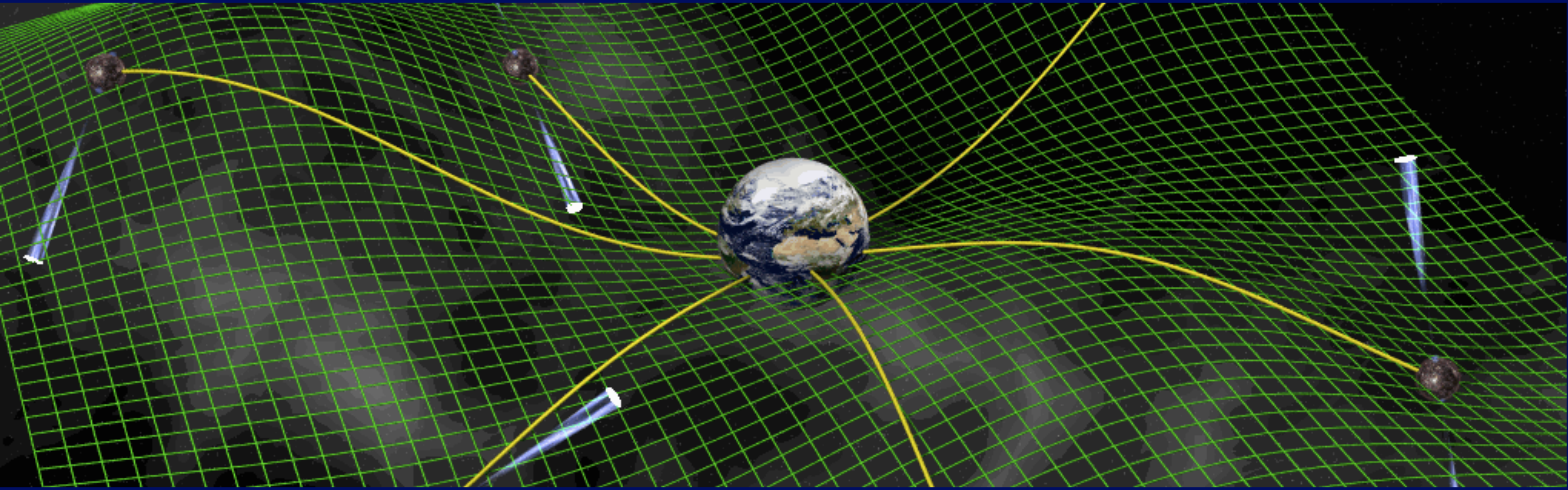
Developments in low-frequency gravitational-wave searches in the European Pulsar Timing Array



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@ GR21

New York City, 13 July 2016

The European Pulsar Timing Array (EPTA)

- Effelsberg Radio Telescope (Germany)
- Nançay Radio Telescope (France)
- Lovell Telescope (UK)
- Westerbork Synthesis Radio Telescope (Netherlands)
- Sardinia Radio Telescope (Italy)
- LEAP - European phased-array telescope

- Max Planck Institute for Radio Astronomy
- Paris Observatory
- LPC2E-CNRS
- Jodrell Bank Centre for Astrophysics
- ASTRON
- Astronomical Observatory of Cagliari

- University of Bielefeld
- University of Amsterdam
- University of Birmingham
- Max Planck Institute for Gravitational Physics
- University of Cambridge
- University of Edinburgh

