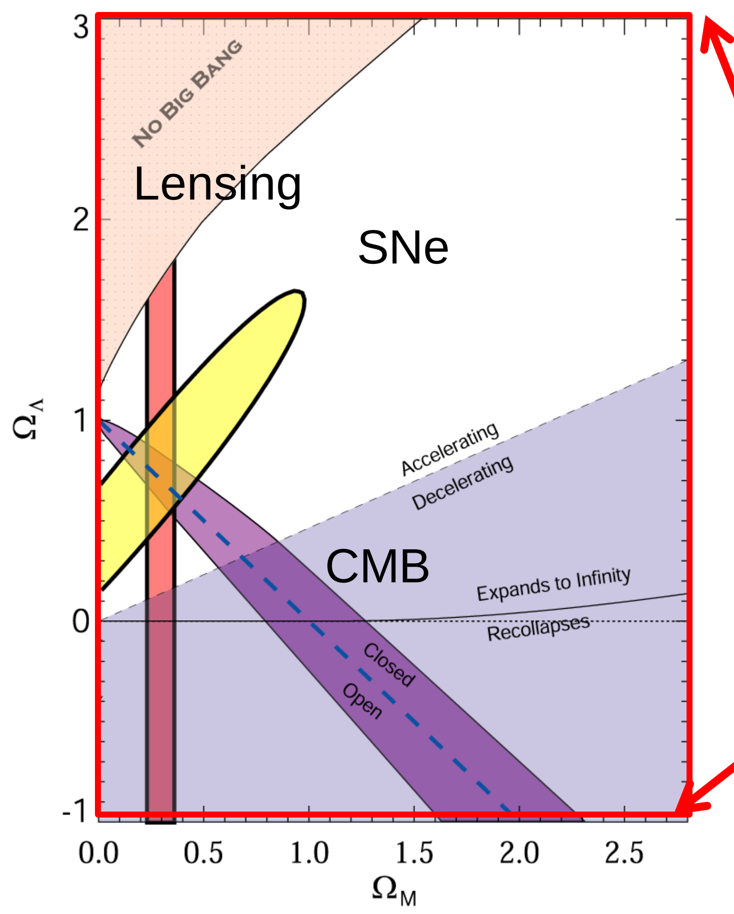
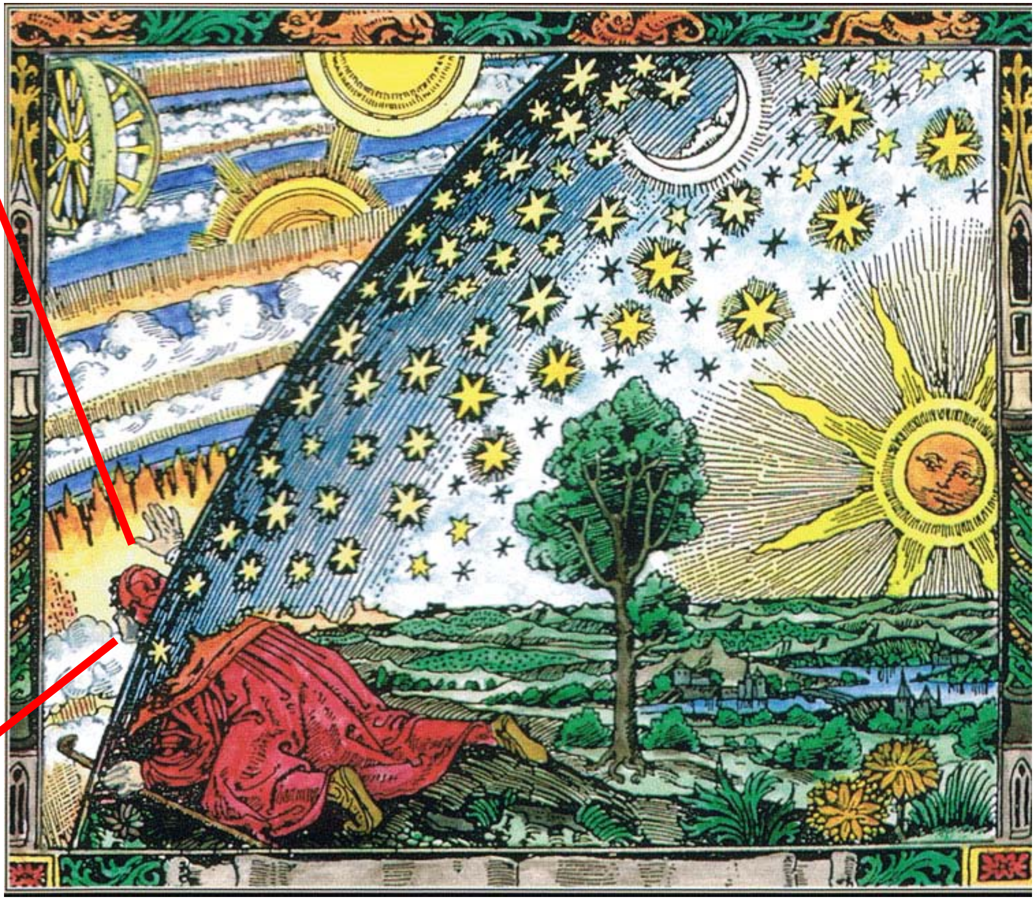
Cosmological Prospects with HSC and PFS

Richard Ellis (Caltech)





IPMU

Oct 6th 2011

Dark Energy: Nobel Prize in Physics 2011

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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(THE SUPERNOVA COSMOLOGY PROJECT)
Received 1998 September 8; accepted 1998 December 17

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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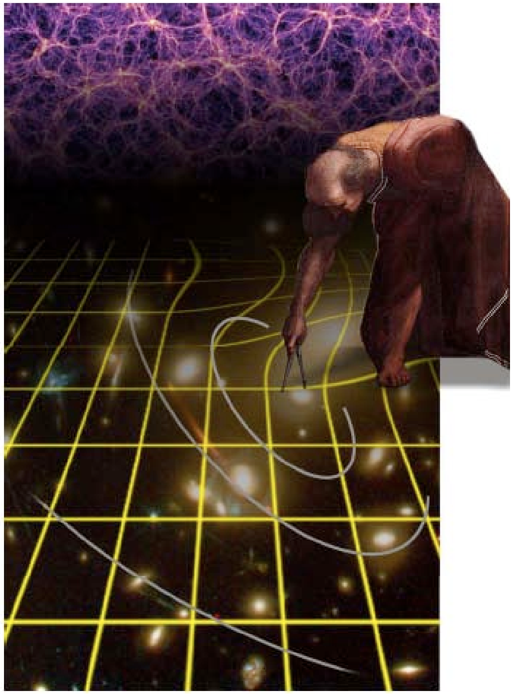
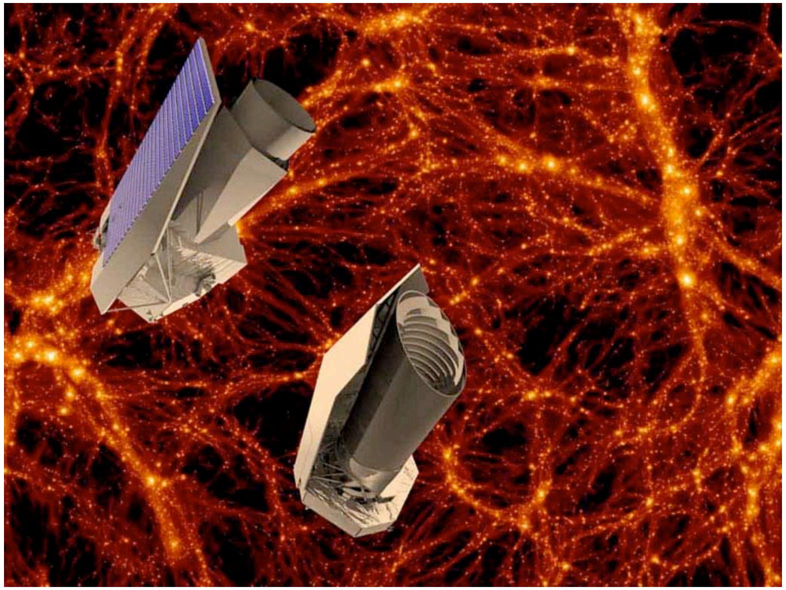
Received 1998 March 13; revised 1998 May 6

EUCLID Mission Accepted by ESA

1.2m telescope @ L2 under ESA's Cosmic Vision program





Optical/IR imaging to H=24 over 20,000 deg^2 for weak gravitational lensing (40 galaxies arcmin^{-2})

Near-IR spectra with 1:3 sampling over 20,000 deg^2 to H=22 for baryonic acoustic oscillations (1.6 10^8 galaxies)

w to 2%, w_a to 10% using two methods

Outline

- Review of methods for probing dark energy
    - Current status and limitations
    - Associated requirements
    - New ideas
    - Implications for PFS/HSC

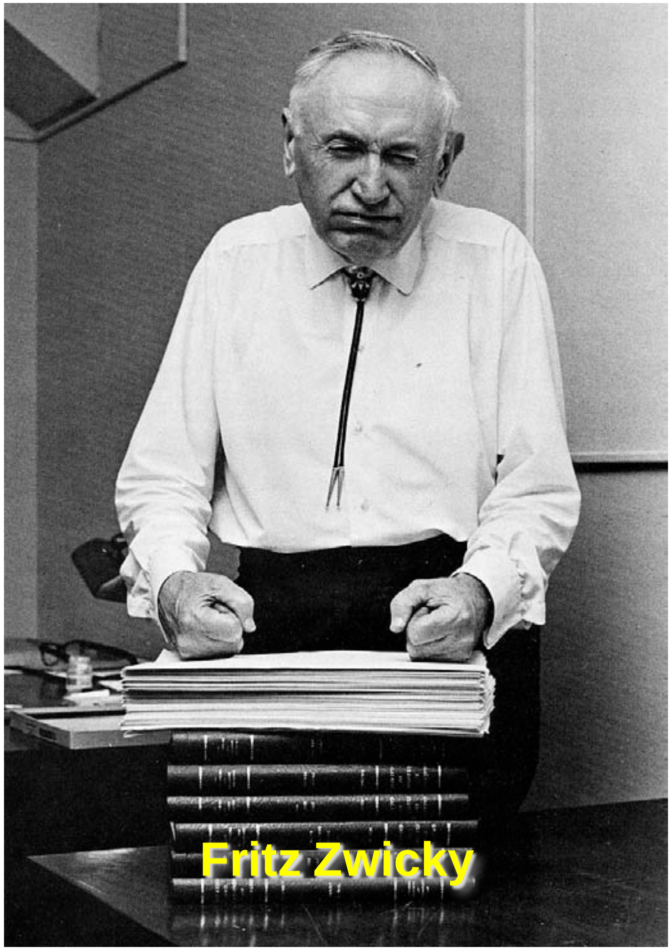
- PFS Science Vision
    - Cosmology (near and far)
    - Galaxy formation
    - Unforeseen science

- Status of PFS
    - Collaboration
    - Technical issues
    - Science planning

AIM: LOTS OF DISCUSSION – LESS FORMAL THAN HI-Z TALK!

