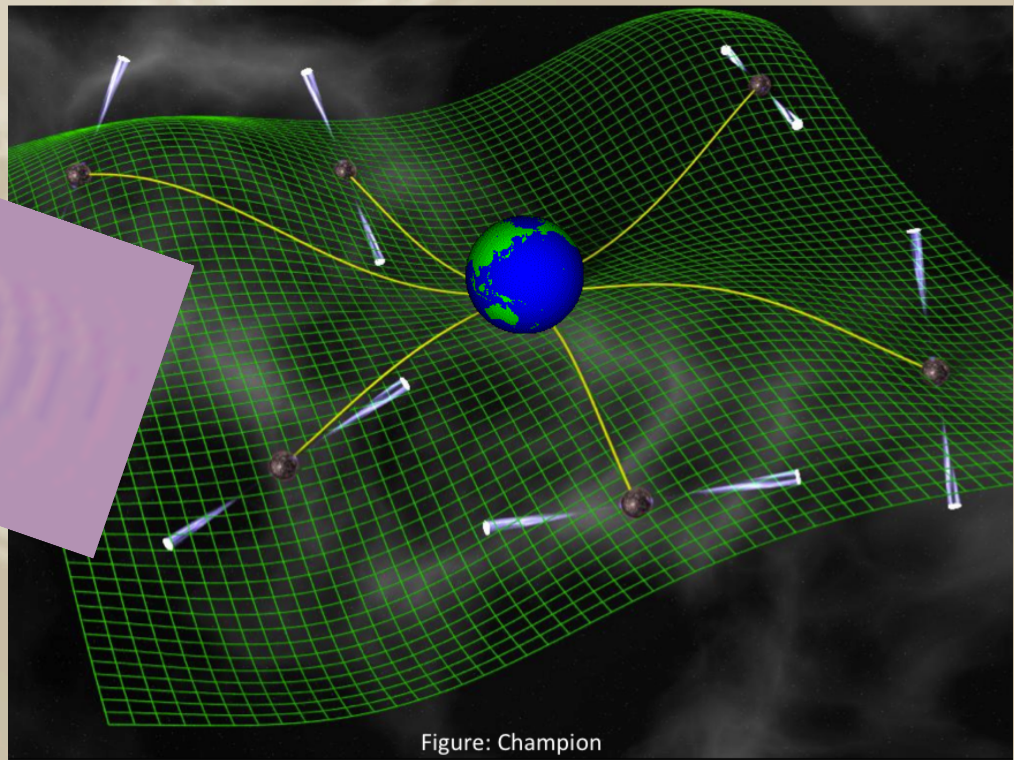
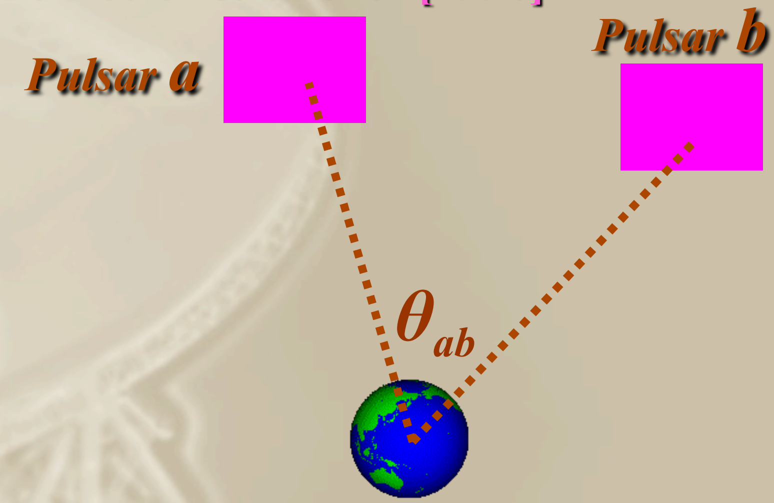


Figure: Champion

A pulsar timing array (PTA) for detecting a stocastic Background of GW (GWB)

Idea first discussed by Romani [1989] and Foster & Backer [1990]

- **Clock errors**
  All pulsars have the same TOA variations:
  Monopole signature
- **Solar-System ephemeris errors**
  Dipole signature
- **Gravitational waves background**
  Quadrupole signature



$$\zeta(\theta_{ab}) = \frac{3}{2}\left(\frac{1-\cos\vartheta_{ab}}{2}\right)\log\left(\frac{1-\cos\vartheta_{ab}}{2}\right) - \frac{1}{4}\left(\frac{1-\cos\vartheta_{ab}}{2}\right) + \frac{1}{2} + \frac{1}{2}\delta_{ab}$$

Hellings & Downs [1983]: correlation that an isotropic and stocastic GWB leaves on the timing residuals of 2 pulsars *a* and *b* separeted by an angle θ_{ab} in sky

Can separate these effects provided there is a sufficient number of widely distributed pulsars

[adapted from Manchester]

Data analysis for a stocastic GWB

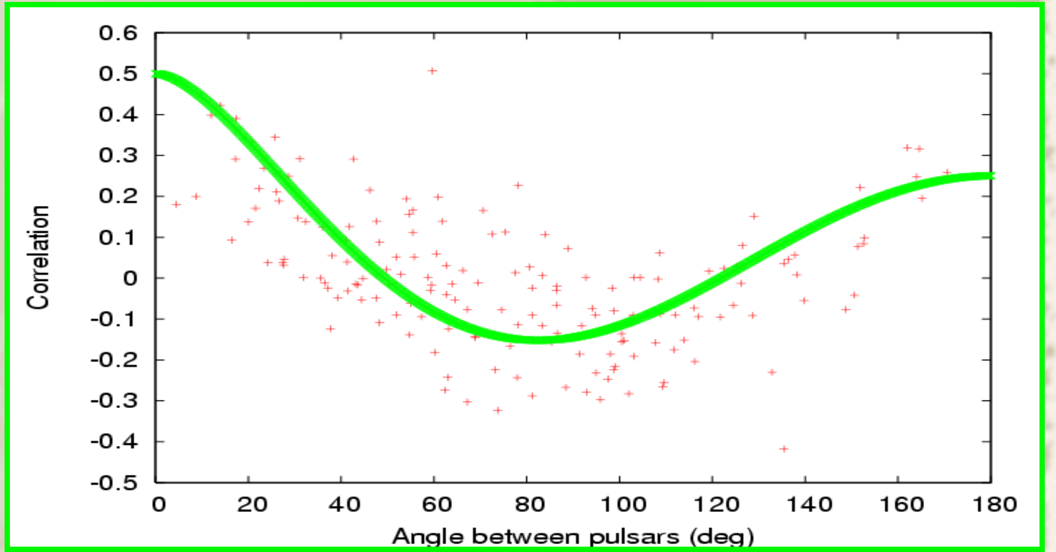
Spherical harmonic decomposition

[Burke 1975, Dettweiler 1979, Jaffe & Backer 2003, Demorest et al 2005]

