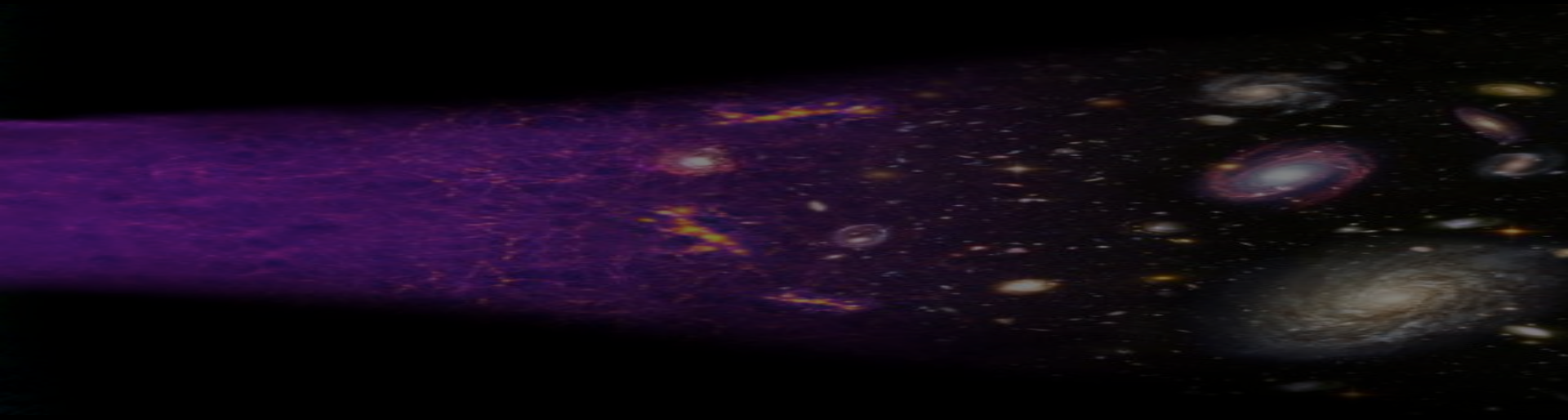
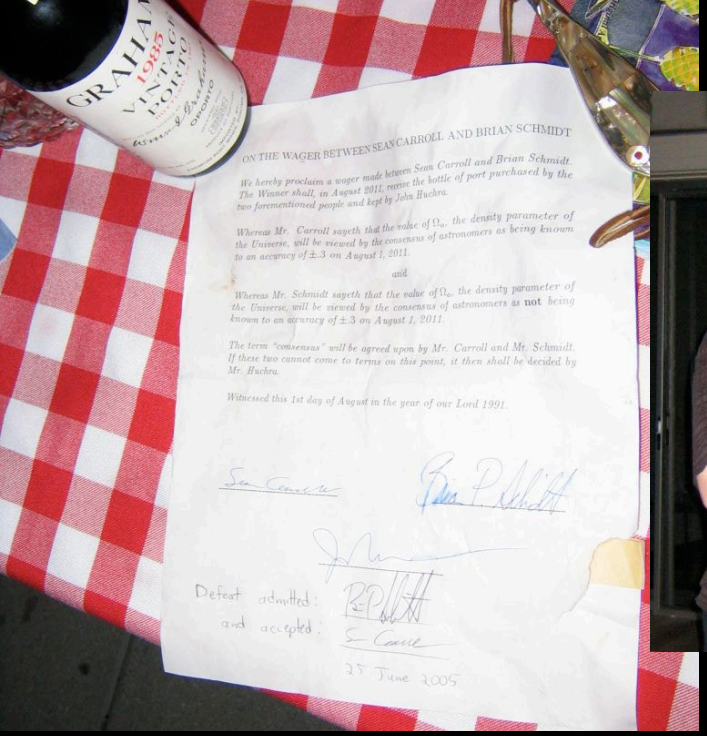


Distinguishing dark energy models

What do we know?
What can we learn?

Tamara Davis
University of Queensland


The prize
CO2
CH3CH2OH



ON THE WAGER BETWEEN SEAN CARROLL AND BRIAN SCHMIDT

We hereby proclaim a wager made between Sean Carroll and Brian Schmidt. The Winner shall, in August 2011, receive the bottle of port purchased by the two forementioned people and kept by John Huchra.

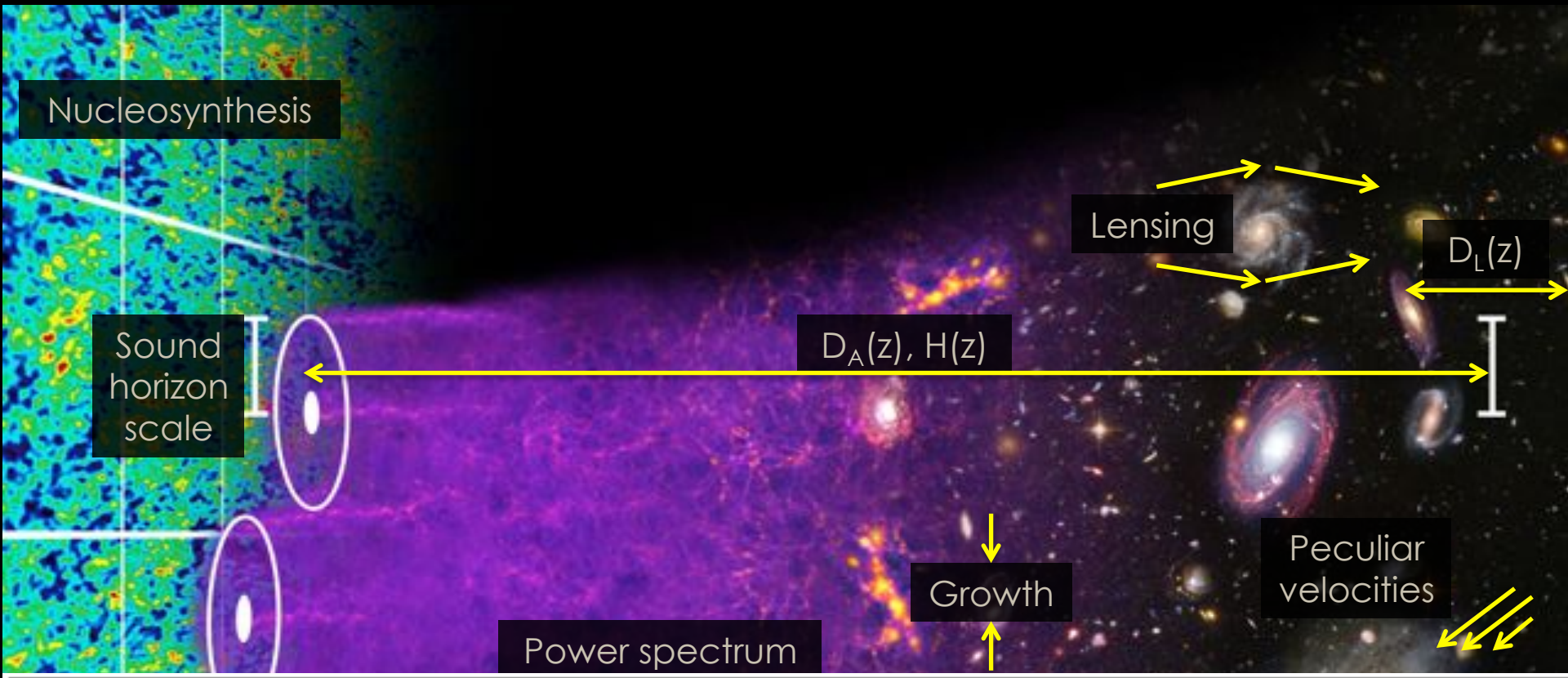
Whereas Mr. Carroll sayeth that the value of Ω_0, the density parameter of the Universe, will be viewed by the consensus of astronomers as being known to an accuracy of ±0.3 on August 1, 2011.

Whereas Mr. Schmidt sayeth that the value of Ω_0, the density parameter of the Universe, will be viewed by the consensus of astronomers as **not** being known to an accuracy of ±0.3 on August 1, 2011.

The tern "consensus" will be agreed upon by Mr. Carroll and Mr. Schmidt. If these two cannot come to terms on this point, it then shall be decided by Mr. Huchra

Witnessed this 1st day of August in the year of our Lord 1991.

Many types of observations = concordance



	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025

1.4% precision

Our task now is different

ΛCDM is an excellent model that explains a wide variety of measurements

A lot of what we are doing now are self-consistency checks

It is very difficult for a new model to explain all the observations

But also difficult to calculate all the effects in different models

We need to invest similar energy in perfecting other models if we want to test them

What is Dark Energy?

Inhomogeneities

Massive void

Many voids

Backreaction

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

New Theory

f(R)

TeVeS

Galileon

New Component

Vacuum energy

Quintessence

Other dark energy

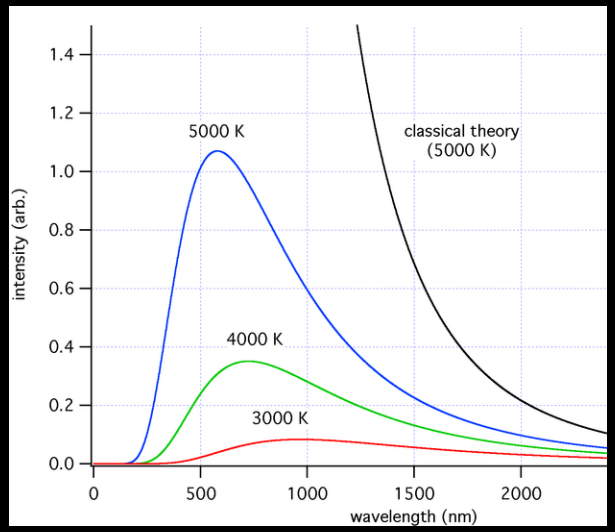
Do we want to test other models?

In praise of vacuum energy

It is predicted by quantum

It has the right equation of state

It is simple and works with GR (Λ)



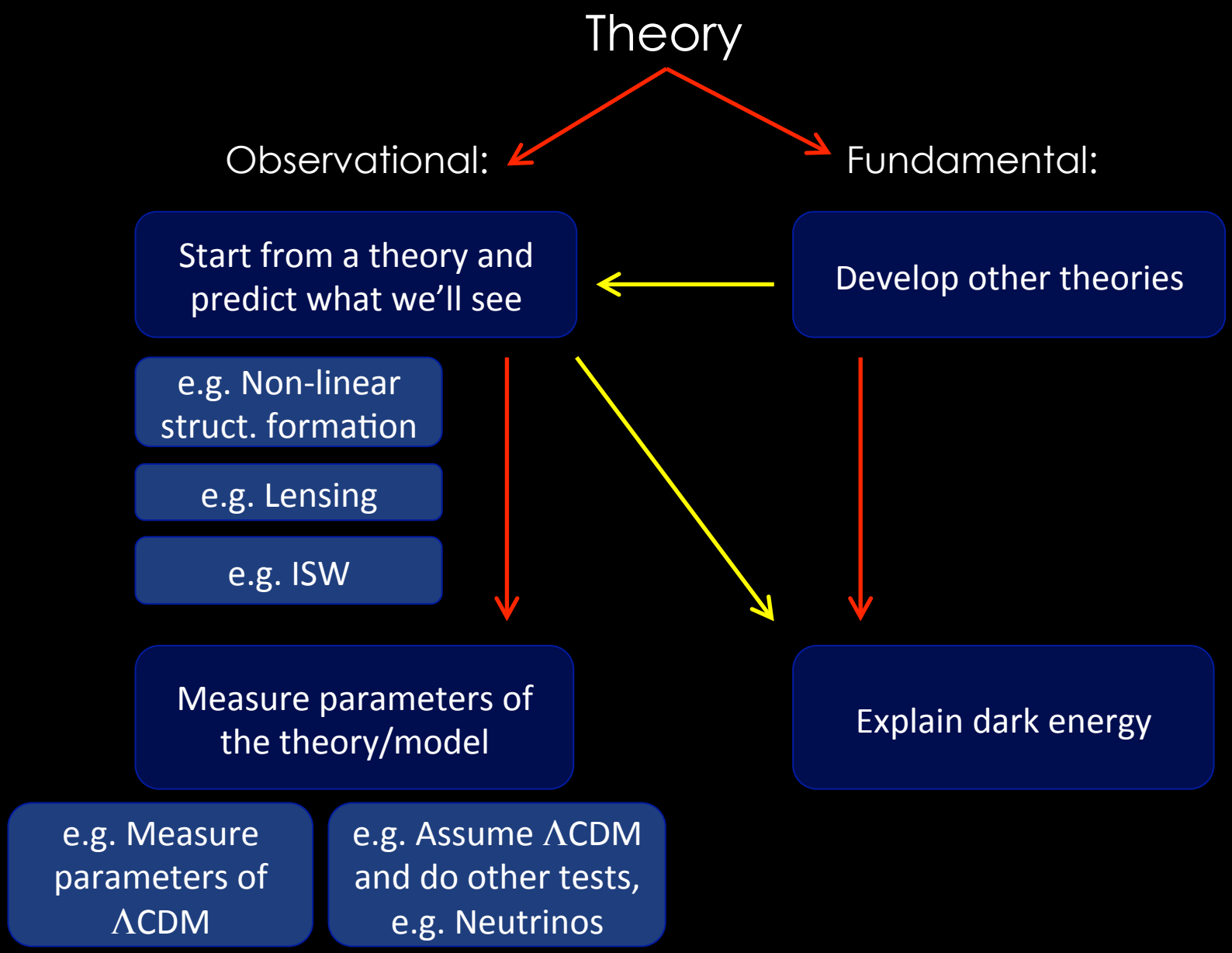
Is the magnitude problem, really a problem?

- Ultra-violet catastrophe
- Quantum gravity could fix it?
- Quantised spacetime?

Is the coincidence problem really a problem?

- Depends on your measure
- Only if you ignore anthropic arguments

Streams of investigation



The rest of this talk

- Model Testing vs Parameter fitting
- Model dependence of large-scale structure (LSS) measurements (including BAO)
- What BAO alone actually tell us

- New technique for using LSS as a ruler => Topology
- New technique for standard candles => AGN
- Old technique for standard clocks => Supernovae

- New observational survey => OzDES

MODEL TESTING VS PARAMETER FITTING

What is the value of [parameter]?

[Matter density; equation of state of dark energy; Hubble's constant…]

Data combination

Model

Parameters

Model

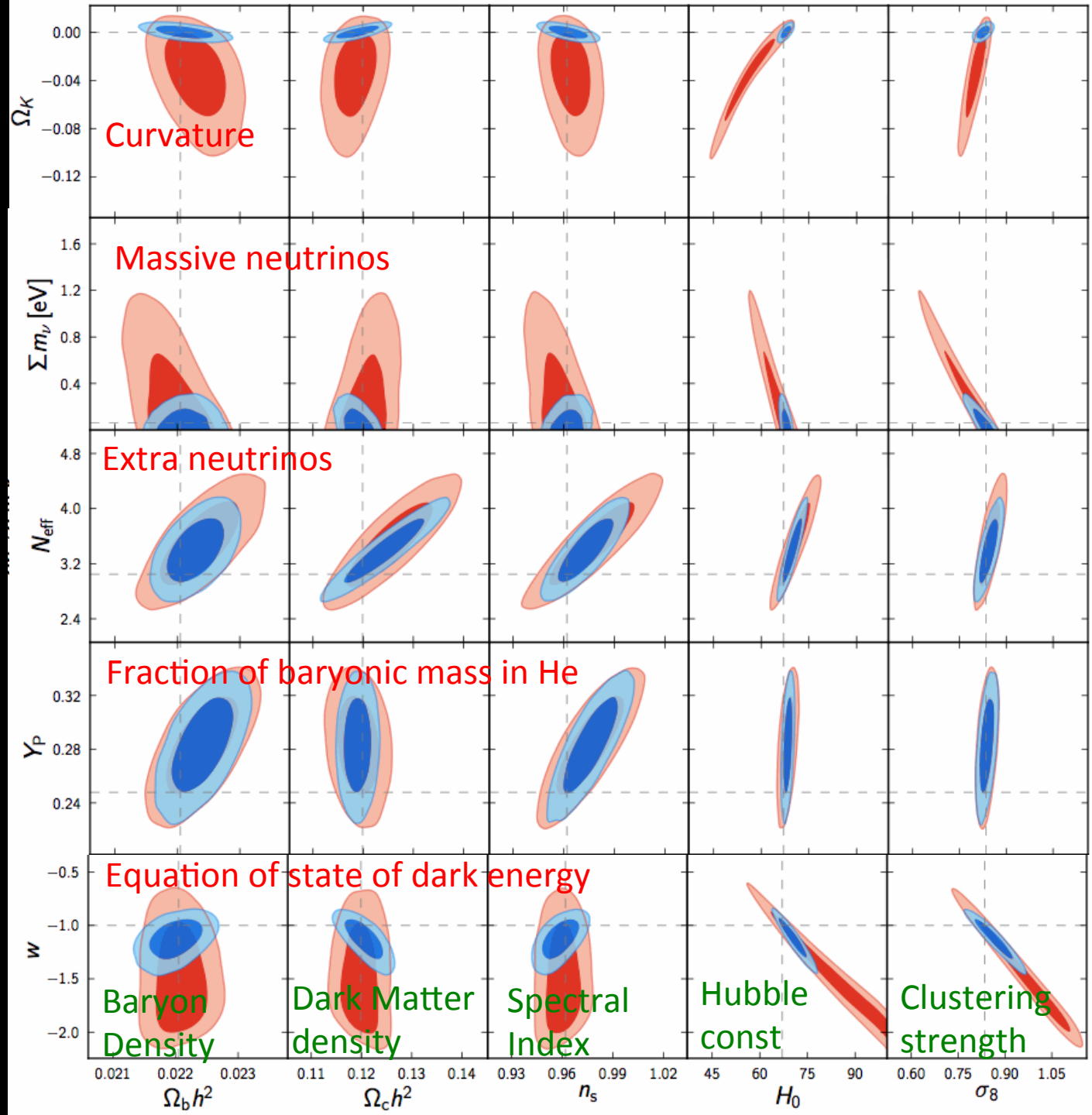
Model

Model	Parameter	CMB + WiggleZ	+ H_0	+ SN-Ia	+ BAO	+ H_0 + BAO
Flat ΛCDM	$100\Omega_b h^2$	2.238 ± 0.052	2.255 ± 0.050	2.240 ± 0.053	2.239 ± 0.050	2.253 ± 0.050
	$\Omega_{CDM} h^2$	0.1153 ± 0.0027	0.1145 ± 0.0026	0.1150 ± 0.0028	0.1152 ± 0.0024	0.1146 ± 0.0024
	100θ	1.039 ± 0.002	1.040 ± 0.002	1.039 ± 0.003	1.039 ± 0.002	1.039 ± 0.002
	τ	0.083 ± 0.014	0.084 ± 0.014	0.083 ± 0.014	0.083 ± 0.014	0.084 ± 0.014
	n_s	0.964 ± 0.012	0.968 ± 0.012	0.965 ± 0.013	0.964 ± 0.012	0.968 ± 0.011
	$\log(10^{10} A_s)$	3.084 ± 0.029	3.086 ± 0.029	3.085 ± 0.030	3.083 ± 0.029	3.086 ± 0.029
	Ω_m	0.290 ± 0.016	0.283 ± 0.014	0.288 ± 0.017	0.289 ± 0.013	0.284 ± 0.012
	$H_0 [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	68.9 ± 1.4	69.6 ± 1.3	69.1 ± 1.6	69.0 ± 1.2	69.5 ± 1.2
	σ_8	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017
Flat wCDM	$100\Omega_b h^2$	2.265 ± 0.062	2.253 ± 0.057	2.228 ± 0.055	2.247 ± 0.056	2.253 ± 0.056
	$\Omega_{DM} h^2$	0.1164 ± 0.0036	0.1146 ± 0.0030	0.1157 ± 0.0030	0.1147 ± 0.0029	0.1148 ± 0.0030
	100θ	1.039 ± 0.003	1.039 ± 0.003	1.038 ± 0.003	1.039 ± 0.003	1.039 ± 0.003
	τ	0.084 ± 0.015	0.084 ± 0.014	0.082 ± 0.014	0.084 ± 0.014	0.084 ± 0.014
	n_s	0.975 ± 0.019	0.968 ± 0.014	0.962 ± 0.014	0.967 ± 0.014	0.968 ± 0.014
	$log[10^{10}$	3.096 ± 0.031	3.086 ± 0.030	3.082 ± 0.029	3.085 ± 0.030	3.086 ± 0.030
	w	-0.525 ± 0.293	-1.007 ± 0.084	-1.062 ± 0.072	-0.973 ± 0.086	-1.008 ± 0.085
	Ω_m	0.487 ± 0.132	0.283 ± 0.018	0.844 ± 0.028	0.294 ± 0.018	0.284 ± 0.018
	H_0	55.2 ± 8.4	69.7 ± 2.1	70.5 ± 2.3	68.4 ± 2.0	69.7 ± 2.1
	σ_8	0.664 ± 0.110	0.826 ± 0.032	0.844 ± 0.028	0.815 ± 0.033	0.827 ± 0.032
ΛCDM	$100\Omega_b h^2$	2.215 ± 0.055	2.263 ± 0.054	2.256 ± 0.054	2.252 ± 0.054	2.262 ± 0.052
	$\Omega_{CDM} h^2$	0.1118 ± 0.0039	0.1162 ± 0.0039	0.114 ± 0.0042	0.1150 ± 0.0038	0.1161 ± 0.0038
	100θ	1.038 ± 0.003	1.040 ± 0.003	1.040 ± 0.003	1.040 ± 0.003	1.040 ± 0.003
	τ	0.086 ± 0.014	0.088 ± 0.015	0.089 ± 0.014	0.088 ± 0.015	0.088 ± 0.014
	n_s	0.958 ± 0.013	0.970 ± 0.013	0.969 ± 0.013	0.968 ± 0.013	0.969 ± 0.013
	$\log(10^{10} A_s)$	3.072 ± 0.031	3.101 ± 0.031	3.096 ± 0.031	3.096 ± 0.031	3.101 ± 0.030
	Ω_m	0.454 ± 0.058	0.287 ± 0.029	0.303 ± 0.038	0.302 ± 0.020	0.288 ± 0.016
	Ω_k	-0.046 ± 0.017	0.001 ± 0.008	-0.005 ± 0.012	-0.004 ± 0.006	0.000 ± 0.005
	$H_0 [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	54.65 ± 3.8	69.86 ± 3.6	67.7 ± 4.7	67.6 ± 2.3	69.9 ± 3.6
	σ_8	0.782 ± 0.024	0.838 ± 0.023	0.825 ± 0.026	0.829 ± 0.022	0.838 ± 0.023

WiggleZ final results: Parkinson et al. 2012

CMB: Model extensions

Planck XVI, 2013
+BAO (blue)



CMB: Model extensions

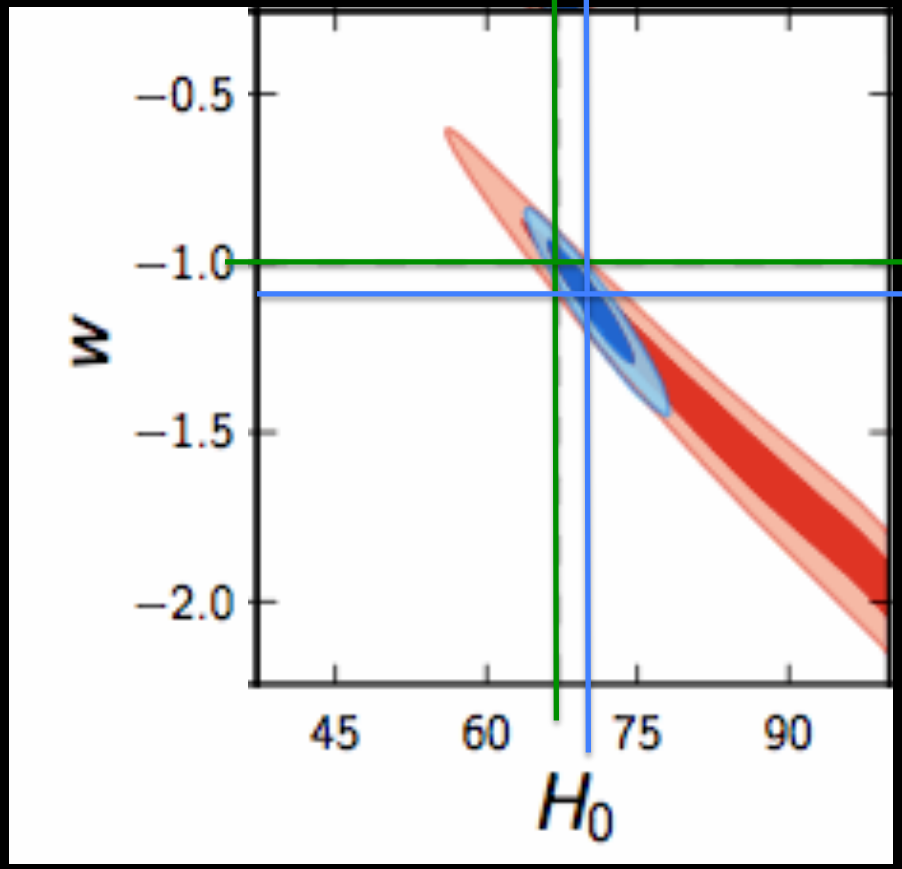
Best fit in standard model (ΛCDM)

Best fit in extended model (wCDM)

Planck+WP+highL +BAO
$H_0 = 67.80 \pm 0.77$

Planck+WP+highL +BAO
$H_0 = 71 \pm 4$ (?)

