Searches in Astrophysics and Cosmology

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Outline

- Methodology and recent trends in Astro-statistics
- Five real-life examples:

1. Cosmological parameters
2. Neutrino mass
3. Photometric redshifts
4. Galaxy shapes and classification
5. Exo-planets

modern Astro-Statistics books

- Lyons (1991)
- Press et al. (1992)
- Lupton (1993)
- Babu & Feigelson (1996)
- Sivia (1996)
- Cowan (1998)
- Starck & Murtagh (2002)
- Martinez & Saar (2002)
- Wall & Jenkins (2003)
- Saha (2003)
- Gregory (2005)
- Hobson et al. (2009)

Recent trends

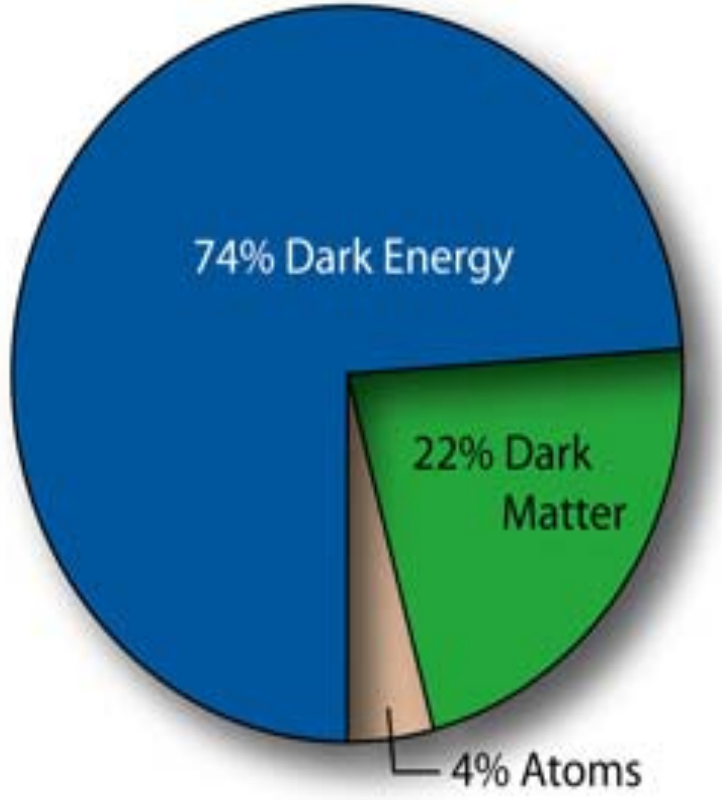
- Astro-Statistics is more ‘respectable’.
- In Cosmology, Bayesian approaches are more popular (since 90s) than Frequentist methods.
- More awareness of model selection methods (e.g. Evidence, AIC, BIC, …).
- Computer intensive methods (e.g. MCMC) are more common, and free packages available.

Example 1:
cosmological parameters

“Evidence” for the Dark Universe

Observational data

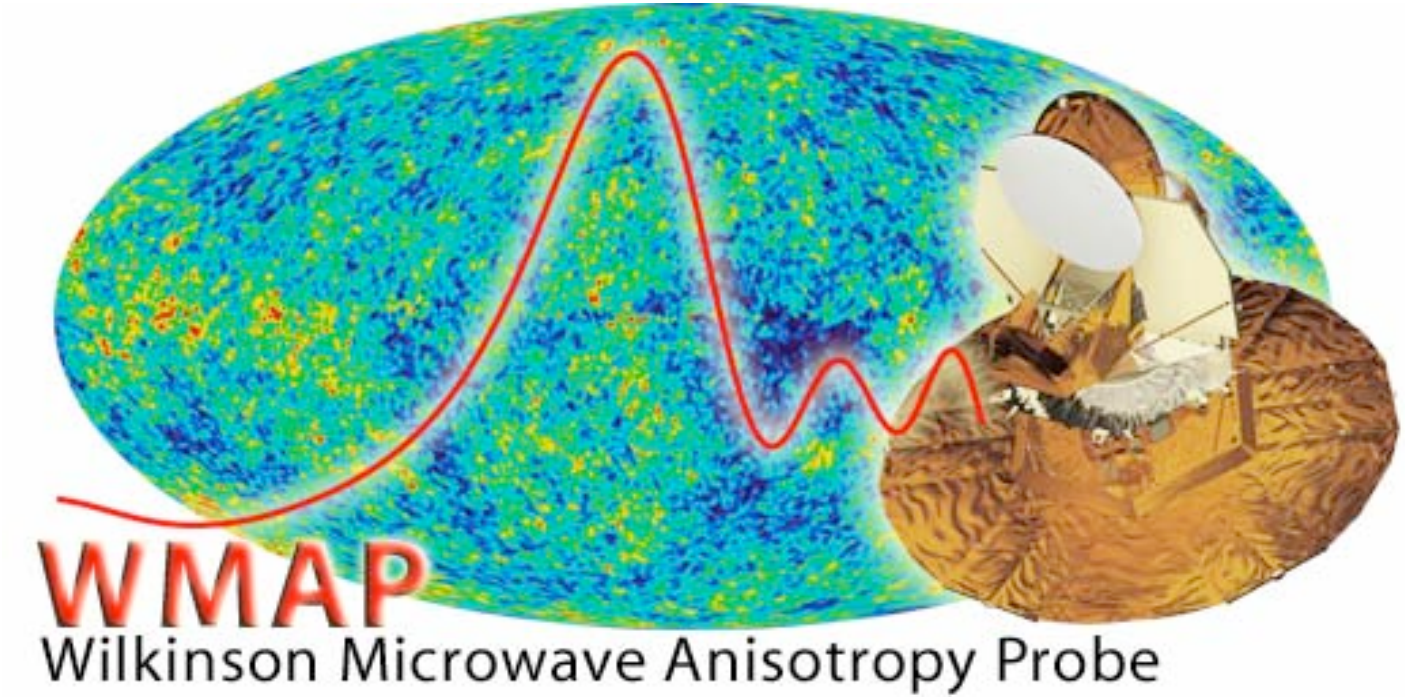
- Type Ia Supernovae
- Galaxy Clusters
- Cosmic Microwave Background
- Large Scale Structure
- Gravitational Lensing



Physical effects:

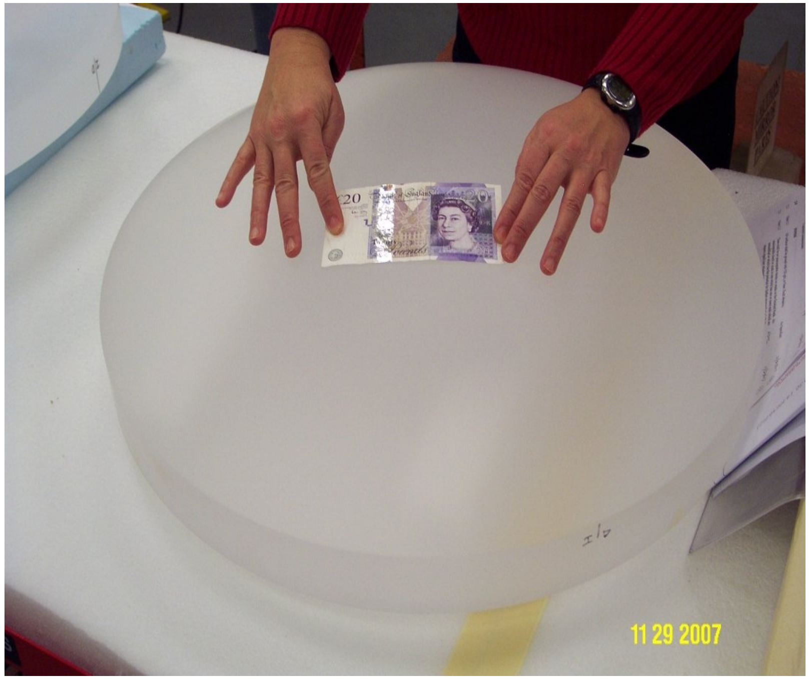
- Geometry
- Growth of Structure

“WMAP ++ Cosmology”



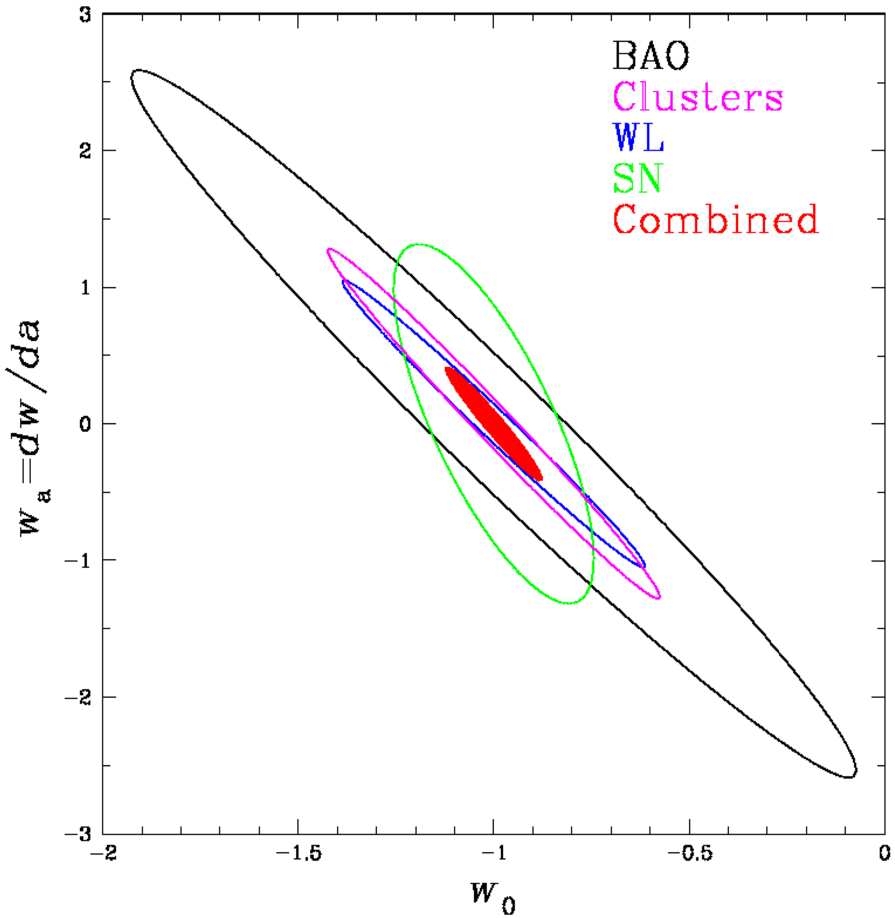
The Dark Energy http://www.darkenergysurvey.org

DARK ENERGY SURVEY



Fisher Matrix FoM as a tool for decision making by funding agencies

$w(z) = w_0 + w_a(1-a)$ 68% CL



Example: FoM for Dark Energy Survey is a factor 4.6 tigther compared to near term projects

Sources of uncertainties

- Cosmological (parameters and priors)
- Astrophysical (e.g. cluster M-T, biasing)
- Instrumental (e.g. PSF)

Use and Abuse of

- Priors
- Marginalization
- Evidence

How to choose a prior?
(e.g. on the curvature)

* Theoretical prejudice

(e.g. "according to Inflation the universe must be flat")

* Previous observations

(e.g. "we know from WMAP the universe is flat to within 2%")

* Parameterized ignorance (e.g. "uniform prior, Jeffrey's prior, or Entropy prior?")

Can we rule out w = -1?

WMAP 7-year Cosmological Interpretation

TABLE 4
SUMMARY OF THE 68% LIMITS ON DARK ENERGY PROPERTIES FROM *WMAP* COMBINED WITH OTHER DATA SETS

Section	Curvature	Parameter	$+\mathrm{BAO}+H_0$	$+\mathrm{BAO}+H_0+D_{\Delta t}$ [a]	$+\mathrm{BAO}+\mathrm{SN}$ [b]
Section 5.1	$\Omega_k = 0$	Constant w	-1.10 ± 0.14	-1.08 ± 0.13	-0.980 ± 0.053
Section 5.2	$\Omega_k \neq 0$	Constant w	-1.44 ± 0.27	-1.39 ± 0.25	$-0.999^{+0.057}_{-0.056}$
		Ω_k	$-0.0125^{+0.0064}_{-0.0067}$	$-0.0111^{+0.0060}_{-0.0063}$	$-0.0057^{+0.0067}_{-0.0068}$
			$+H_0+\mathrm{SN}$	$+\mathrm{BAO}+H_0+\mathrm{SN}$	$+\mathrm{BAO}+H_0+D_{\Delta t}+\mathrm{SN}$
Section 5.3	$\Omega_k = 0$	w_0	-0.83 ± 0.16	-0.93 ± 0.13	-0.93 ± 0.12
		w_a	$-0.80^{+0.84}_{-0.83}$	$-0.41^{+0.72}_{-0.71}$	$-0.38^{+0.66}_{-0.65}$

Bayesian Evidence: To BE or not to BE?

$$p(d|\mathcal{M}) \equiv \int_{\Omega_{\mathcal{M}}} p(d|\theta, \mathcal{M}) p(\theta|\mathcal{M}) \mathrm{d}\theta \quad \text{(Bayesian evidence).}$$

$$B_{01} \equiv \frac{p(d|\mathcal{M}_0)}{p(d|\mathcal{M}_1)} \quad \text{(Bayes factor).}$$