Two point correlation

Correlating the time derivative of the residuals [Hellings & Downs 1983]

Directly correlating the time residuals [Jenet et al 2005, + ...]



Bayesian analysis

[van Haasteren, Levin, McDonald, Lu 2008, + ... + Ellis & Cornish 2016]

Robust: deals easily with unevenly sampled data, variable number of tracked pulsars, etc.

Marginalisation: deals easily with all systematics of known functional form, including the timing model

Capable to simultaneously measure the amplitude and the shape of the GWB

GW from discrete sources: a spiral-in binary

For a coalescing BH binary [e.g Thorne 87]

$$h_s = 4\sqrt{\frac{2}{5}}\ \frac{GM_c}{c^4 D}[\pi\ f\ (1+z)]^{2/3}$$

f = freq of GW
D = comoving distance of the source
z = redshift of the source
M_c = $M_c = (M_1 M_2)^{5/3}(M_1+M_2)^{-1/5}$

The expected signature is a periodic GW signal with period twice the orbital period of the binary: well away from the last stable orbit it is expected a sinusoidal effect on the pulsar timing residuals

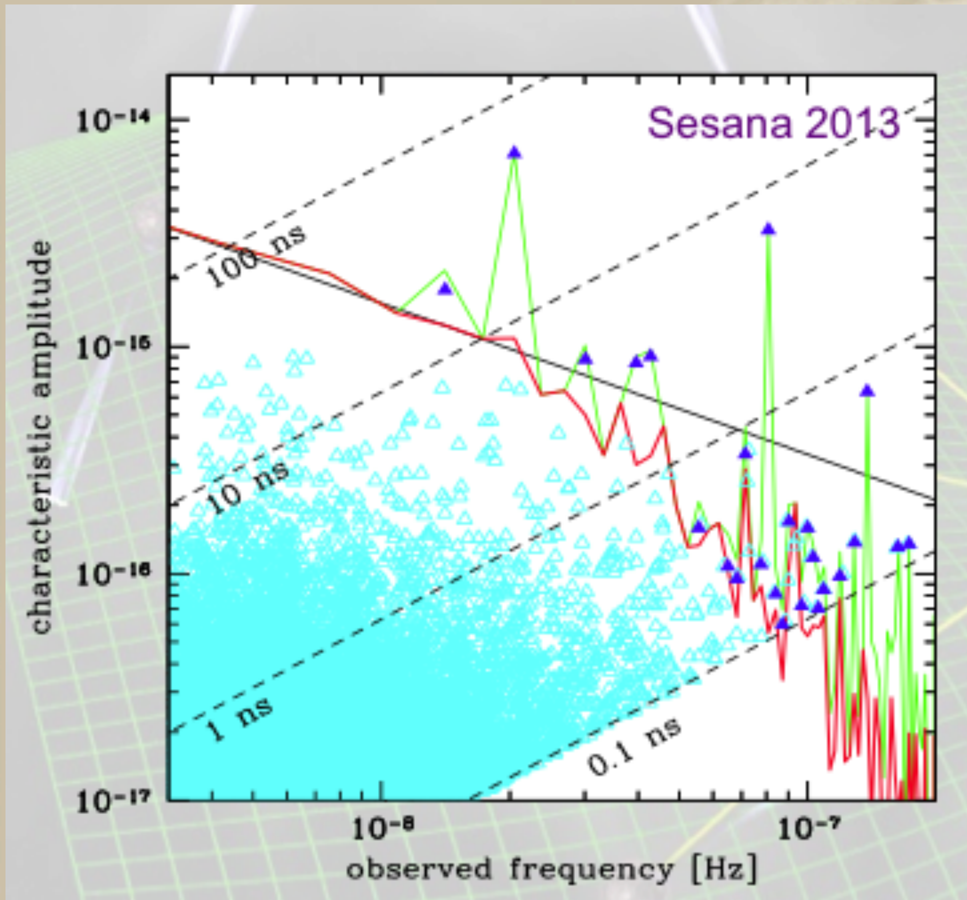
To give an order of magnitude estimate, at the last stable orbit (i.e. immediately before merging), the expected strain is [Sathyaprakash & Schutz 2009]

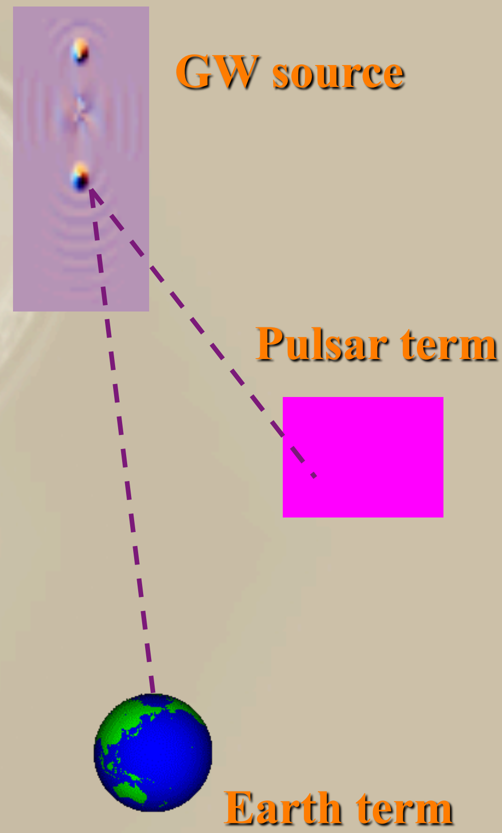
$$h_{s,LSO} \approx 10^{-13}\left(\frac{M_{BH}}{10^{10} M_{sun}}\right)\left(\frac{1\ \mathrm{Gpc}}{D}\right)$$

at a frequency

$$f_{LSO} \approx 440\ \mathrm{nHz}\left(\frac{10^{10}\ M_{sun}}{M_{BH}}\right)$$