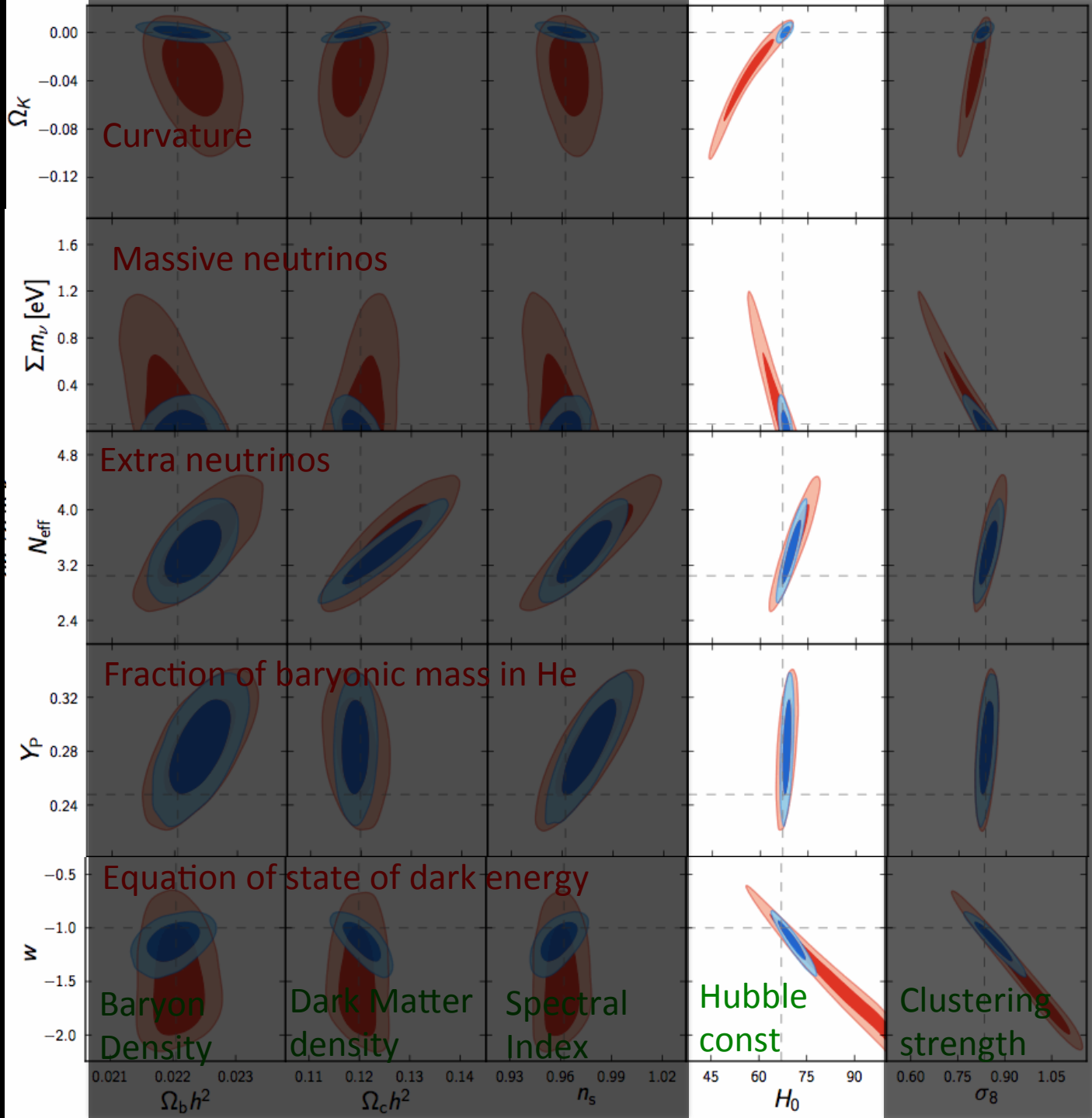
Dark energy equation of state



Hubble's constant

CMB: Model extensions

Planck XVI, 2013
+BAO (blue)



MODEL DEPENDENCE OF LARGE SCALE STRUCTURE & BAO

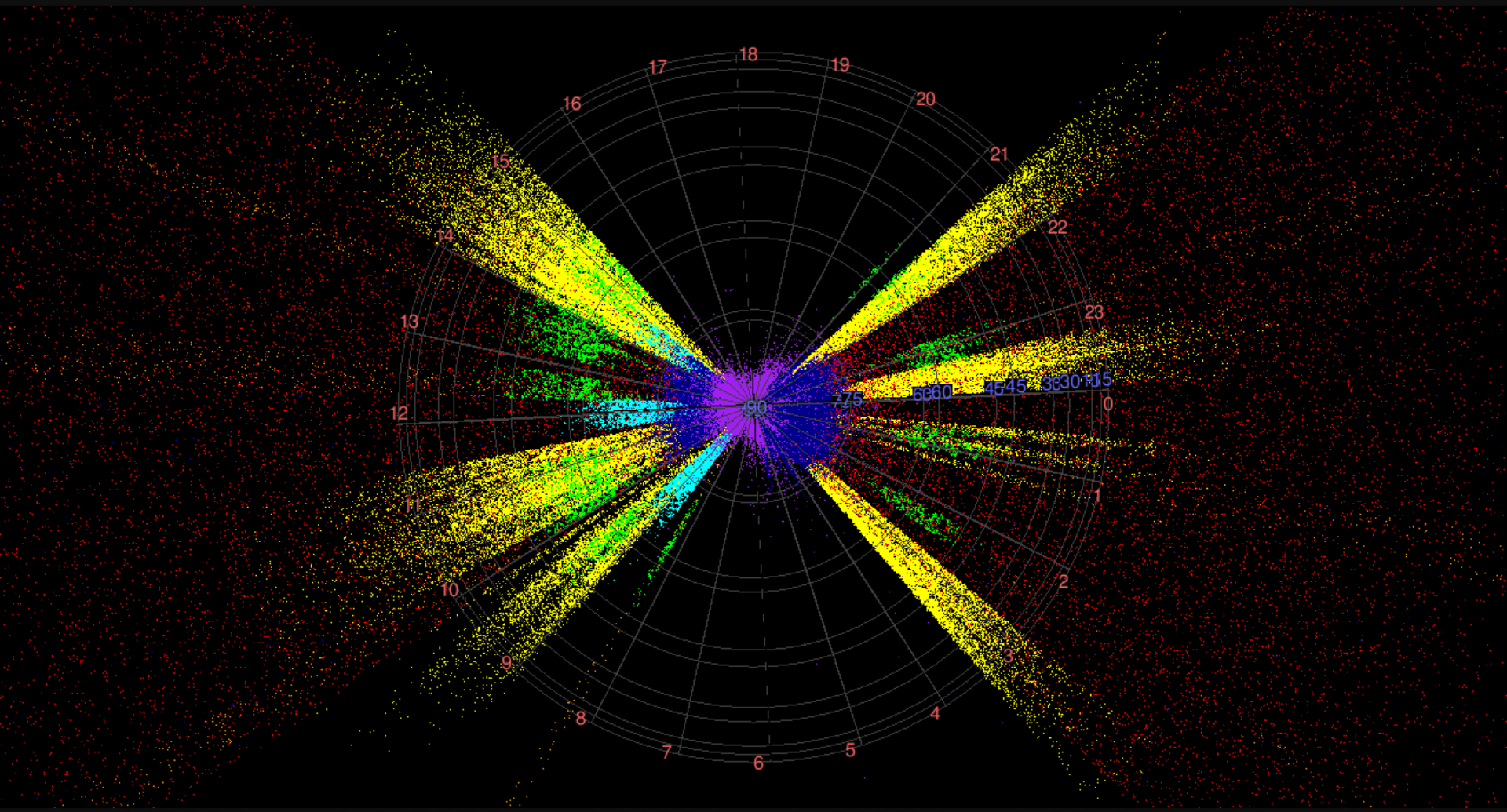
WiggleZ

WiggleZ survey fields
(compared to other AAT surveys)

7 equatorial fields, each 100-200 deg^2

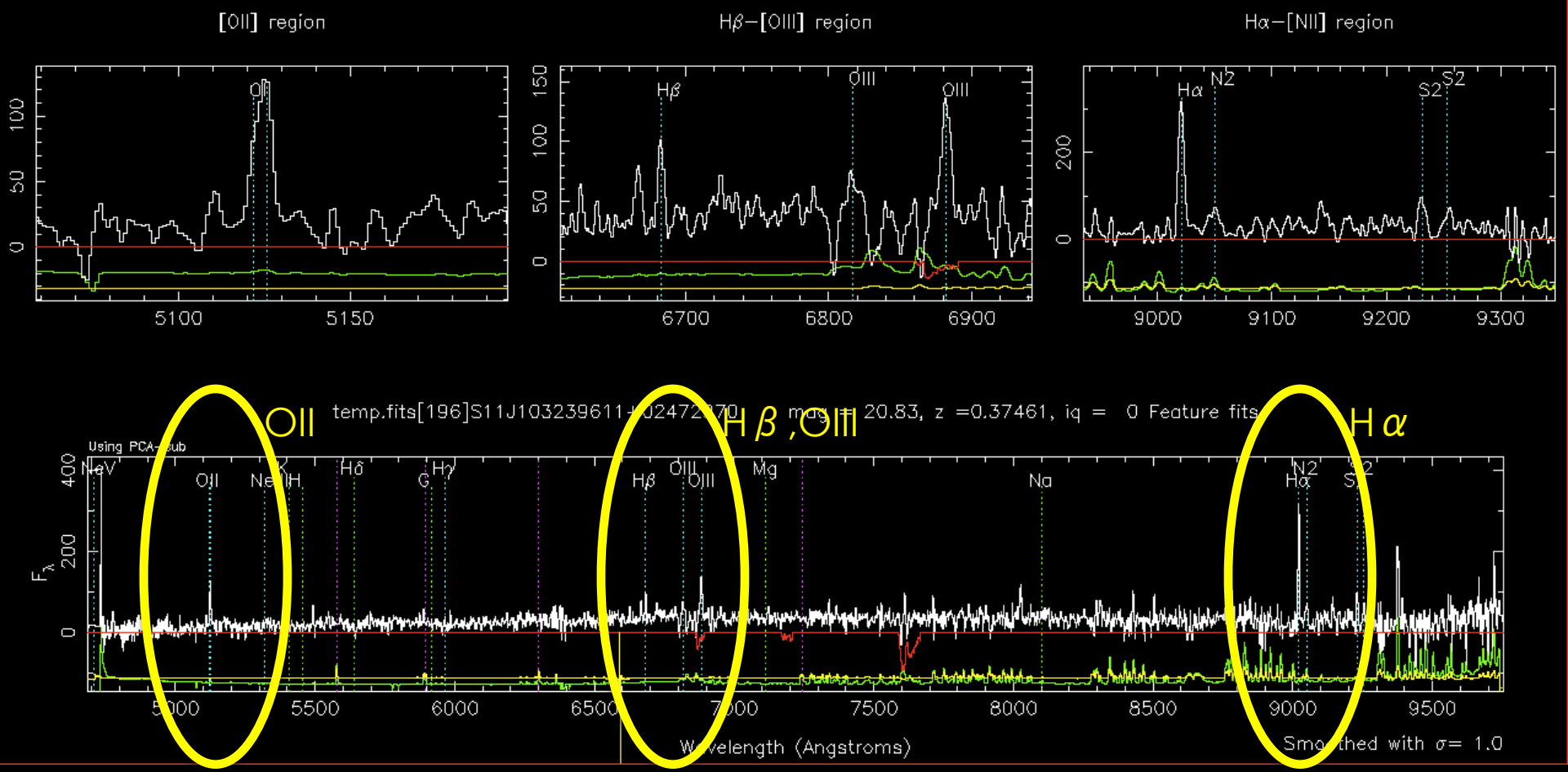
>9° on side, ~3 x BAO scale at $z > 0.5$

Physical size ~ 1300 x 500 x 500 Mpc/h

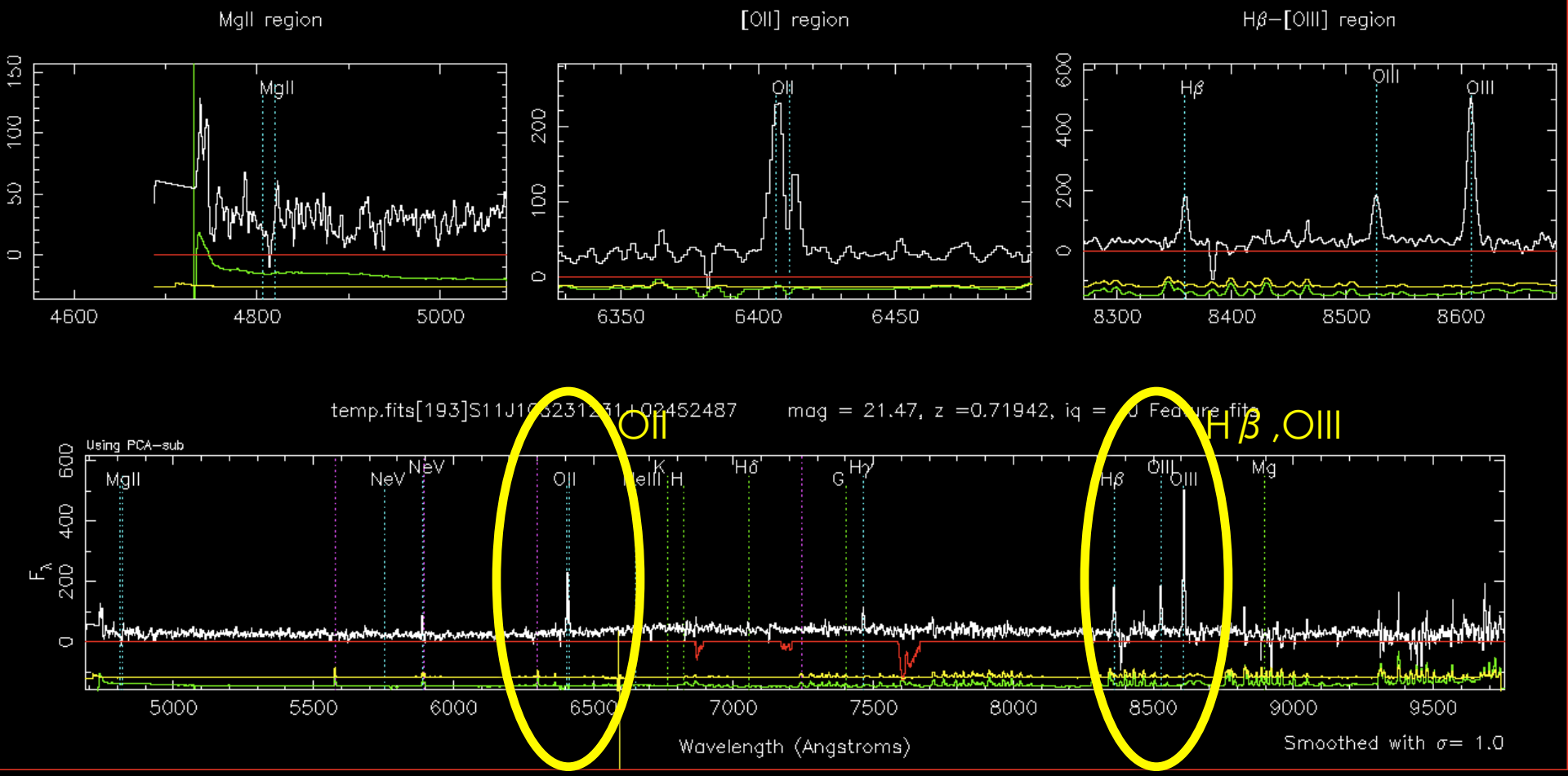


6dFGS (purple), 2dFGRS (blue), MGC (navy), GAMA (cyan), 2SLAQ-LRG (green), WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at z=1.