Two rogue cosmic ingredients

Dark Matter (1933 -)



Dark Energy (1998 -)

HSC and PFS promise fabulous progress in years up to Euclid

Many Earlier Hints of a Cosmological Constant

1984: Turner, Steigman & Krauss and, independently, Peebles invoked Λ to reconcile data with inflation and age discrepancy between old stars and that suggested in a low density Universe

1990: Efstathiou, Sutherland & Maddox demonstrated clustering of galaxies in 2-D APM survey of 2. 10^6 galaxies was incompatible with SCDM (Ω=1), proposing ΛCDM model

1995: Ostriker & Steinhardt summed up observational constraints ahead of supernovae data arguing for consideration of a non-zero Λ

1998-9: Results from SCP and HiZ supernovae teams demonstrate accelerating Universe

1999: Mike Turner coins the term `dark energy'

Implications of Cosmic Acceleration

Why not Λ? two puzzles:

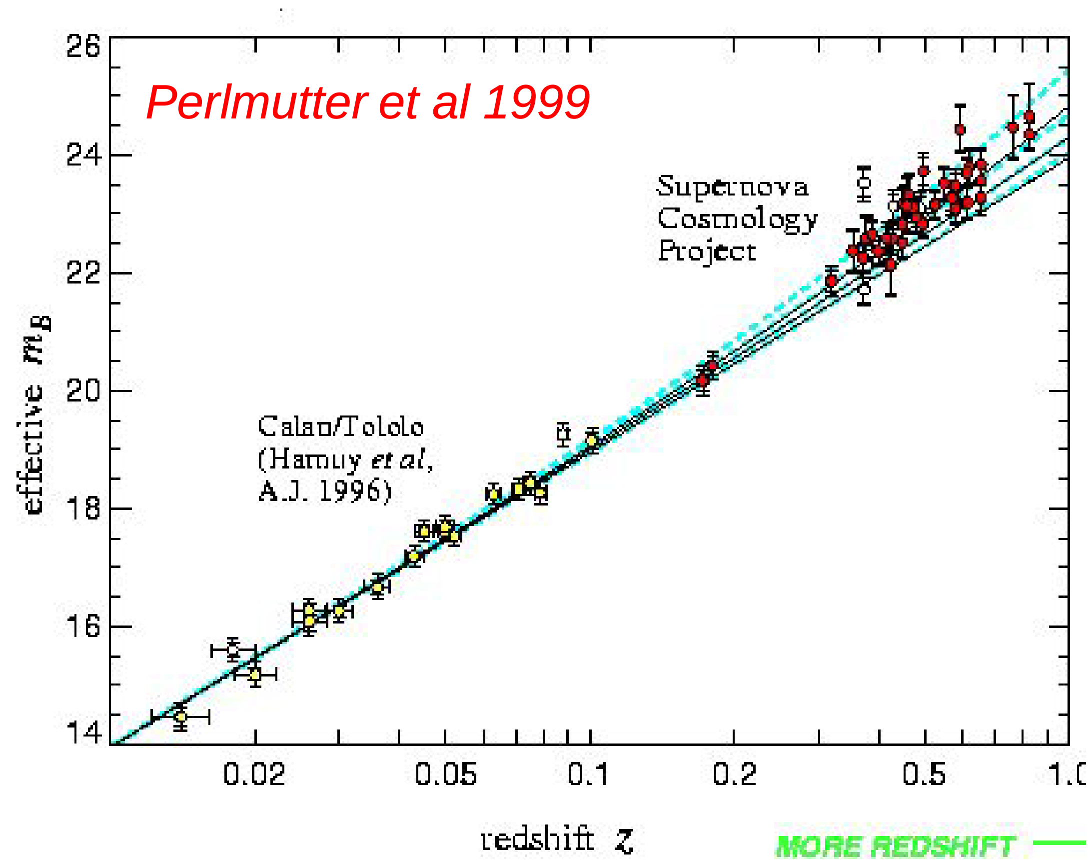
- Quantum field theory suggests $\Lambda = 8\pi G m_P^4$

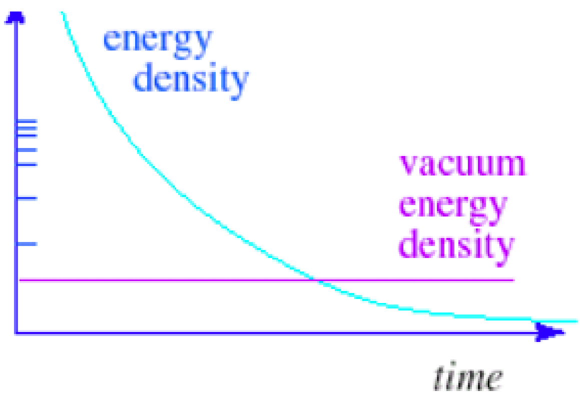
  (10^{120} larger than data)

- Why acceleration now?

  $\rho_M \propto R^{-3}$ (matter)

  ρ_{vac} = const (vacuum)





New physics: "dark energy"

- a scalar field: possibly time-dependent

- modification to GR gravity?

Characterizing Dark Energy as a Scalar Field

• Cosmic acceleration could be caused by a new property of space - a negative pressure p

• Can characterise its behaviour via the equation of state of the vacuum

$$p = f(\rho)$$

where ρ is the relevant energy density. The parameter w is introduced where

$$p / \rho = w$$

• Can view this as a theoretical generalisation of the cosmological constant Λ

$w = -1$ corresponds to a cosmological constant

$w < -1/3$ required for acceleration today

• Why should w be time-invariant? Perhaps it evolves e.g.

$$w(t) = w_o + w_a (1 - a(t))$$

Consumer's Guide to Observing Dark Energy

The Popular Methods

- Type Ia Supernovae: $d_L(z)$ to $z \sim 2$
  - Most well-developed and ongoing with rich datasets
  - Key issue is physics/evol^n: *do we understand SNe Ia?*
- Weak lensing: G(t) to $z \sim 1.5$
  - Less well-developed; ground vs space, needs photo-z's
  - Key issues are *fidelity, calibration*
- Baryon "wiggles": $d_A(z)$, H(z) to $z \sim 3$
  - Late developer: cleanest *requiring huge surveys*

See US DETF (Kolb et al) & ESA-ESO reports (Peacock et al).

Method I: Supernova Surveys

First generation surveys:

- Supernova Cosmology Project (Perlmutter et al 99)
- Hi Z Supernova Project (Riess et al 98)
- Extensions using HST (Knop et al 03, Riess et al 04)

Second generation surveys:

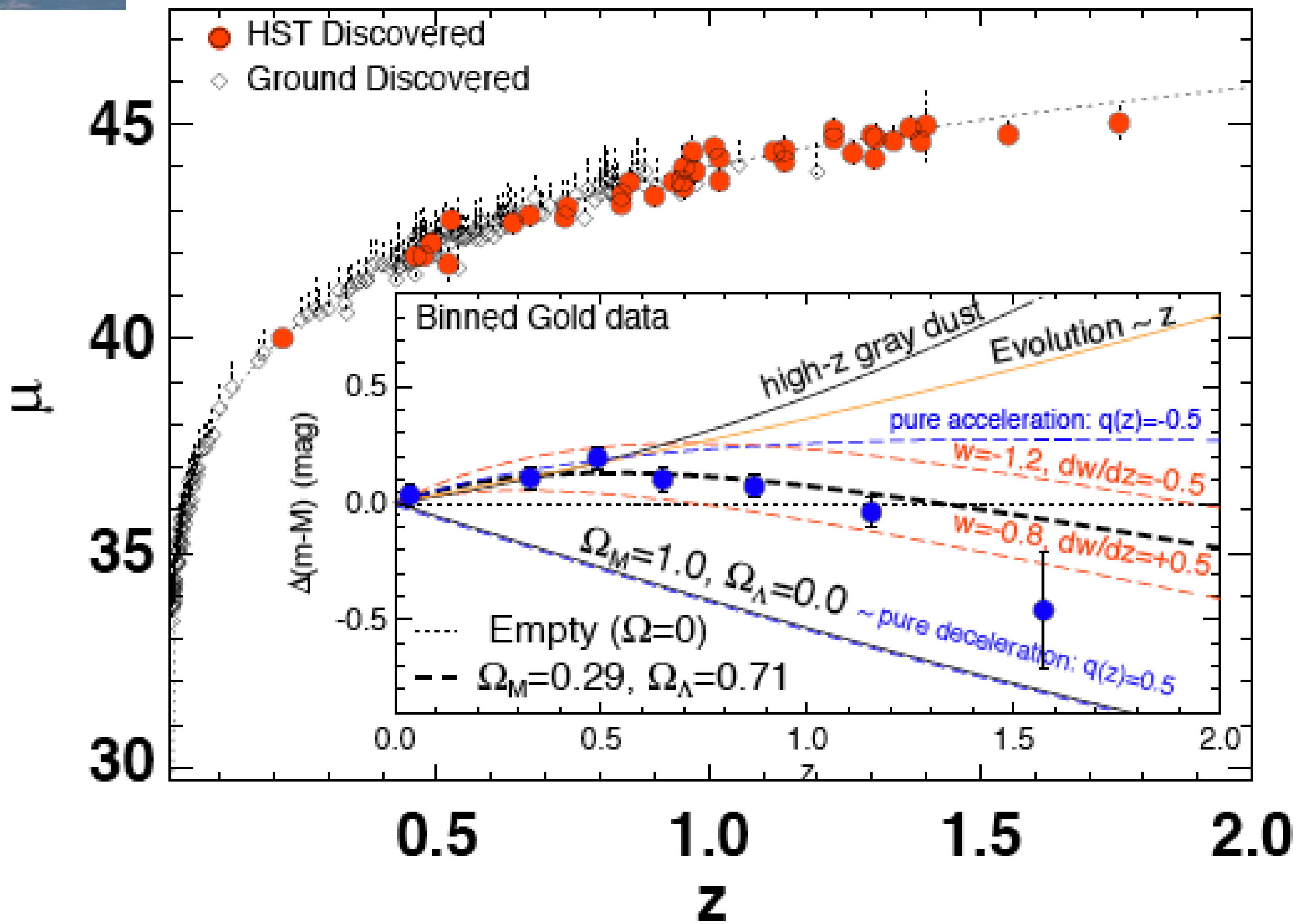
- CFHT SN Legacy Survey (Astier et al 06, Conley/Sulllivan et al 11)
- ESSENCE project (Woods-Vasey et al 07, Foley et al 09)
- Carnegie IR survey (Freedman et al 09, Stritzinger et al 11)
- HST: z > 1 clusters (Suzuki et al 11), deep fields (Riess et al 07)
- Intermediate depth: SDSS2 (Kessler et al 09)

Fundamental Issues:

- Progenitor physics: evolution, host galaxy dependencies etc
- Dust extinction, photometric calibration

Might there be a systematic floor in the use of SNe in precision studies?

