The population of neutron stars: looking through theory, simulation and observation

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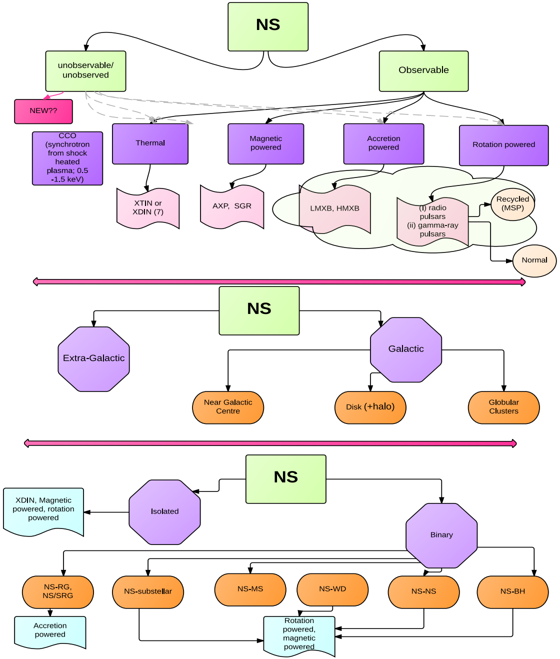
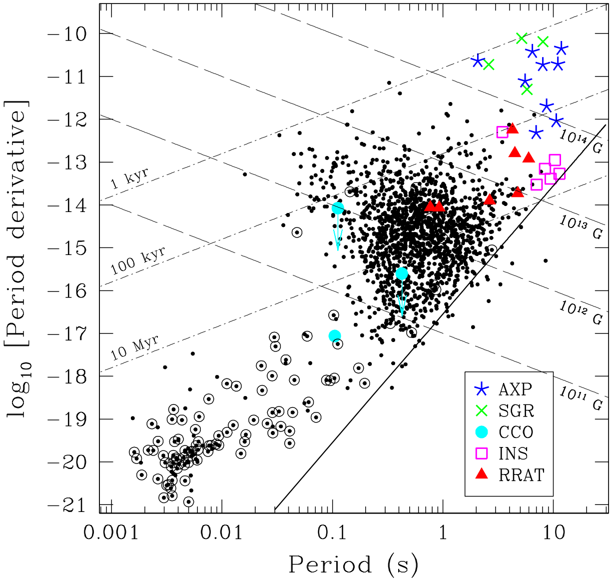
Neutron Stars: A brainstorming workshop @NCRA-TIFR, Pune

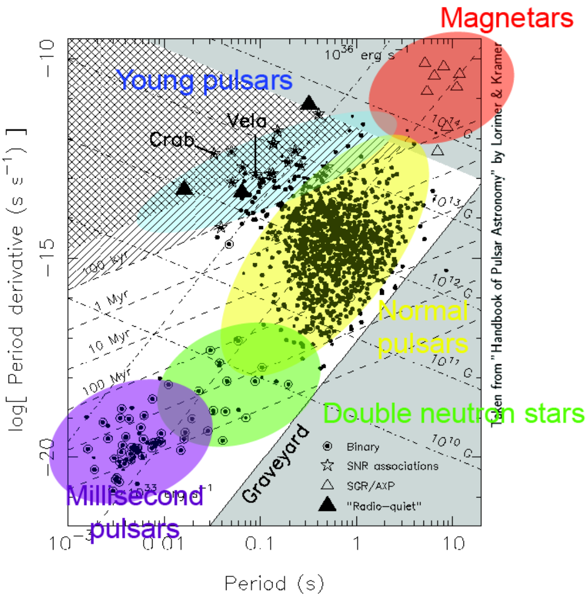
20-November-2014


NS
unobservable/ unobserved
Observable
NEW??
CCO (synchrotron from shock heated plasma; 0.5 -1.5 keV)
Thermal
Magnetic powered
Accretion powered
Rotation powered
XTIN or XDIN (7)
AXP, SGR
LMXB, HMXB
(i) radio pulsars (ii) gamma-ray pulsars
Recycled (MSP)
Normal
NS
Extra-Galactic
Galactic
Near Galactic Centre
Disk (+halo)
Globular Clusters
NS
XDIN, Magnetic powered, rotation powered
Isolated
Binary
NS-RG, NS/SRG
NS-substellar
NS-MS
NS-WD
NS-NS
NS-BH
Accretion powered
Rotation powered, magnetic powered