Example spectrum: z=0.37



Example spectrum: z=0.72

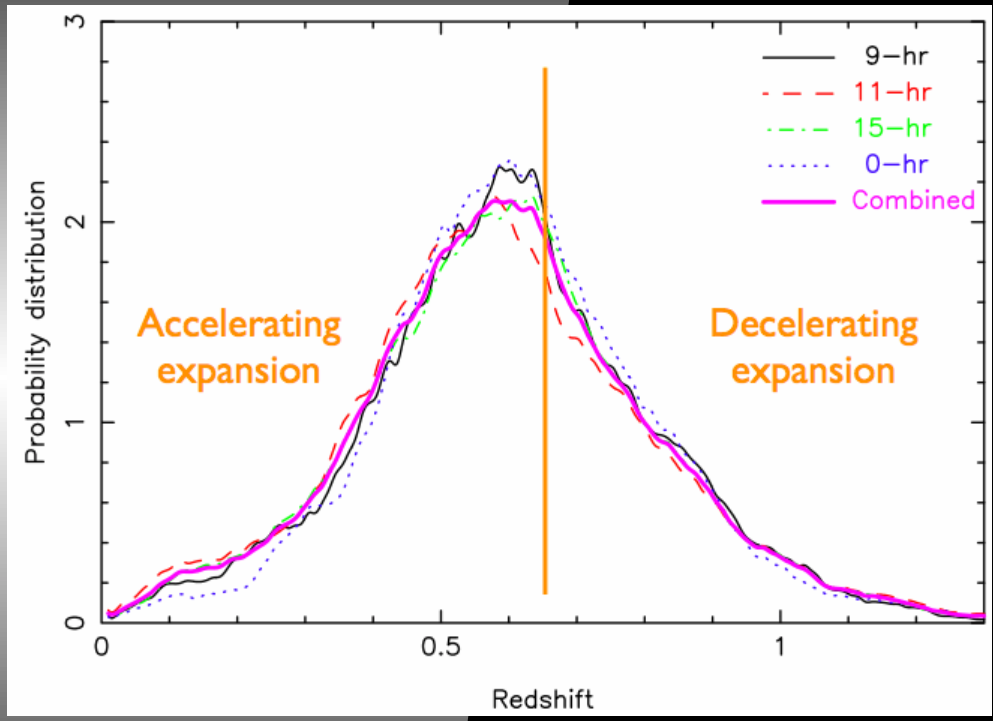


Redshifts become less certain above $z \sim 1$ because we lose $H\beta$

Understanding our survey

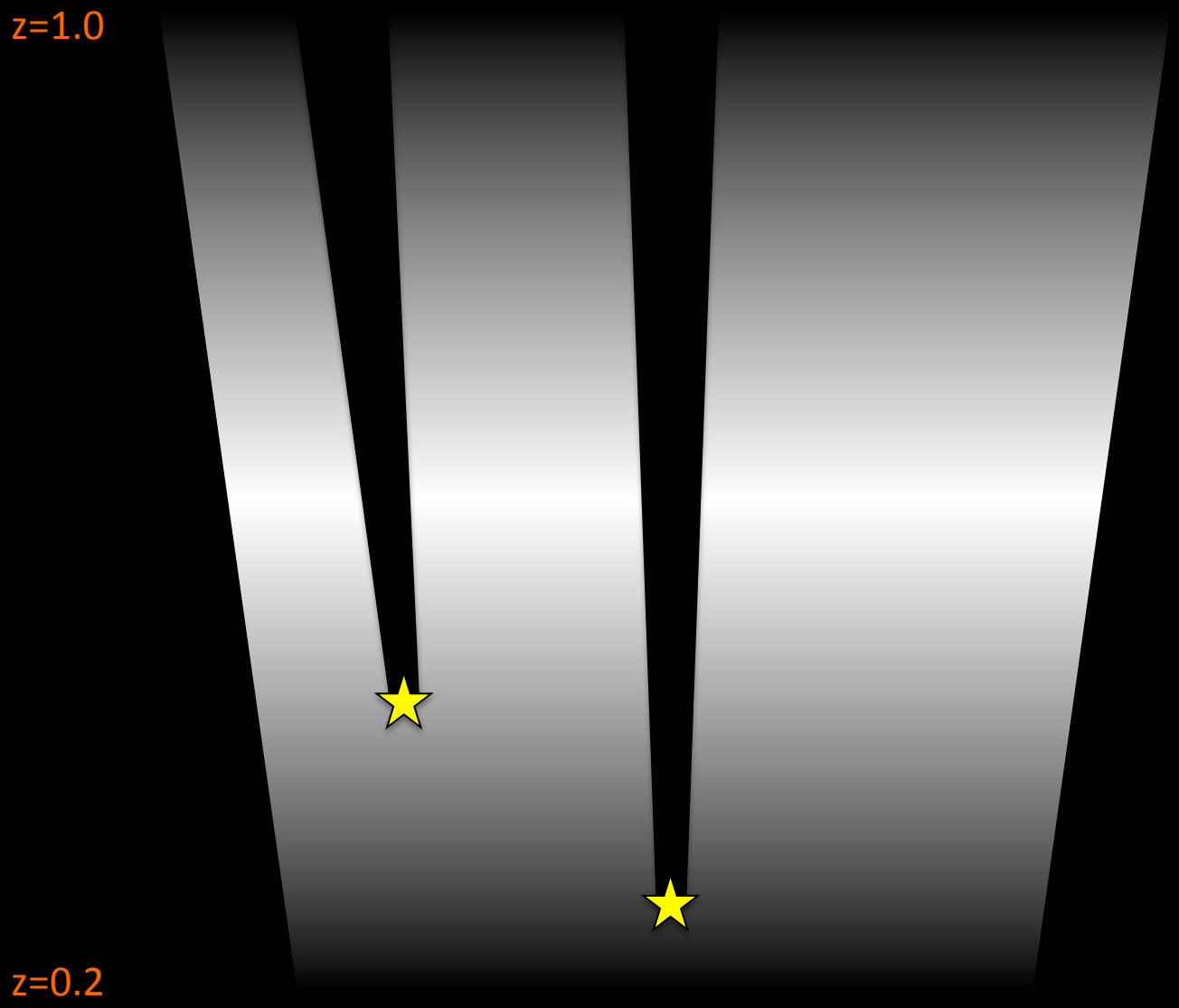
z=1.0

Redshift distribution

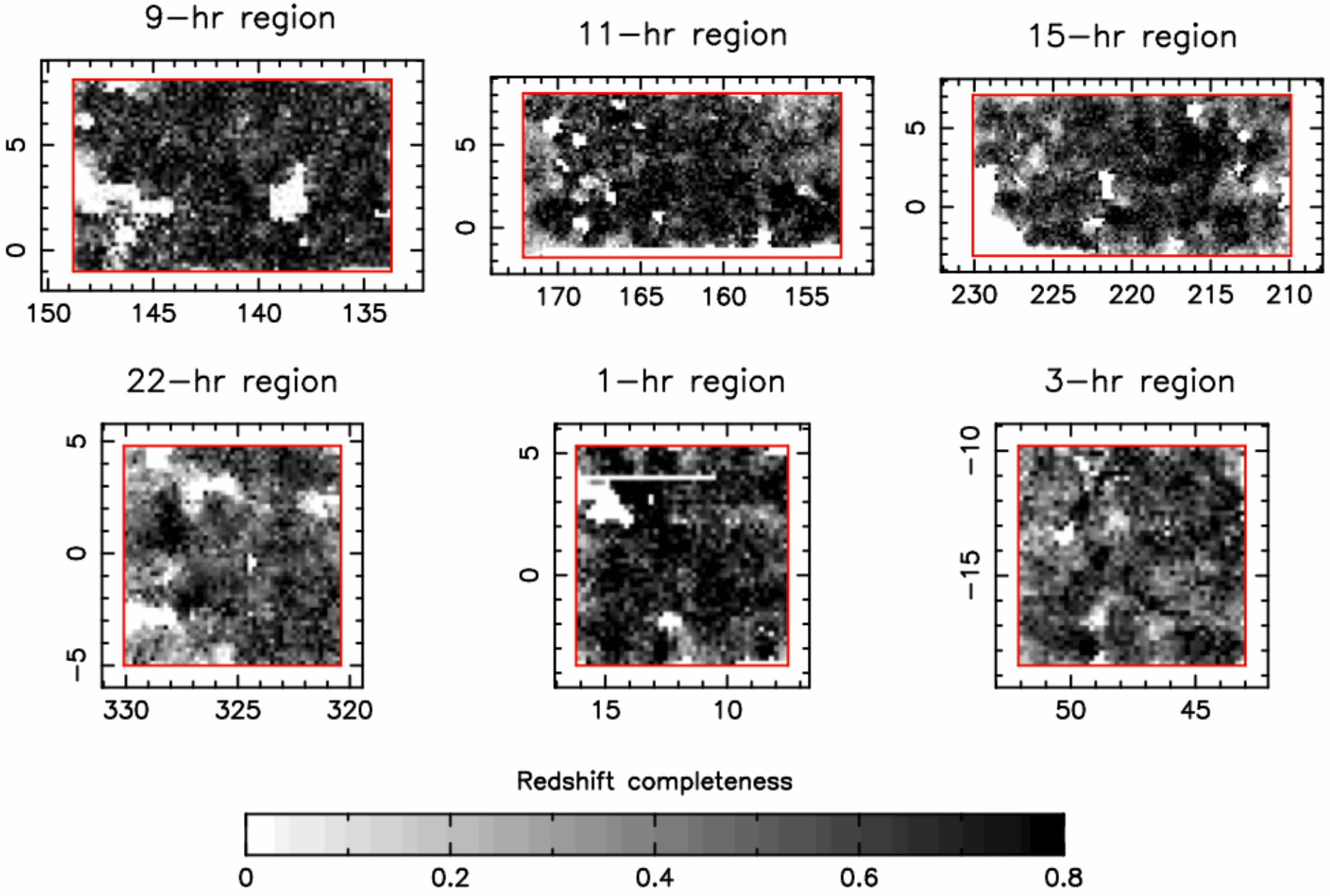


z=0.2

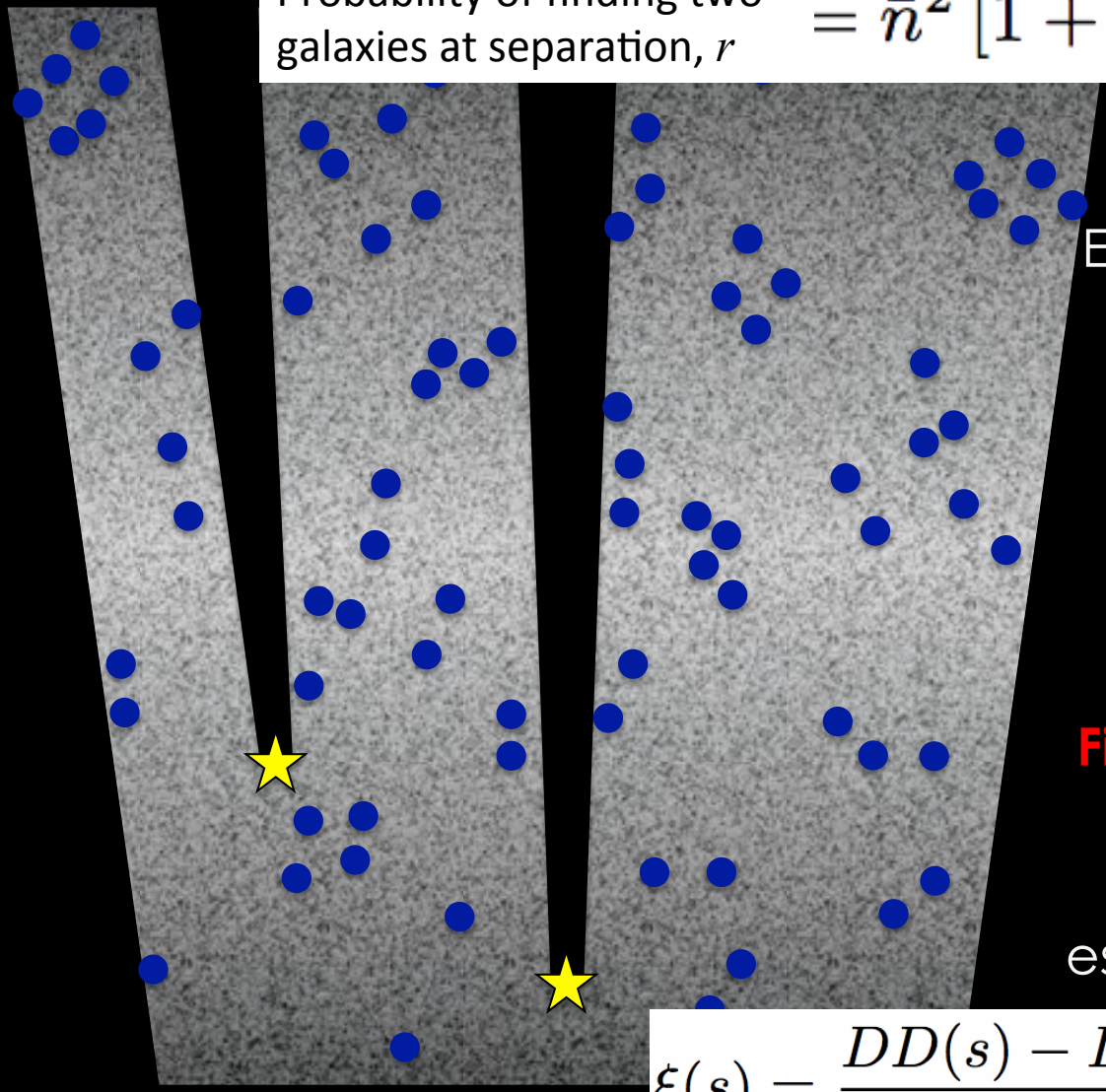
Understanding our survey



WiggleZ regions



Understanding our survey



Probability of finding two galaxies at separation, r

$$= \bar{n}^2 \left[1 + \xi(r)\right] \delta V_1 \delta V_2$$

Excess likelihood of finding two galaxies at separation r

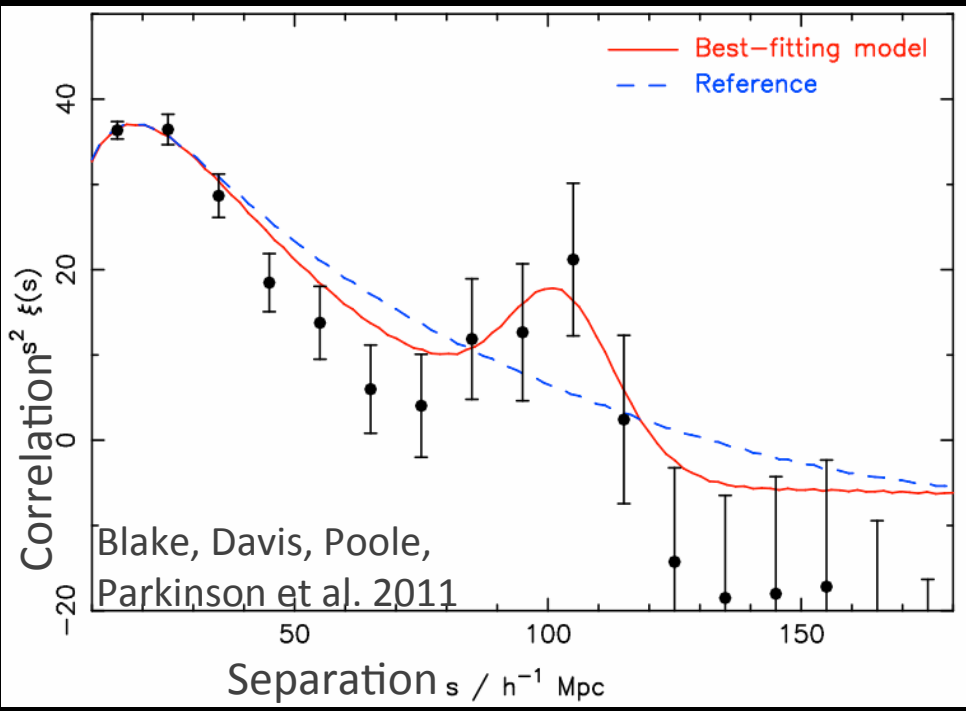
Need to calculate distances!!
Fiducial model.

Landy-Szalay estimator (1993)

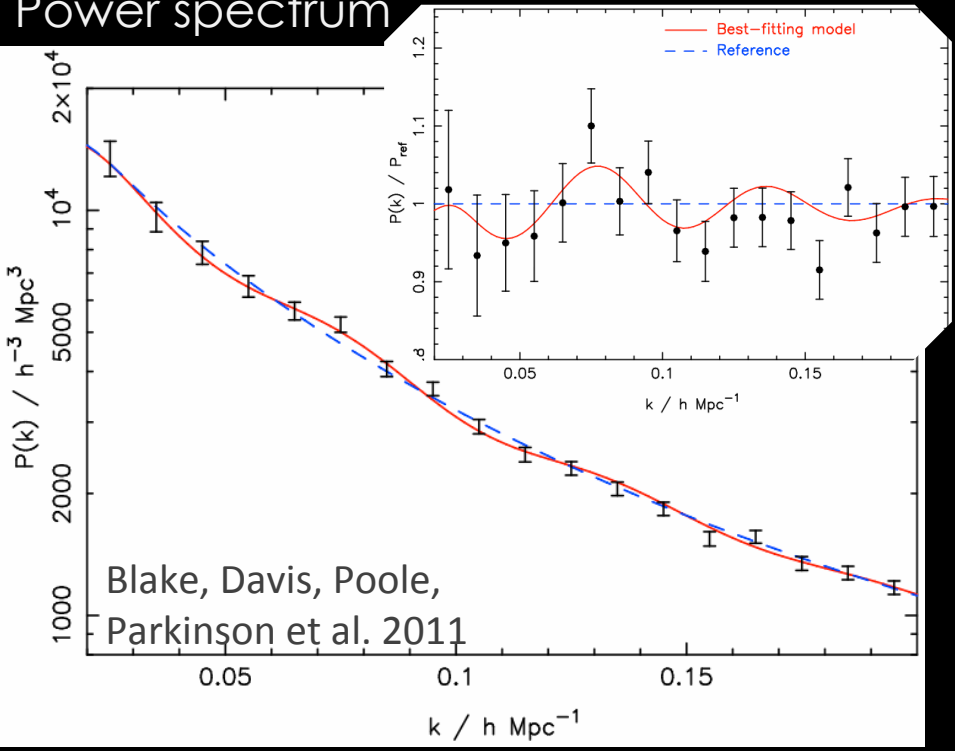
$$\xi(s) = \frac{DD(s) - DR(s) + RR(s)}{RR(s)}$$