Deep GOODS Survey

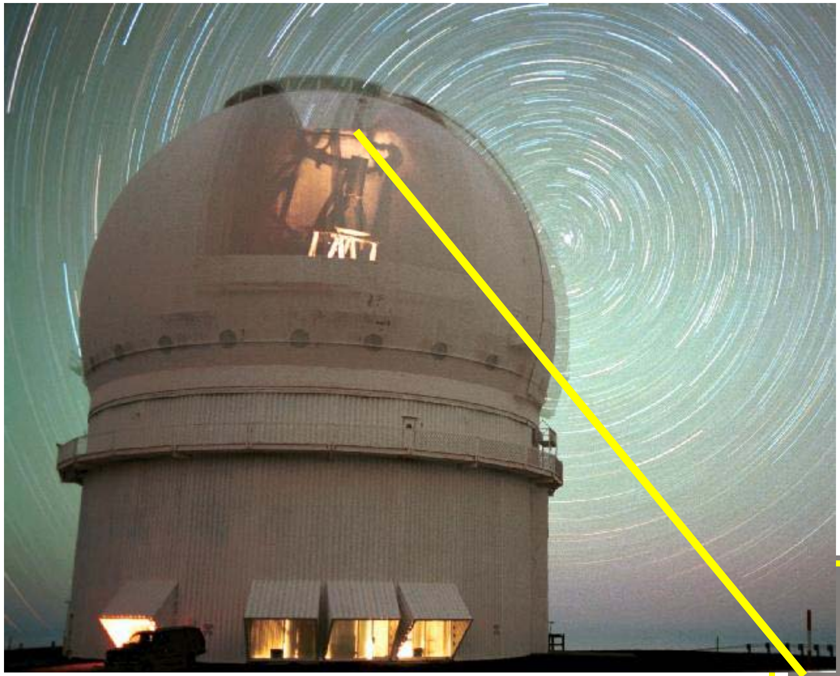


23 HST SNe Ia with z > 1; w < 0 (98% confidence)

Claim to witness decelerating era remains controversial

Riess et al Ap J 659, 98 (2007)

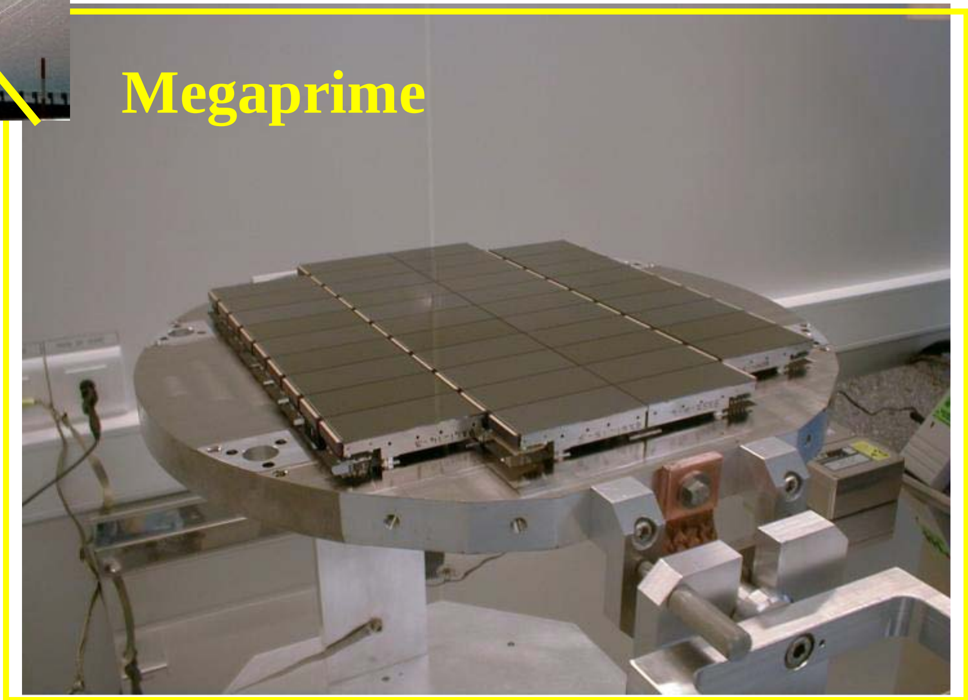
CFHT Legacy Survey (2003-2008)



Deep Synoptic Survey

`Rolling search’

Four 1 × 1 deg fields in ugriz
5 nights/lunation
5 months per accessible field
2000 SNe 0.3 < z < 1



<u>Caltech role: verify utility of SNe for cosmology</u>

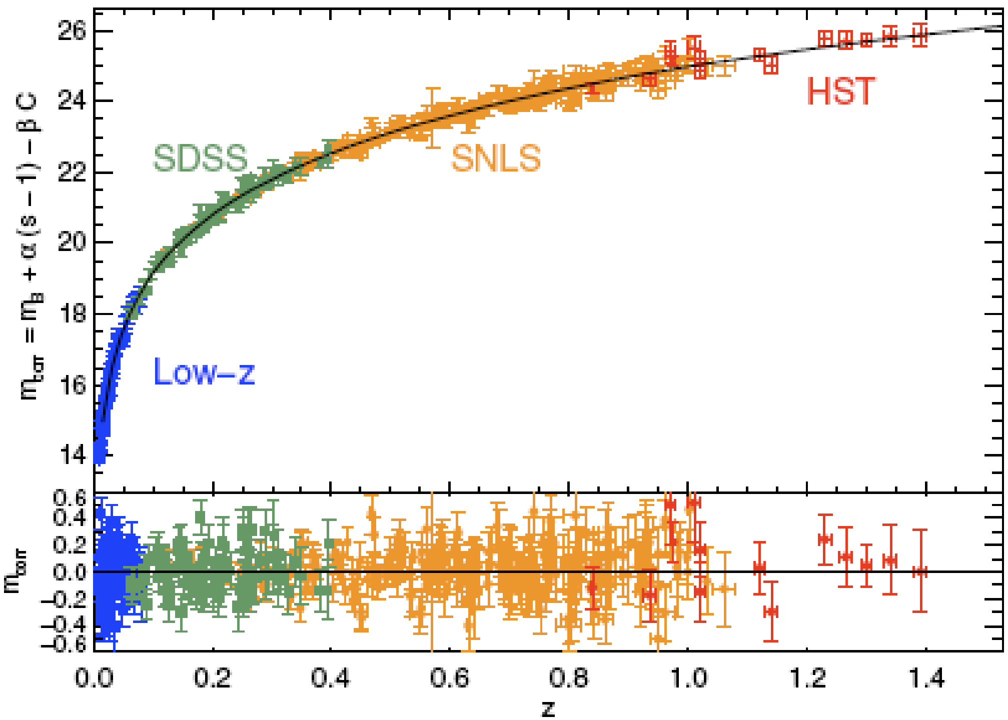
Sullivan+Nugent+RSE

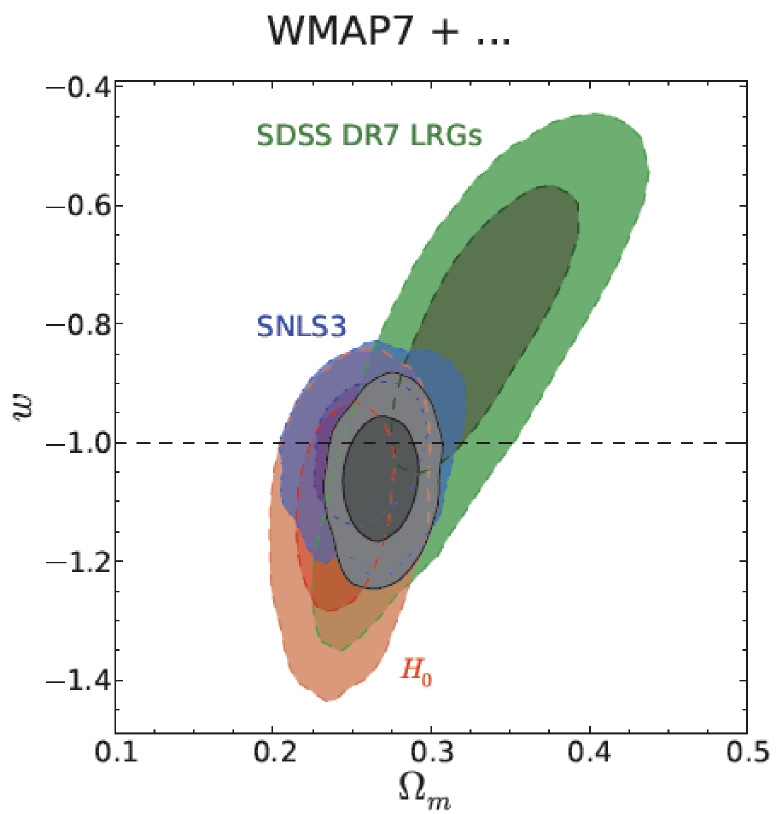
Detailed spectral followup of 0.4<z<0.7 SNe Ia

HST studies of local SNe Ia

State of the Art in DE – SNLS

Precision study of 472 intermediate redshift SNe Ia





$\Omega_m = 0.269 \pm 0.015$ and $w = -1.061^{+0.069}_{-0.068}$ (including systematics)

Systematic errors ≈ statistical errors

Systematic errors dominated by photometric calibration; if this could be fixed Δw~2%!