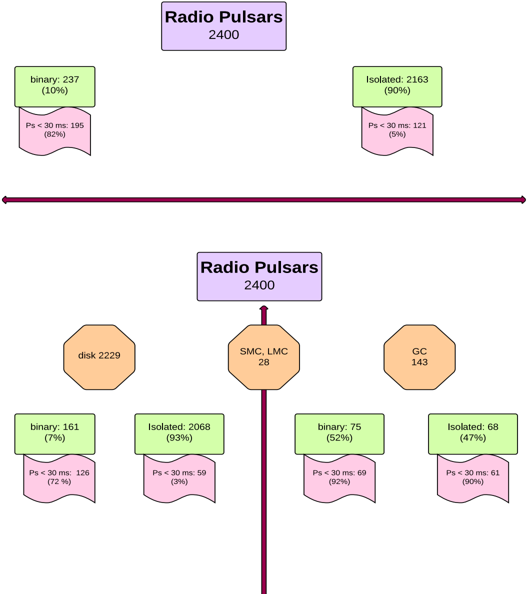
Rotation powered, magnetic powered, and thermal NS population



Rotation powered, magnetic powered, and thermal pulsar population



Radio (+gamma) pulsar population



Methods to study pulsar popularion

Full Dynamical Approach

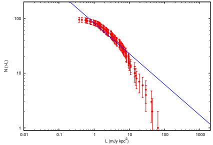
(i) simulate pulsar parameters
(ii) model evolution
(iii) model observational limits
(iv) compare with observations
is used for normal disk pulsars

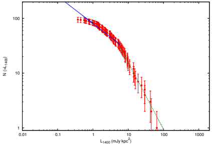
This approach is extremely difficult for GC pulsars, as
one needs to model the GCs and the effect of GC properties on pulsar evolution.

Snapshot Approach

Simple

Just fit the observed distribution.
Hui, Cheng & Taam, 2010, ApJ, 714, 1149 (HCT10)
fitted the observed luminosities of GC pulsars as power laws.





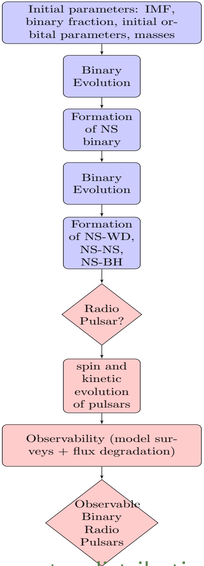
$N = N_0 \, L^{-\beta}$ giving $\log N = \log N_0 - \beta \, \log L$
N_0 is no. of pulsars with $L \geq 1 \text{ mJy kpc}^2$
we got $N_0 \sim 72$, $\beta = 0.56$, HCT10 got $N_0 \sim 68$, $\beta = 0.58$, (wrong distance of Ter5)
we got $N_{0,h} \sim 165$, $\beta_h = 1.21$ and $N_{0,l} \sim 72$, $\beta_l = 0.55$

Bagchi & Lorimer, 2011, AIPC, 1357, 173

Improved

Example for recyled pulsars in GCs:
Bagchi, Lorimer & Chennamangalam
2011, MNRAS, 418, 477
Assumption: minimum observed luminosity = just observable over unmodelled selection biases.
Results: (i) log-normal is the best fitted luminosity model with mean −1.1 and standard deviation 0.9 (same as normal disk pulsars [FK06])
(ii) No correlation between cluster properties and pulsar number!!
A study within full dynamical approach is needed