A spiral-in binary: some interesting cases





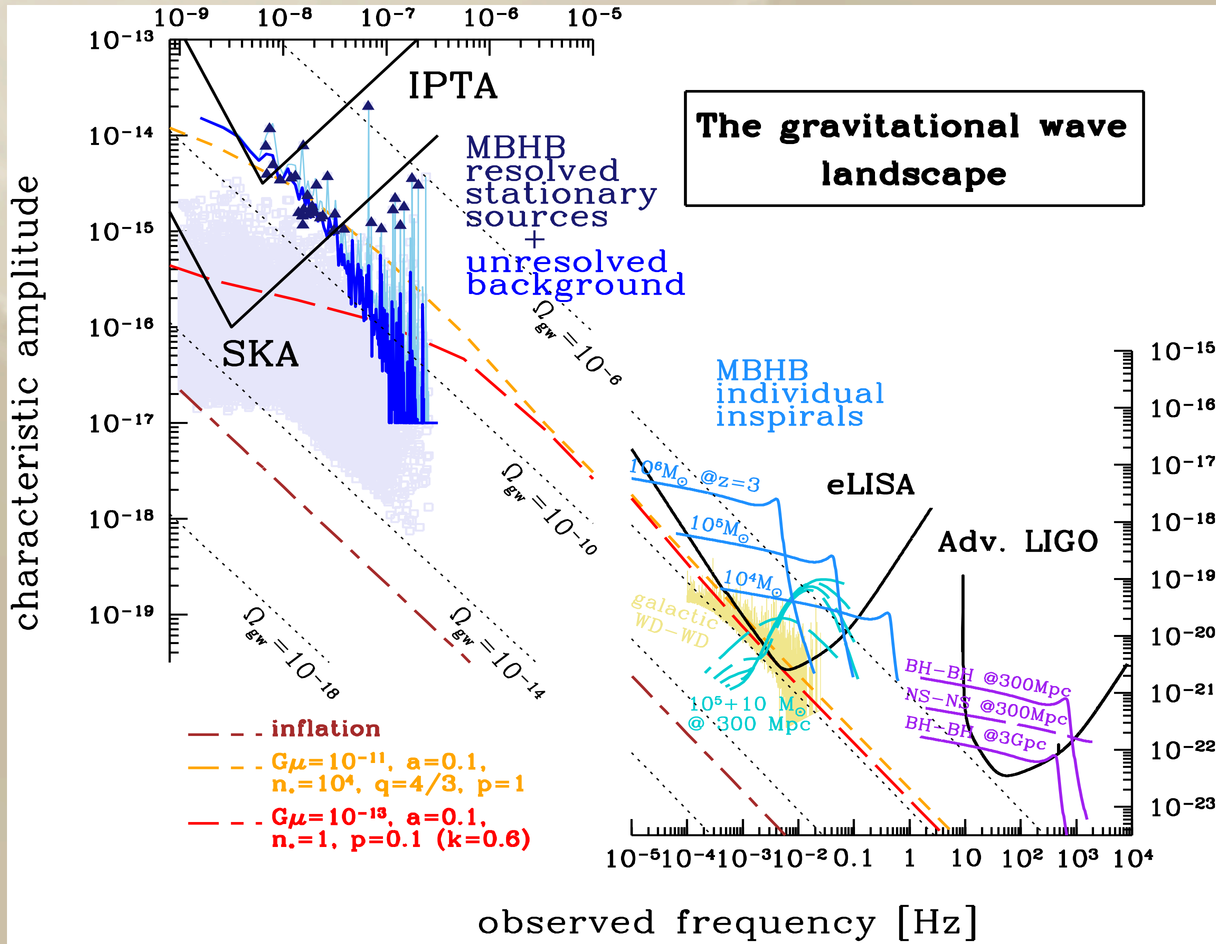
At least one SMBH+SMBH will induce timing residual of order 5-50 ns
[Sesana et al 2013]

Signal contains information from two distinct epochs !

Pulsar Timing array(s): the frequency space

Note the complementarity in explored frequencies with respect to the current and the future GW observatories, like advLIGO, advVIRGO and eLISA