Conley et al (2011); Sullivan et al (2011)

Systematic Errors (SNLS)

Description	Ω_m	w	Rel. Area [a]	w for $\Omega_m = 0.27$	Section
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058	
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85	$-1.08^{+0.10}_{-0.11}$	Section 4.4
Calibration	$0.191^{+0.095}_{-0.104}$	$-0.92^{+0.17}_{-0.23}$	1.79	-1.06 ± 0.10	Section 5.1
SN model	$0.195^{+0.086}_{-0.101}$	$-0.90^{+0.16}_{-0.20}$	1.02	-1.027 ± 0.059	Section 5.2
Peculiar velocities	$0.197^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.03	-1.034 ± 0.059	Section 5.3
Malmquist bias	$0.198^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.07	-1.037 ± 0.060	Section 5.4
Non-Ia contamination	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058	Section 5.5
MW extinction correction	$0.196^{+0.084}_{-0.100}$	$-0.90^{+0.16}_{-0.20}$	1.05	-1.032 ± 0.060	Section 5.6
SN evolution	$0.185^{+0.088}_{-0.099}$	$-0.88^{+0.15}_{-0.20}$	1.02	-1.028 ± 0.059	Section 5.7
Host relation	$0.198^{+0.085}_{-0.102}$	$-0.91^{+0.16}_{-0.21}$	1.08	-1.034 ± 0.061	Section 5.8

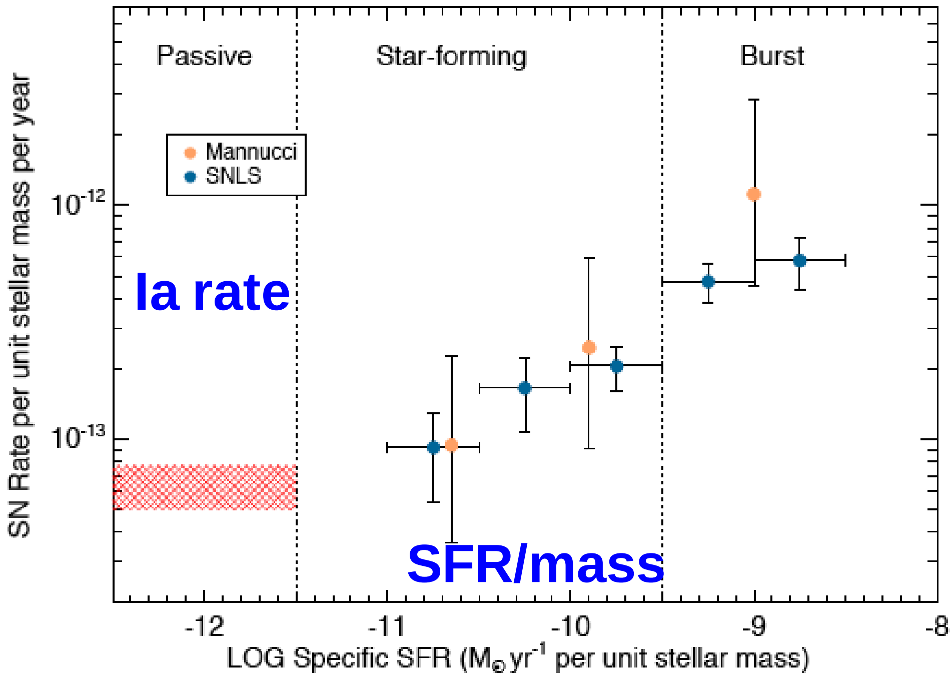
Table 9
Calibration Systematics

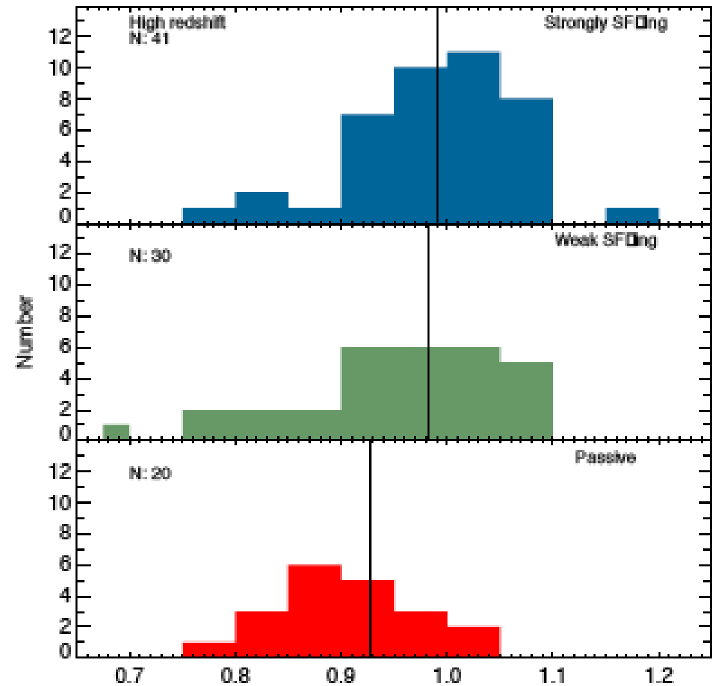
Description	w for $\Omega_m = 0.27$	Rel. Area	Section
Stat only	-1.031 ± 0.058	1	
All calibration	-1.06 ± 0.10	1.79	Section 5.1
Colors of BD 17° 4708	-1.075 ± 0.075	1.31	Section 5.1.7
SED of BD 17° 4708	-1.026 ± 0.073	1.23	Section 5.1.8
SNLS zero points	-1.030 ± 0.069	1.21	Section 5.1.1
Low-z zero points	-1.044 ± 0.065	1.13	Section 5.1.2
SDSS zero points	-1.028 ± 0.060	1.02	Section 5.1.4
MegaCam bandpasses	-1.017 ± 0.066	1.20	Section 5.1.5
Low-z bandpasses	-1.027 ± 0.059	1.04	Section 5.1.6
SDSS bandpasses	-1.026 ± 0.059	1.02	Section 5.1.6
HST zero points	-1.027 ± 0.058	1.03	Section 5.1.3
NICMOS nonlinearity	-1.029 ± 0.059	1.05	Section 5.1.3

The limiting precision is (arguably) not the number of distant SNe but primarily a self-consistent photometric calibration and poorly-understood host-dependencies

Conley et al (2011)

SNe Ia Properties Depend on Host Galaxy - I





stretch

SN Ia rate correlates with specific star formation rate of host

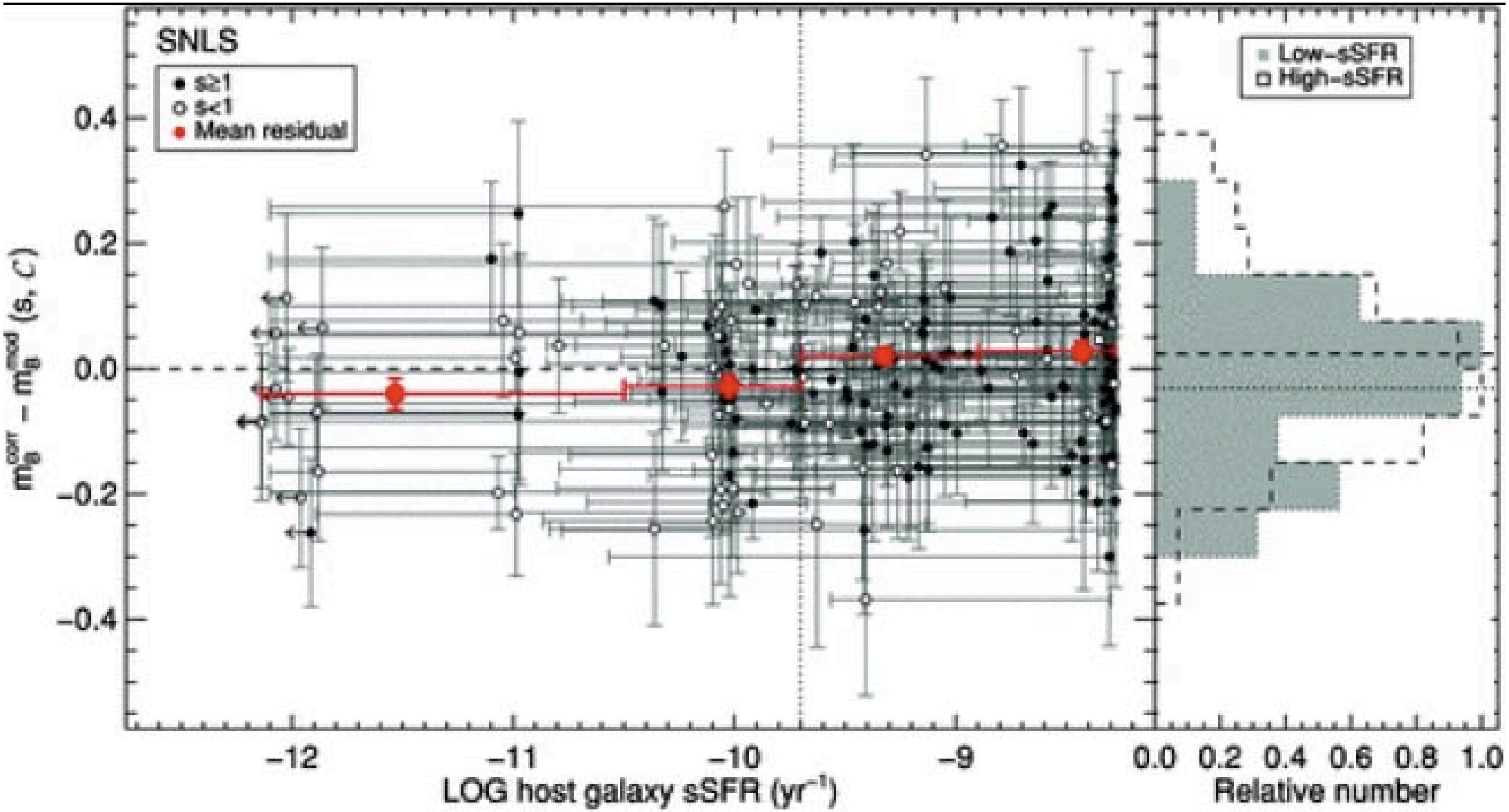
Light curve `stretch' likewise correlates

SN properties depend on mix of stellar population and hence redshift

Sullivan et al Ap J 648, 868 (2006)

Redshift bias predicted & <u>observed:</u> Howell et al Ap J 667, L37 (2007)

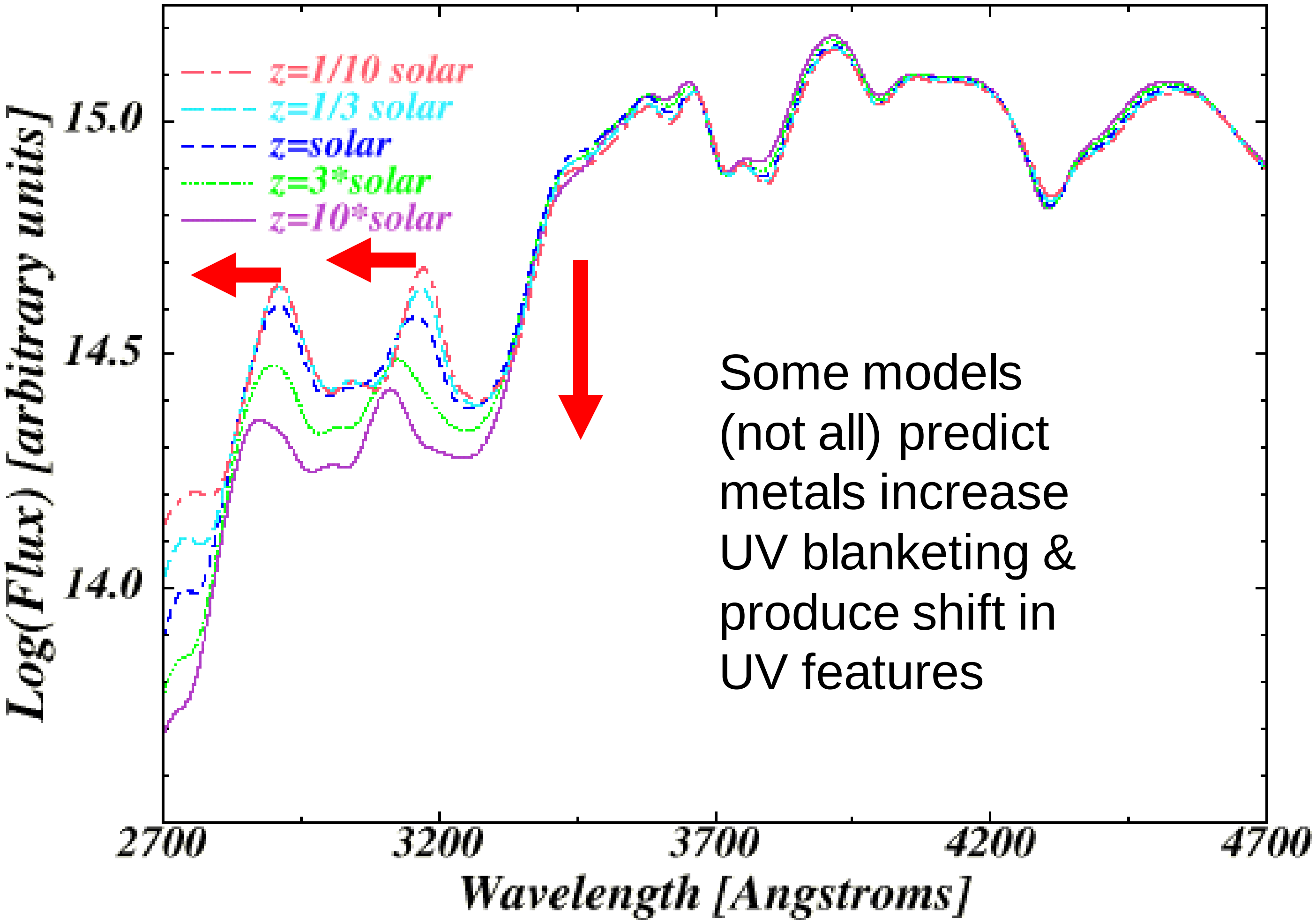
SNe Ia Properties Depend on Host Galaxy - II