Correlation function vs Power spectrum

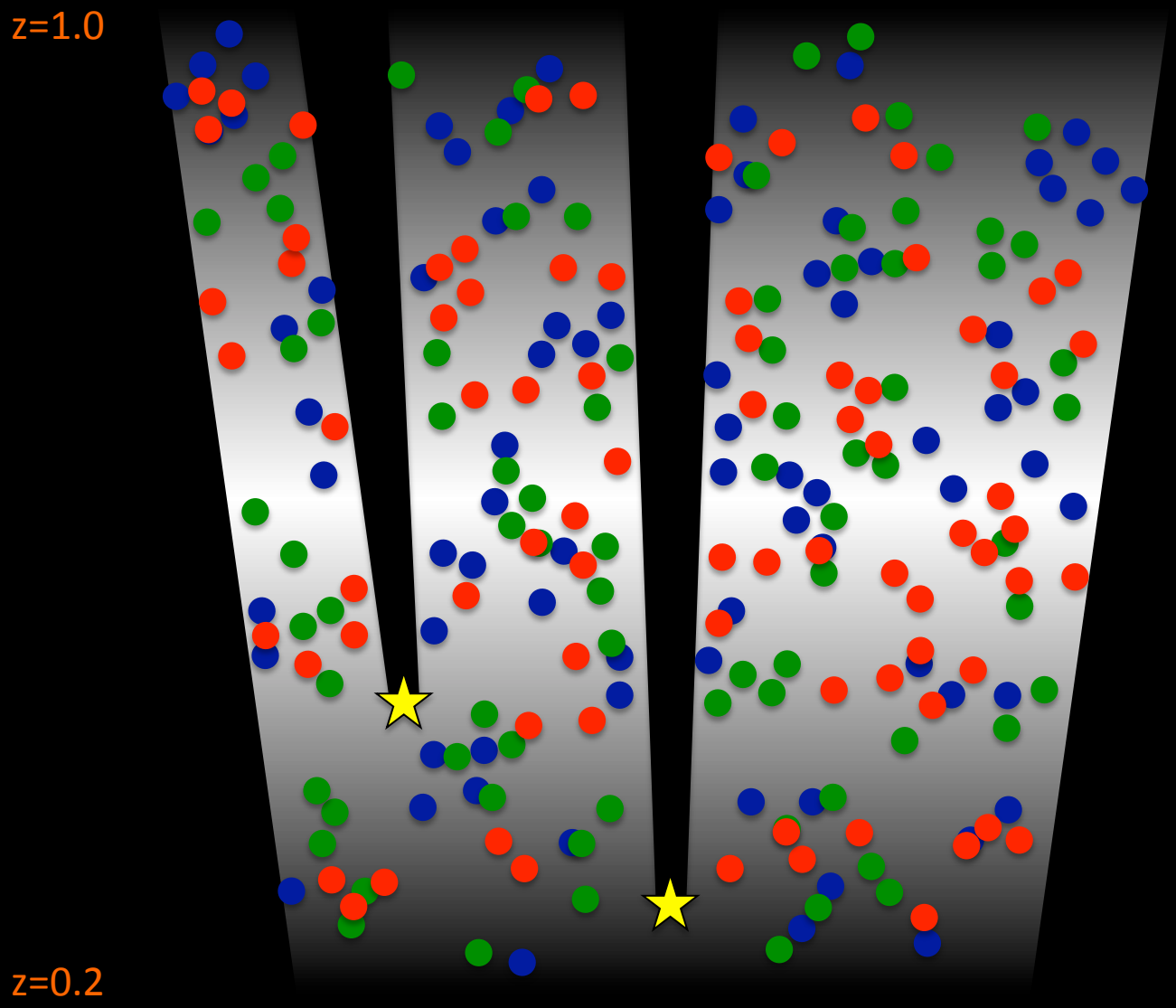
Correlation Function



Power spectrum

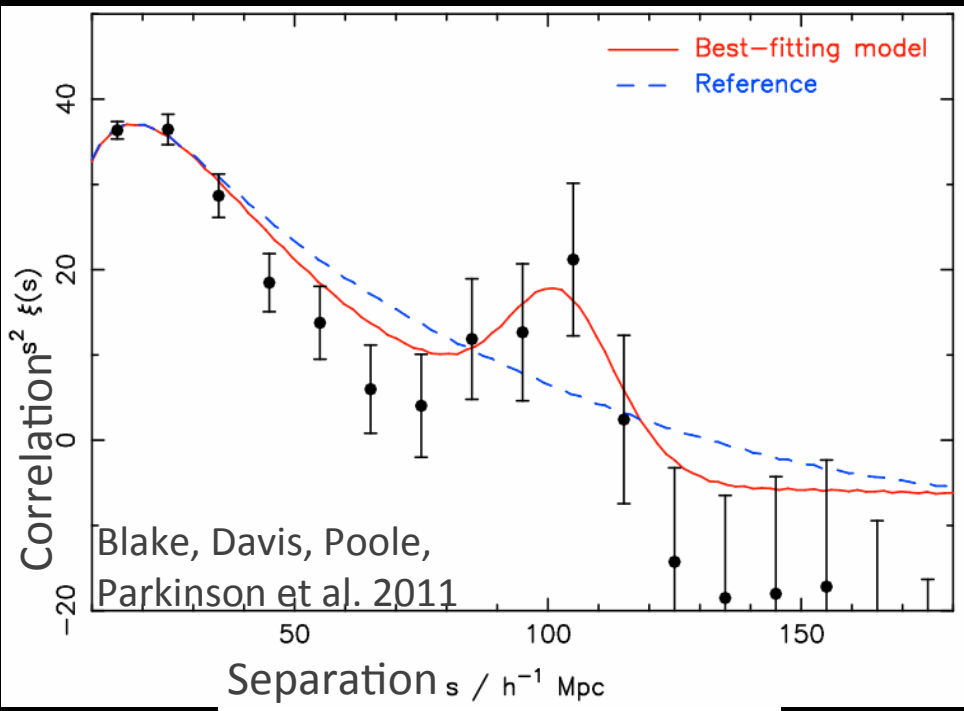


Understanding our survey

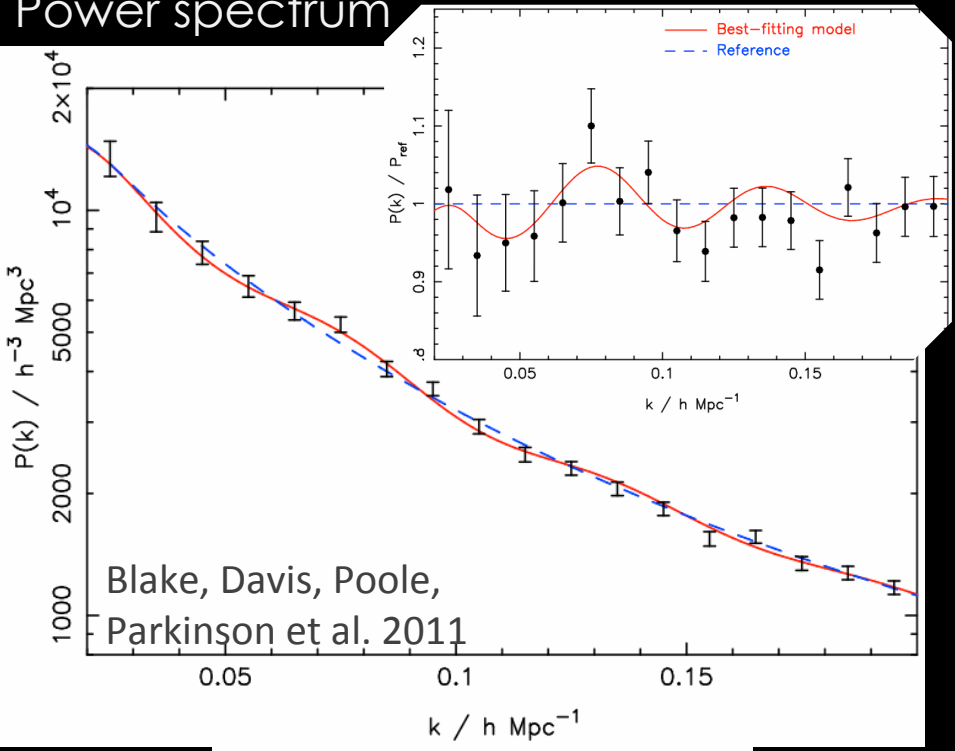


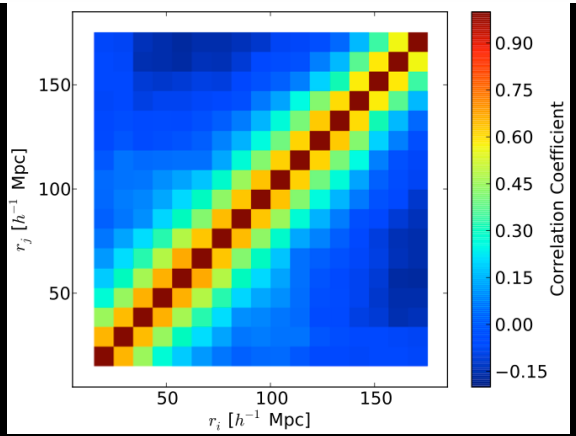
Correlation function vs Power spectrum

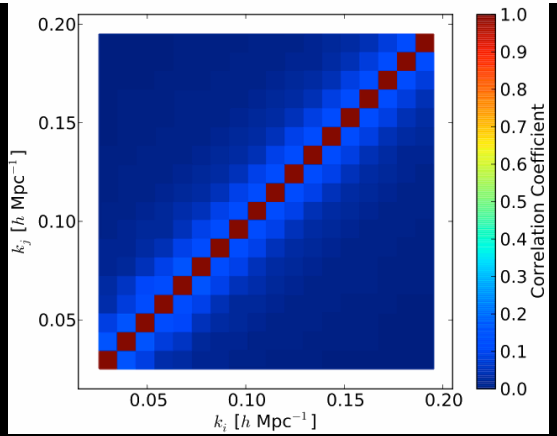
Correlation Function



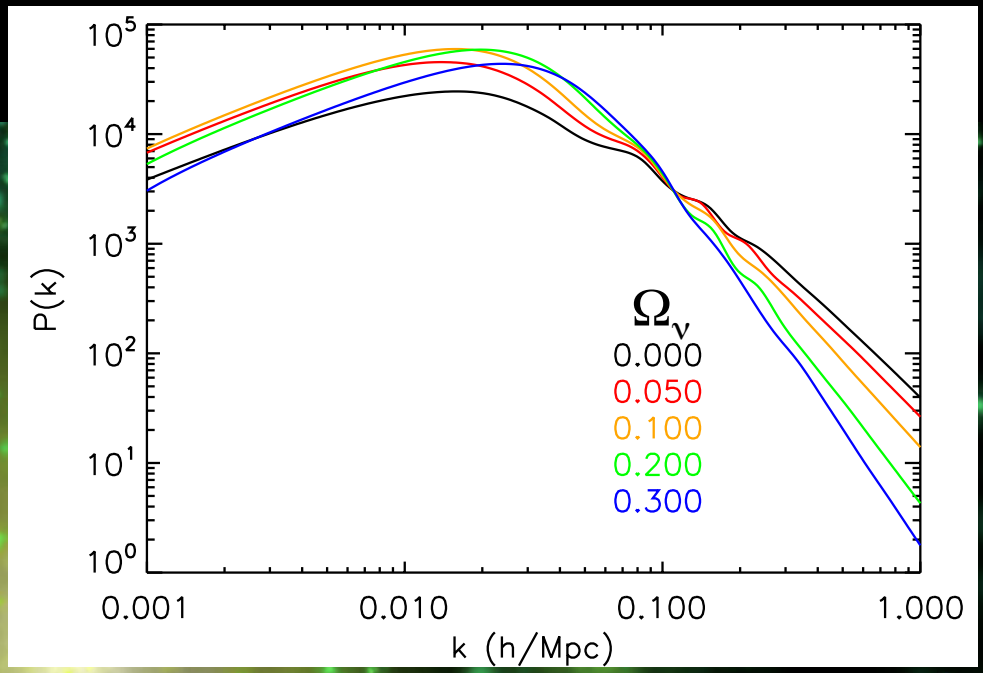
Power spectrum







Make model



GREGORY POOLE
THE GIGGLEZ
SIMULATION SUITE

SWIN BUR *NE*

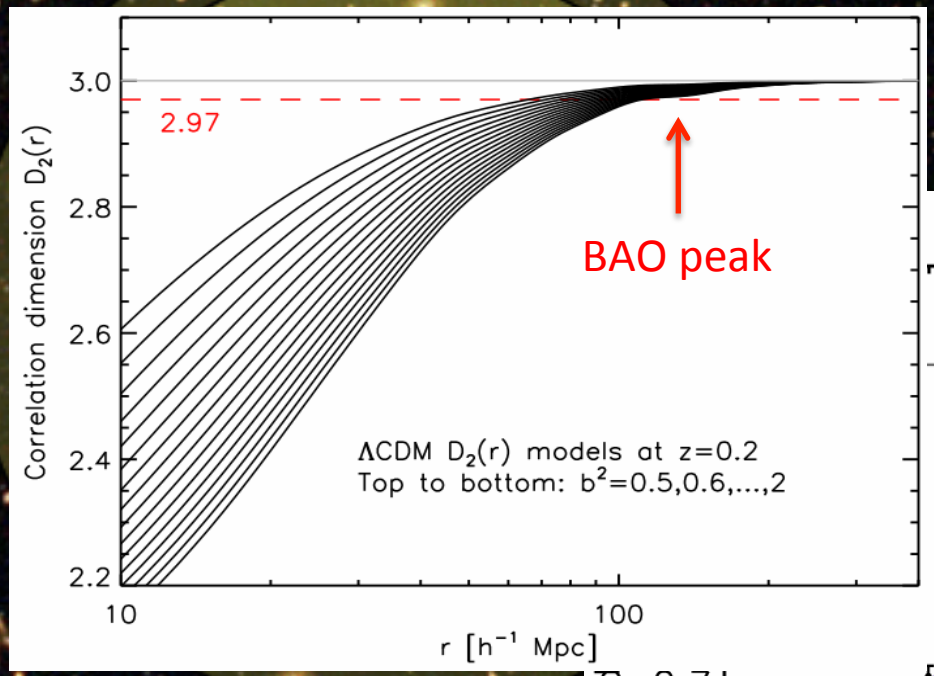
CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

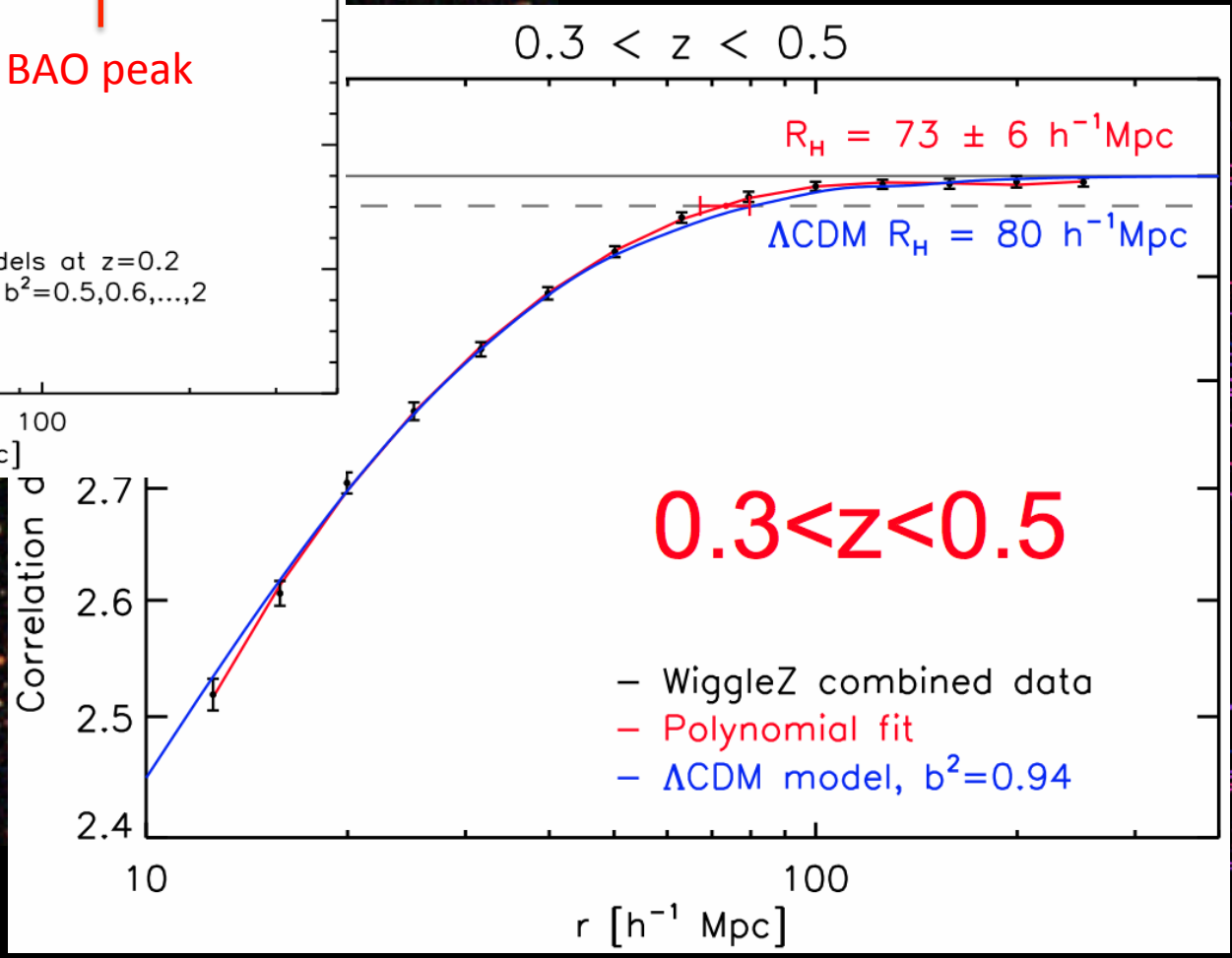
Use sims to make non-linear corrections

ASSUMPTION(?): HOMOGENEITY

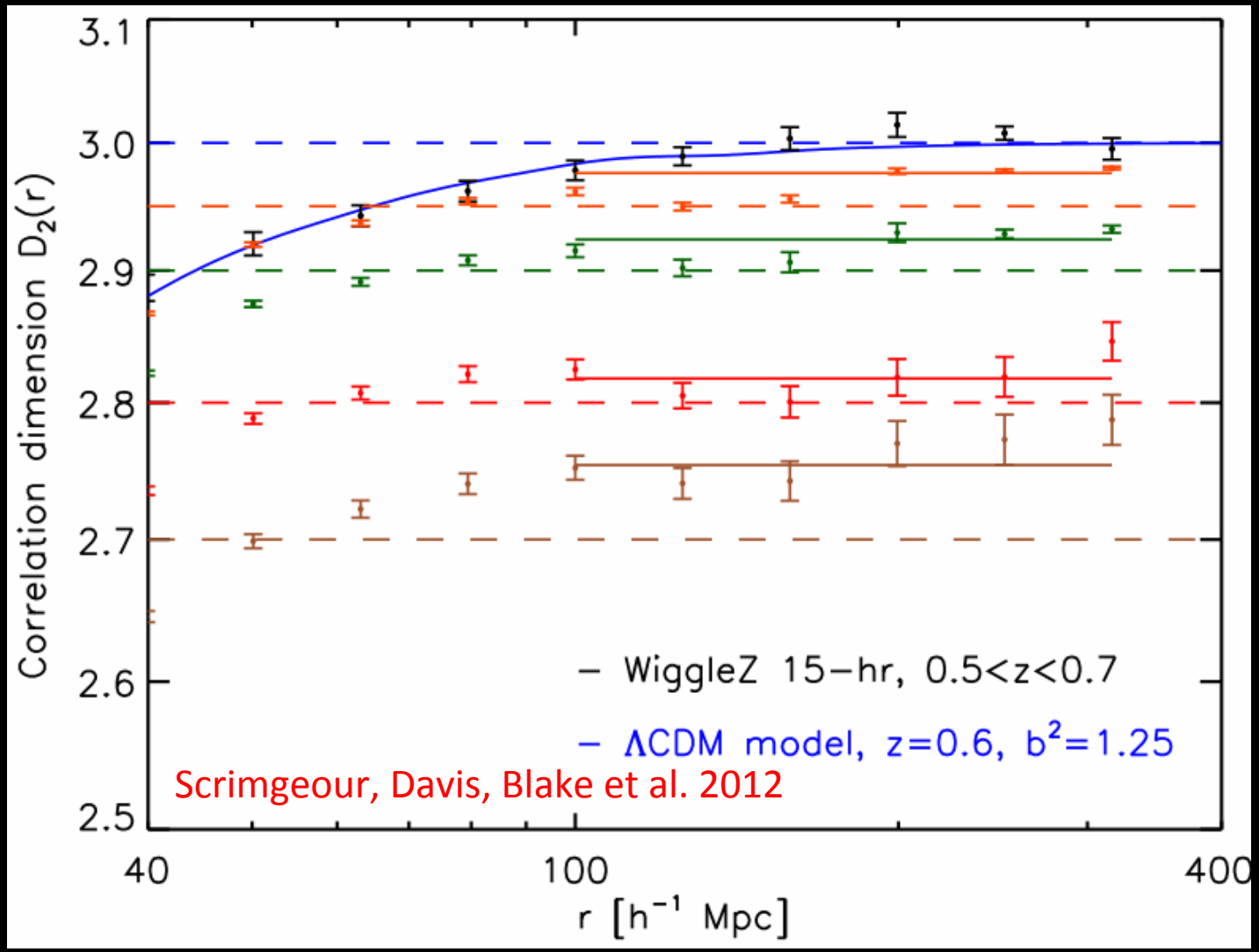
Fractal dimension (Scrimgeour et al., 2012)

$$N(<r) \propto r^{D_2}$$





Fractal models



MEASURING THE DISTANCE SCALE

Measuring the distance scale

Two Tangential One Radial

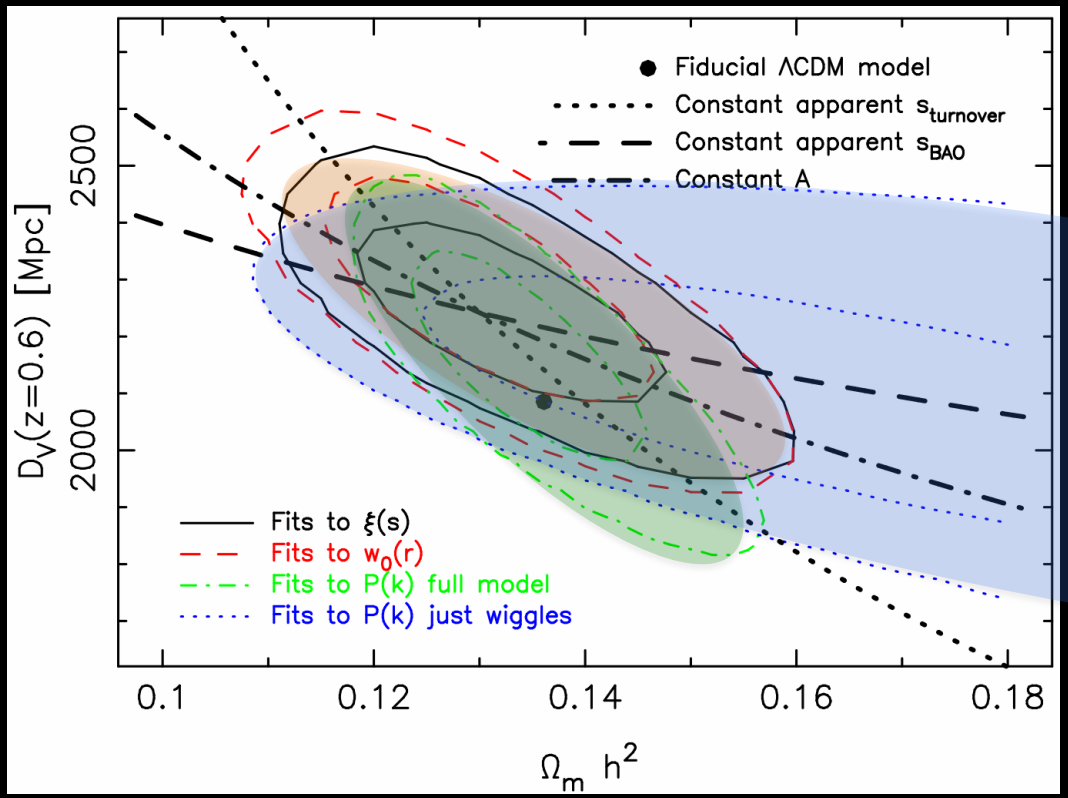
$$D_V(z) = \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

$$d_z \equiv \frac{r_s(z_d)}{D_V(z)}$$ BAO

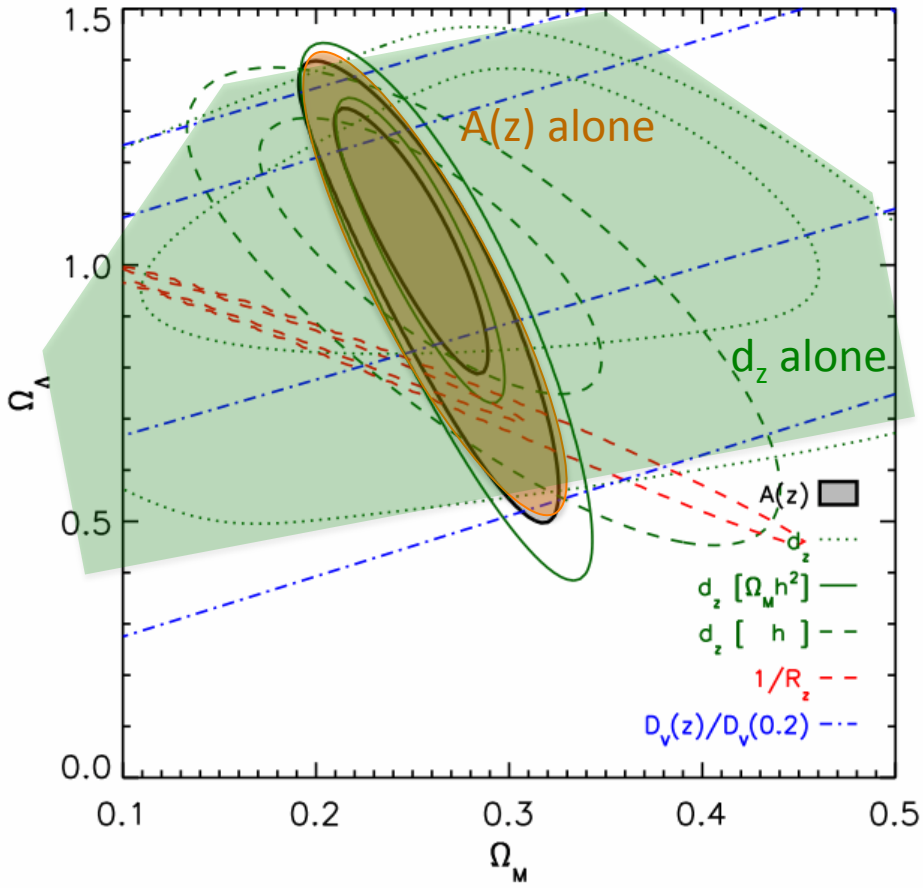
$$A(z) = \frac{\sqrt{\Omega_m H_0^2}}{cz} D_V(z)$$

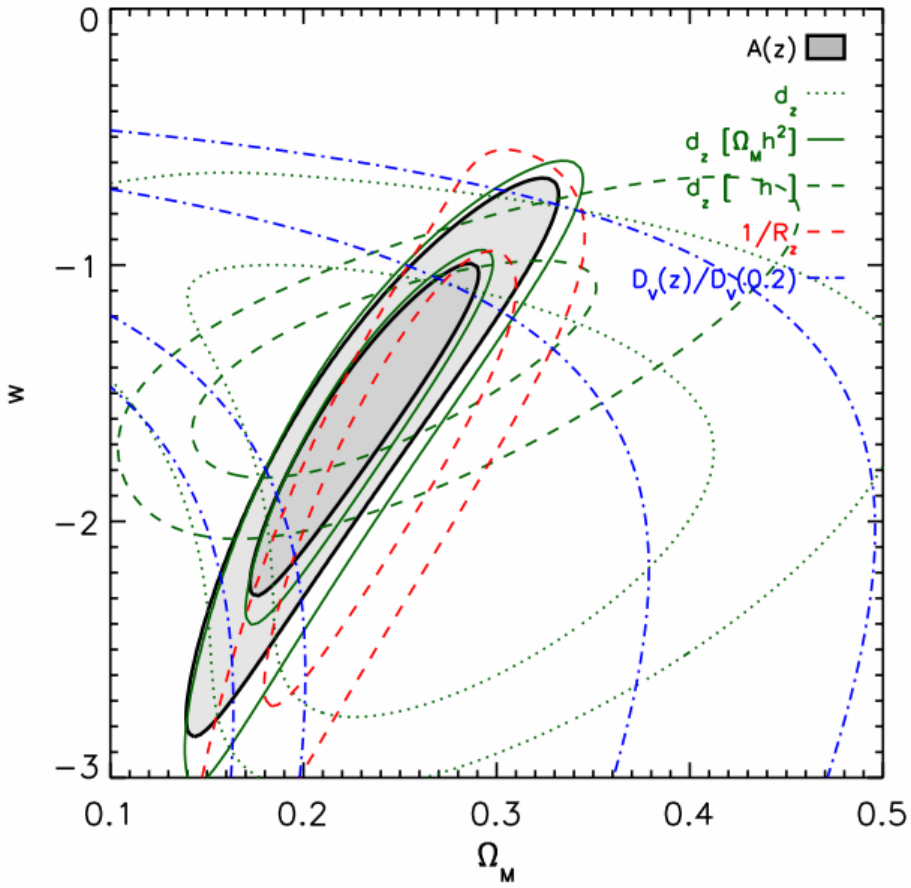
$$\theta_A \equiv \frac{r_s(z_*)}{d_A(z_*)}$$ CMB