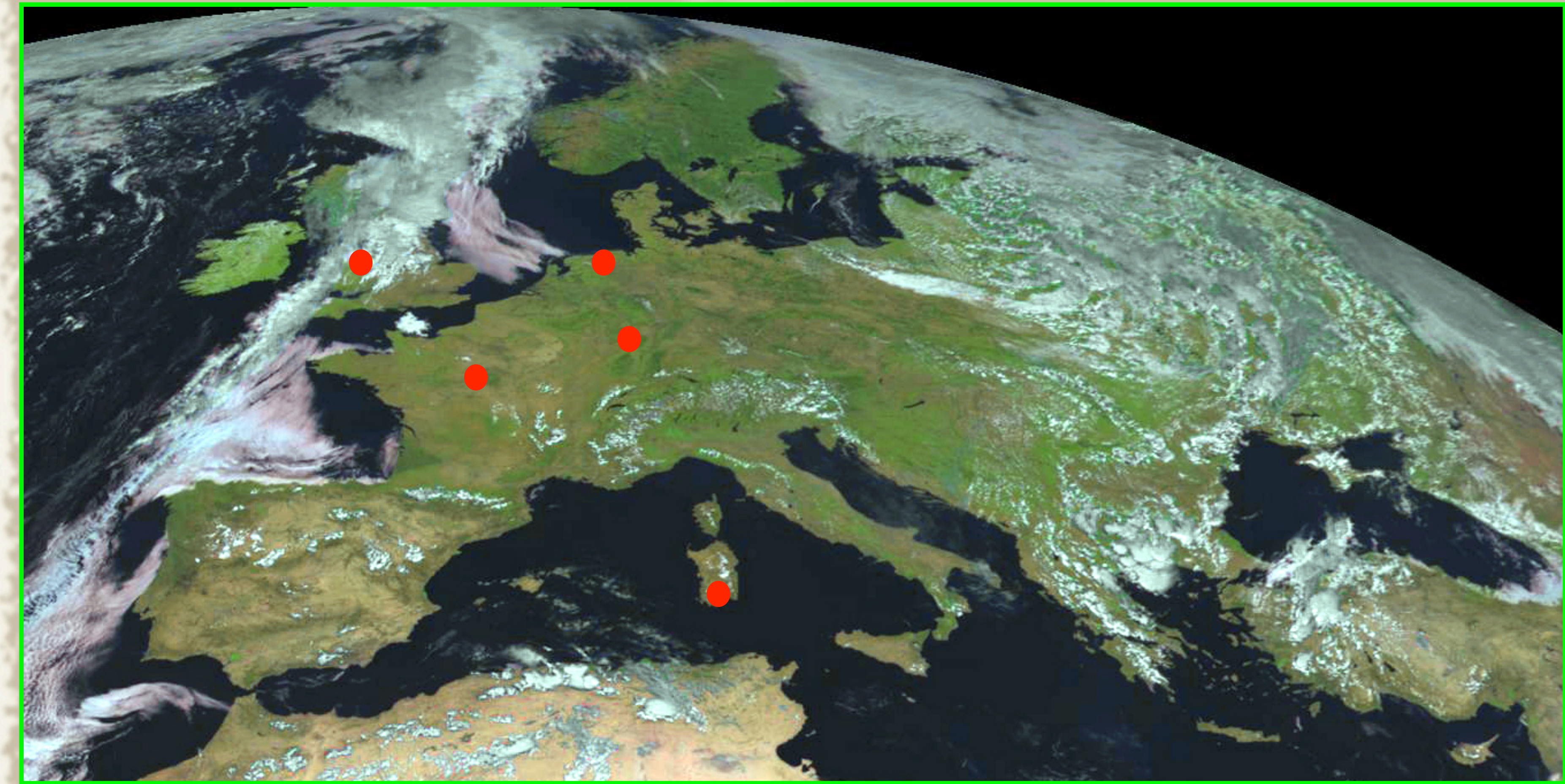
- **Expected sources:**
  - binary super-massive black holes in early Galaxy evolution
  - cosmic strings
  - cosmological sources
- **Types of signals:**
  - stochastic (multiple)
  - periodic (single)
  - burst (single)



[Janssen et a 15]