Even allowing for a stretch and color correction (S,C), Sullivan et al argue there is a higher order dependence of SN Ia luminosity on the host specific SFR. Including this reduces Hubble diagram scatter but its physical origin is unclear!

Sullivan et al (2010)

Do SNe Ia Evolve? UV Probes Metallicity

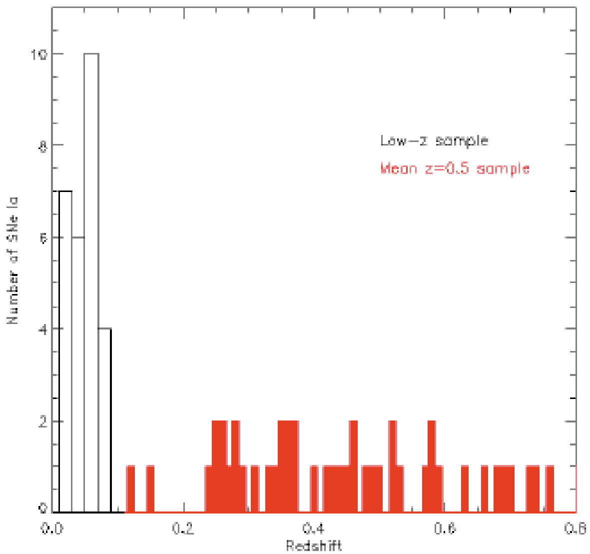


Some models (not all) predict metals increase UV blanketing & produce shift in UV features

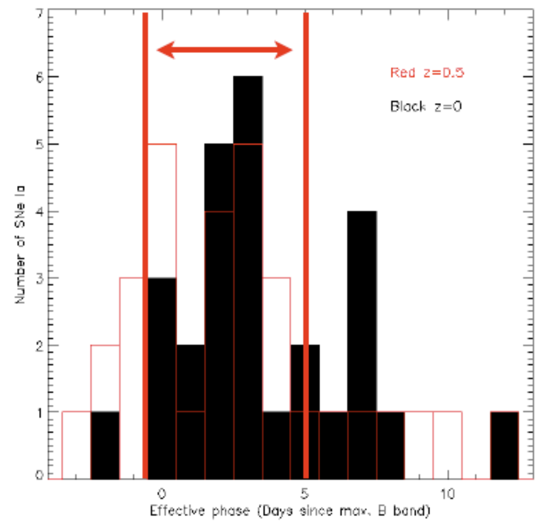
UV dependence expected from deflagration models when metallicity is varied in outermost C+O layers (Lenz et al Ap J 530, 966, 2000)

UV Evolution in SNe Ia? Update

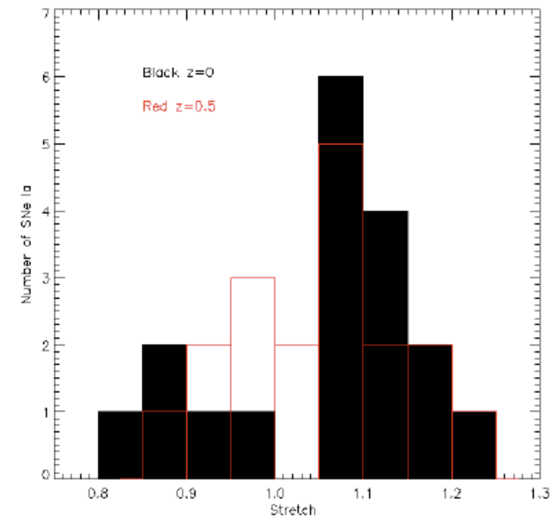
Redshift



Phase

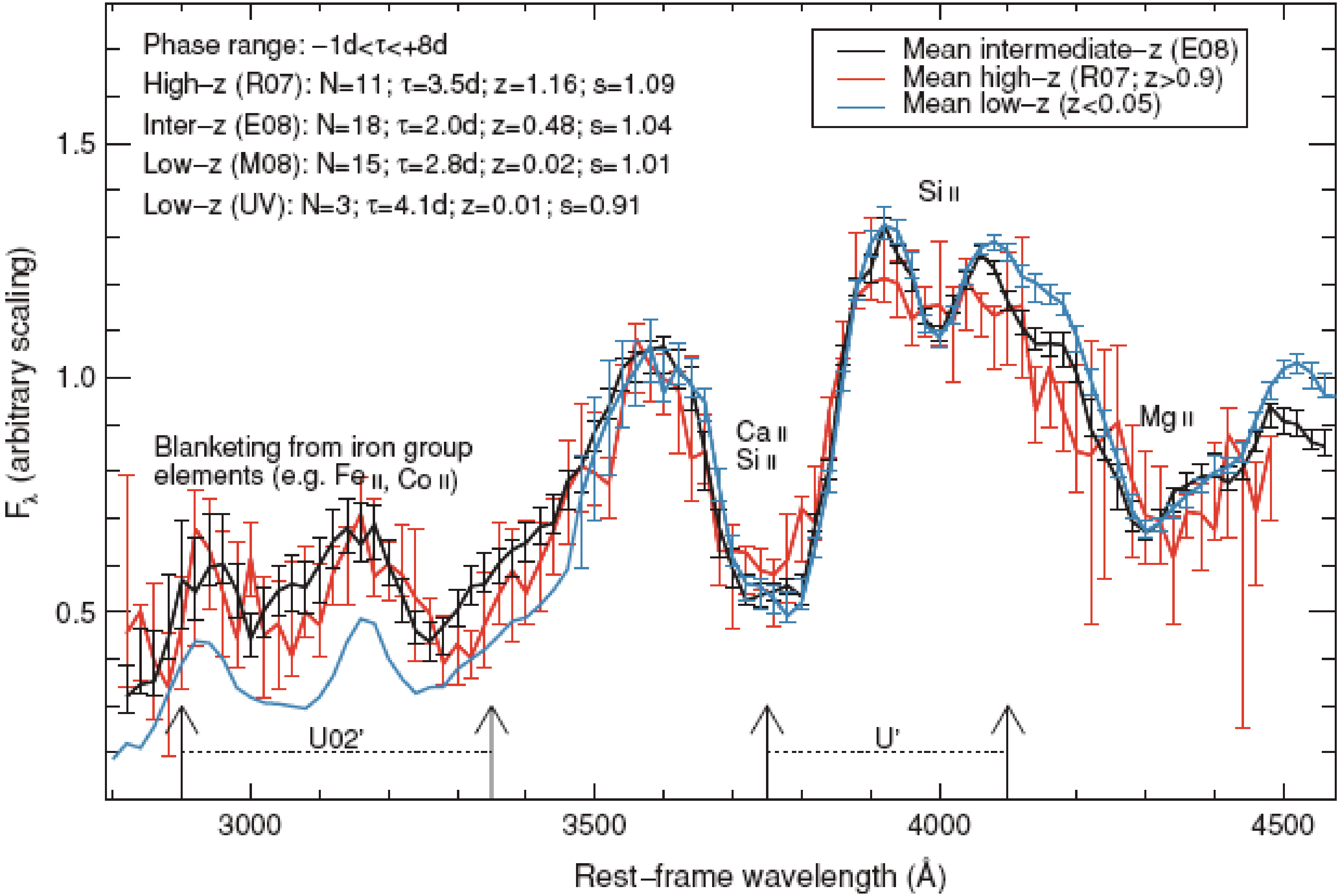


Stretch



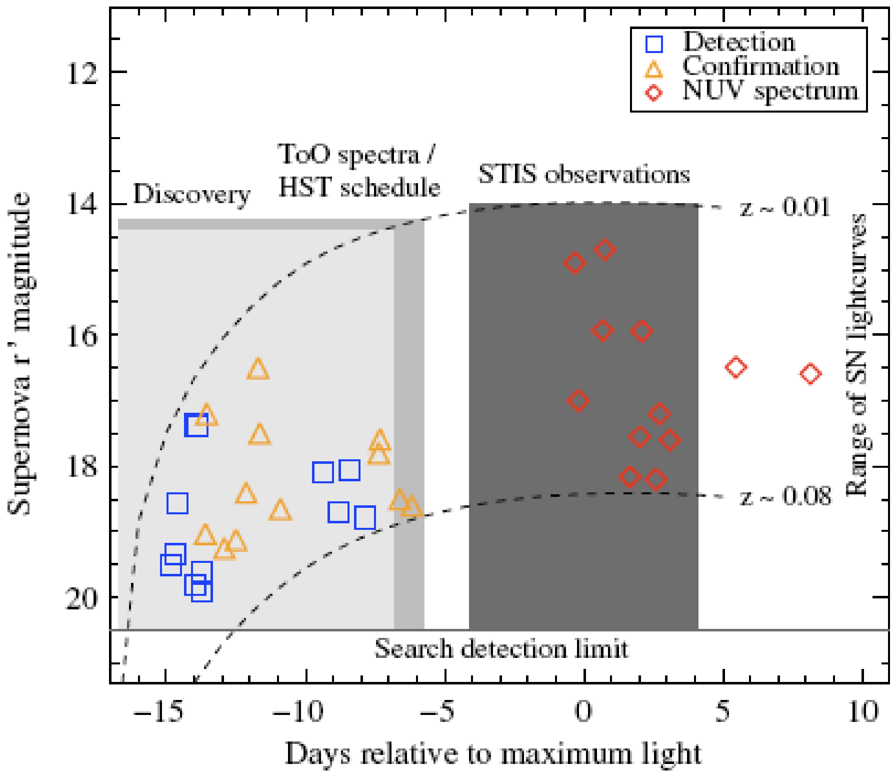
- Ellis et al (2008) – Keck rest-frame UV spectra for 36 z~0.5 SNLS SNe Ia
- Sullivan et al (2009) – comparison with 11 Riess et al z>1 HST grism spectra
- Cooke et al (2011) – comparison with 12 local HST STIS UV spectra
- Maguire et al (in prep) – increased sample to 28 local HST STIS UV spectra