KIAA @ Peking University, JPL, Swinburne University

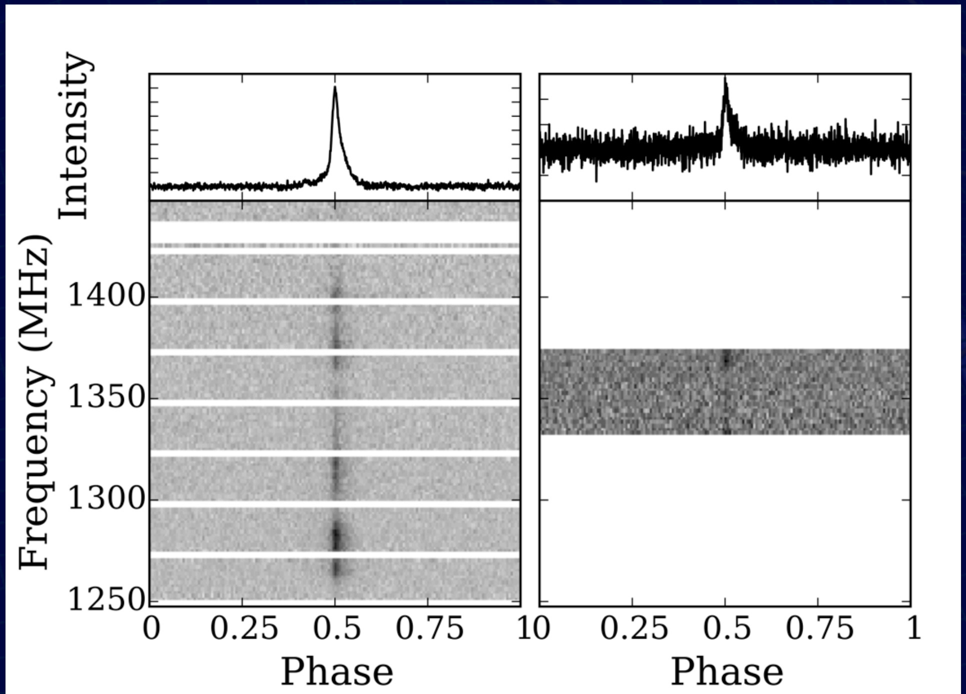
The EPTA DR 1.0 and relevant results

• 2011: van Haasteren et al. 2011: 1st EPTA limit on stochastic GW Background (SGWB)
5 MSPs, 3 telescopes, max time-span 10 yrs, obs. freq: 1380 - 2048 MHz

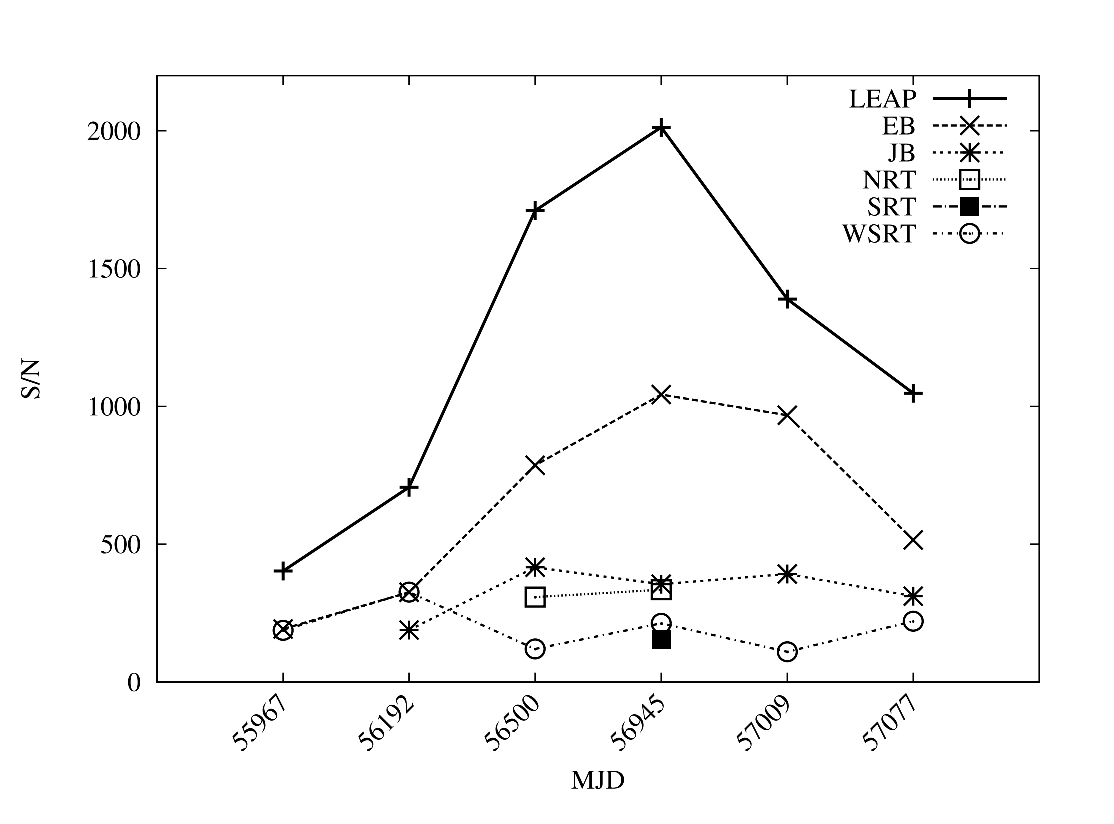
• 2015/2016: EPTA DR 1.0: Full EPTA data set from 'Legacy' backends (data processors)
• EPTA DR 1.0 + Astrometry & Astrophysics: Desvignes et al. 2016
42 MSPs, 4 telescopes, max time-span: 17yrs (24 yrs), obs. freq: 323 - 2639 MHz
• EPTA DR 1.0 used for noise analysis & data sensitivity evaluation, GW strain upper limits, SGWB, Continuous GWs (CGWs)
• Systematic efforts for using (cross-checking) different statistical methods, analysis codes
Noise characterisation, limits on SGWB, anisotropies in the SGWB, CGWs
• EPTA DR 1.0 used for the IPTA DR 1.0