The PTA collaborations

EPTA: The partner institutions



University of Manchester, JBO, GB

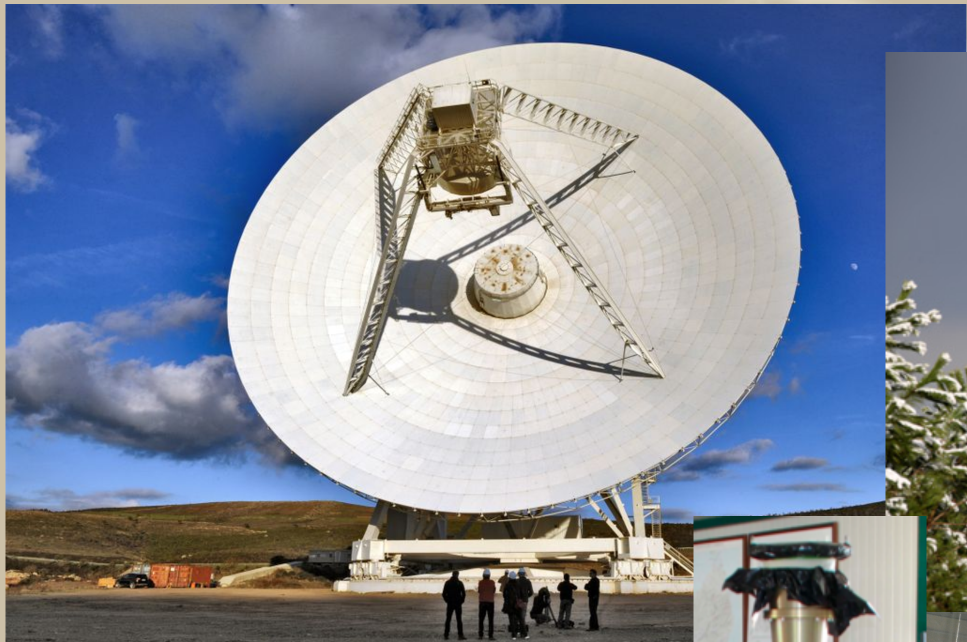
ASTRON,Un.Leiden,Un.Amsterdam NL

INAF Osservatorio Astronomico di Cagliari, ITA

Nancay Observatory, FR

Max-Planck Institut fur Radioastronomie, GER

Sardinia Radio Telescope

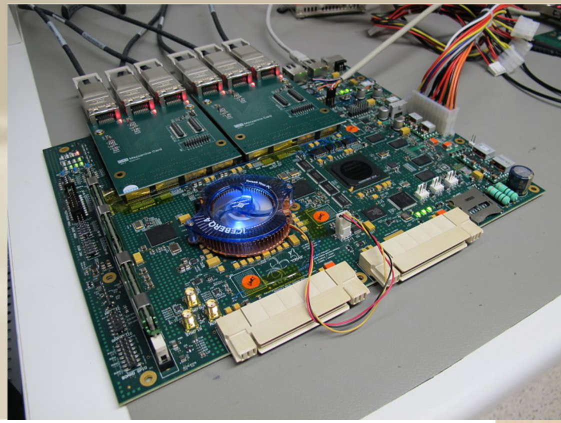


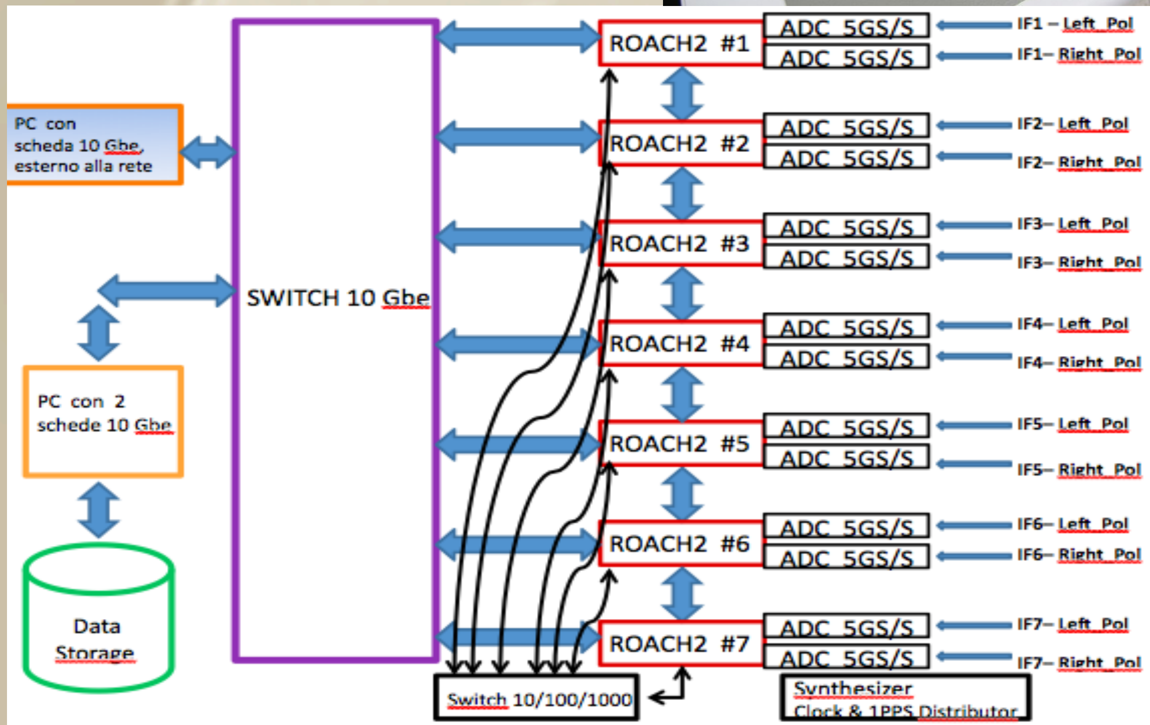
64 m dish designed for maximum efficiency at all the frequencies btw 0.3-110 GHz

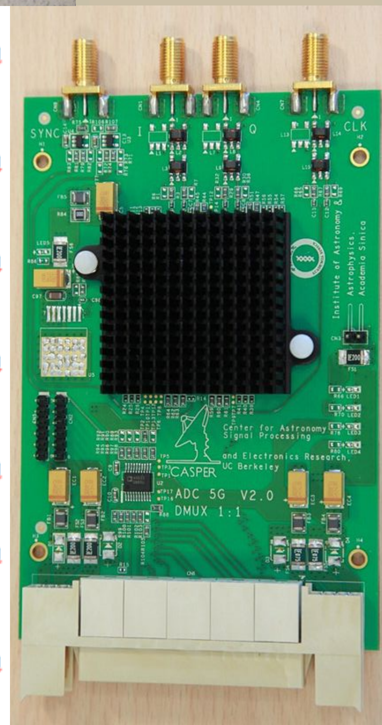
Equipped so far with 4 receiver bands: 0.3-0.4 GHz ; 1.2-1.7 GHz ; 5-7 GHz ; 18-26 GHz

[Stringhetti et al 15; Prandoni et al 16]

SARDARA:
the state-of-the-art back-end for SRT







Acquiring data from 14 IFs x 2 GHz BW each

LEAP

Large European Array for Pulsars (originally funded by EU grant for 5 years)

Combining "coherently" all the 5 major European telescopes, SRT is part of the best available telescope at 20cm-band for timing before SKA era…

+

…unique capability of SRT in removing interstellar medium effects, thanks to the dual band 0.35+1.40 GHz receiver

Current best limits on amplitude of the GW background from SMBH binaries

(with a GW spectral idx -2/3 at 2.8 nHz (i.e. P_{GW}=1 yr) for H_o = 73 km s^{-1} Mpc^{-1})

NANOGrav

Arzoumanian et al., 2015: A < 1.5 x 10^{-15}

EPTA

Lentati et al., 2015: A < 3 x 10^{-15}

(robust limit including additional effects)

PPTA

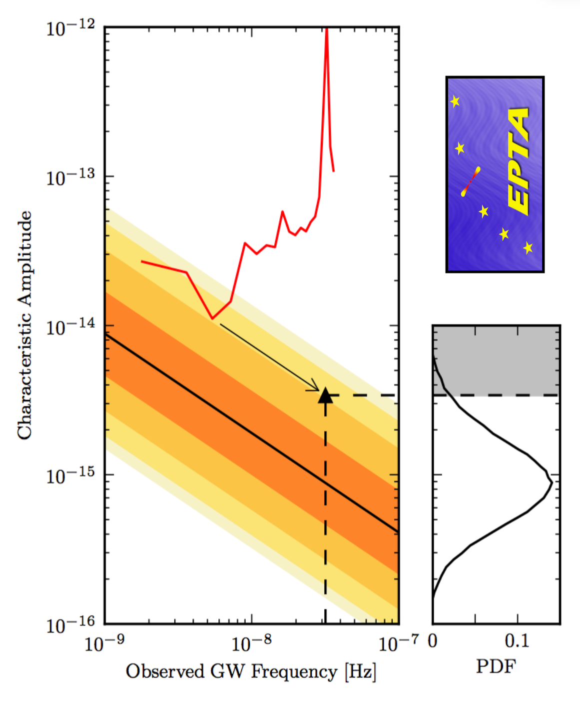
Shannon et al., 2015:

A < 1.0 x 10^{-15} [Ω_{GW} < 2.3 x 10^{-10}]