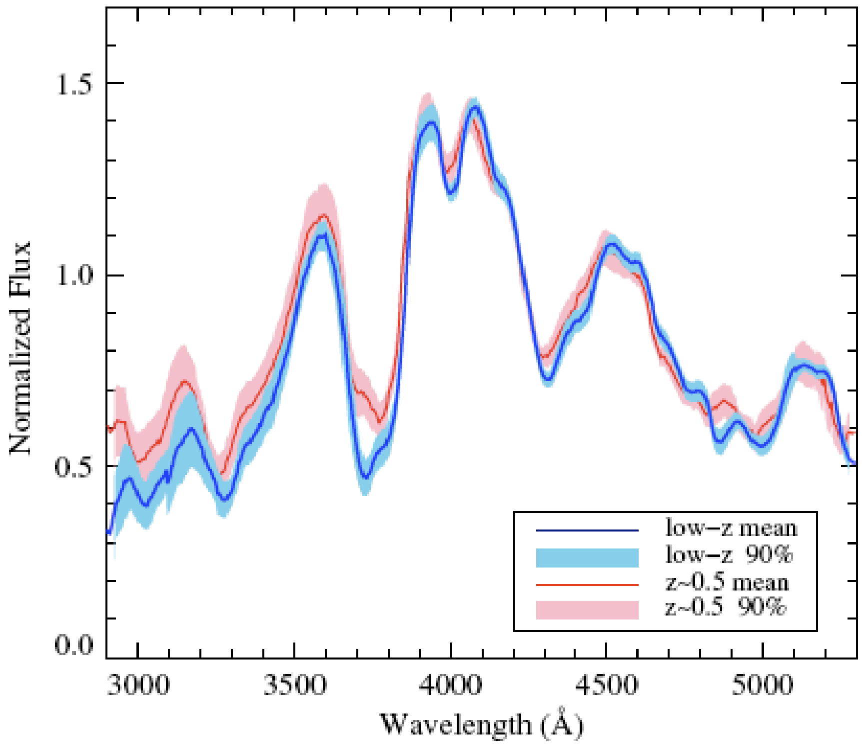
Early Comparison (0.5 < z < 1.2)



Sullivan et al (2009)

Initial HST STIS – Keck Comparison 0 < z < 0.5



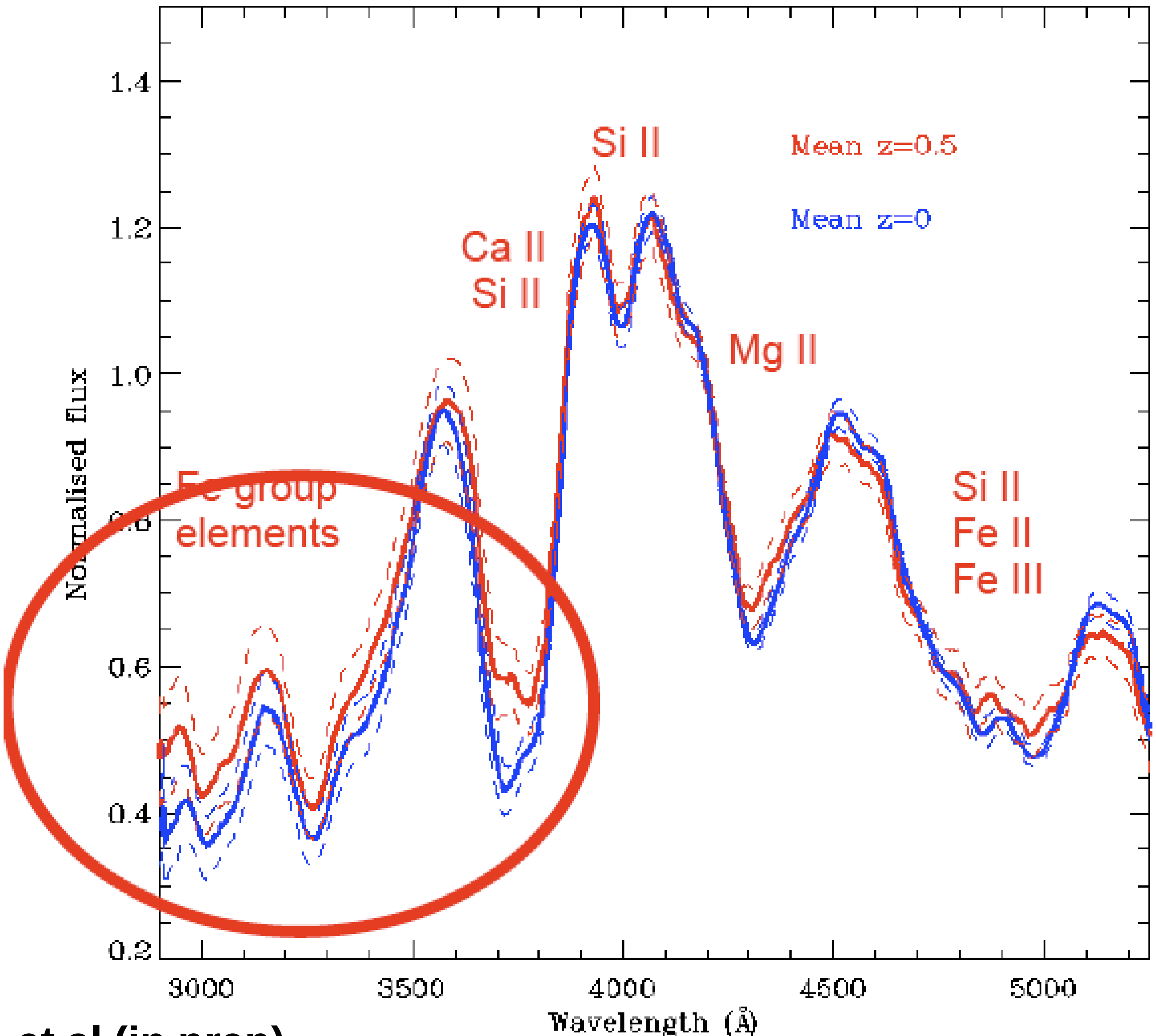


Palomar Transient Factory (PTF) revolutionizes early discovery of SNe Ia so that HST can be triggered in time for UV maximum light spectrum

Initial comparison of 12 local UV spectra with z~0.5 Keck sample shows tantalizing differences!

Cooke et al (2011)

Latest Results $0<z<0.5$: Preliminary

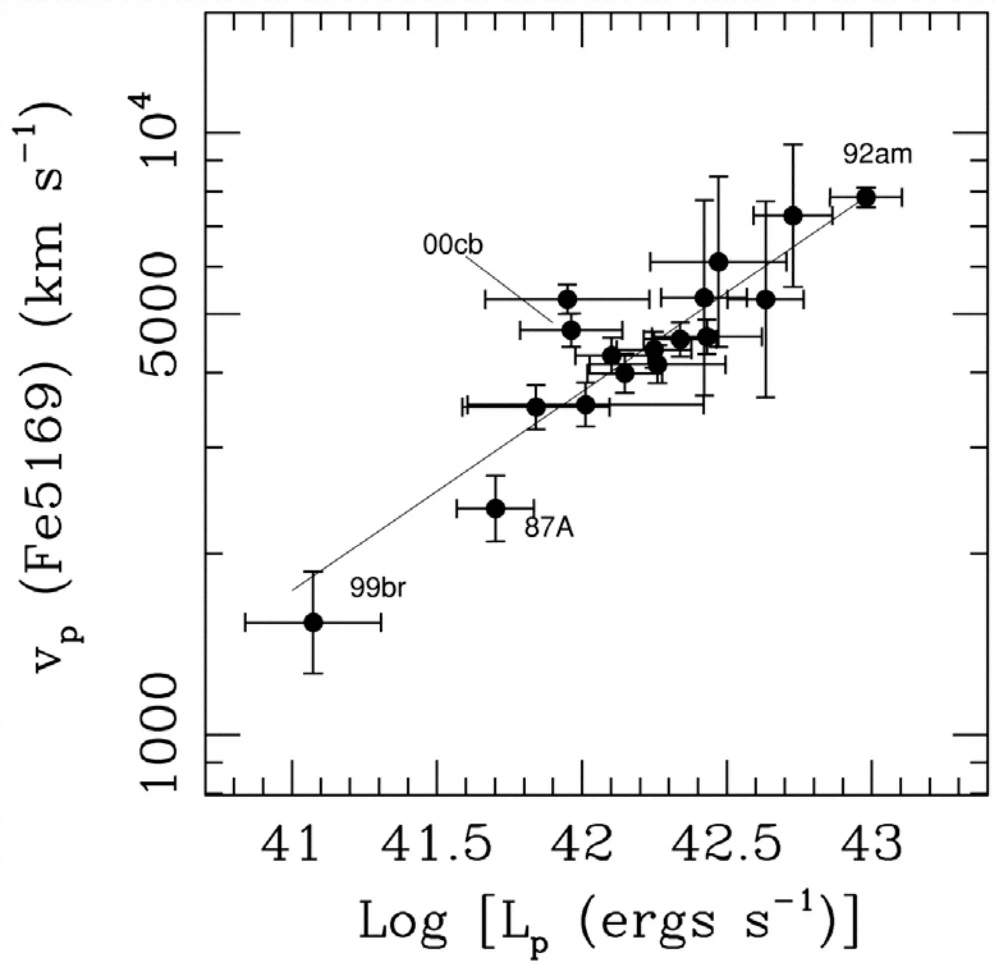


Maguire et al (in prep)

New Ideas - I: Cosmology from SNe IIP?