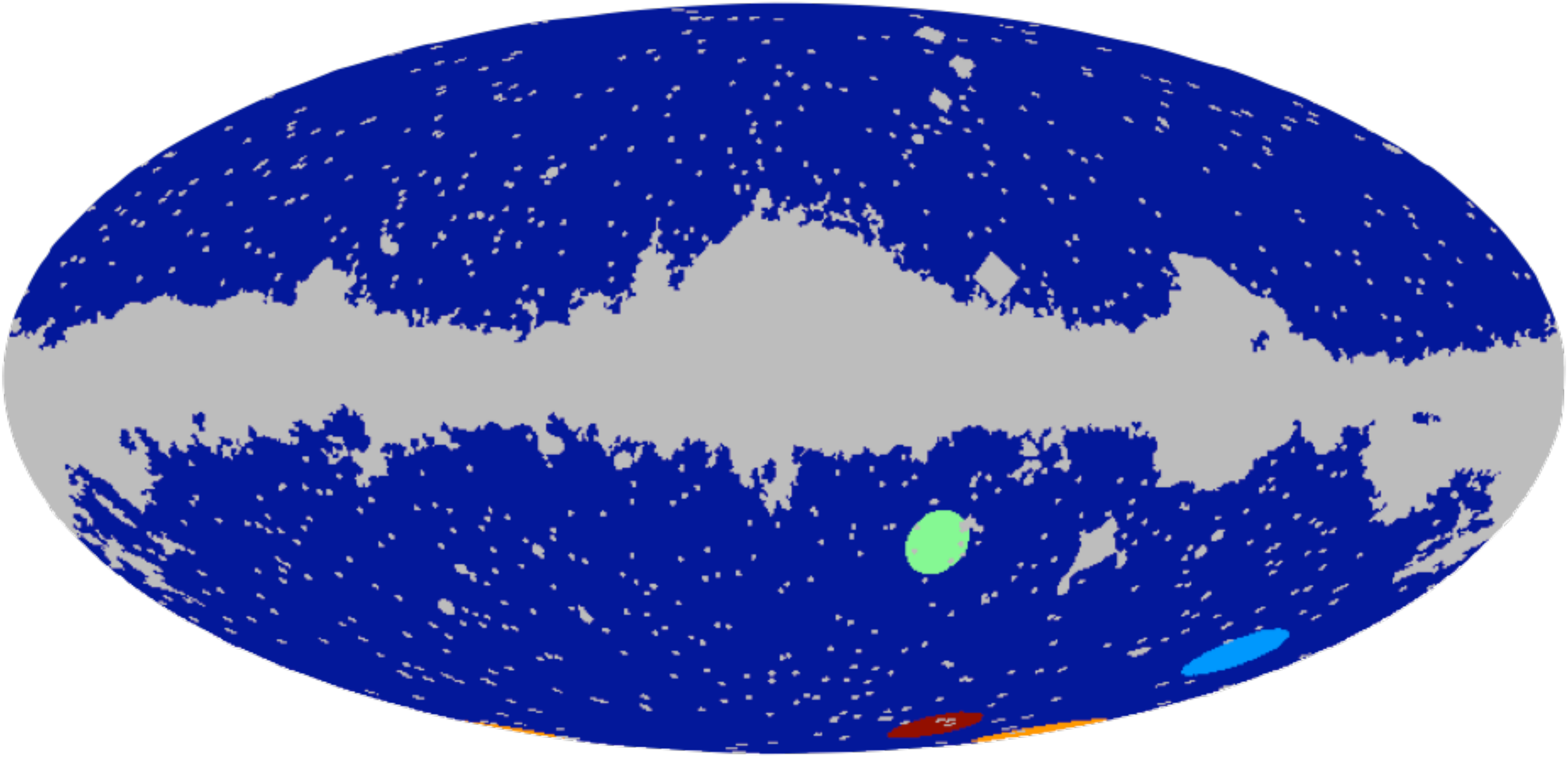
e.g. B=1 weak; B=5 strong

But how sensitive to assumed priors?

Variations: AIC, BIC, DIC,…

e.g. Liddle (2007), Trotta (2008), Efstathiou (2009)

WMAP 7-Year:
circles in the CMB sky?

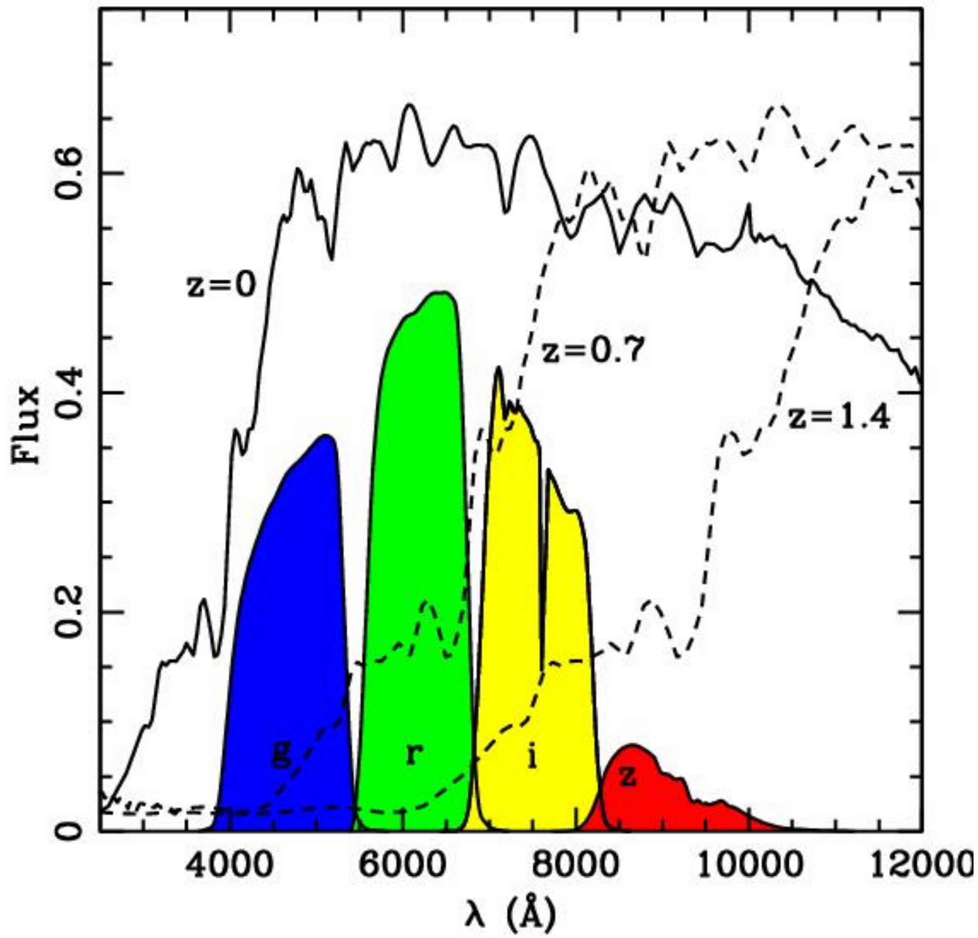


Fenney, Peiris, Johnson & Mortlock (2010)