Extending our data sets

- 4 telescopes from EPTA DR 1.0: Use new generation of backends
  Wider bandwidths, better data quality

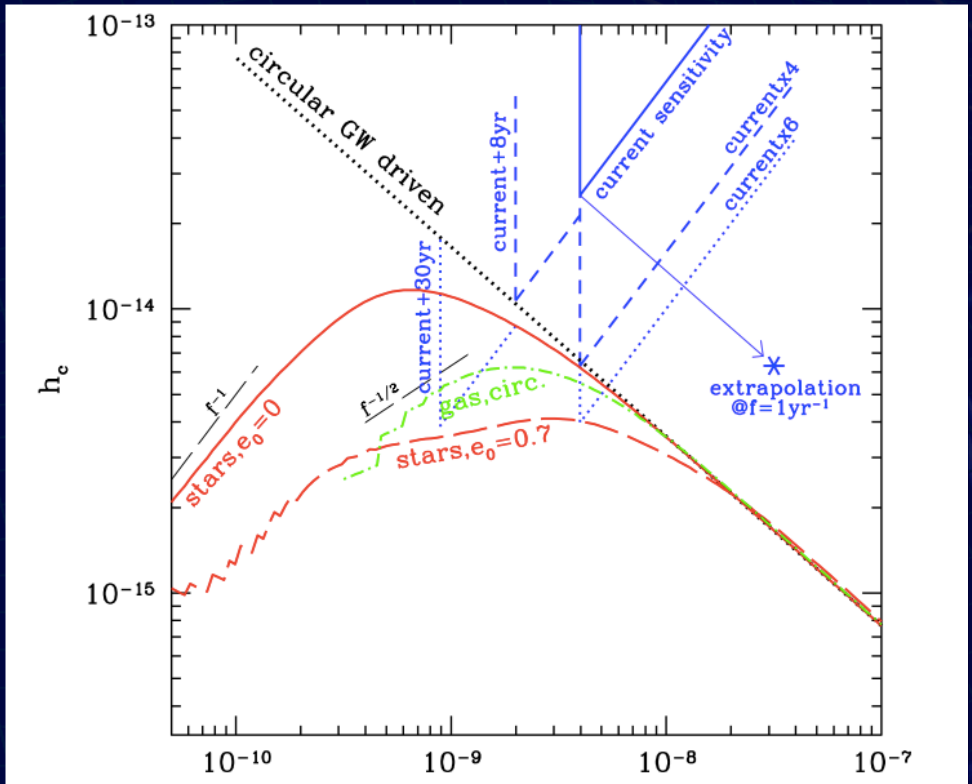


- SRT finished commissioning, PSR observations ongoing
- Monthly LEAP observations (Bassa et al. 2016)