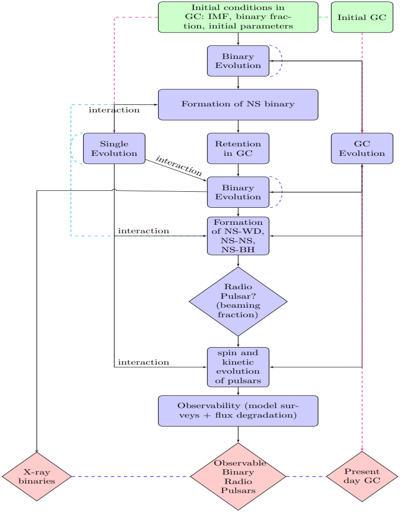
Population synthesis - full dynamical approach for binary radio pulsars



final parameter distributions

psrpop: http://psrpop.sourceforge.net/ (fortran code)
psrpoppy: http://samb8s.github.io/PsrPopPy/ (python, will be updated as psrpopbinpy)

Population synthesis - full dynamical approach for binary radio pulsars in globular clusters



$$L_\nu = aP^p\dot{P}_s^q$$

$p \sim 1$, $q \sim 1$: Gun & Ostriker; 1970, ApJ, 160, 979

$p \sim -1$, $q \sim 1/3$: Vivekanand & Narayan; 1981, J. Astrophys. Astron., 2, 315. ; Prószyński and Przybycień ; 1984, Pulsar statistics: A study of pulsar luminosities, in "Birth and Evolution of Neutron Stars: Issues Raised by Millisecond Pulsars", eds. S. P. Reynolds and D. R. Stinebring (NRAO, Greenbank, West Virginia, 1984), p. 151 ; Emmering & Chevalier; 1989, ApJ, 345, 931

$p \sim -0.7$, $q \sim 0.28$: Lorimer et al.; 1993, MNRAS, 263, 403 (did not model observational bias, but demnstrated its presence).

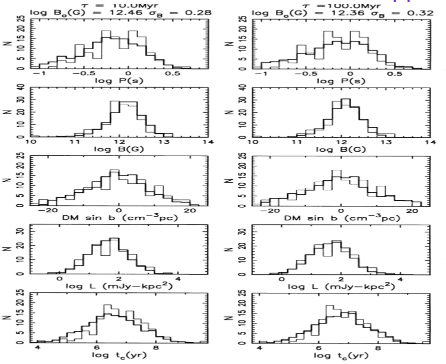
$$L_{400} = 10^{-10.05\pm0.84}\left(\frac{B_S}{P_s^2}\right)^{0.98\pm0.03} \quad \text{if } \frac{B_S}{P_s^2} \leq 10^{13}\,\mathrm{Gs}^{-2}, \tag{5a}$$

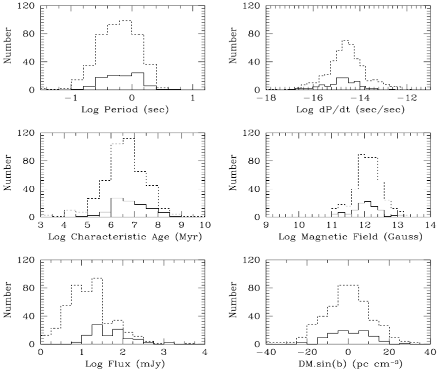
$$L_{400} = 10^{2.71\pm0.60} \quad \text{if } \frac{B_S}{P_s^2} > 10^{13}\,\mathrm{Gs}^{-2}. \tag{5b}$$

G. M. Stollman, *Astron. Astrophys.* **170** (1986) 48.

Equation (5a) can be approximated to Eq. (4) with $p = -1.47$, $q = 0.49$ which can be further simplified as $p = -1.5$, $q = 0.5$. Stollman also gave a physical explanation for this law within the framework of Ruderman–Sutherland model

Understanding normal, radio pulsars in the Galactic disk (+halo) – full dynamical approach