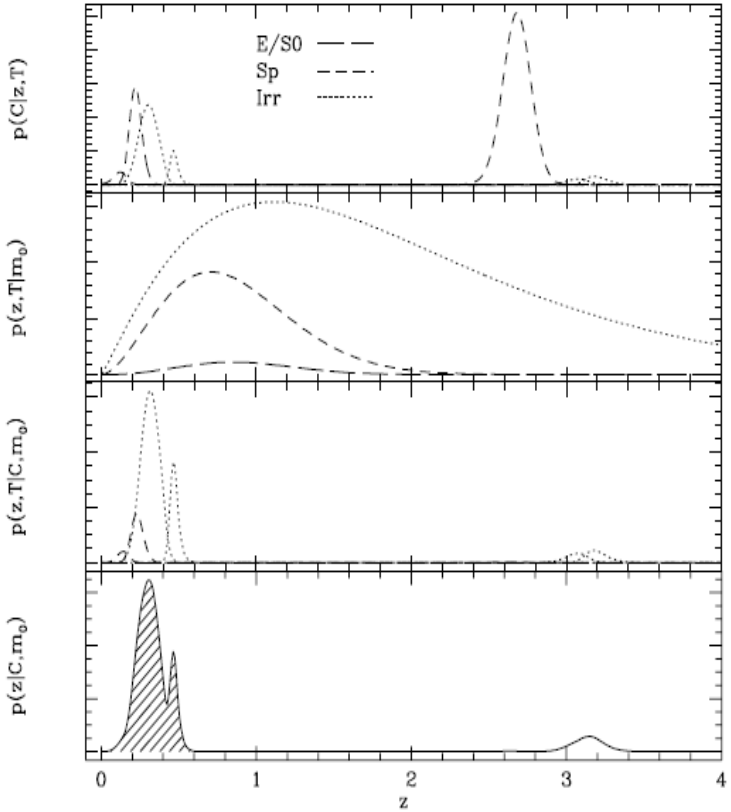
Example 2:
Photometric Redshifts

Photometric redshift

- Probe strong spectral features (4000 break)
- Difference in flux through filters as the galaxy is redshifted.



Bayesian Photo-z



Redshift z

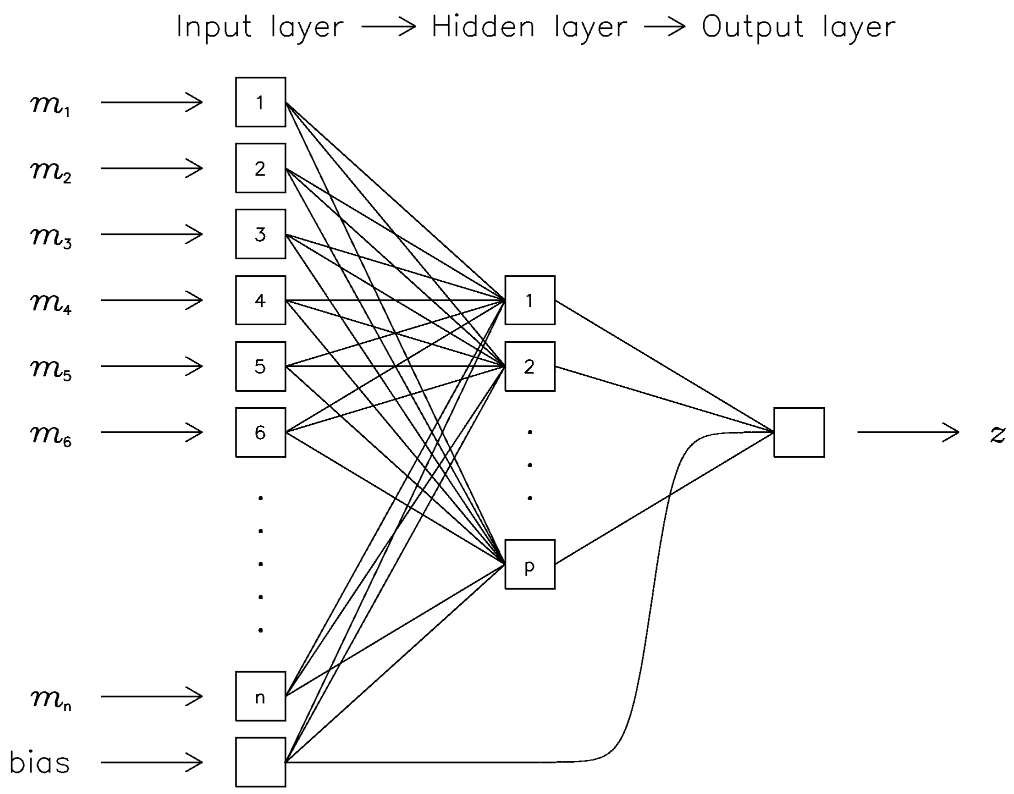
$p(C|z,T)$ ***likelihood***

$p(z,T|m_0)$ ***prior***

Benitez 2000 (BPZ)

ANNz - Artificial Neural Network

Input: magnitudes



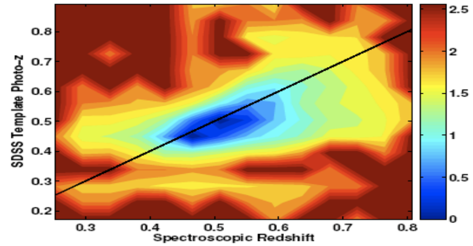
Output: redshift

Collister & Lahav 2004

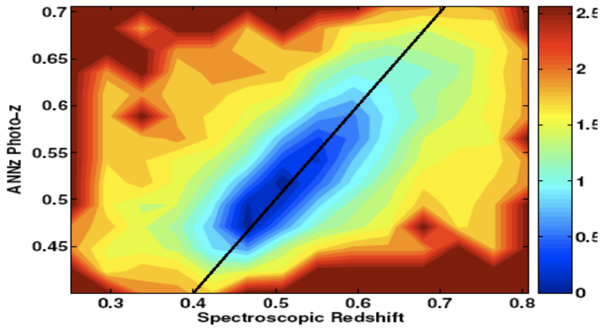
http://www.star.ucl.ac.uk/~lahav/annz.html