$$\mathcal{R}(z_*) = \sqrt{\Omega_m h^2}\, d_A(z_*)$$



Many ways to use BAO

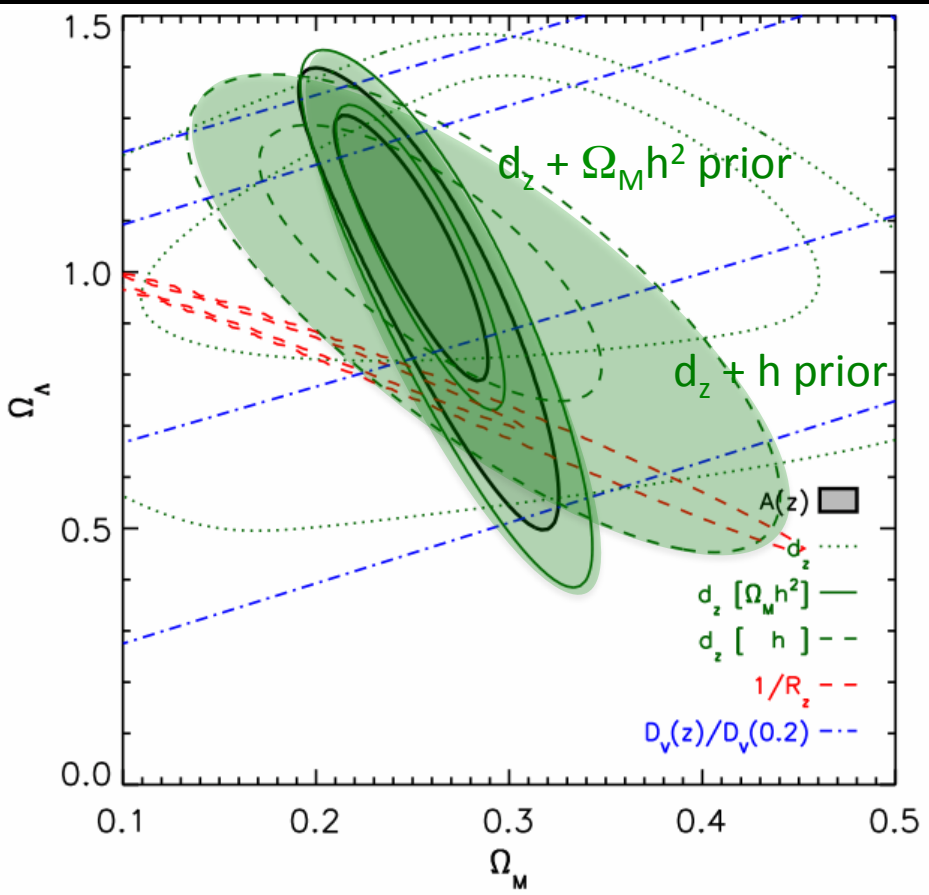


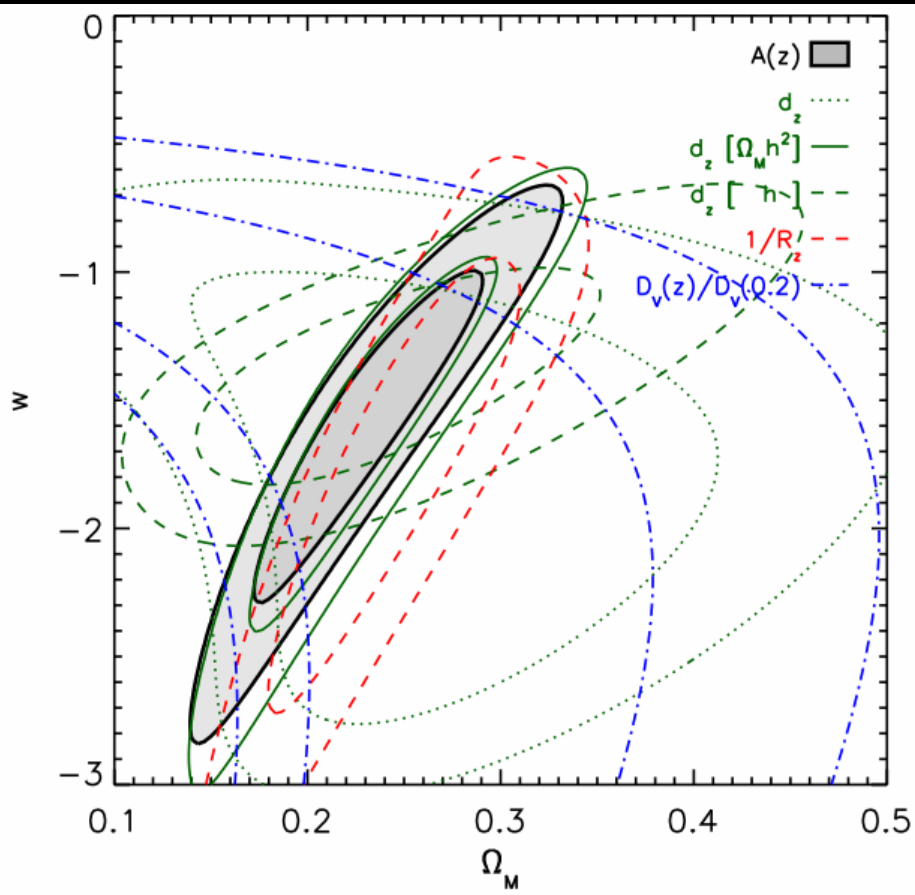


$$A(z) = \frac{\sqrt{\Omega_{\rm m} H_0^2}}{cz} D_V(z) \qquad d_z \equiv \frac{r_s(z_{\rm d})}{D_V(z)}$$

(Fig: Davis; Data from Percival et al. 2010 and Blake et al. 2011)

Many ways to use BAO

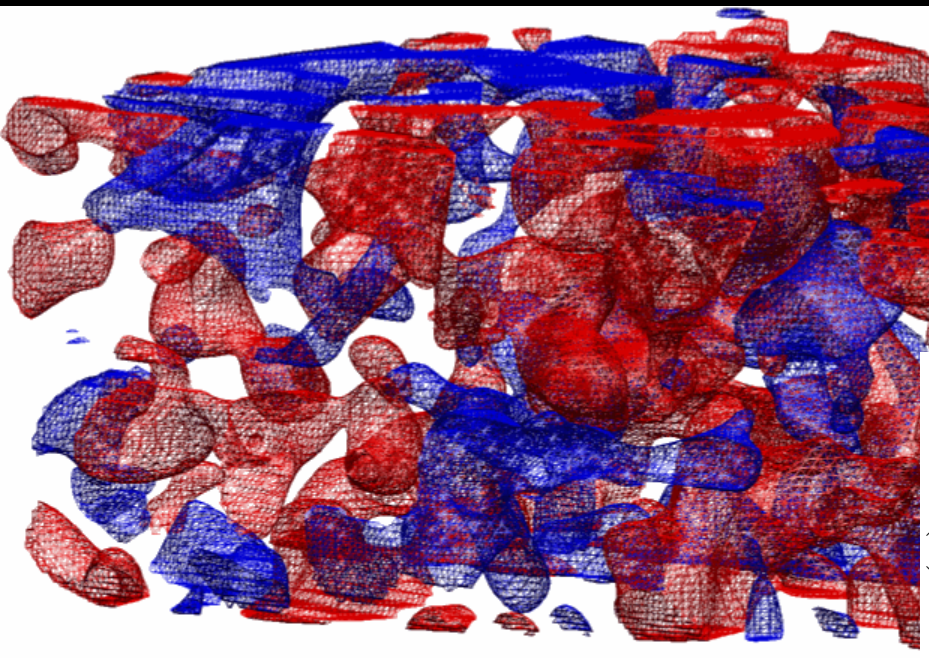




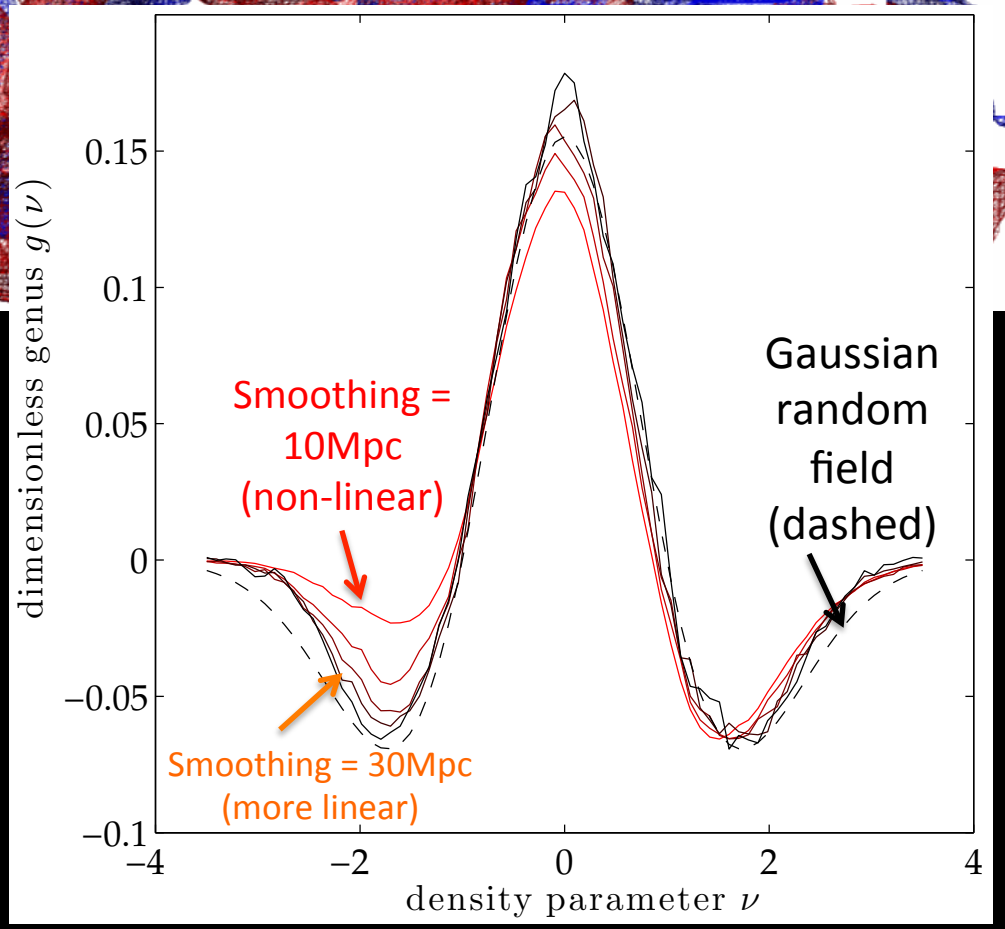
$$d_z \equiv \frac{r_s(z_\mathrm{d})}{D_V(z)}$$

NEW STANDARD RULER
- TOPOLOGY

Topology: Genus curve

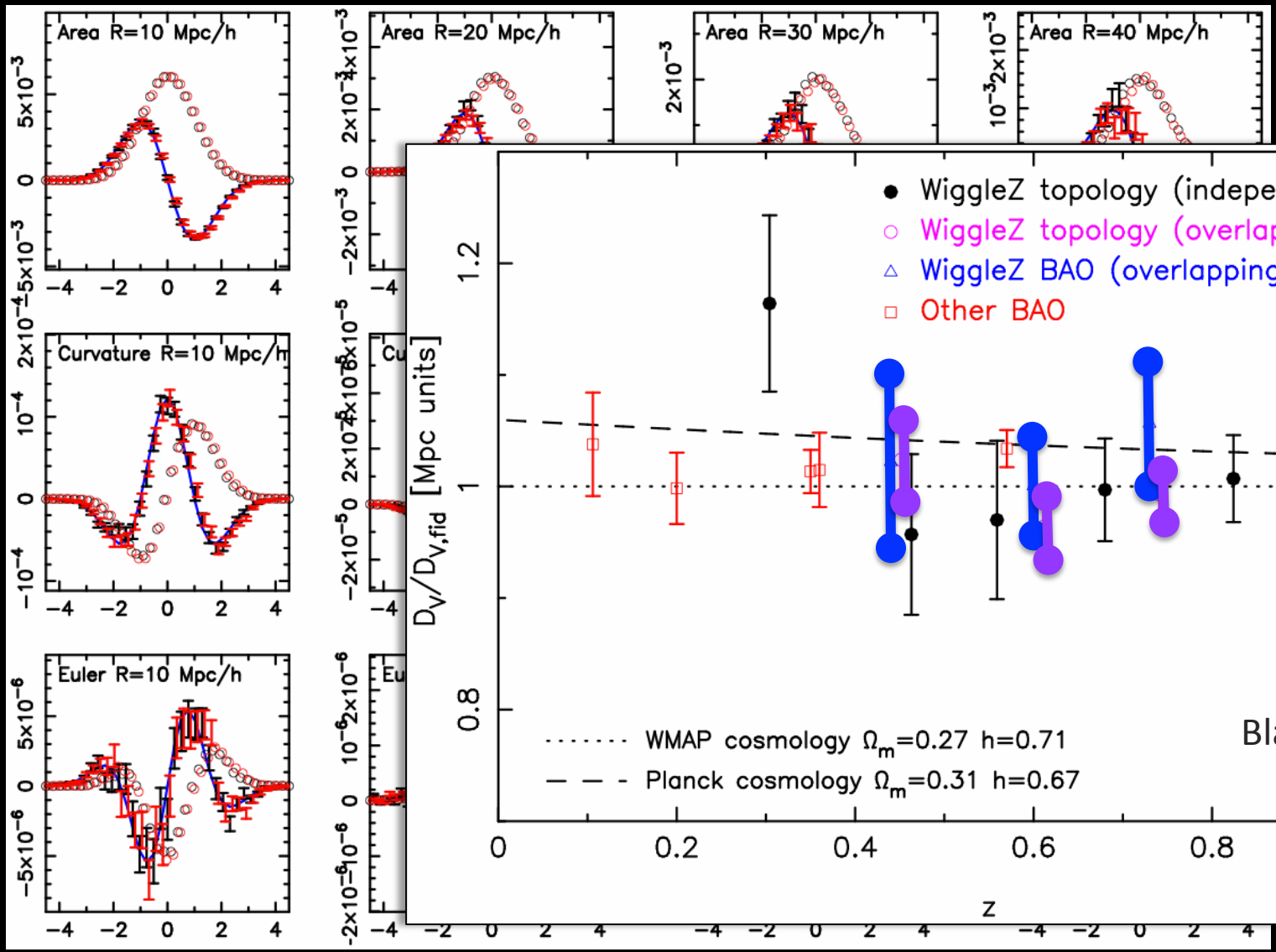


Berian James



Quantifying Topology – Minkowski Functionals

Black = WiggleZ
Red = GiggleZ

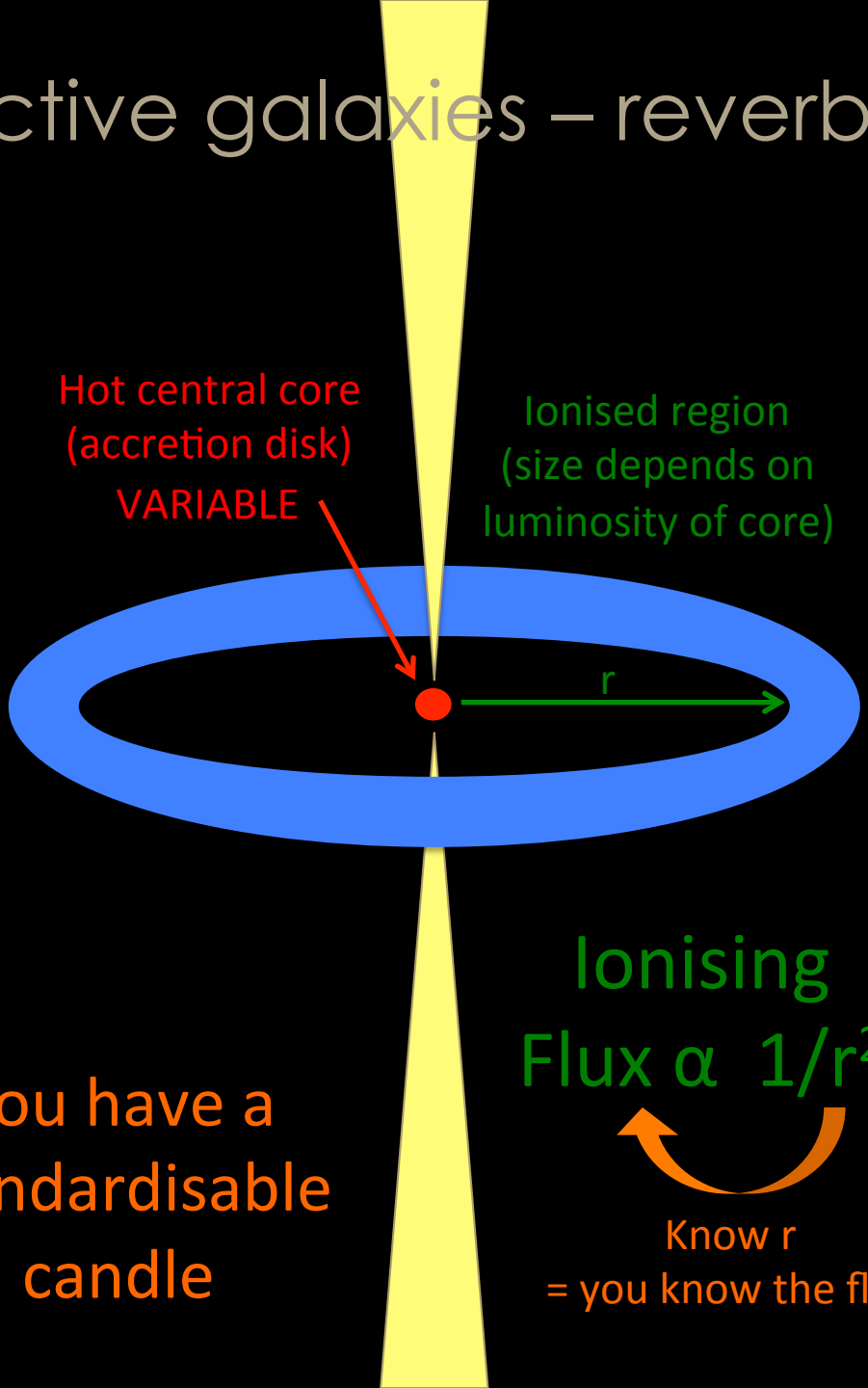


Blake, James, Poole 2013 (submitted)

NEW STANDARD CANDLE

- QUASARS (AGN)

Active galaxies – reverberation mapping



You have a standardisable candle

Ionising Flux α $1/r^2$

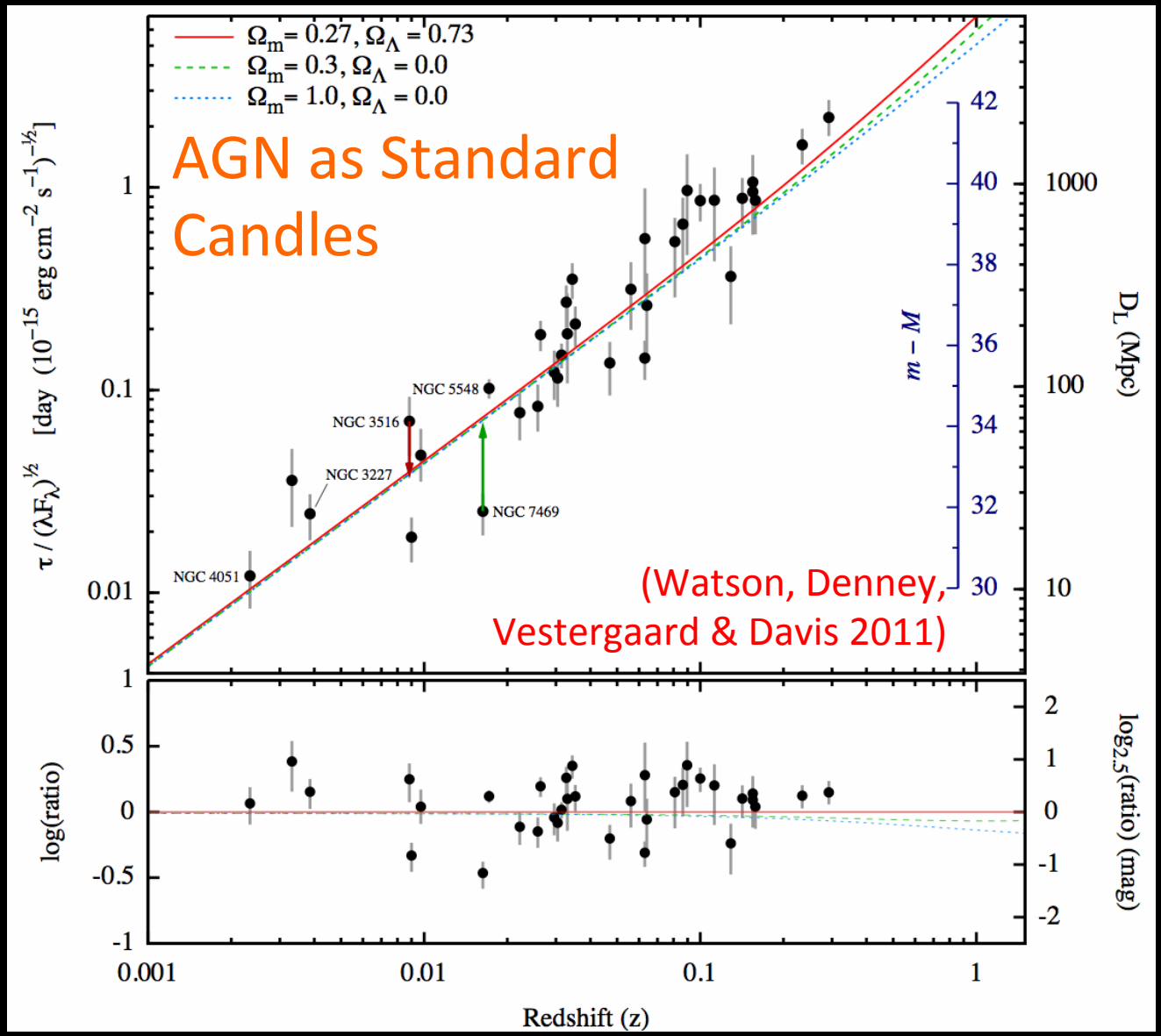
Know r
= you know the flux

Time Delay !!

$r = ct$

Measure t
= you know r

First Quasar Hubble Diagram



Scatter
σ ~ 0.50mag

Observational uncertainty contributes
σ ~ 0.36mag

Potentially
σ ~ 0.16mag

Biggest contributor is extinction uncertainty
σ ~ 0.10mag

NEW SURVEY

- OZDES

zDES

Spectroscopic follow-up of Dark Energy Survey targets

100 nights awarded on AAT

Over 5 years

First observations two weeks ago!