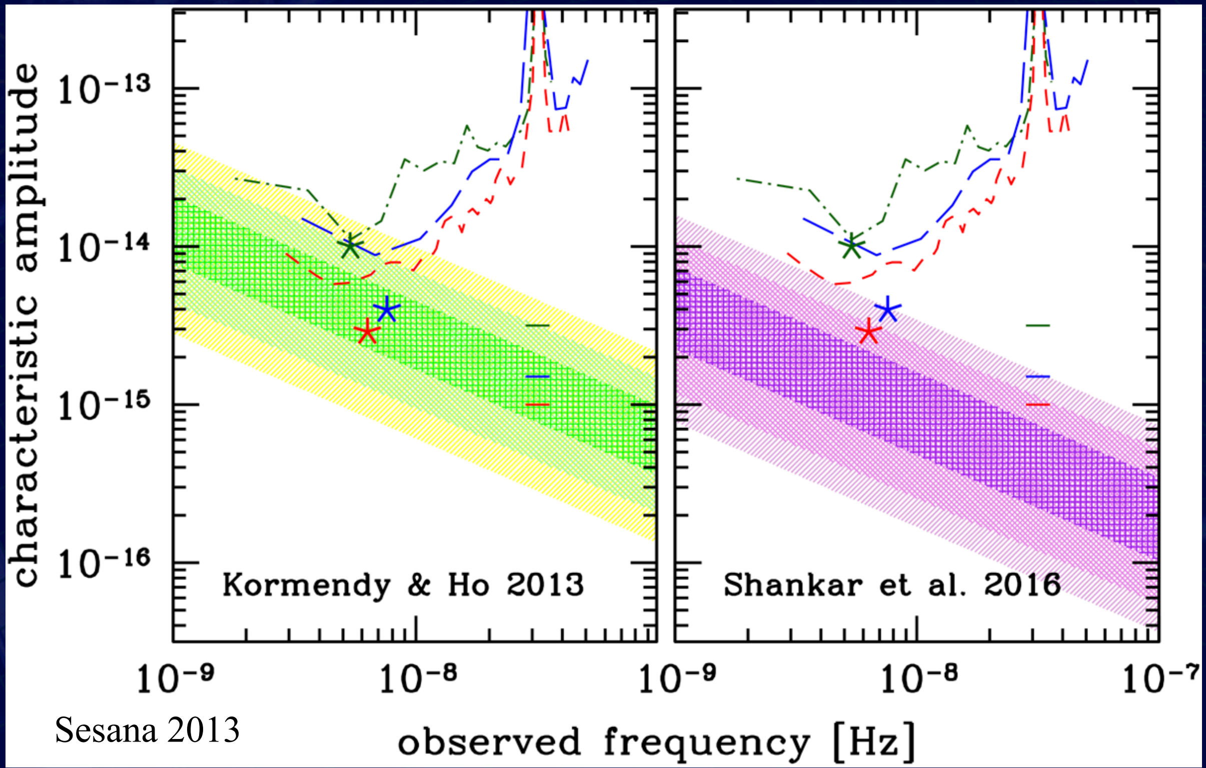


GW searches - understanding the low S/N regime

- PTAs expect to first see GW signals at low S/N
- S/N will increase by extending/improving data sets
- We are unsure of the details of the expected signal from SMBHBs (environmental coupling, eccentricities, SMBH-Galaxy scaling relations; SMBH mass - velocity dispersion)