1.5M LRGs (“MegaZ”) photo-z code comparison

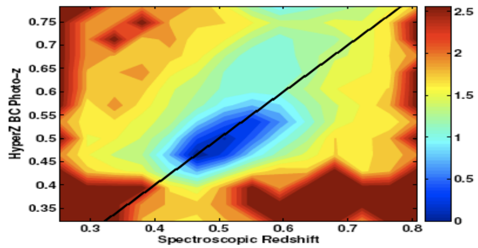
SDSS



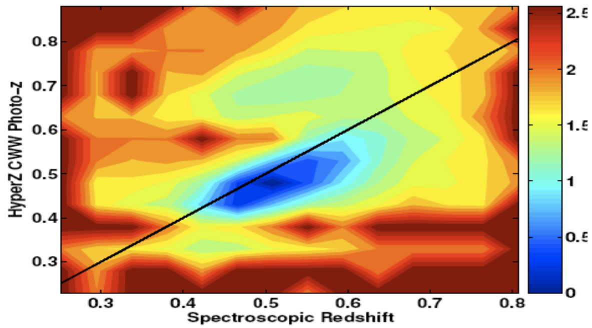
ANNz



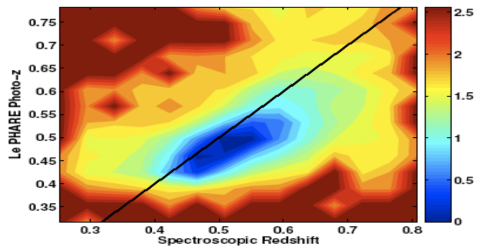
HpZ+BC



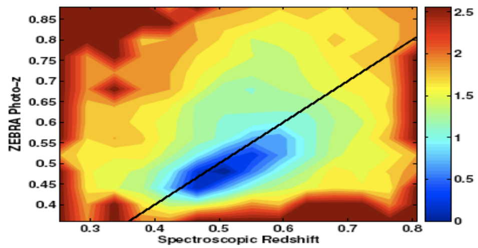
HpZ+WWC



Le PHARE



Zebra



Abdalla, Banerji, Lahav & Rashkov

Cf. PHAT (Hildebrandt et al. 2010)

Example 3:
Neutrino mass

KATRIN

- Next generation tritium beta decay spectrometer
- Sensitivity $m_\beta < 0.2$ eV at 90% C.L.
- 5σ detection threshold at $m_\beta = 0.35$ eV
- KATRIN Design Report Angrik et al. (2005)

Frequentist analysis!

www.fzk.de

Host, Lahav, Abdalla & Eitel 2007, PRD

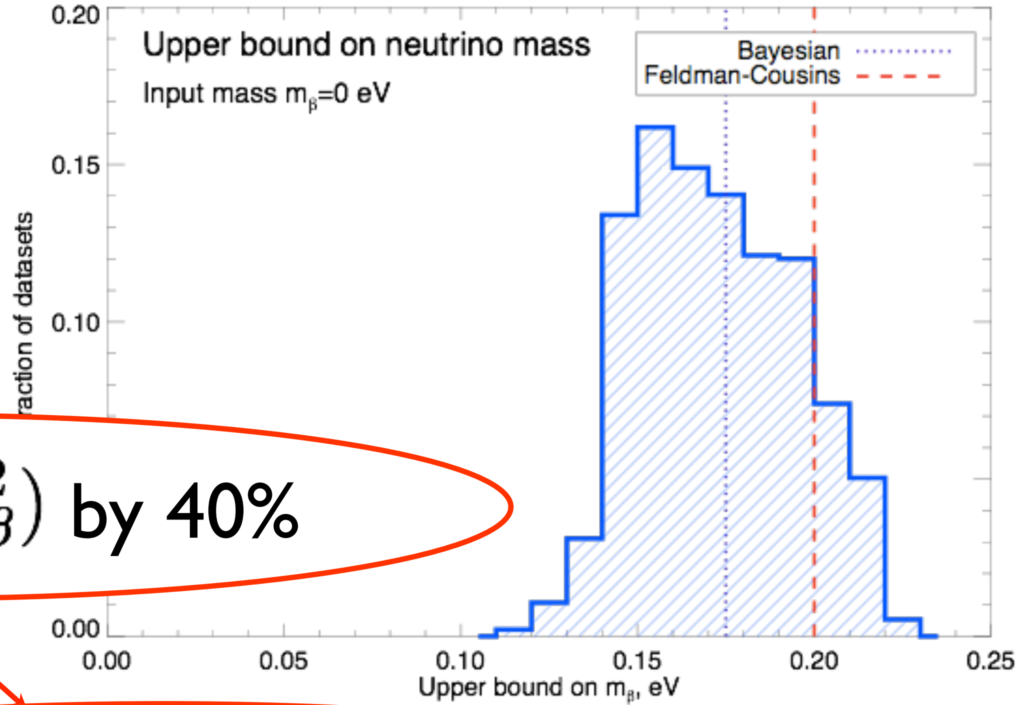
1) Null result

- **Assume zero mass**
- Frequentist reference:

$m_\beta < 0.20$ eV, 90%C.L.

Reducing $\sigma(m_\beta^2)$ by 40%

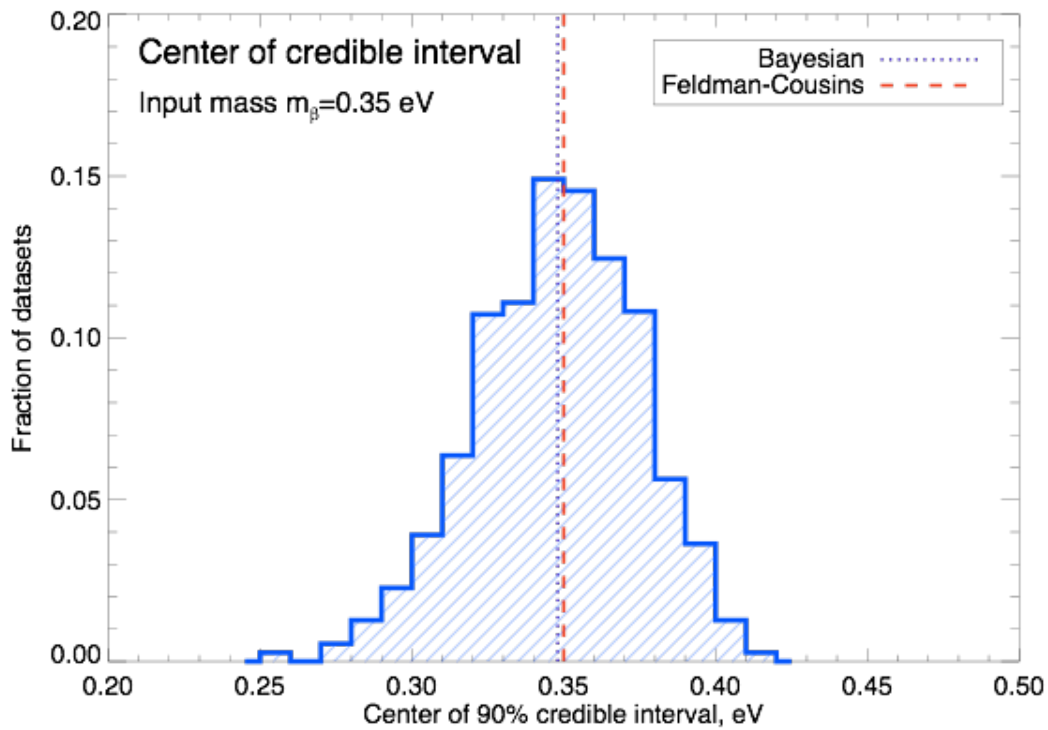
- Find upper limit in each



$\rightarrow m_\beta < 0.17$ eV, 90%C.L.