INTERNATIONAL PULSAR TIMING ARRAY IPTA

Verbiest et al., 2016: A < 1.7 x 10^{-15}

(based on relatively old data only)



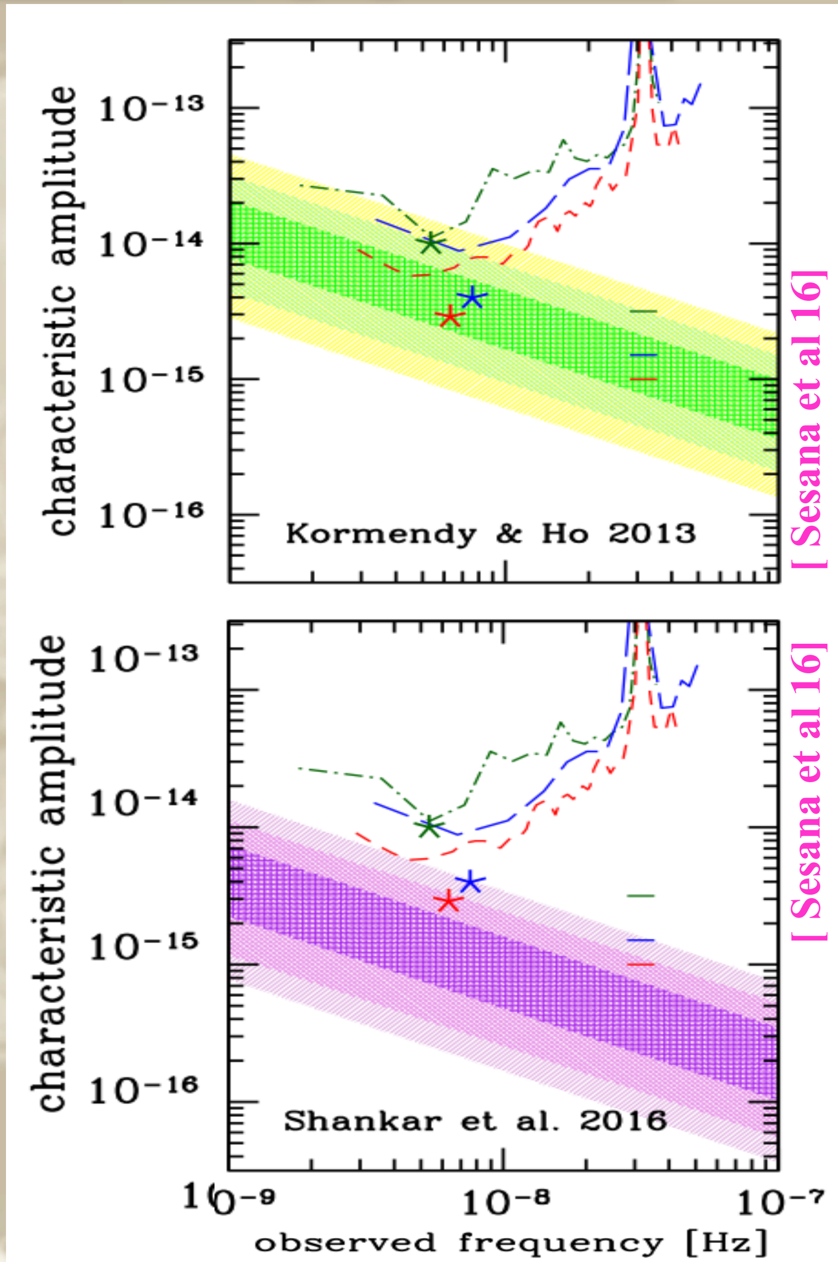
[Lentati et al. 15]

Limits on stochastic GWB vs models

The present limits have entered expected (on 2013) range

Theoretical amplitude depends on merger rate, galaxy evolution and cosmology, plus many assumptions which are difficult to set "a priori"...

- **SMBHB stalling**
  [Arzoumanian et al 16]
- **SMBHB eccentricity**
  [Arzoumanian et al 16]
- **Environmental coupling**
  [Shannon et al. 15]
- **Bias-high in the relation M_{SMBH}-σ (M_{SMHB} vs Velocity Dispersion)**
  [Bernardi et al 07, Shankar et al 16; Sesana et al 16]