Sesana 2013

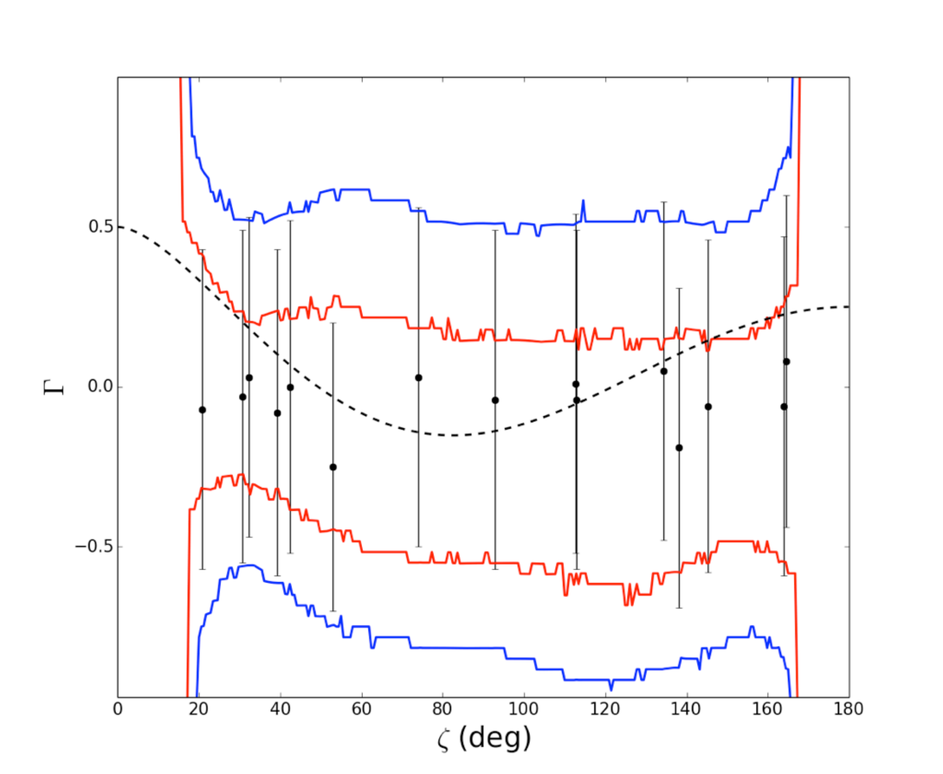


Sesana 2013

- We must be prepared for the unexpected
- We must be prepared to evaluate low S/N signals that may look like GW signals