2) Discovery potential

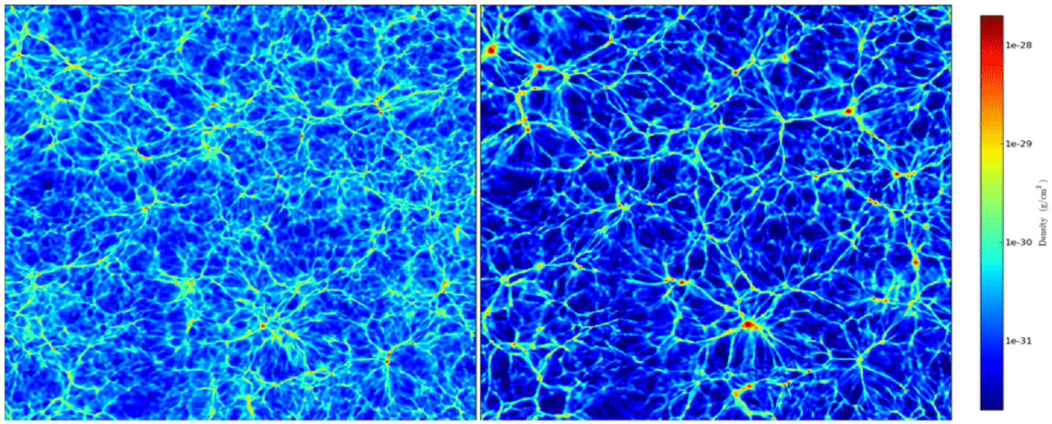
- Assume m_β = 0.35 eV
- 1000 posteriors
- Recover input regardless of analysis



Neutrino mass from galaxy surveys

700,000 galaxies with ANNz photo-z within 3.3 $(\mathrm{Gpc}/h)^3$

0.05 eV < Total neutrino mass < 0.28 eV (95% CL)



BBC News

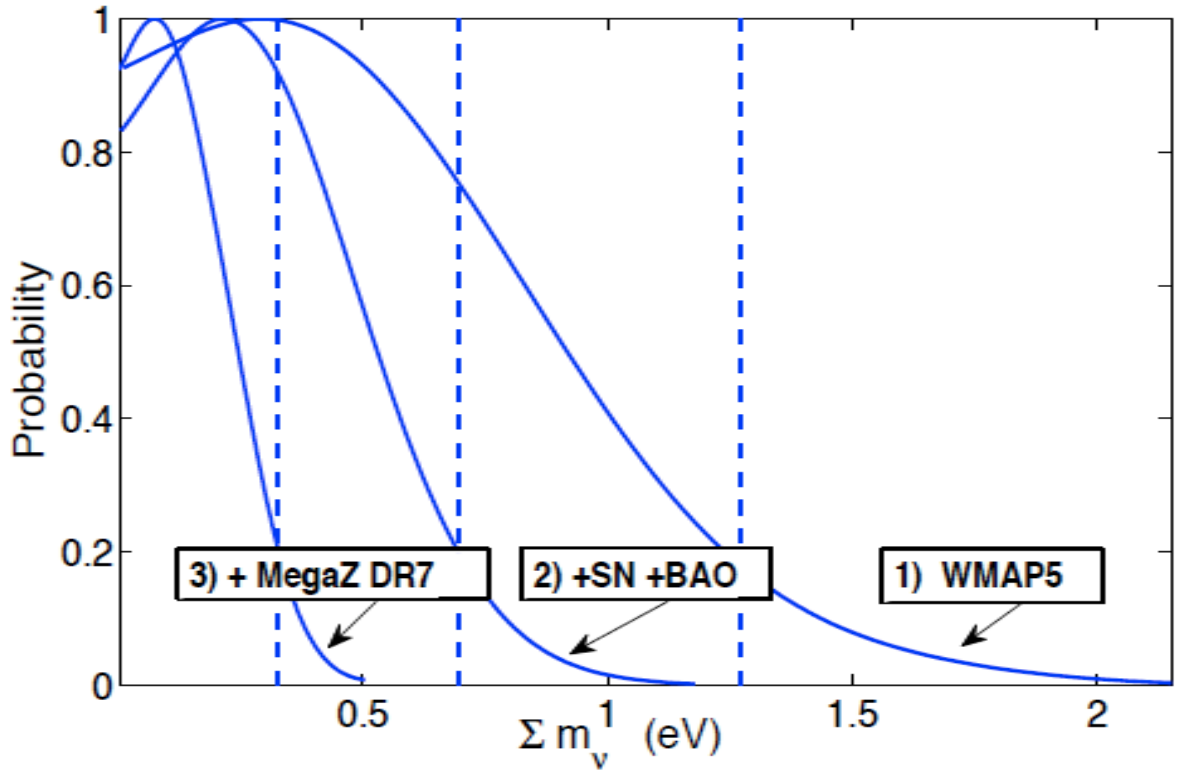
Neutrino 'ghost particle' sized up by astronomers

11:48 GMT, Tuesday, 22 June 2010 12:48 UK

Thomas, Abdalla & Lahav, PRL (2010)

Upper limits on total Neutrino mass

Total mass < 0.28 eV (95% CL)



Thomas, Abdalla & Lahav, PRL (2010) 0911.5291

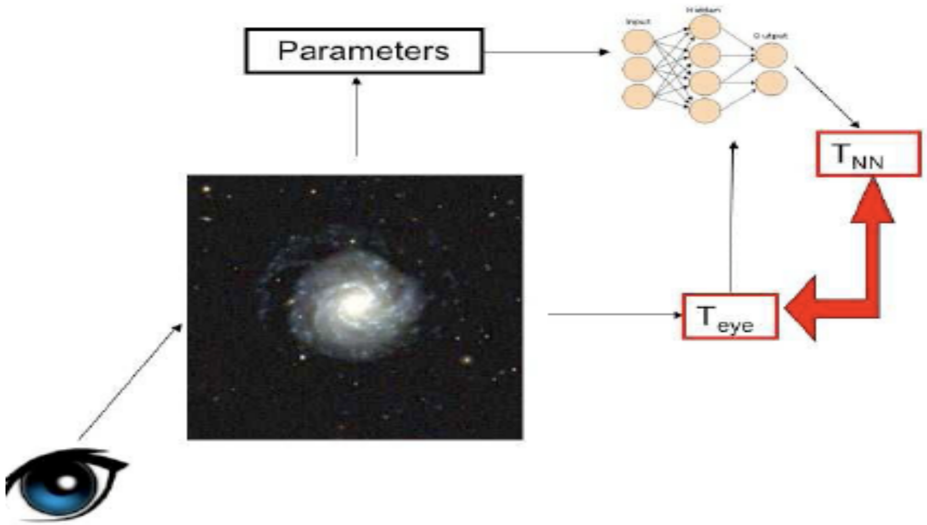
Example 4:
galaxy shapes and classification

GALAXY ZOO 2

- One Million galaxies classified by 100,000 people!