AAO

SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian National University

The University of Queensland AUSTRALIA

CSIRO

The University of Sydney

MACQUARIE UNIVERSITY SYDNEY ~ AUSTRALIA

The University of Melbourne

OzDES Targets

Supernovae
~ 4000 type Ia
$z < 1.2$

AGN
~ 500 reverb'n mapped
$z < 3.0$

Galaxy Clusters
counts +
~ 20 z's/cluster

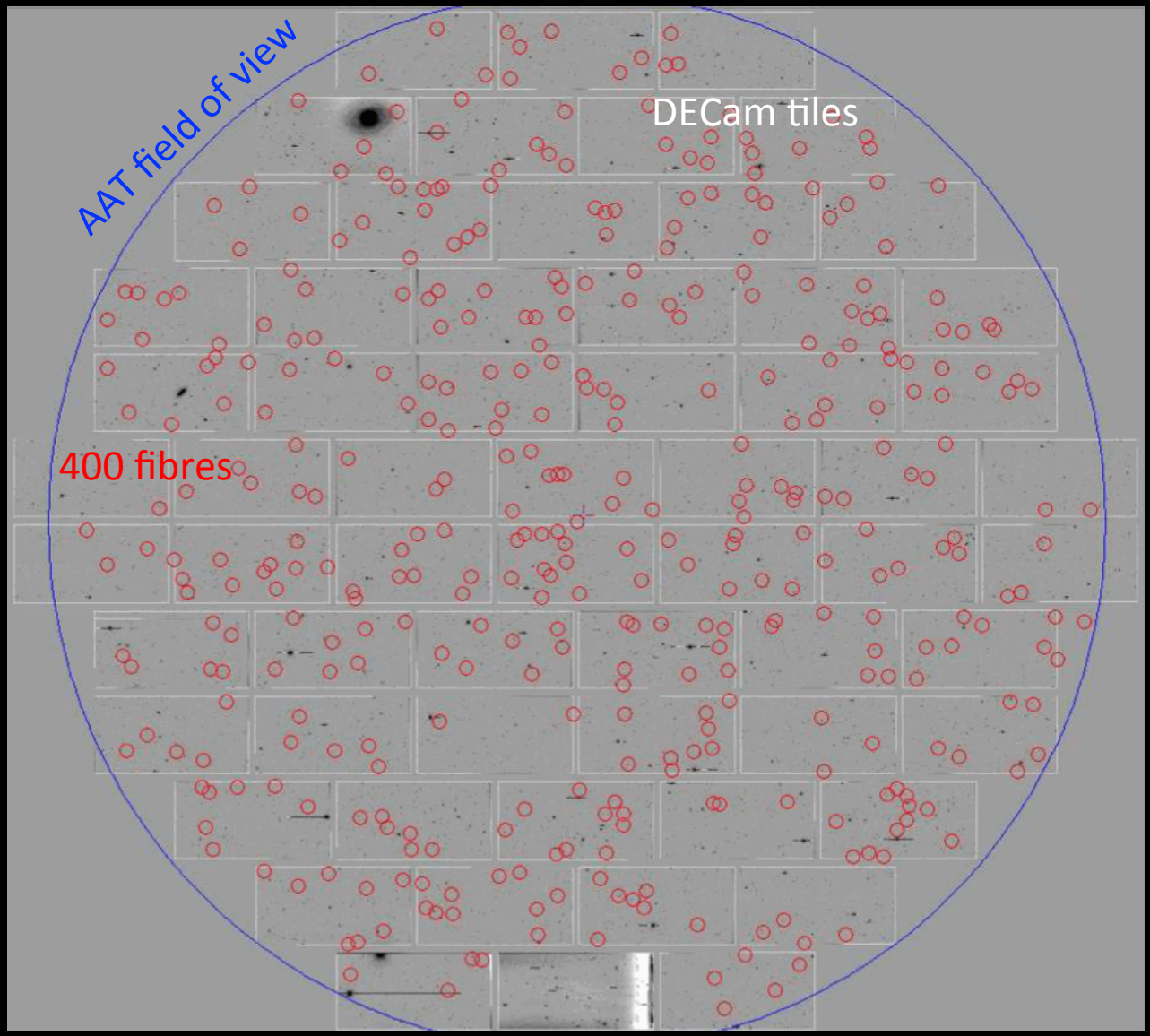
Strong lenses
~ a few

Radio galaxies
ATLAS 21cm
~2500

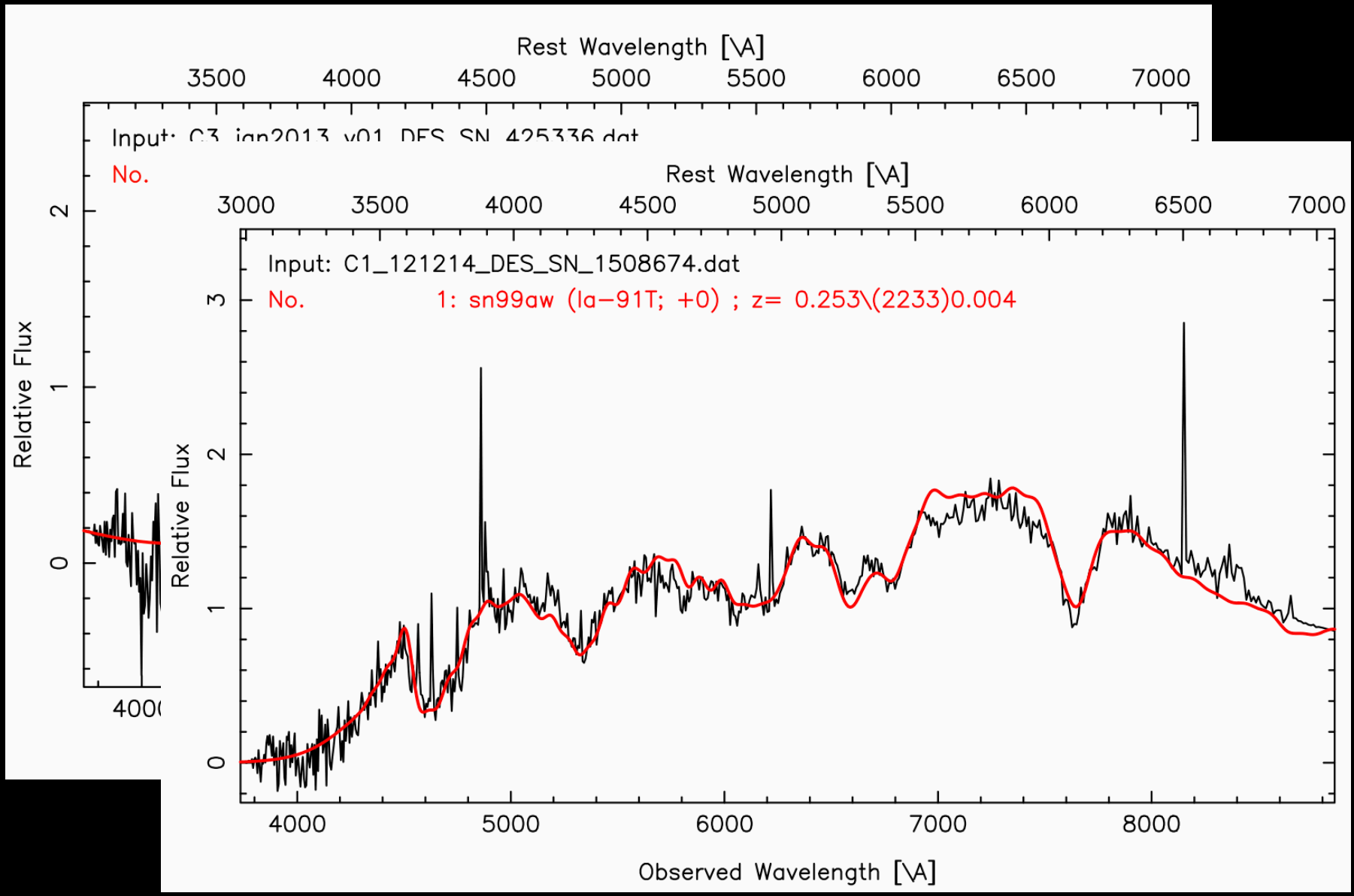
Other transients

Photo-z calibration

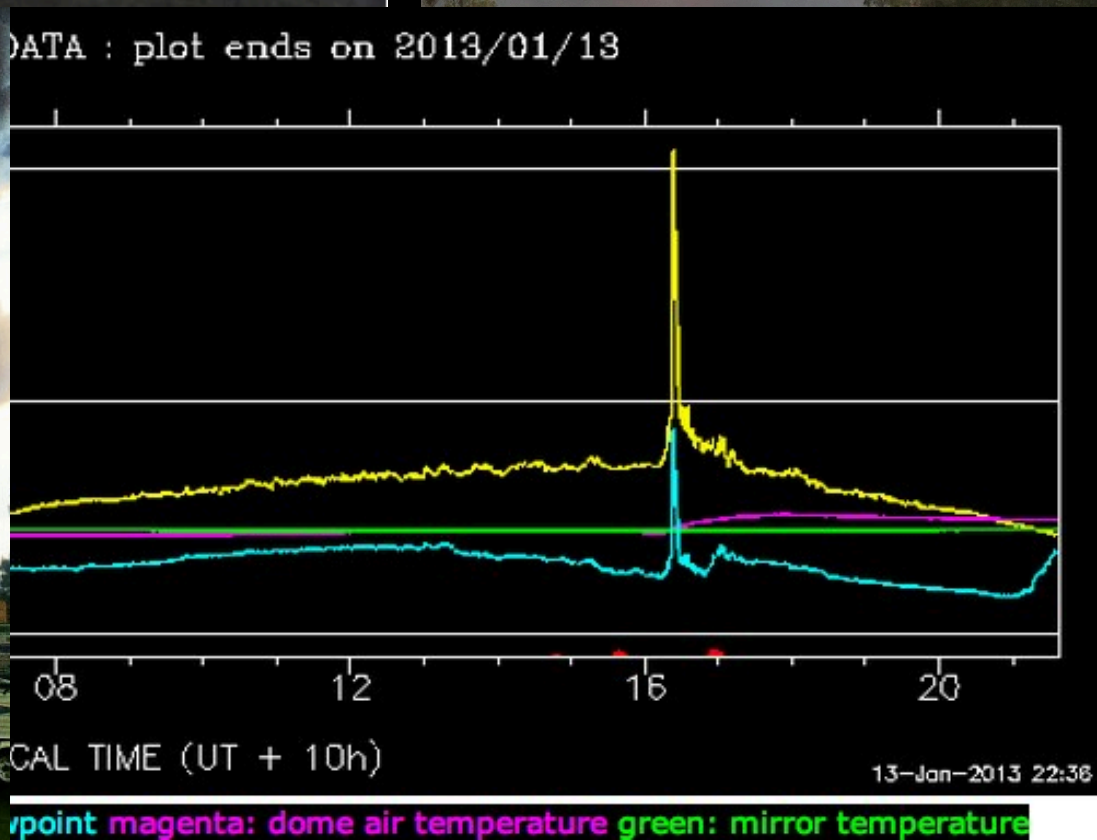
Why the AAT is a good match...



First DES SNe spectroscopically confirmed



The AAT in January 2013…


DATA : plot ends on 2013/01/13
08
12
16
20
CAL TIME (UT + 10h)
13-Jan-2013 22:36
vpoint magenta: dome air temperature green: mirror temperature

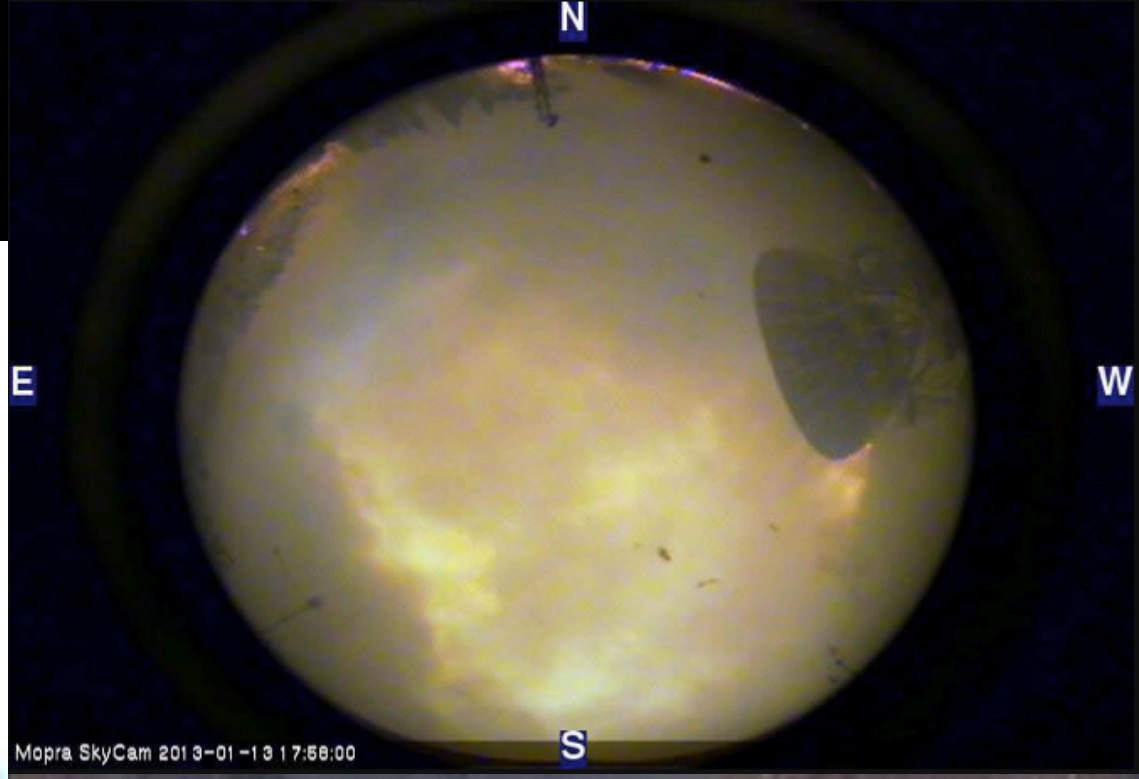

FTS site webcam 2013-01-13 10:


FTS site webcam 2013-01-13 10:51:19


FTS site webcam 2013-01-13 10:06:05
2013-01-
10:06:35


HATSouth @ SSO 2013-01-13 22:15:30


House


N
E
W
S
Mopra SkyCam 2013-01-13 17:56:00

But all is well.

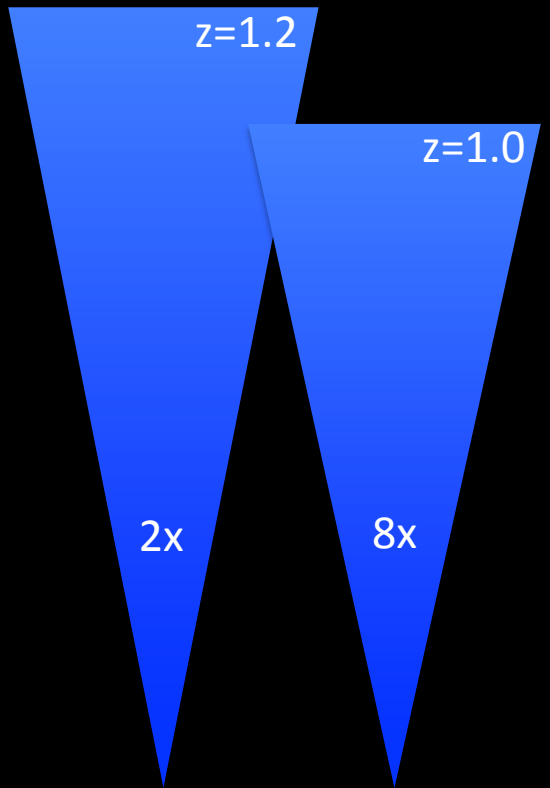
(Except maybe for these.)

Ángel R. López-Sánchez

(Small print: This photo was taken before the fires.)

OzDES SNe

10 Fields
30 sq deg
g r i z
~ 5 day cadence
for 5 months



DES discovers 10,000 SNe (approx)

Target all Active SNe: 10 per field /year
Target as many host galaxies as possible: 400 per field / year
(repeatedly return to field to build up depth on hosts)

4,000 have well-sampled light curves

(The rest go to bigger scopes)

2/3 host redshifts with AAT

Catch 500 while active

Comparison: SNLS = 472

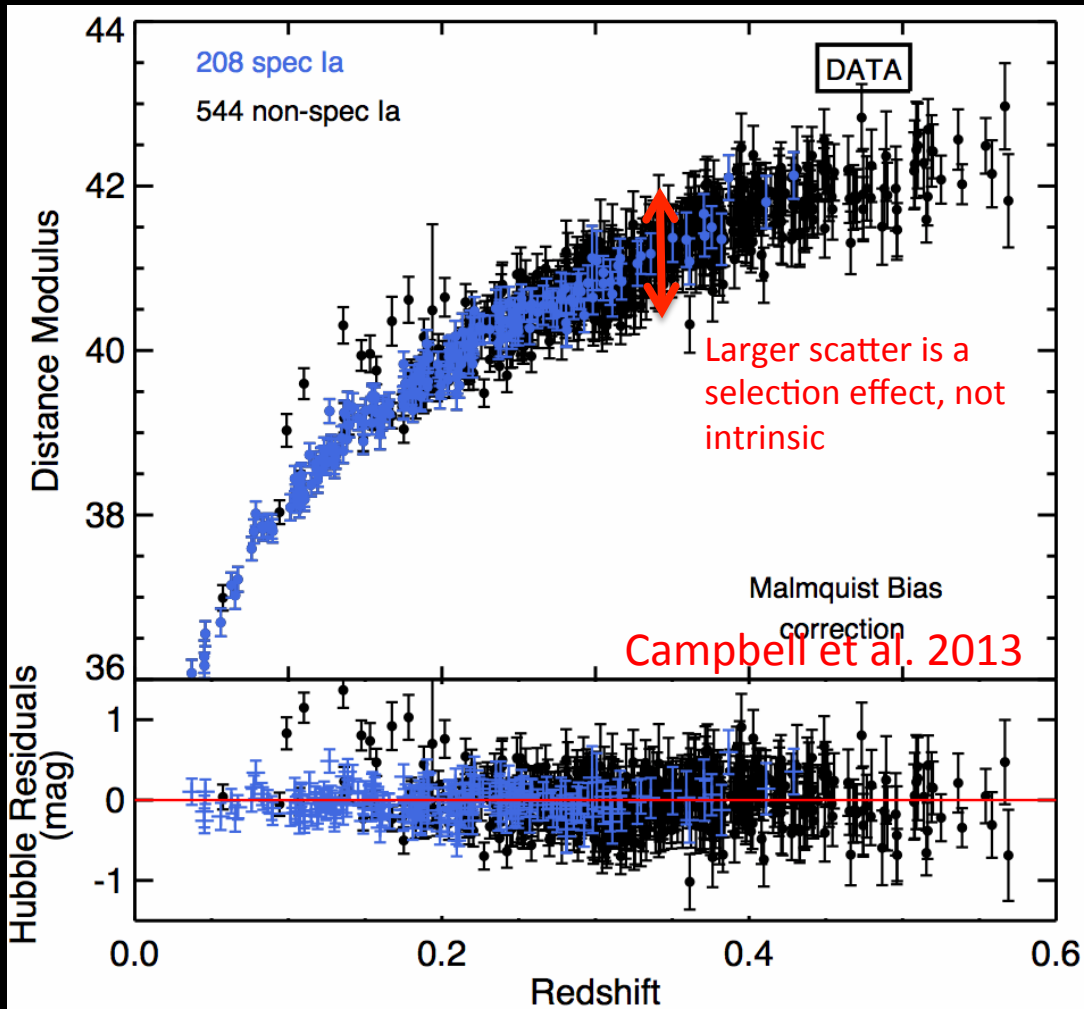
Host galaxy cosmology

Proof of concept using
SDSS-II (Campbell et al. 2013)
SNLS (Lidman et al. 2013)

Photometric SN classification achieved 96% purity

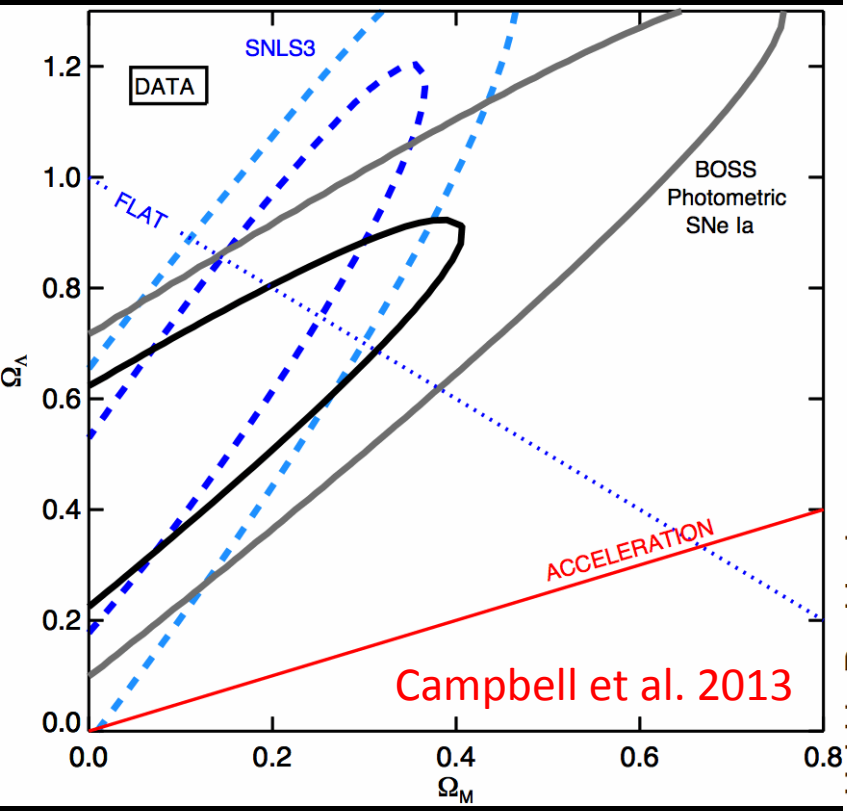
Sufficient to give unbiased cosmological results

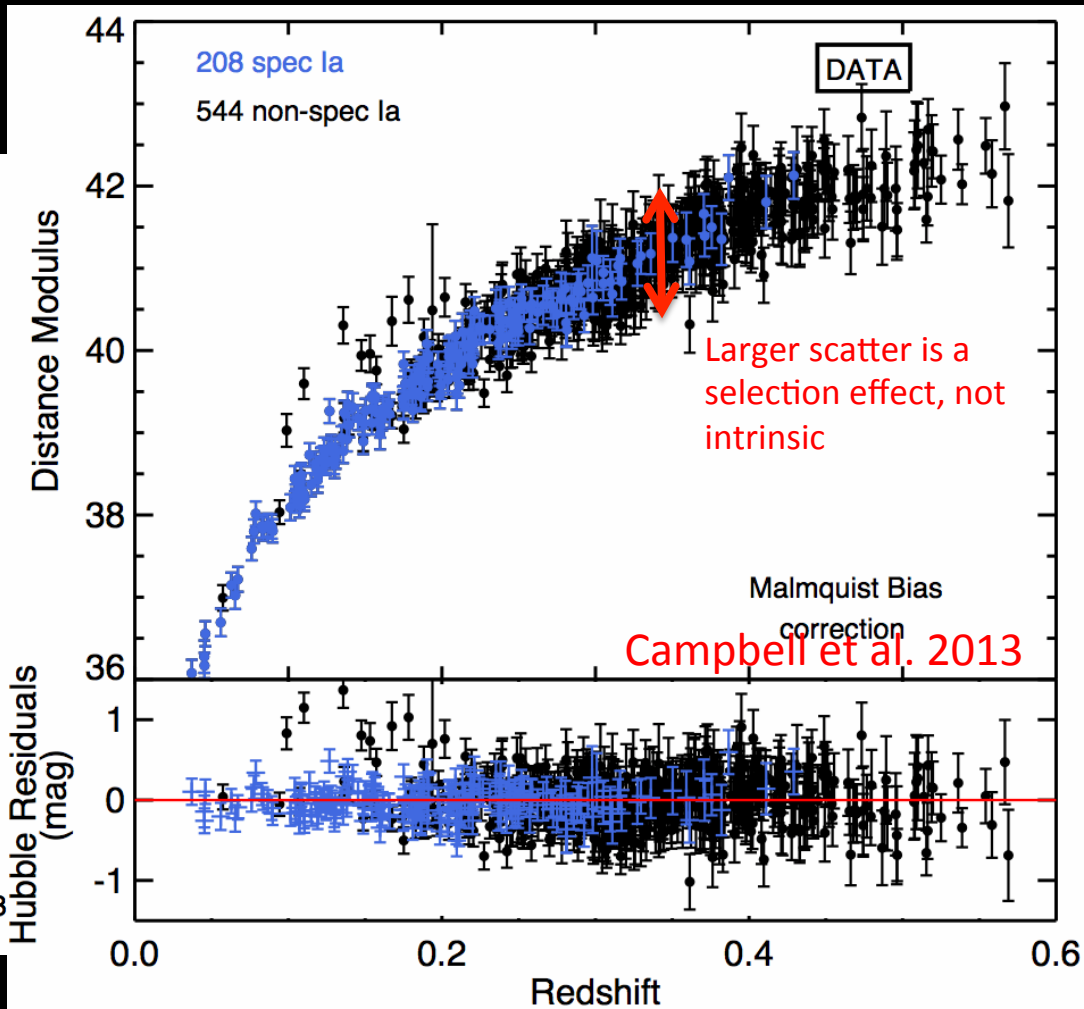
(Campbell et al. 2013)