GWB at low S/N

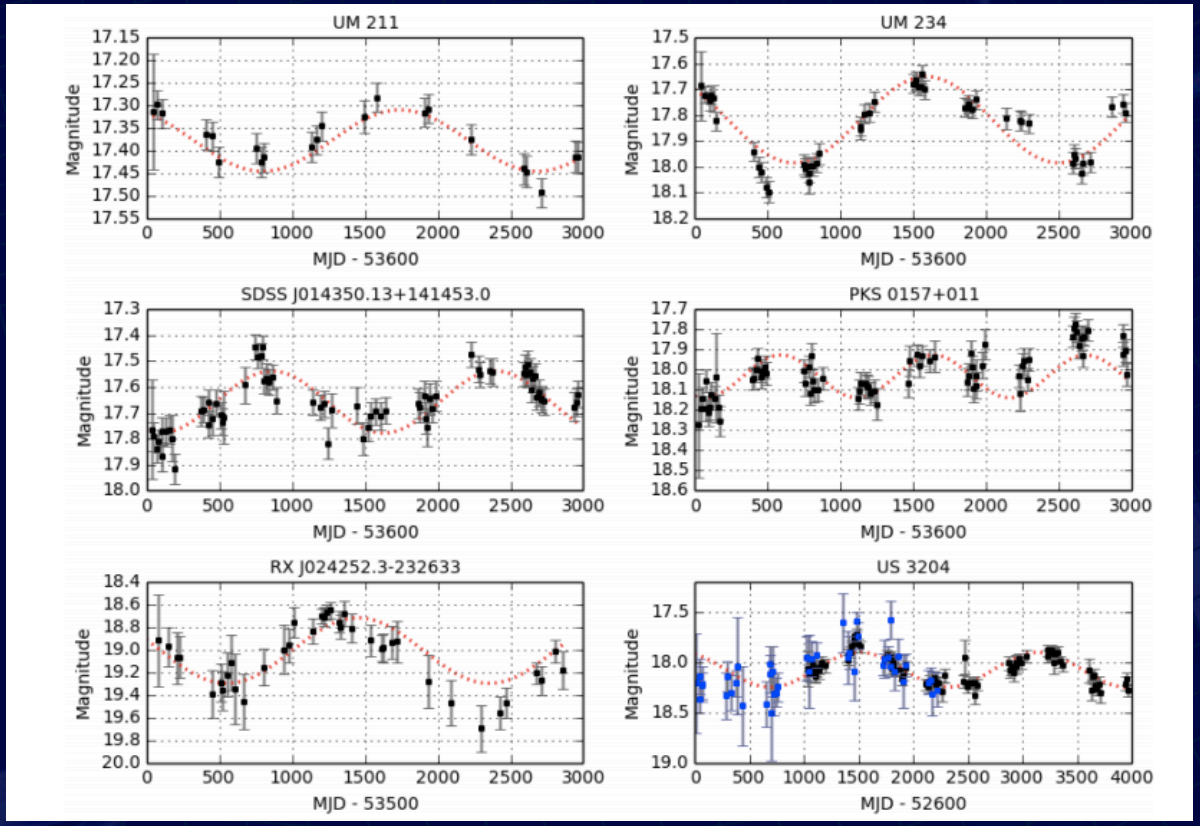
• GWB search: Search for a red-spectrum signal, with a given spatial correlation
• Significant dependency on present pulsar stochastic timing noise
• Important to have confidence in single-pulsar noise characterisation
• Important to understand effects of Solar system ephemeris used
PTAs are aware of differences between various SSEs
• Important to evaluate the probability of a red-spectrum signal being a common correlated vs uncorrelated
(e.g. robust Bayesian evidence evaluation, robust simulation generation/FAP estimation, sky-position scrambling, phase-shifting, see also Taylor et al. (2016))
• Angular cross-correlation measurements - still far from conclusive
• We can only follow a low-S/N signal over time and compare changes to expectations