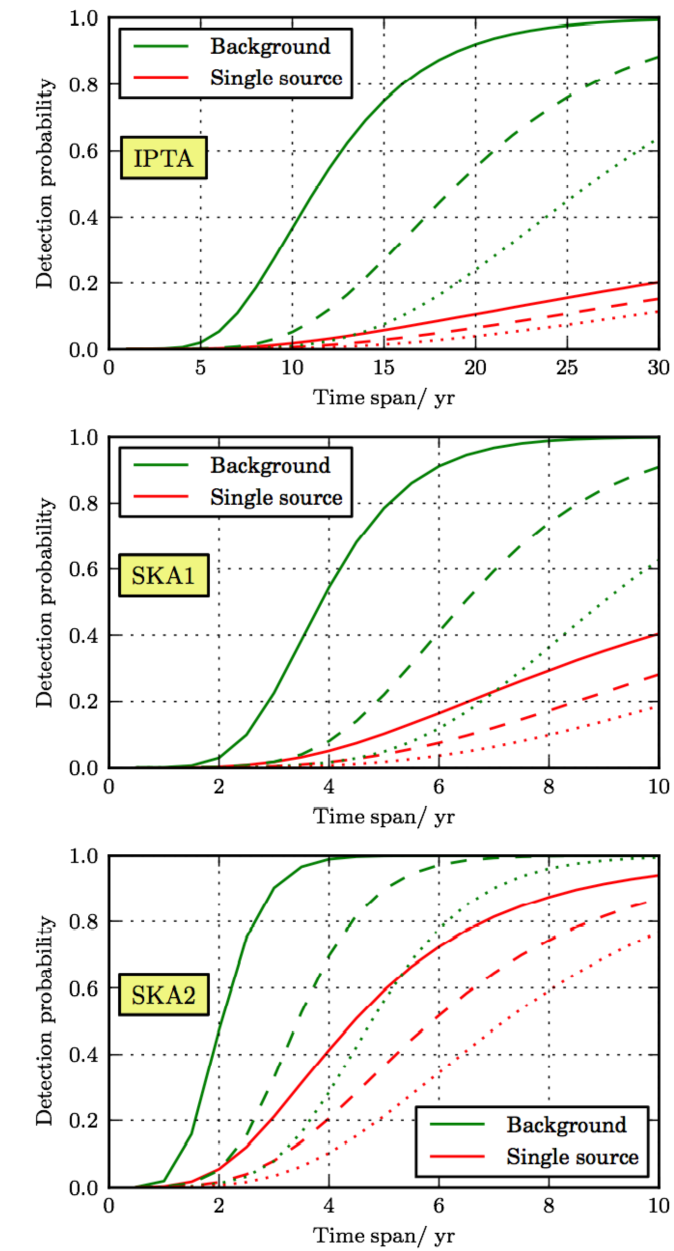


Timing array(s): from limits to GWBs detection

Current projects are evolving in pace with predictions. Then at least very significant limits (and hopefully a detection) should be achieved within few years by IPTA

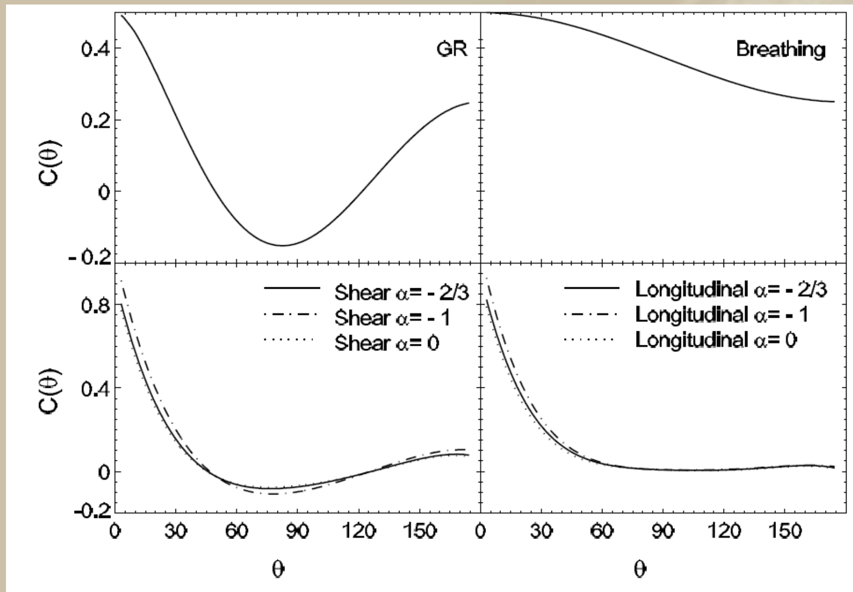
Unless the galaxy assembling model has to be rewritten, the detection and a basic studies of the GWB [spectrum, anisotropy) and of many single sources is warranted with phase 1 of SKA

Full nanoHz-GW astronomy and implied fundamental physics tests will take place with phase 2 of SKA



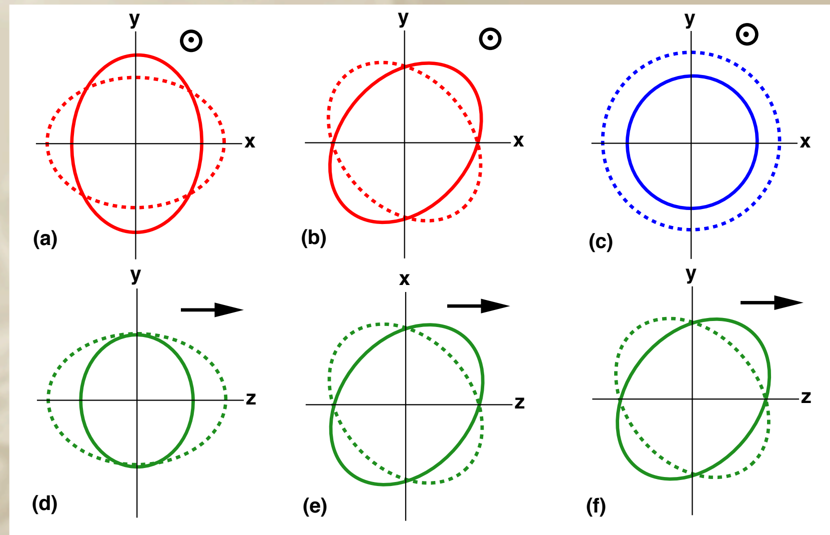
[Rosado, Sesana & Gair 15]

Fundamental physics tests



[Lee et al. 2009]

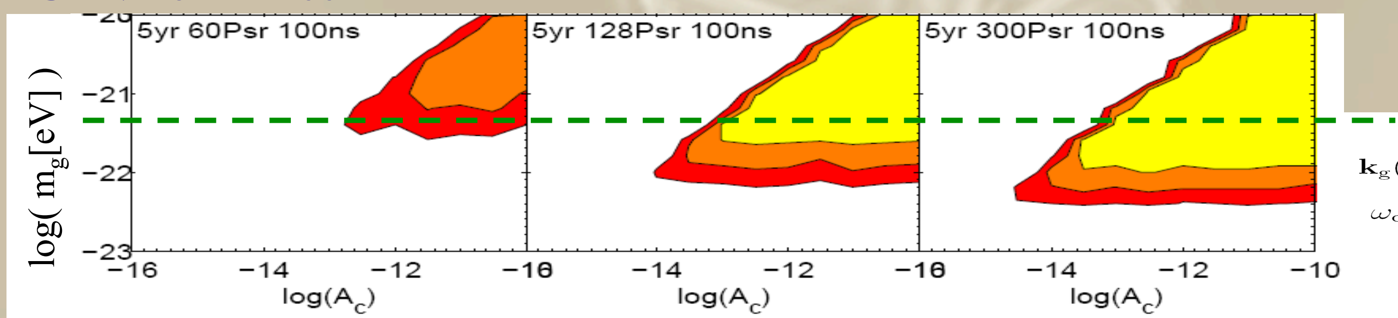
Tests of the polarization "modes" of the GWs



[Chamberlin & Siemens 2012]

Graviton mass

- - - - = present solar system limit



$$\mathbf{k}_g(\omega_g) = \frac{(\omega_g{}^2 - \omega_{cut}{}^2)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}$$

$$\omega_{cut} = m_g c^2/\hbar$$

[Lee et al. 2010]

Other activities in the Radio with SRT: timing of putative GW emitting neutron stars & rapid response to triggers

Outside
GCN
IAUCs
Other
ATel on Twitter and Facebook
ATELstream
Community Site
OS: Dashboard Widget

The Astronomer's Telegram

Post a New Telegram | Search | Information
Telegram Index
Obtain Credential To Post | RSS Feeds | Email Settings

Present Time: 3 Apr 2014; 10:19 UT

This space for free for your conference.