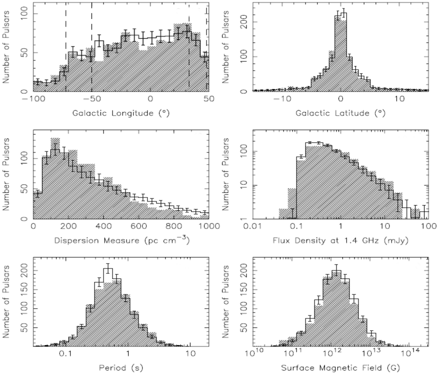


Bhattacharya, Wijers, Hartman, Verbunt; 1992, A&A, 254, 198

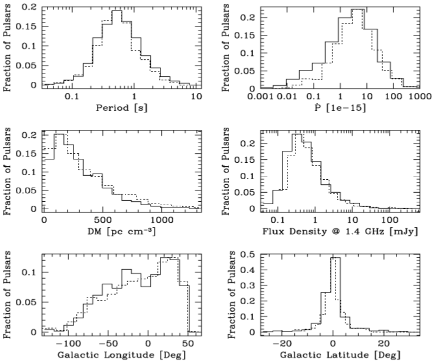
Mukherjee, Kembhavi; 1997, ApJ, 489, 928

Magnetic field does NOT decay. (Almost same results)

Understanding normal, radio pulsars in the Galactic disk (+halo) – full dynamical approach



Faucher-Giguére, Kaspi; 2006, ApJ, 643, 332



Ridley, Lorimer; 2010, MNRAS, 404, 1081

Almost same results.

Understanding radio+gamma-ray millisecond pulsars in the Galactic disk

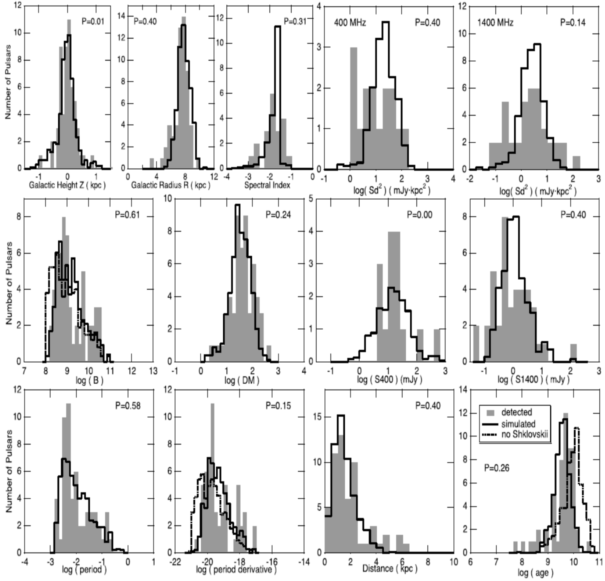


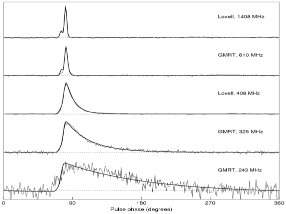
FIG. 6.—Distributions of various characteristics indicated for detected (*shaded histograms*) and simulated (*unshaded histograms*) MSPs from the Galactic disk. Also indicated is the *p*-value of the Kolmogorov-Smirnov test of the binned detected and simulated sample distributions at a significance level of $\alpha = 5\%$. The dotted histograms represent the simulated distributions without the Shklovskii effect.

Story, Gonthier, Harding; 2007, ApJ, 671, 713 (full dynamical method)

- Abundance of binary and millisecond pulsars
- Eccentric binaries (NS-WD) as a result of interactions with other stars (Bagchi & Ray; 2009, ApJ, 701, 1161)
- Luminosity distribution is the same as for disk pulsars (Bagchi, Lorimer & Chennamangalam; 2011, MNRAS, 418, 477)
- Average B_s is 2-5 times larger in the globular cluster pulsars (Konar; 2010, MNRAS, 409, 259)
- **Study within full dynamical framework yet to be done**