Lentati et al. 2015

CGW at low S/N

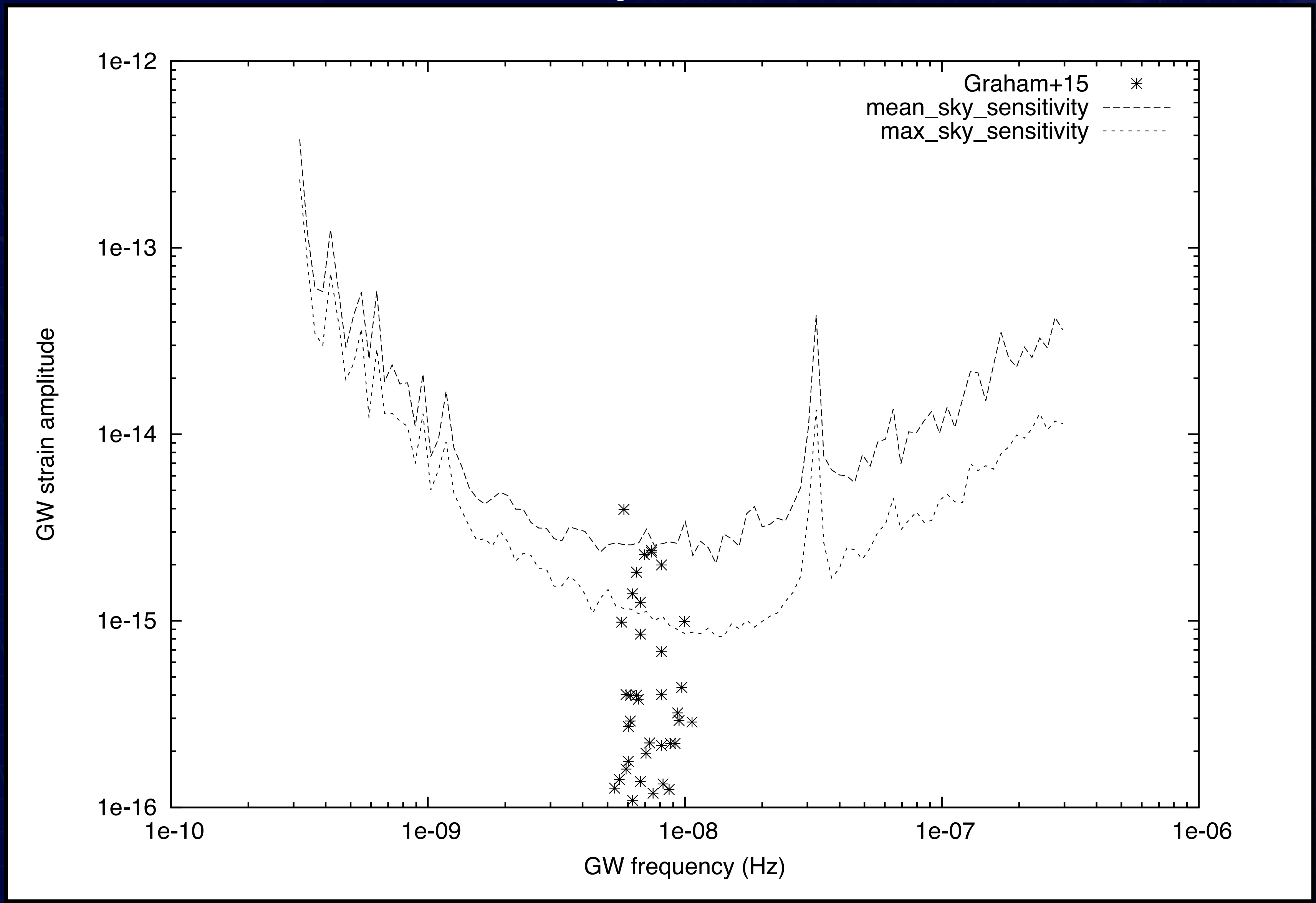
- For CGWs: advantage of independent data
- Targeted search => increase of signal's significance
- We may not be able to fully confirm a candidate,
- but maybe we can say it's possible (i.e. we cannot reject it)
- => do targeted searches for low S/N signals



Many candidates appearing in literature, mostly optical light-curves of quasars

e.g. Graham et al. 2015
111 candidates in this study alone

Can we observe any of the candidates?



Using Cramer-Rao lower bound: Which sources we may see at 1-σ level ?

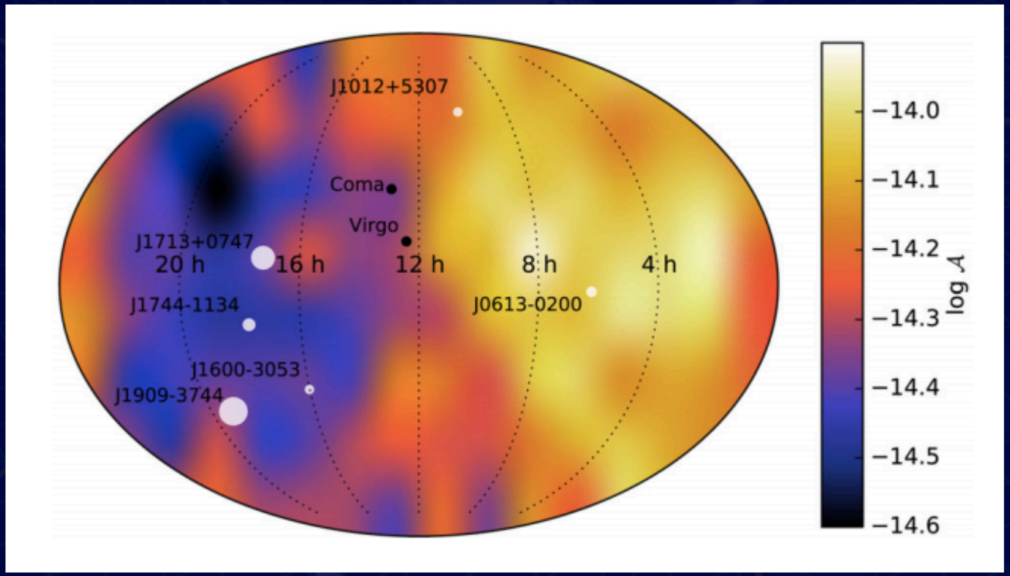
Note: $A \propto M^{5/3}$, mass errors ~ 1dex