Lintott et al.

Galaxy zoo and machine learning



		GALAXY ZOO		
		Elliptical	Spiral	Star/Other
A	ELLIPTICAL	91%	0.08%	0.5%
N	SPIRAL	0.1%	93%	0.2%
N	STAR/OTHER	0.3%	0.3%	96%

Banerji, Lahav et al. (0908.2033)

Cosmic shear measurement

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:

GREAT08 (Bridle et al.); GREAT10 (Kitching et al.)

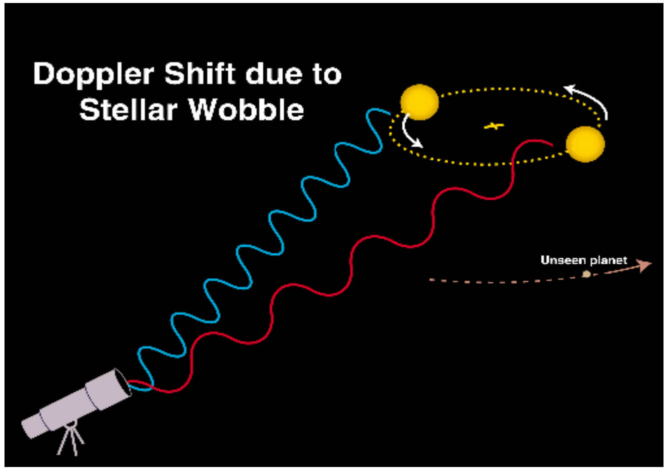
Example 5: Exo-planets

Modelling orbits of planets

(i) Given the wobble of the host star,

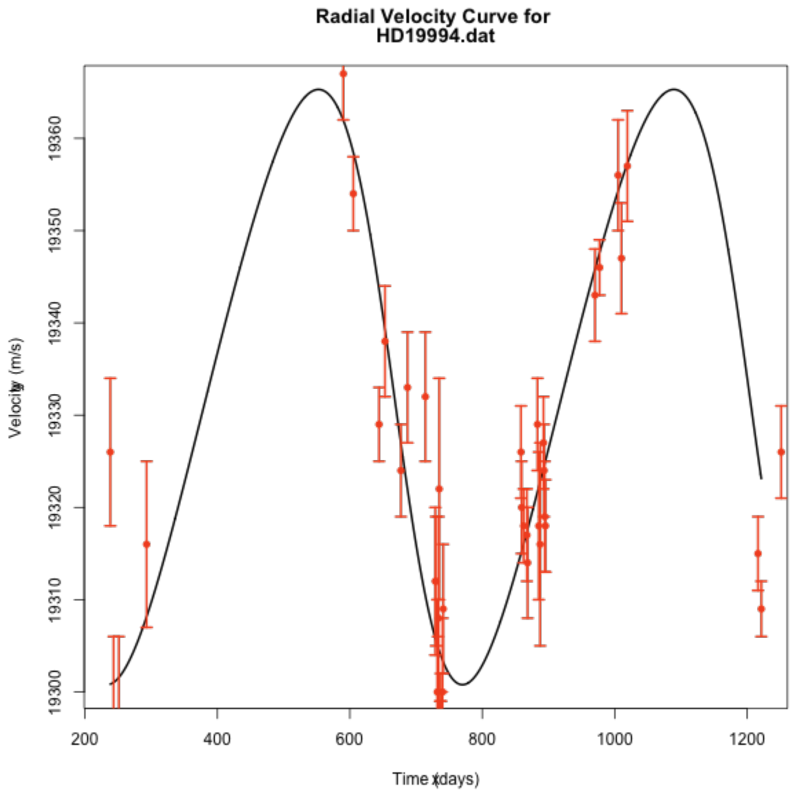
is there evidence for 0,1,2,3,… planets?

(ii) What are the parameters and associated errors of each detected planet?



ExoFit: orbital parameters from radial velocity data

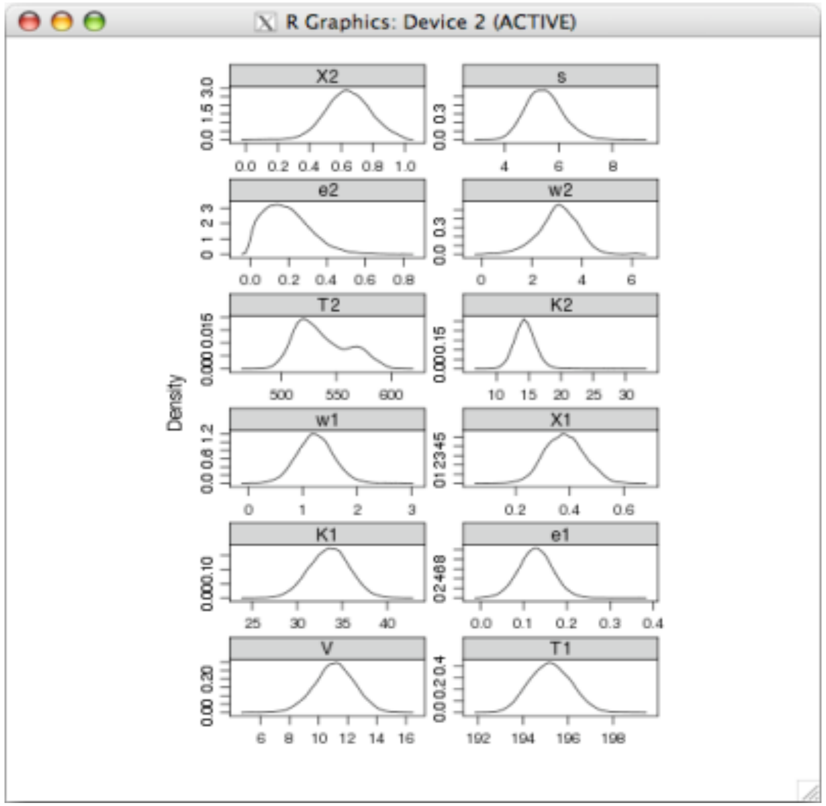
- Publically available
- Easy to use and fast
- Bayesian approach, with emphasis on priors, implemented by Markov Chain Monte Carlo (MCMC).