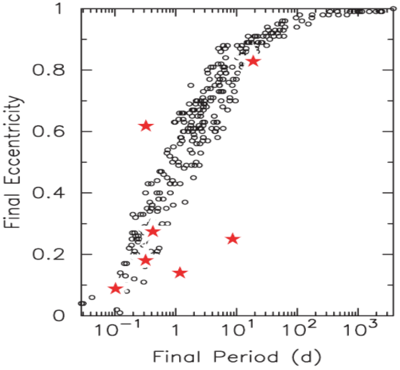
- Mass seggregation is happening (not completely done - timescale is 10,000 times than the age) – but still many massive stars near the centre.
- Many BH, NS, WDs near the centre.
- No pulsar discovered yet? WHY????
- "potentially observable population of pulsars in the inner parsec $\sim$ 200" – Chennamangalam & Lorimer; 2014, MNRAS, 440, 86. [can be improved even with 1 or 2 detection(s).]
- Number density of stars very high
- Formation of binary due to tidal capture is highly probable.
- 3-body stellar interactions are important (as discussed for globular clusters).
- Stars very close to it orbiting around it.
- NS-MS, NS-WD, NS-NS, NS-BH orbiting around the centre? – Three body problem?
- Interesting for gravitational waves (Kocsis, Ray, Portegies Zwart; 2012, ApJ, 752, 67), testing theories of gravity (Liu et al.; 2012, ApJ, 747, 1), Dark-matter (Bramante & Linden; 2014, PRL, 113, 191301), mass-seggregetation (Chanamé & Gould; 2002, ApJ, 571, 320) ....

- There is diffuse electron cloud in the Galaxy - density highest near the centre.
- Photons in the pulsar beam get scatterd by these electrons - the pulse get smeared. Is that making pulsars undetectable?
- Efforts with higher and higher frequency (where the effect of the scattering is less). But no sucess yet :(
- Pulsars are intrinsically fainter at high frequency ($L \propto \nu^{-1.7}$)
- Dynamical effects?? .... high acceleration



Understanding NS-NS population (radio pulsar) in the Galactic disk (+halo)

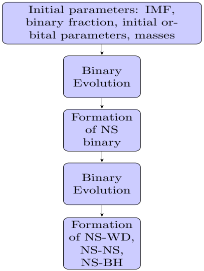
(usually discusses Ps, P_{orb}, e; not location)



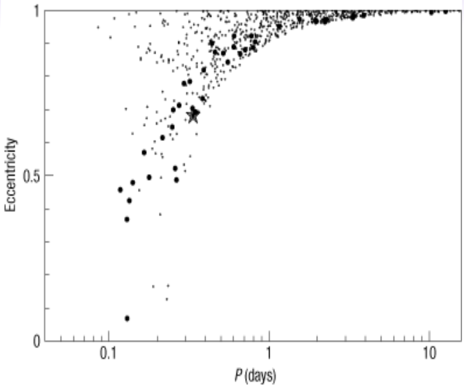
Dewi, Podsiadlowski, Sena, 2006, MNRAS, 368, 1742

many more ...... Ihm et al., 2006, ApJ, 652, 540 (explained eccentricity)

Selection Biases NOT included

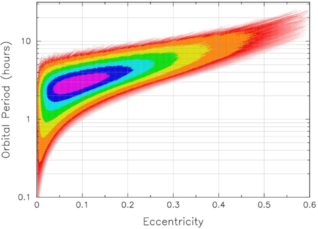


Understanding NS-NS population (radio pulsar) in the Galactic globular clusters



Only DNS binaries produced with merger times less than or similar to 10 Gy are plotted. Each 'bold' point marks a binary that has survived until today but will merge within a Hubble time, whereas the initially created DNS systems are marked by the small dots (most of which have merged). The star marks the parameters for the M15-C system, showing that it could indeed be produced by an exchange encounter of a field NS with an LMXB (or qLMXB) containing a NS and $0.4 M_{\odot}$ secondary. Grindlay, Portegies Zwart, McMillan; 2006, Nature Physics, 2, 116

- Evolution of binaries containing massive stars (but unequal masses).
- Test theories of gravity
- Gravitational waves



Can be tested if we discover NS-BH systems.