Preliminary analysis: We can do ~30%-20% with blind searches

Follow-up targeted searches could push that down by ~10%

Quasi-qualitative tests
(Quasi-quantitative tests)

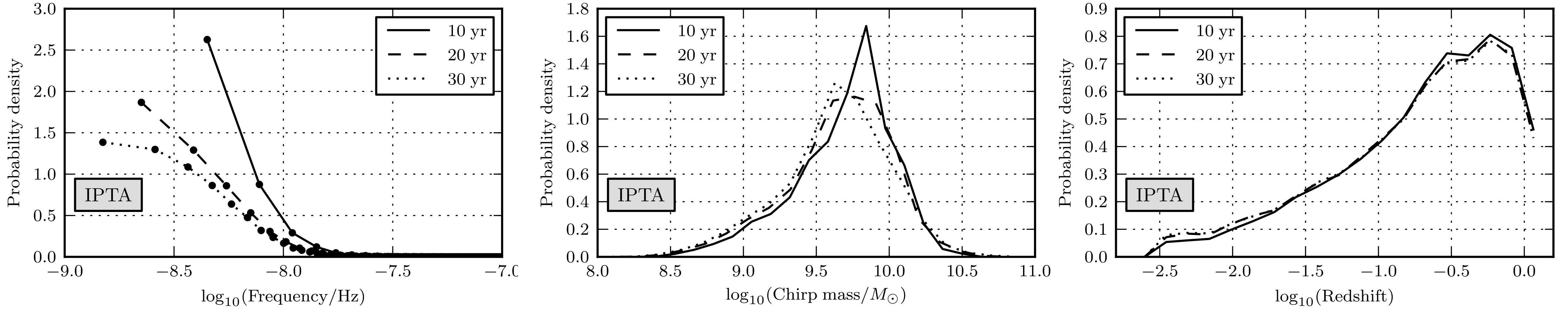
• Targeted search must improve the detection statistic
• Is a GW-correlated signal more probable than correlated signals of different origin?
• Is the signal sky-position (in)dependent (tough one for the moment)?



EPTA; Babak et al. 2016

• Is the signal present across the time-span
• Is the S/N contribution to the signal by pulsars reasonable?
• Are the results reproducible by independent pipelines?
• Do our FAPs make sense ? => Simulations- construct receiver operating characteristic (ROC) curves = detection probability Vs FAP
• Do results change as expected with new additional data?

Comparison to theory



Rosado, Sesana & Gair 2015

- We repeat these calculations

(i) using updated models (Shankar et al. 2016 scaling relations)
(ii) assuming low-S/N signal detections instead of clear detections of FAP~0.1

Summary and outlook

- EPTA: significant number of analysis methods and codes for noise analysis/mitigation and GW searches
- We work in understanding the low S/N regime, where we can possibly start seeing signals resembling GWs
- We work on developing systematic methods and tests to asses the probability of such signals being GW
- We will have to follow such signals over years to see if it they build up as expected
- We work on predicting the probability of such signals based on theoretical models
- We are improving our data quality; as individual telescopes and LEAP