Fast Outflows Massive Stars
Wind-fed and Colliding-wind binaries
Geneva, Switzerland
30 June - 1 July, 2014

[Previous | Next | ADS]

Observations of H1743-322 with the Sardinia Radio Telescope: upper limits

ATel #8849; *E. Egron (INAF-OAC), M. Bachetti (INAF-OAC), A. Pellizzoni (INAF-OAC), A. Trois (INAF-OAC), M. N. Iacolina (INAF-OAC), M. Pilia (INAF-OAC), S. Loru (INAF-OAC), A. Navarrini (INAF-OAC), R. Ballhausen (Remeis/FAU/ECAP), S. Corbel (AIM/CEA), W. Eikmann (Remeis/FAU/ECAP), F. Fuerst (CalTech), V. Grinberg (MIT), I. Kreykenbohm (Remeis/FAU/ECAP), M. Marongiu (INAF-OAC), M. Nowak (MIT), A. Possenti (INAF-OAC), K. Pottschmidt (CRESST/GSFC/UMBC), J. Rodriguez (AIM/CEA), J. Wilms (Remeis/FAU/ECAP)*
on 21 Mar 2016; 11:02 UT
Credential Certification: Elise Egron (egron@oa-cagliari.inaf.i

Subjects: Radio, Binary, Black Hole, Transient

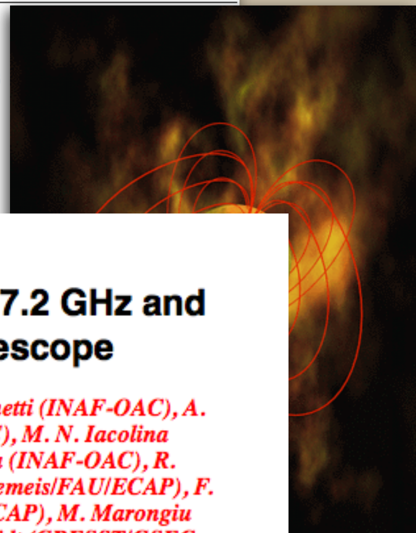
Tweet | Recommend 2

A new outburst of the Galactic black hole low-mass X-ray binary H1743-322 wa February 28 using Swift/BAT (Lin et al., ATel #8751), less than a year after it (#7652). A series of Swift ToO observations were then performed in order to

[Previous | Next | ADS]

etection by Sardinia Radio Telescope of radio pulses at 7 GHz from the Magnetar PSR J1745-2900 in the Galactic center region

ATel #5053; *Marco Buttu (INAF-Osservatorio Astronomico di Cagliari), Nichi D'Amico INAF-OAC), Elise Egron (INAF-OAC), Maria Noemi Iacolina (INAF-OAC), Pasqualino*



[Previous | Next]

Detection of GRS 1915+105 and SS 433 at 7.2 GHz and 21.4 GHz with the Sardinia Radio Telescope

ATel #8921; *E. Egron (INAF-OAC), A. Pellizzoni (INAF-OAC), M. Bachetti (INAF-OAC), A. Navarrini (INAF-OAC), A. Trois (INAF-OAC), M. Pilia (INAF-OAC), M. N. Iacolina (INAF-OAC), A. Melis (INAF-OAC), R. Concu (INAF-OAC), S. Loru (INAF-OAC), R. Ballhausen (Remeis/FAU/ECAP), S. Corbel (AIM/CEA), W. Eikmann (Remeis/FAU/ECAP), F. Fuerst (CalTech), V. Grinberg (MIT), I. Kreykenbohm (Remeis/FAU/ECAP), M. Marongiu (INAF-OAC), M. Nowak (MIT), A. Possenti (INAF-OAC), K. Pottschmidt (CRESST/GSFC/UMBC), J. Rodriguez (AIM/CEA), J. Wilms (Remeis/FAU/ECAP)*
on 7 Apr 2016; 13:47 UT
Credential Certification: Elise Egron (egron@oa-cagliari.inaf.it)

Subjects: Radio, Binary, Black Hole, Neutron Star, Transient

Tweet | Recommend 7

In the frame of radio monitoring of Galactic NS/BH X-ray binaries with the Sardinia Radio Telescope (www.srt.inaf.it), we detected GRS 1915+105 and SS 433 in the C- and K-bands through single-dish on-the-fly mapping centered on the sources.

...will be applied to GW trigger follow-ups

PROPOSAL CODE: S0006
TITLE: Radio follow-up gravitational radiation sources with SRT
P.I. Andrea Possenti
e-mail: possenti@oa-cagliari.inaf.it

Dear Andrea,

The SRT Early Science Program Selection Panel has now completed its work.

Following the scientific assessment by the Time Allocation Committee (TAC) for Italian Radio Telescopes and the technical and operational feasibility, and compliance with ESP requirements by the ESP Selection Panel, your SRT proposal has been awarded 75 h.

Proposal S0006: 75 allotted hours

plus

C3053	Radio follow-up of gravitational radiation sources with ATCA	Australia Telescope Compact Array	Andrea Possenti	17-giu-2015 04:23	4.4	ents

2015

Note from the ATNF Director : A decision on whether to approve this project for scheduling has not yet been made, pending further review of our current policies for NAPA proposals, specifically in regards to the potential claim-staking nature of this request.

2016

All of that in the context of GRAWITA