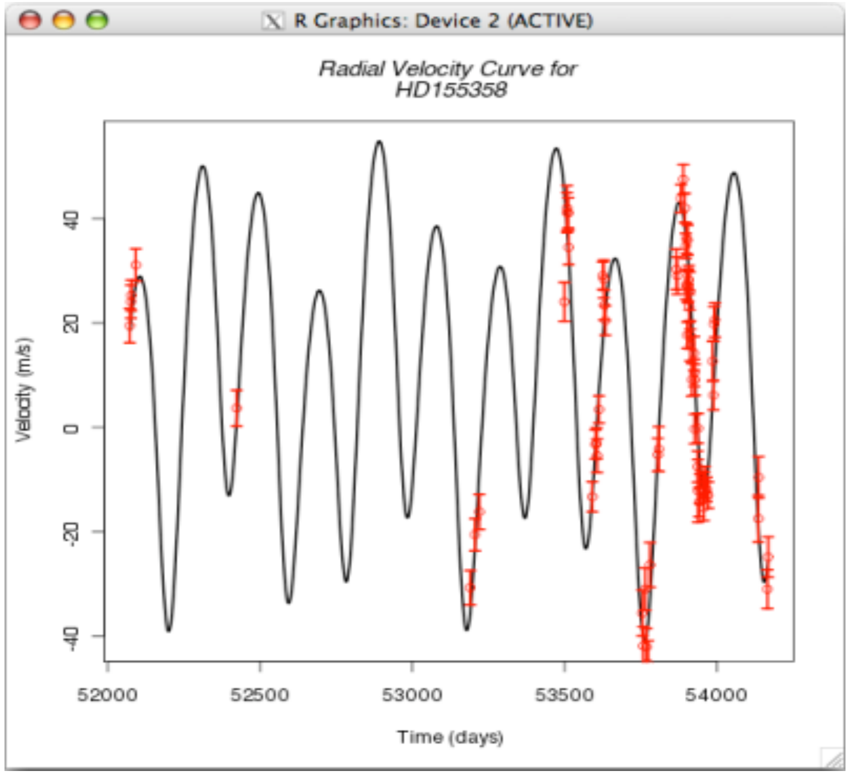


Balan & Lahav (MNRAS, 2009)

www.star.ucl.ac.uk/~lahav/exofit.html

HD155358: 2-planet search with ExoFit



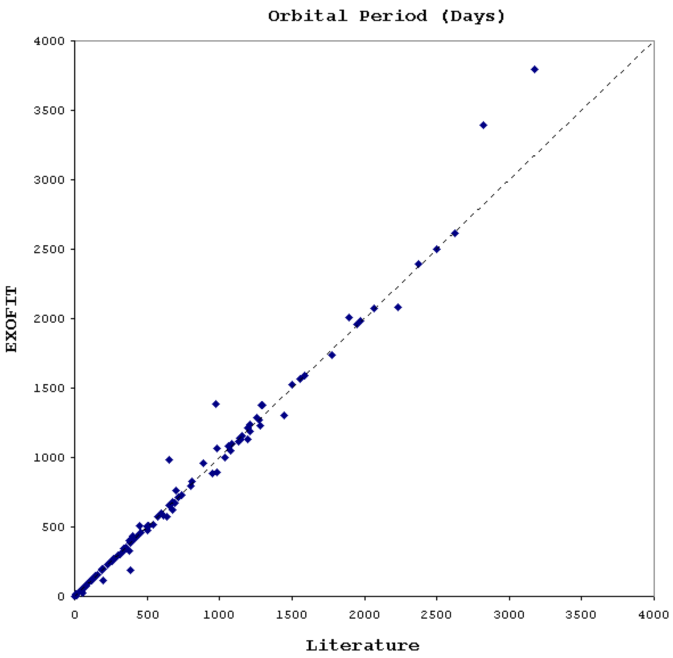


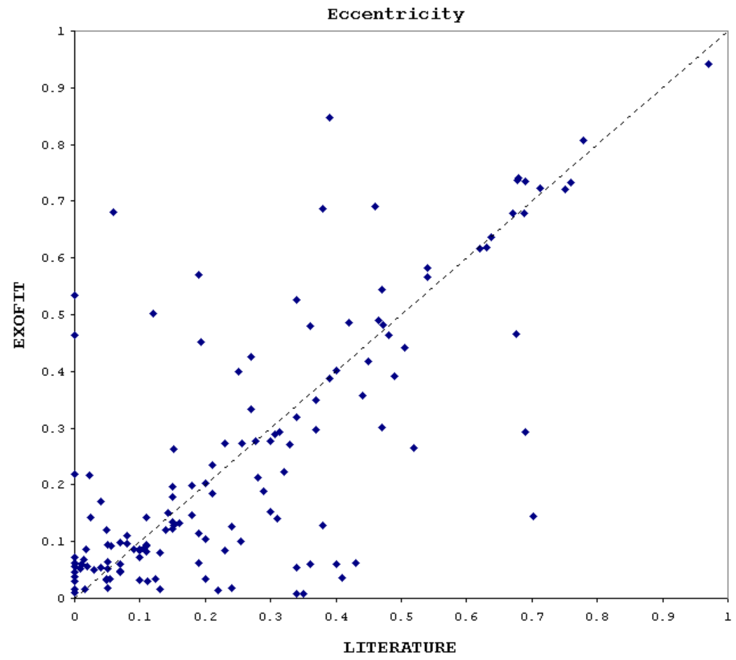
Priors for 2-planet system

Para.	Prior	Mathematical Form	Min	Max
$V_(ms^{-1})$	Uniform	$\frac{1}{V_{max}-V_{min}}$	-2000	2000
$T_1(days)$	Jeffreys	$\frac{1}{T_1 \ln\left(\frac{T_{1\,max}}{T_{1\,min}}\right)}$	0.2	15000
$K_1(ms^{-1})$	Mod. Jeffreys	$\frac{(K_1+K_{1\,0})^{-1}}{\ln\left(\frac{K_{1\,0}+K_{1\,max}}{K_{1\,0}}\right)}$	0.0	2000
e_1	Uniform	1	0	1
ϖ_1	Uniform	$\frac{1}{2\pi}$	0	2π
χ_1	Uniform	1	0	1
$T_2(days)$	Jeffreys	$\frac{1}{T_2 \ln\left(\frac{T_{2\,max}}{T_{2\,min}}\right)}$	0.2	15000
$K_2(ms^{-1})$	Mod. Jeffreys	$\frac{(K_2+K_{2\,0})^{-1}}{\ln\left(\frac{K_{2\,0}+K_{2\,max}}{K_{2\,0}}\right)}$	0.0	2000
e_2	Uniform	1	0	1
ϖ_2	Uniform	$\frac{1}{2\pi}$	0	2π
χ_2	Uniform	1	0	1
$s(ms^{-1})$	Mod. Jeffreys	$\frac{(s+s_0)^{-1}}{\ln\left(\frac{s_0+s_{max}}{s_0}\right)}$	0	2000

Following Gregory 05

Comparison of ExoFit vs. Literature





From a new uniformly-derived catalogue of 200 exo-planets
(Balan, Lever, Lahav, in preparation)

Summary

- Five real-life examples:

  Cosmological parameters

  Neutrino mass

  Photometric redshifts

  Galaxy shapes and classification

  Exo-planets

- Future Challenges in Astro-Statistics

Further input much needed from statistics

- Model selection methodology
- MCMC machinery and extensions
- Detection of non-Gaussianity and shape finders
- Blind de-convolution (eg. PSF)
- Object classification
- Comparing simulations with data
- Visualisation
- VO technology