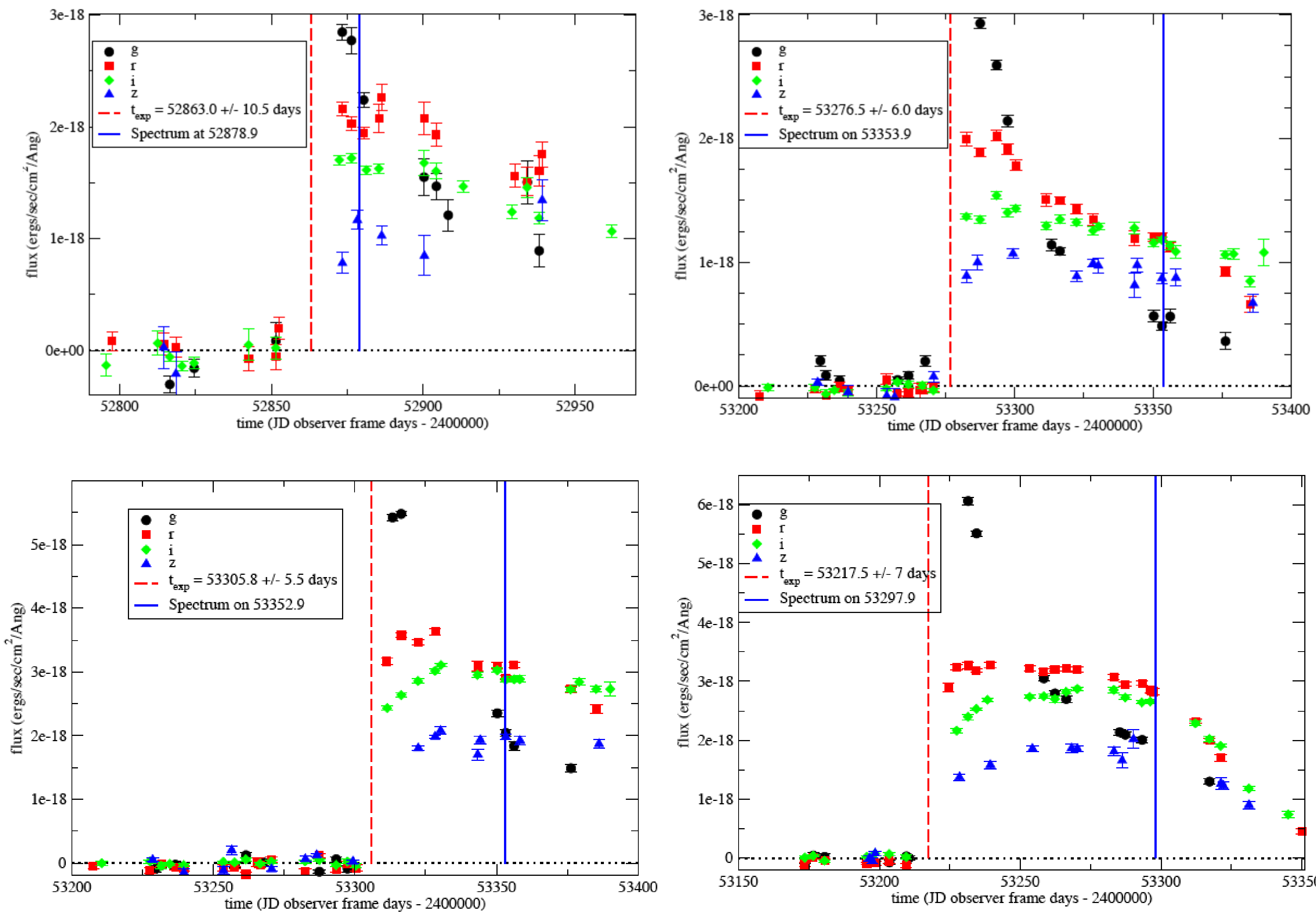
Hamuy & Pinto (2002) propose a new "empirical" correlation (0.29 mag, 15% in distance) between the expansion velocity on the plateau phase and the bolometric luminosity with reddening deduced from colors at the end of plateau phase.

Ultimately the Hubble diagram of SNe IIP could provide an independent verification of the cosmic acceleration, but more importantly be more promising probe of dark energy with JWST/TMT/E-ELT

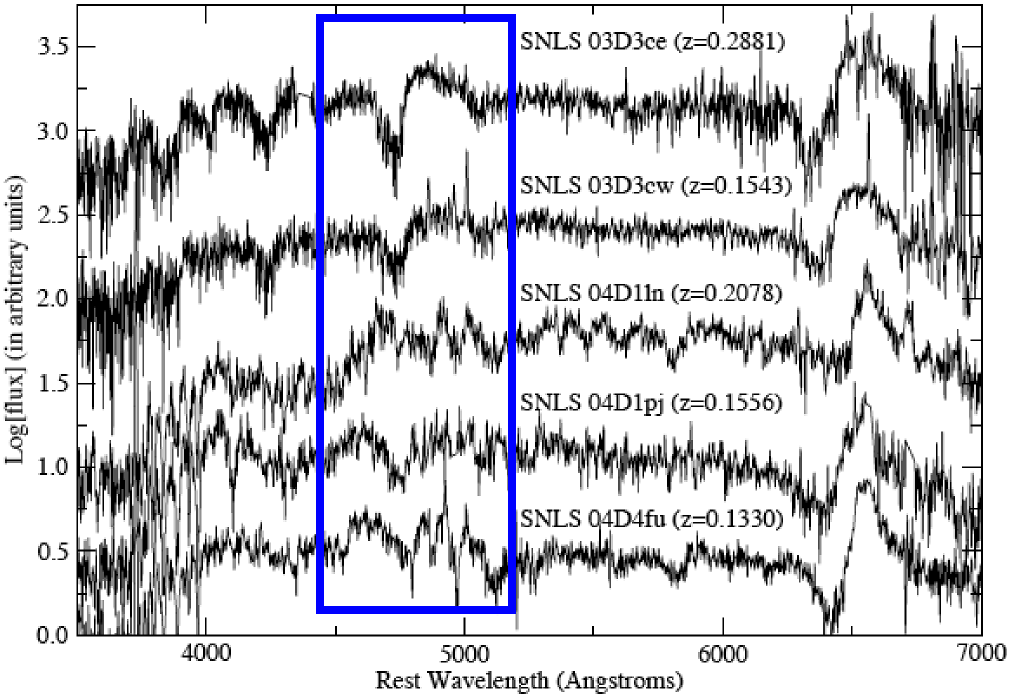


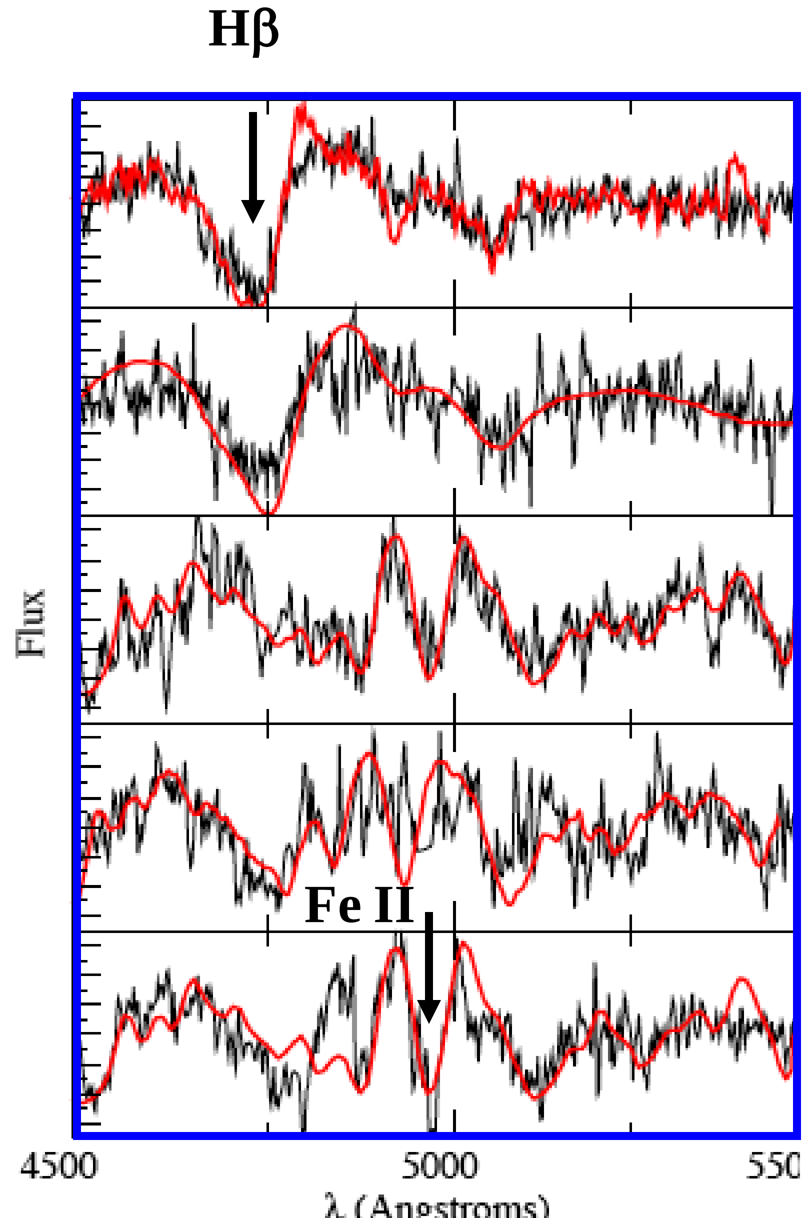
Nugent et al Ap J 645, 841 (2006)