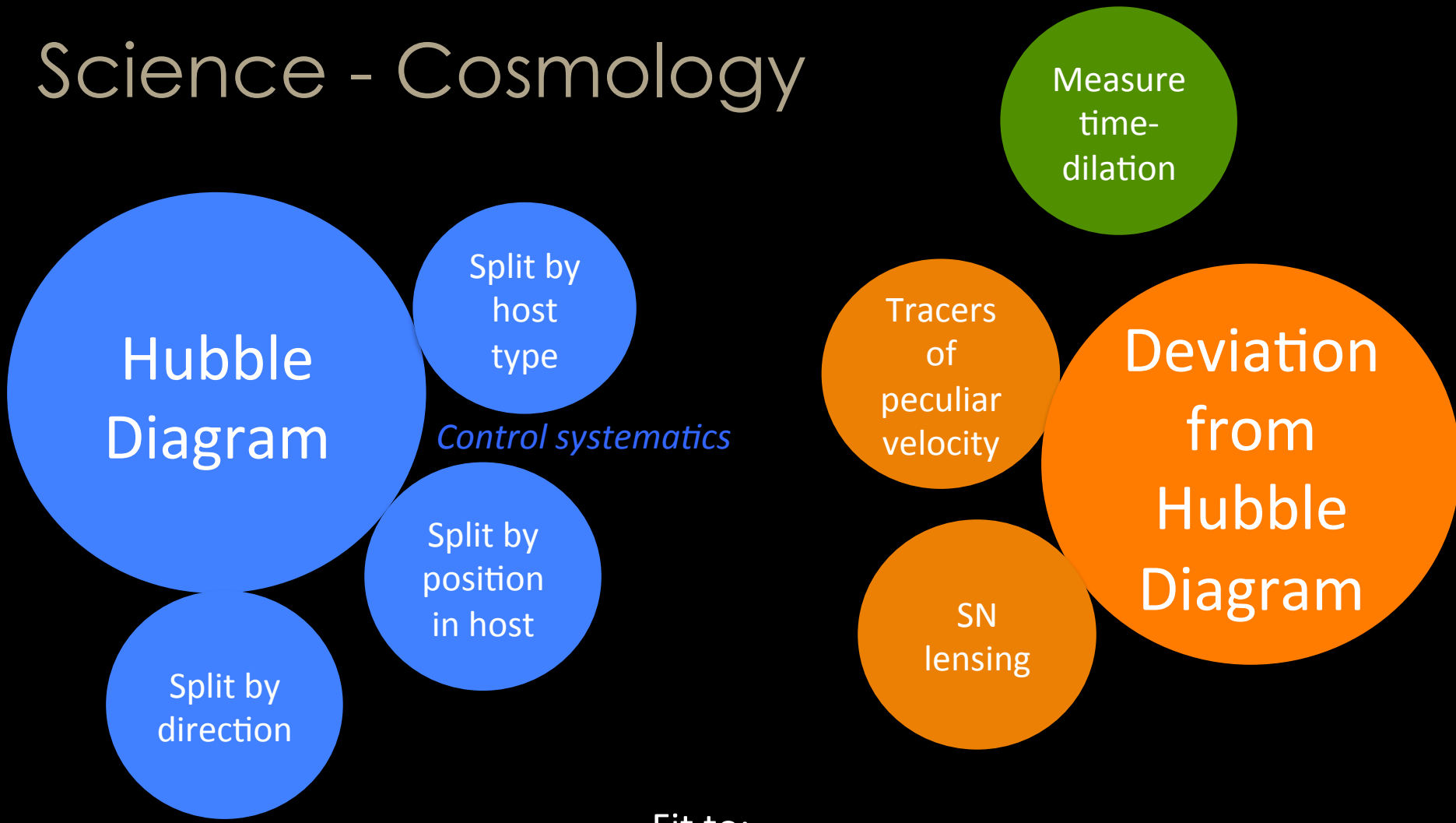
Host galaxy cosmology

Proof of concept using
SDSS-II (Campbell et al. 2013)
SNLS (Lidman et al. 2013)





Science - Cosmology



Fit to:

- Standard cosmological model
- Modifications of gravity
- Inhomogeneous models
- Time-varying or anisotropic dark energy

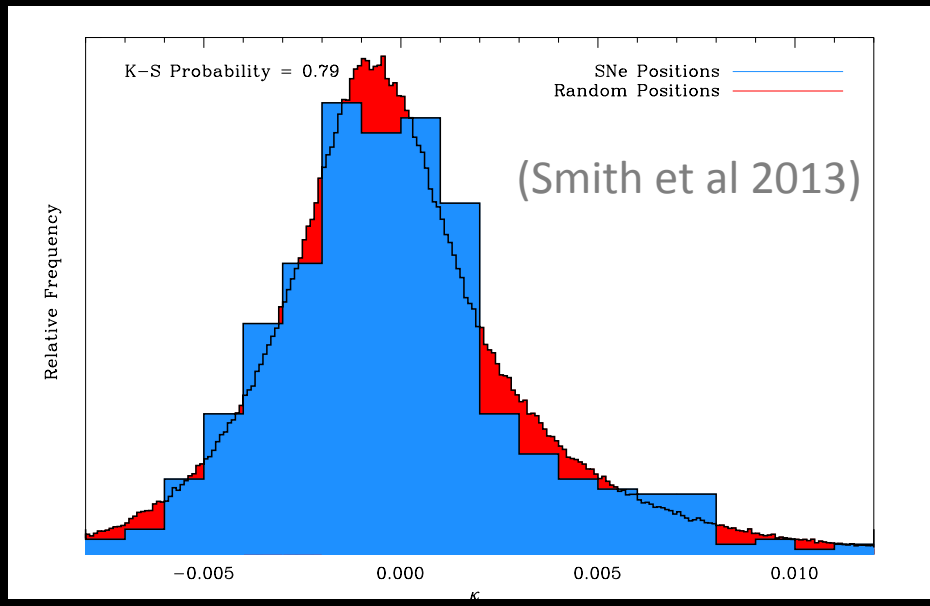
Weak Lensing of SNe

- Apparent SN luminosities affected by lensing convergence

$$\kappa = \frac{3H_0^2\Omega_m}{2c^2}\sum_i \Delta_{\chi_i}\chi_i\frac{\chi_{\rm SN}-\chi_i}{\chi_{\rm SN}}\frac{\delta_i}{a}$$

- Already measured by SDSS-II and BOSS (Smith et al 2013)
  - correlation between SN Hubble residual and convergence

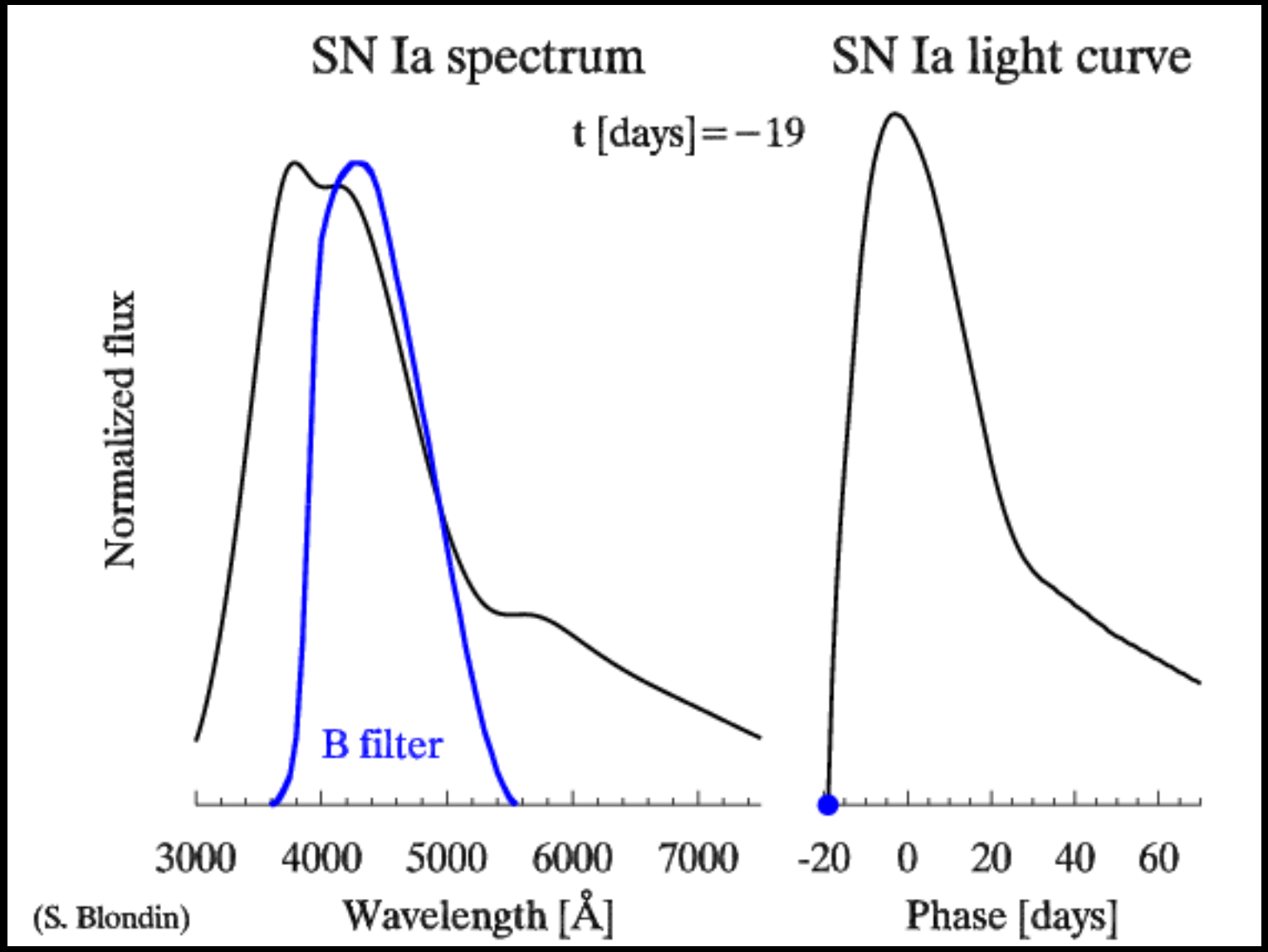
- New SALT fit parameter



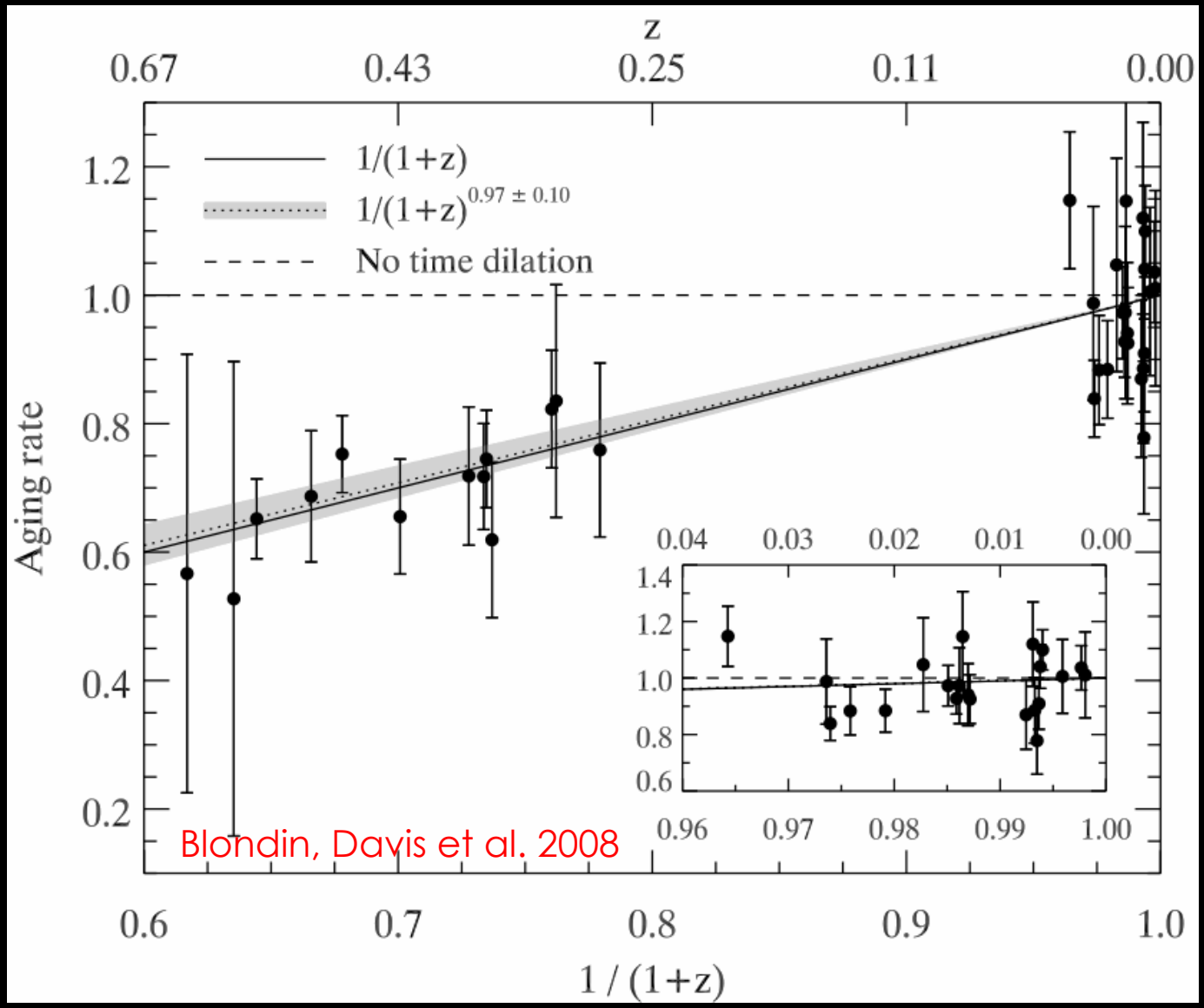
$$\mu = m_B - M + \alpha x_1 - \beta c + \mu_{\rm corr}(z)\gamma_\kappa\kappa_{\rm gal}$$