But difficult to detect because of significant flux degradation for NS-BH binaries due to orbital acceleration – SKA will be so sensitive that even degraded flux will be detectable. (Bagchi, Lorimer, Wolfe, 2013, MNRAS, 432, 1303)

(1) Sigurdsson, arXiv:astro-ph/0303312

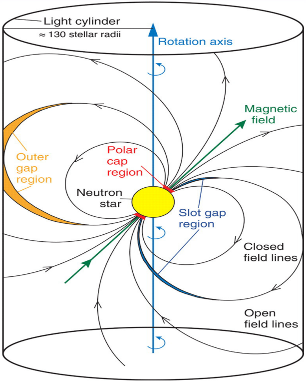
(2) Clausen, Sigurdsson, Chernoff, 2013, MNRAS, 428, 3618

(3) Faucher-Giguŕe & Loeb, 2011, MNRAS, 415, 3951 (formation through 3-body interaction)

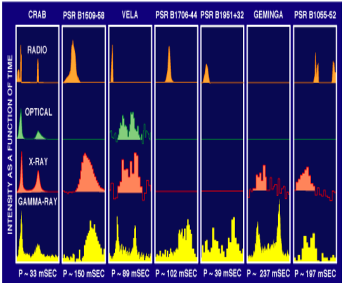
(4) Kiel & Hurley, 2009, MNRAS, 395, 2326

(5) Smits *et al.*, 2009, A & A, 493, 1161

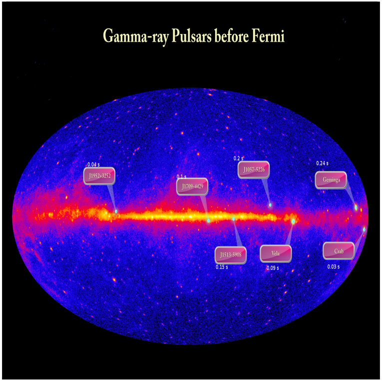
(6) Pfahl, Podsiadlowski, Rappaport, 2005, ApJ, 628, 343

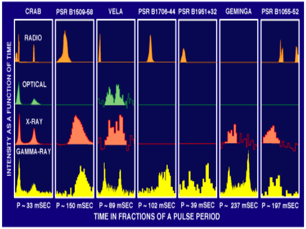


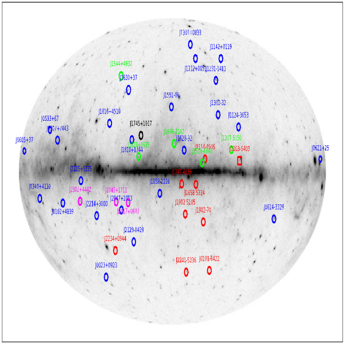
- Gamma radiation from pulsar magnetospheric gaps: Chiang & Romani; 1992, ApJ, 400, 629, ... many others
- McLaughlin & Cordes; 2000, ApJ, 538, 818 used 3 OSSE pulsars and 7 EGRET pulsars (semi-dynamical approach)
  $L_\gamma = 10^{19.4} P^{-8.3} B_{12}^{7/6}\ erg\ s^{-1}$



Understanding gamma-ray pulsars (Fermi: launched in 2008)







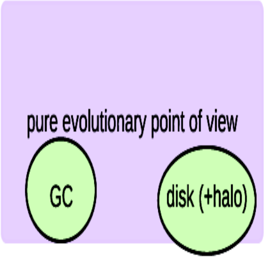
43 radio millisecond pulsars (MSPs) discovered in searches for pulsars in LAT unassociated sources. MSPs discovered at the GBT are shown in blue, while pulsars found with the GMRT are in green, Effelsberg in black, Parkes in red and Nancay in magenta.

- 117 gamma-ray pulsars in the 2nd Fermi catalogue (2013).
- Understanding slot-gap, outer-gap models by matching predicted beam shapes with observed ones - more pulsars will help (Bai & Spitkovsky; 2010, ApJ, 715, 1270 found some inconsistancy).
- short birth periods $P_0 \sim 50$ ms and outer-gap model: Watters & Romani; 2011, ApJ, 727, 123.
- simulating the sensitivities of previous major radio surveys Takata, Wang, Cheng (2011, ApJ, 726, 44) found $\sim 18 - 23$ radio-loud and $\sim 26 - 34$ γ-ray pulsars. more now!!
- Perera, McLaughlin .. et al. (2013, ApJ, 776, 61) found that an outer gap model is good, and $L_\gamma \propto P^{-a}\dot{P}^b$ where $a = 1.36 \pm 0.03$ and $b = 0.44 \pm 0.02$.