- Used to measure bias of foreground galaxies

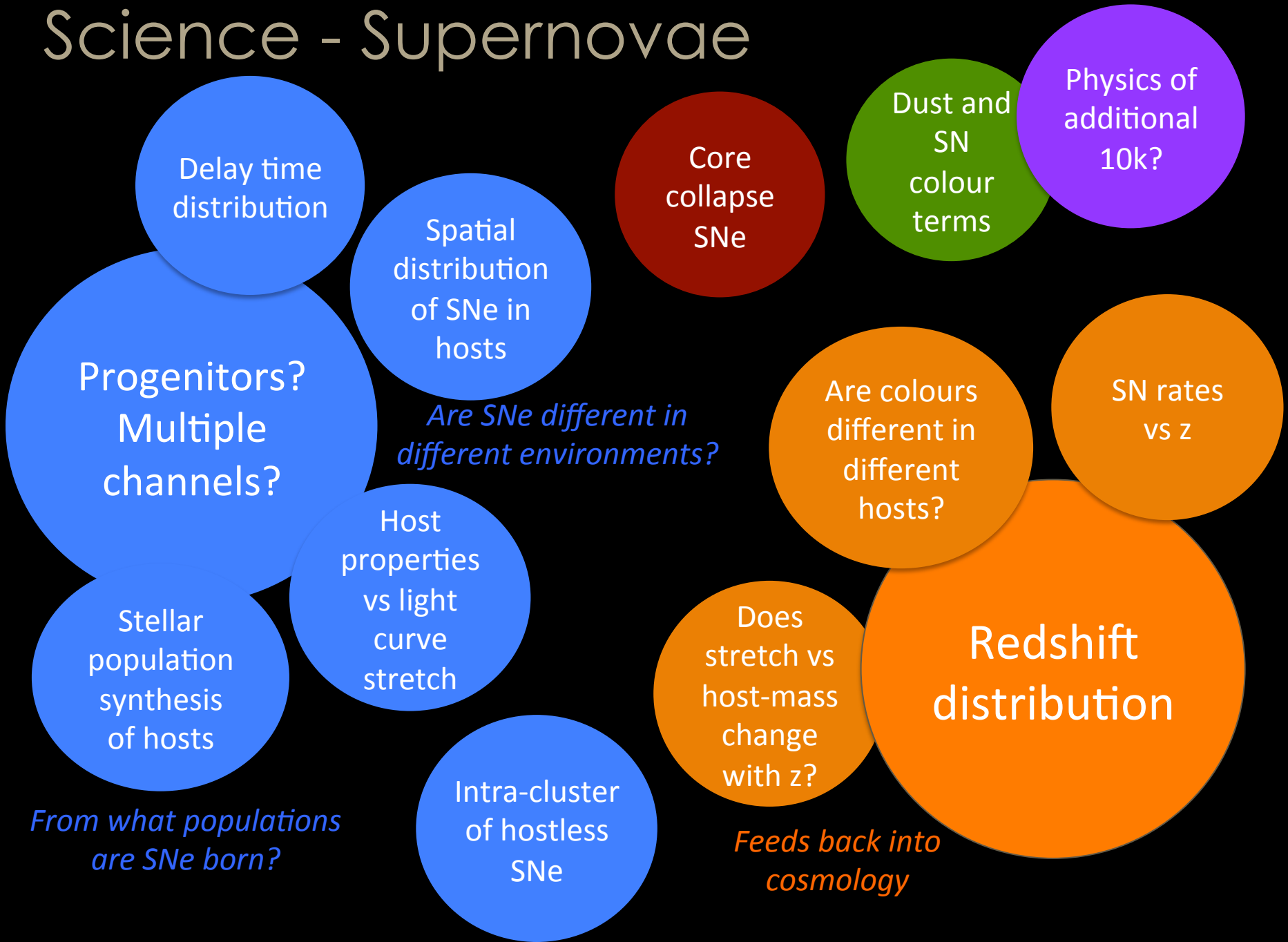
Supernovae as clocks



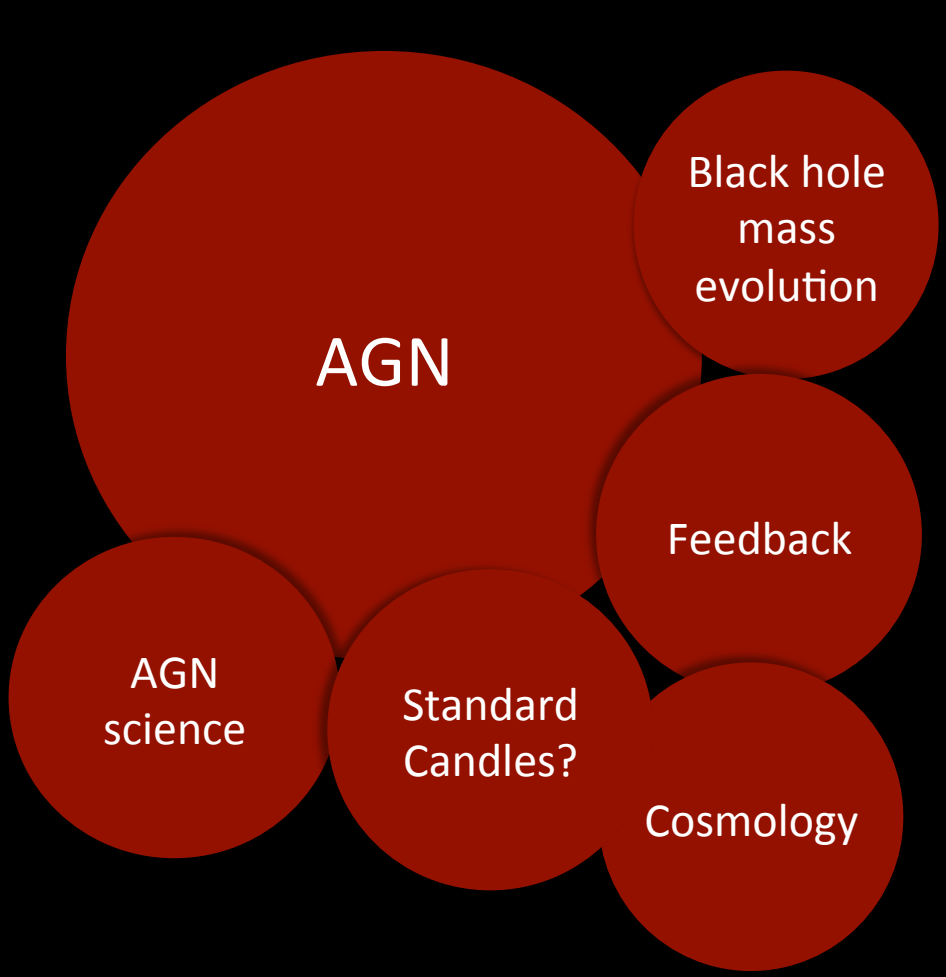
Measure time dilation

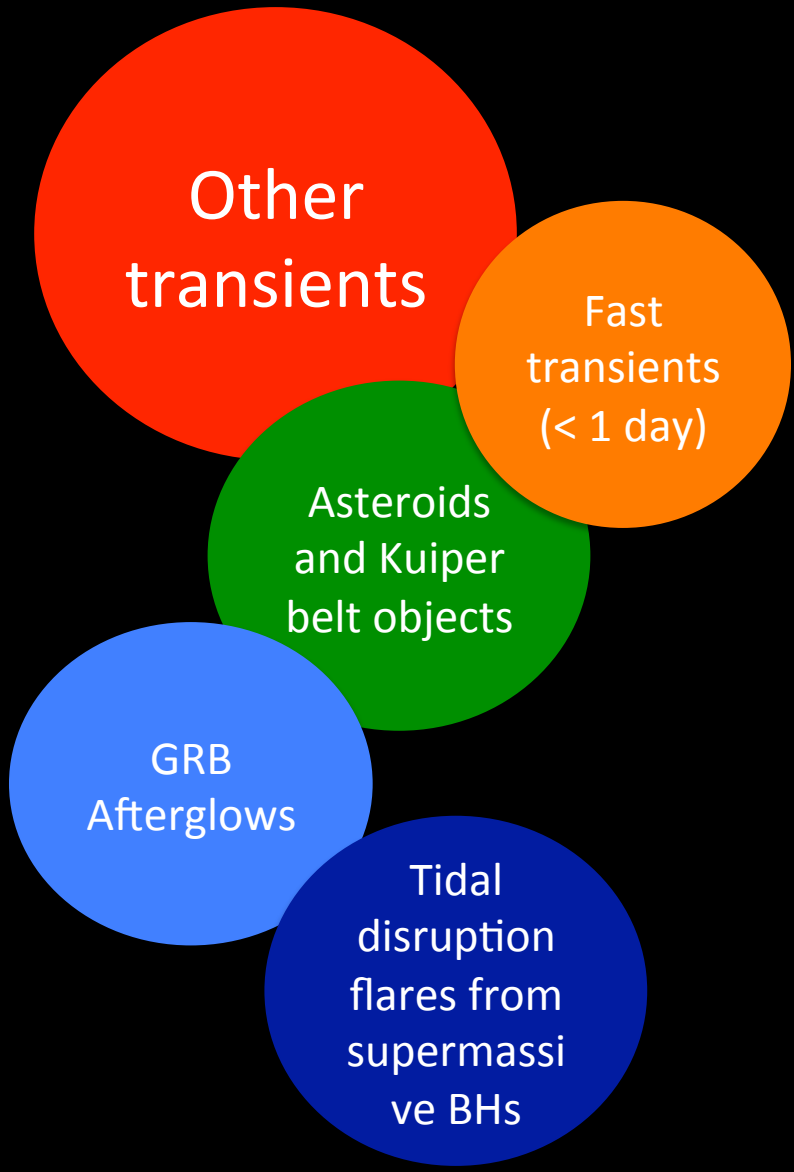


Science - Supernovae

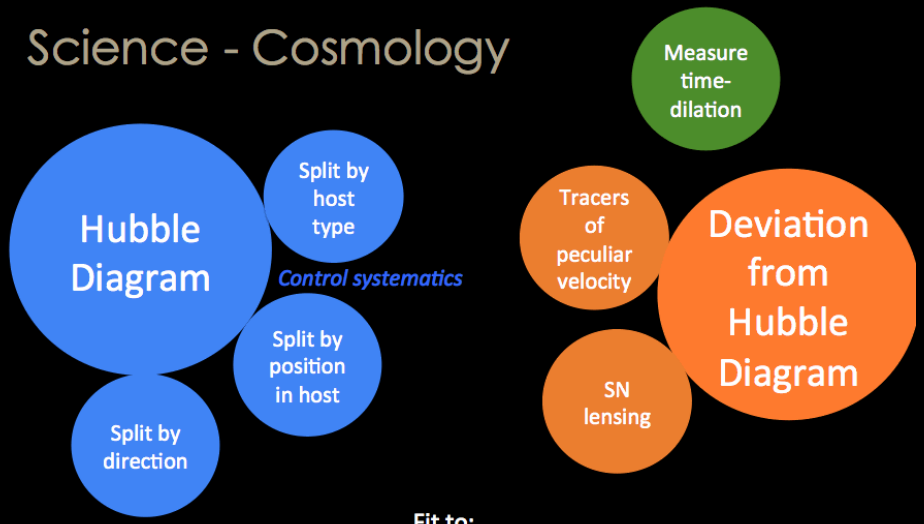


Science – AGN + Other Transients





Science - Cosmology



Fit to:
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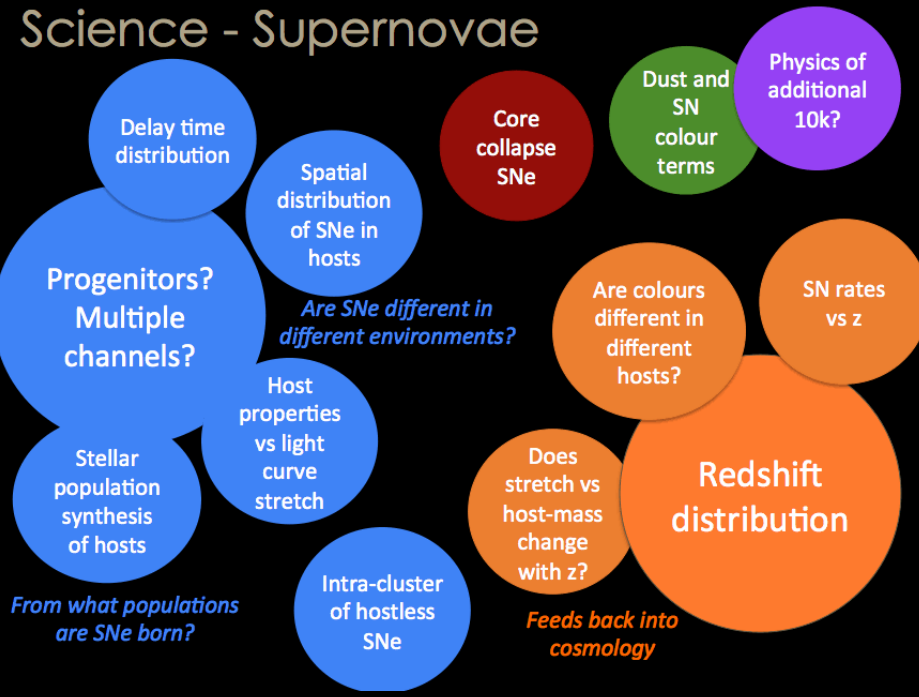
- Modifications of gravity
- Inhomogeneous models
- Time-varying or anisotropic dark energy

Science - Supernovae



Science – The rest!!

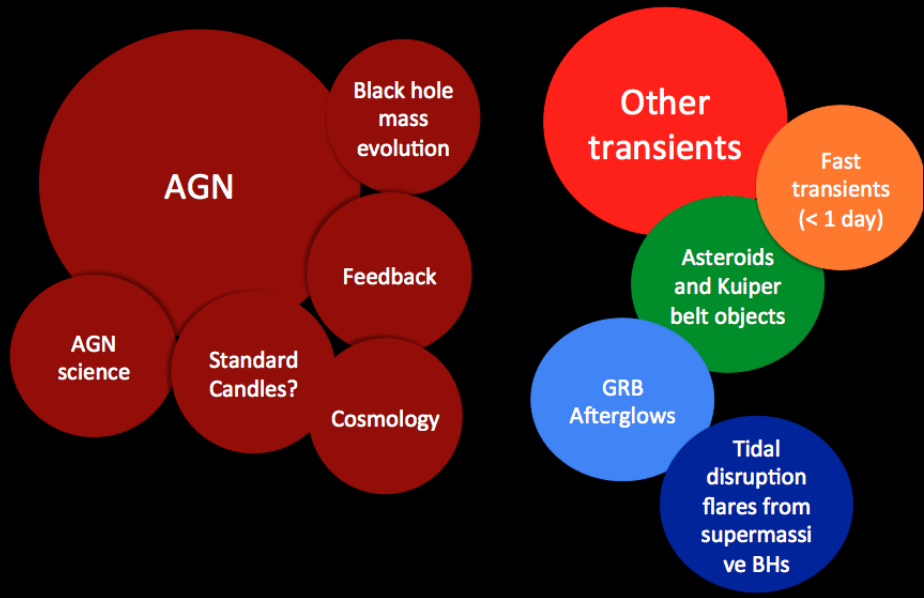
Clusters
- # density vs redshift (cosmology)
- dynamical masses (c.f. SZ)

Radio galaxies
- Get z's for ATLAS targets
- Radio feedback & local environment

Photo-z calibration

Serendipity

Science – AGN + Other Transients



How do we UNDERSTAND dark energy?

Just because we can measure it precisely doesn't mean we understand it.

But not understanding, doesn't mean we can't use it (e.g. electricity, supernovae)

Is it time to test dark energy in the lab?
Can we make hoverboards?

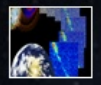
Employment Opportunities with CAASTRO

Positions Currently Open for Applications:

POSITION	LOCATION	CONTACT PERSON	APPLICATIONS DUE
CAASTRO Postdoctoral Researcher on Low-Frequency Radio Astronomy	University of Sydney	Prof Bryan Gaensler	31 October 201
CAASTRO Postdoctoral Researcher on HI Absorption-Line Surveys	University of Sydney	Prof Elaine Sadler	31 October 201
CAASTRO Postdoctoral Researcher on Cosmology	University of Queensland	A/Prof Tamara Davis	31 October 201
CAASTRO Postdoctoral Researcher on Fast Radio Bursts	Curtin University	Prof Steven Tingay	31 October 201
CAASTRO Postdoctoral Researcher on Cosmology	Swinburne University of Technology	A/Prof Chris Blake	31 October 201
CAASTRO Postdoctoral Researcher on Theoretical Galaxy Formation	University of Melbourne	Prof Stuart Wyithe	31 October 201
CAASTRO Postdoctoral Researcher on Epoch of Reionisation Science	University of Melbourne	Prof Rachel Webster	31 October 201
CAASTRO Postdoctoral Researcher on Theoretical Cosmology	University of Melbourne	Prof Stuart Wyithe	31 October 201
CAASTRO Postdoctoral Researcher on Galaxy Evolution	University of Western Australia	A/Prof Martin Meyer	31 October 201
CAASTRO Postdoctoral Researcher on SAMI Science	University of Western Australia	Prof Lister Staveley-Smith	31 October 201
CAASTRO Postdoctoral Researcher on Intensity Mapping	University of Western Australia	Prof Lister Staveley-Smith	31 October 201

LATEST NEWS & UPCOMING EVENTS

New study improves
25 Sep 2013



The Ephemeral Universe with Widefield Low Frequency Arrays
12 Nov 2013

CAASTRO TWEETS @caastro_arc

Tweets Follow

Free @Swinburne lecture tonight: Chris Blake "Observing echoes of the Big Bang in the Universe's most distant light" scienceinpublic.com.au/events/ai
Expand

CAASTRO @caastro_arc 11 Oct

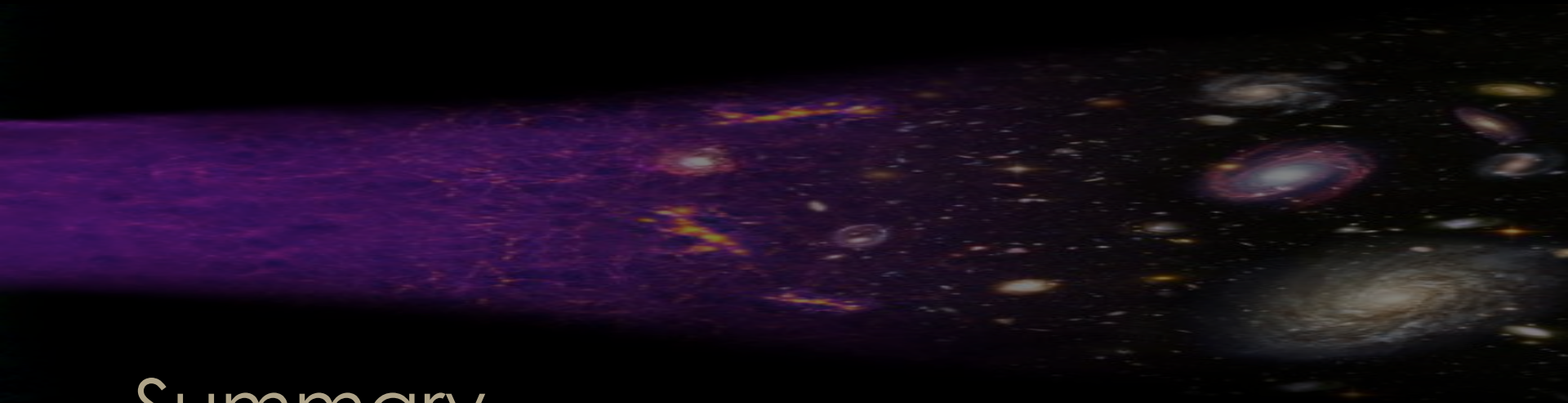
Submission of entries close today for our & @QV_online co-sponsored @scopesInSchools astrophotography competition telescopesinschools.wordpress.c

Show Photo Details

Helen Sim @sky_pointer 11 Oct

Confusing your dark matter with your dark energy? These blokes in the pub will set you straight. ow.ly/pHQLC

Retweeted by CAASTRO



Summary

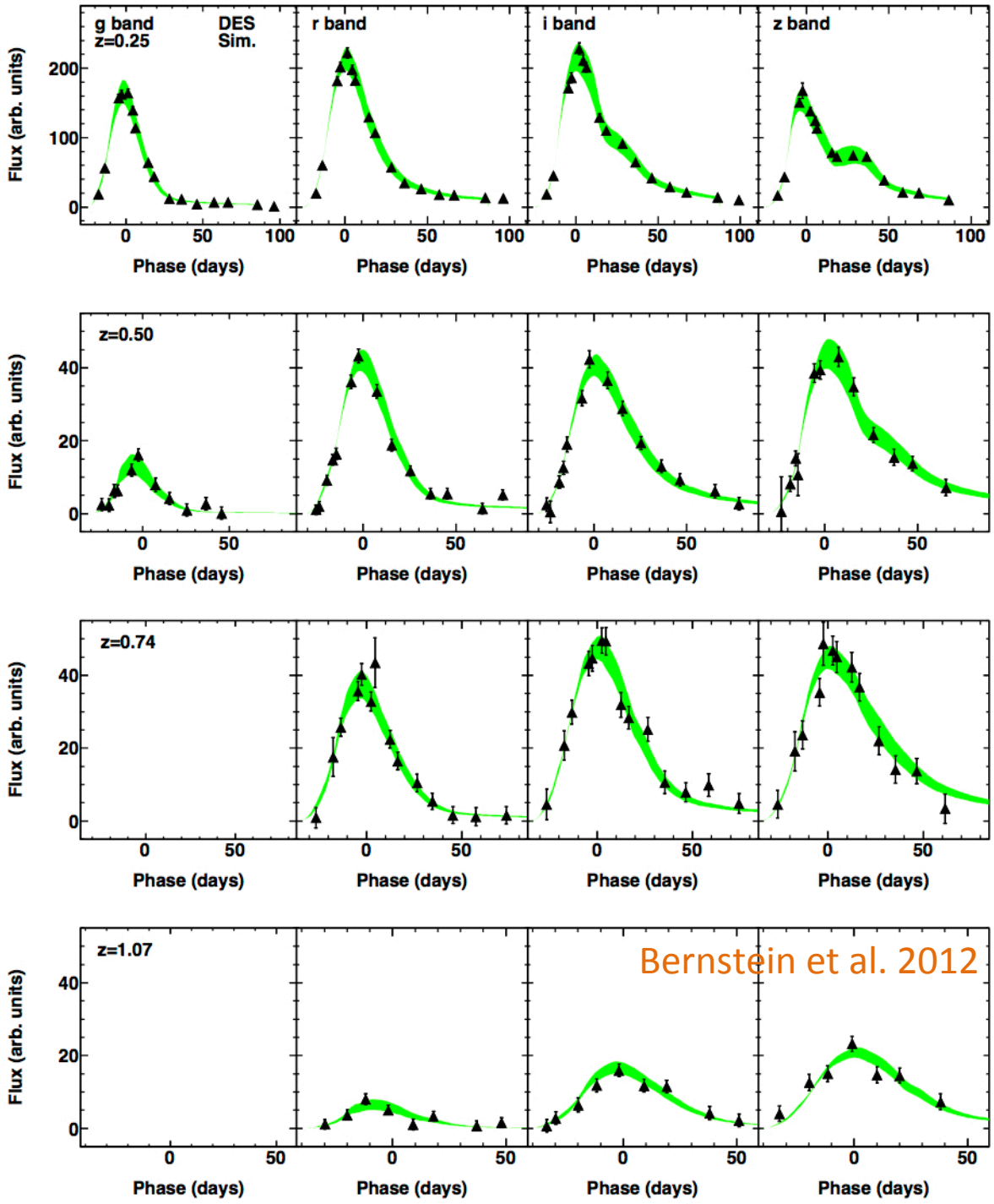
Cosmology is now a precision science
Our results are model dependent (almost always)
We need several streams of investigation:

- Measure behaviour of dark energy? (Difficult, or impossible, without a model.)
- Measure parameters of ΛCDM more precisely
- Test other explanations of dark energy

Lots of new measurements are on their way

Filter	Limiting Mag (Shallow)	Limiting Mag (Deep)
g	24.9	25.6
r	24.3	25.4
i	23.9	25.1
z	23.7	24.8

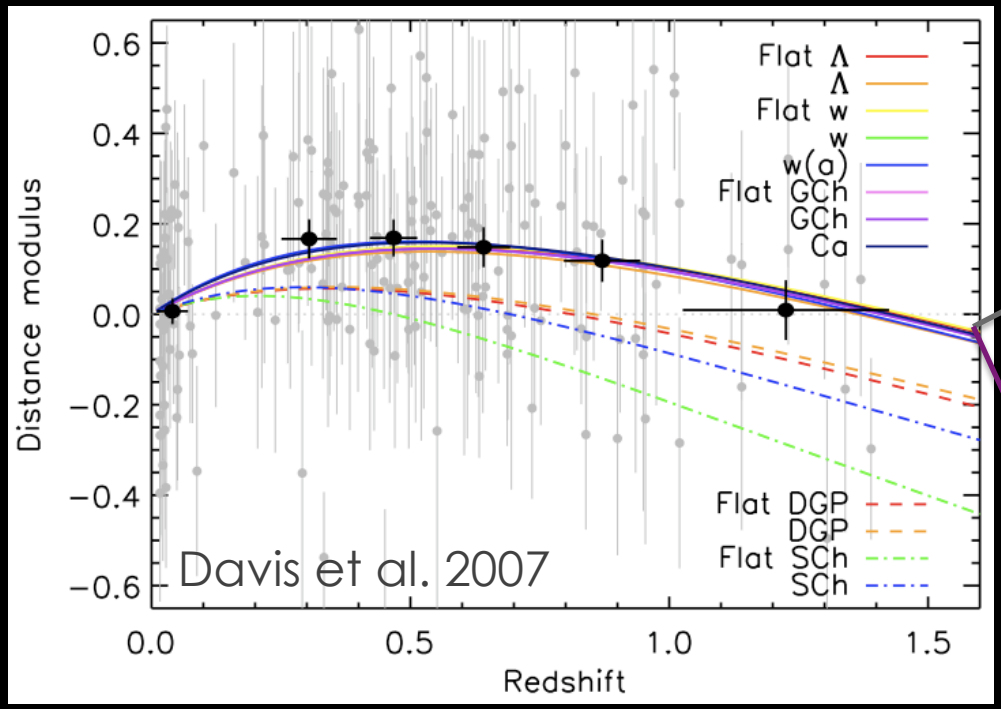
Simulated data

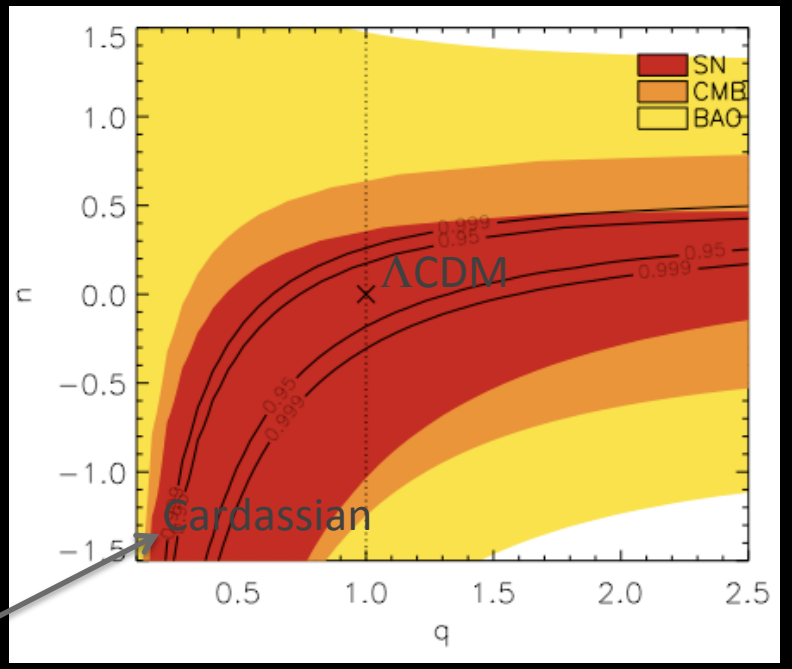


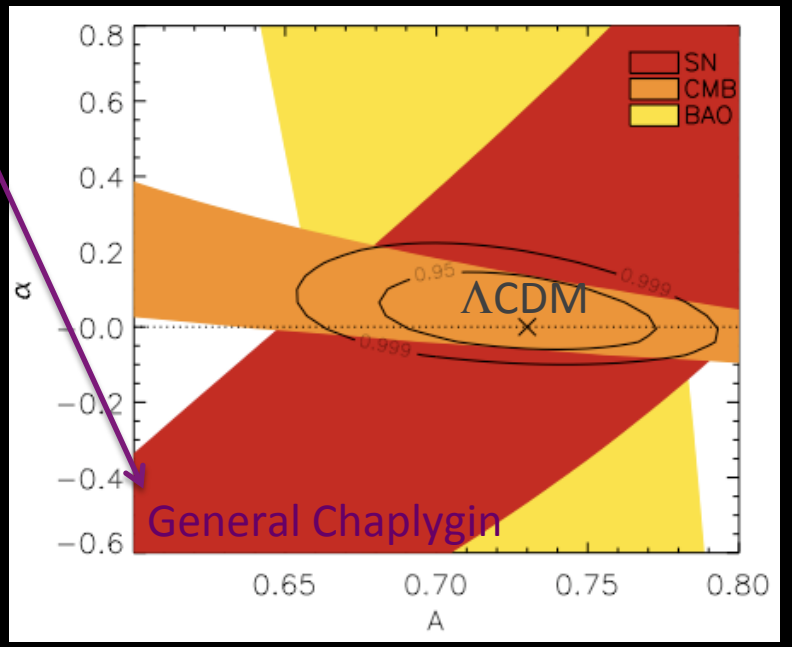
The beginning of knowledge
is the discovery of something
that we do not understand.
- Frank Herbert

What senses do we lack,
that we can not see and hear
another world all around us?
- Frank Herbert (?)

Some models can't be distinguished using only distance data







WiggleZ cosmology fits