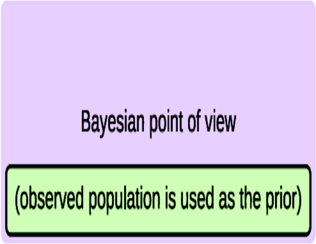
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+Detected+Gamma-Ray+Pulsars (Nov 06, 2014)

total: 161, MSP: 70 (43%), larger than radio (+gamma-ray) pulsars (6%); Binary: 55 (34%), larger than radio (+gamma) pulsars (10%)

Inspiralling/merging NS-NS, NS-BH binaries are sources of gravitational waves in the LIGO band. They are also the source of short-GRBs. So people working in this area are interested to understand the population of such binaries (location, masses, spin, binary parameters) ... formation rate, merger rate, etc ..... but it does not matter whether NSs are observable in em-spectrum or not.



Kalogera, Farr, Podsiadlowski, Ivanova, Rasio, Heinke, Fregeau, Belczynski ...

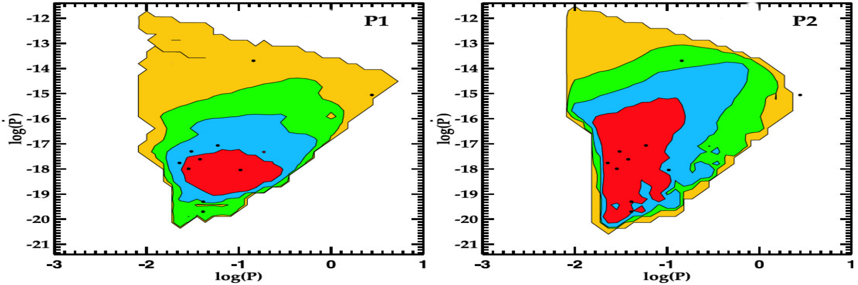


Kalogera, O'Shaughnessy, Kim (Chunglee), Mandel .....

Understanding the total NS-NS, NS-BH population (gravitational waves, GRB)

people in general are concerned about: P_{orb}, e, location, P_s, $\dot{P}_s$

0.2% and 2% NS-NS binaries will have an eccentricity above 0.01 for the Advanced LIGO/VIRGO detector: Kowalska et al., 2011, A & A, 527, 70



(DNS) Oslowski, Bulik, Gondek-Rosińska; Belczyński; 2011, MNRAS, 413, 461

What we want and what we need ...

- discover NS-BH (test theories of gravity, check population synthesis predictions) – sensitive telescope
- pulsars close to the Galactic centre – sensitive telescope
- discover more and more pulsars (better population synthesis, more pulsars to PTA) – sensitive telescope, more telescope time
- improved timing (detect gravitational waves@PTA, test of gravity, constraining EoS) – sensitive telescope, more telescope time

SKA will fulfill ....

- Smits et al., 2009, A & A, 493, 1161 predicts detection of 14000 normal pulsar and 6000 MSPs.
- Smits et al., 2011, A &A, 528, 108 says that a parallax with an accuracy of 20% or less can be measured up to a maximum distance of 13 kpc, which would include 9000 pulsars. Better model of ISM is possible by comparing parallax-distances to DM-distances.

CSIRO website: "The GMRT comprises 30 telescopes distributed over many square kilometres, so it constitutes a very good tes-bed for operations with the Square Kilometre Array (SKA) - but the GMRT is located in an environment that is much more prone to radio frequency interference (RFI) than the SKA sites." – not bad, gives better skill to tackle RFI.

Advantages:

- Presence of many expert scientists/engineers
- SKA related activities going on, e.g., transient search pipe-line (Bhat et al. 2013, ApJS, 206, 2)

Suggestions:

- More international collaboration/activities
- More PRESTO friendly data (to facilitate search)