SNLS Type IIP Multicolor Light Curves



Keck Spectra of z~0.3 SNe IIP

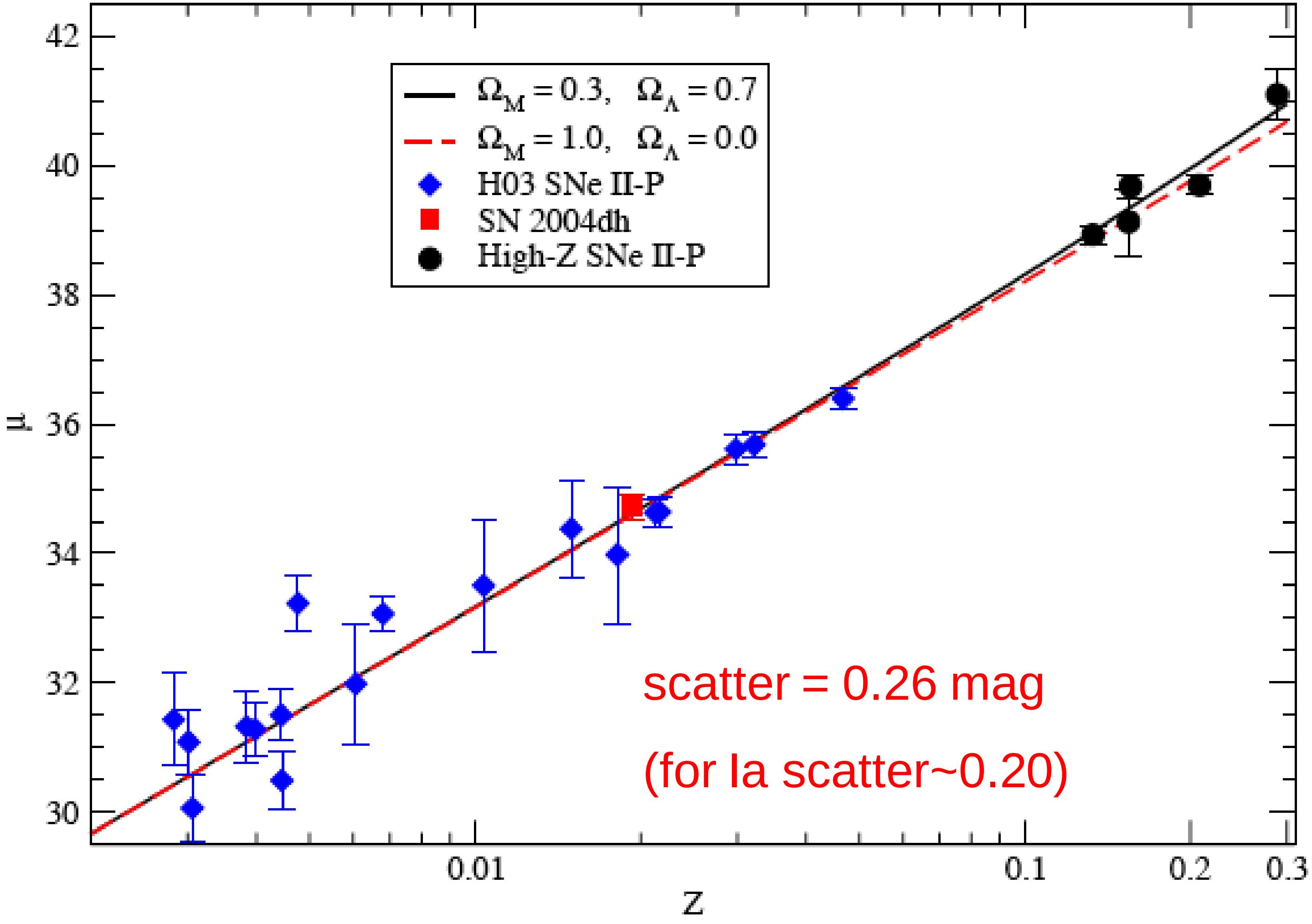




2-3 hour LRIS integrations

Expansion velocities on plateau phase inferred via cross-correlation with Hβ and FeII dominated spectra of local SNeIIP in SUSPECT database

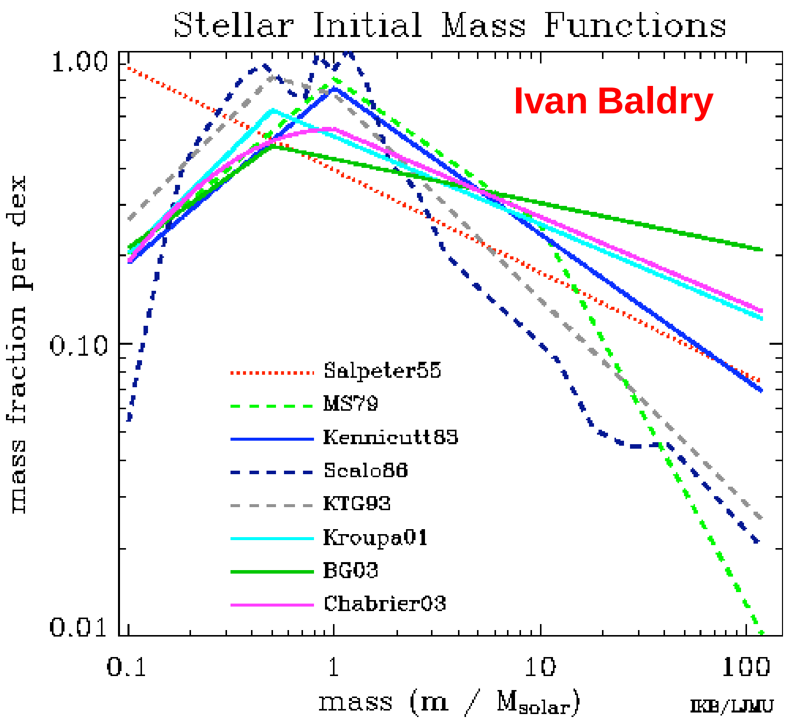
Proof of Concept: Hubble Diagram for SNe IIP

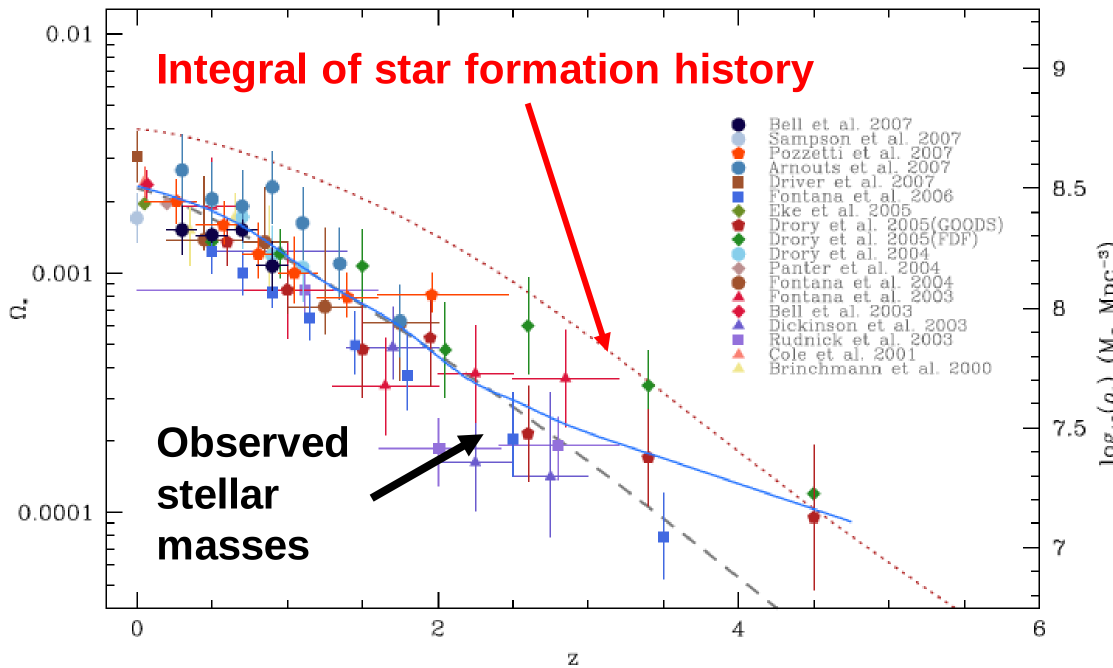


Could detect acceleration with present technology (~15 SNIIP)

More effectively probe to high z with JWST/TMT (Nugent et al 2006)

New Ideas - II: Testing IMF via z>2 SNe IIN?



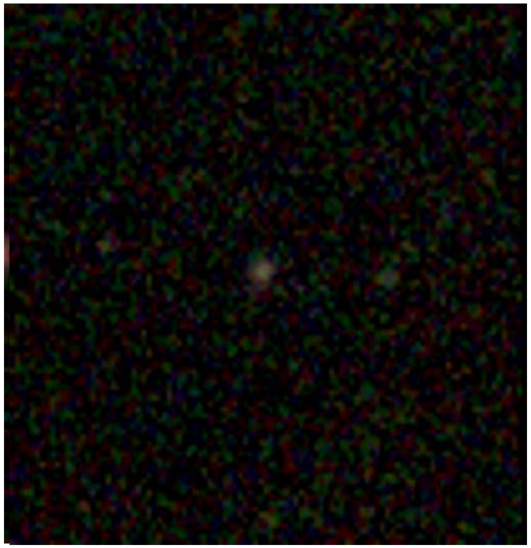


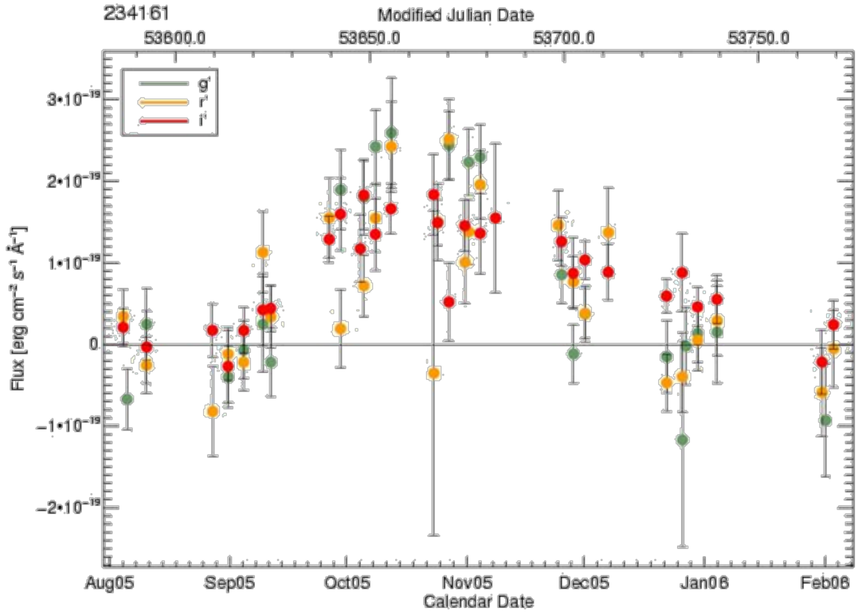
Various workers have proposed top-heavy IMF to explain:

- intense SF in high z galaxies (Baugh et al 2005)
- mismatch between integral of SF and assembled stellar mass (Wilkins et al 2008)

Determining Rate of SNIIN 2<z<3 (M > 40-60$M_\odot$?)

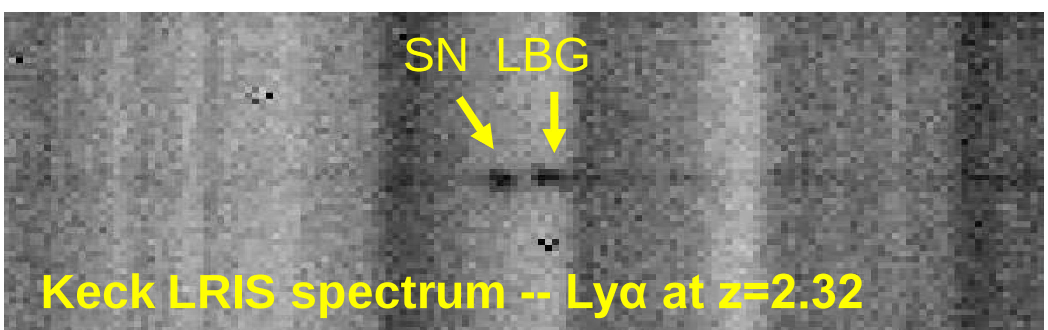
UV luminosity density of searched LBGs c.f. # of SNIIn – tests IMF slope





SNLS light curve

g_{max}= 25.7
r_{max}= 25.2
$i_{,max}$= 25.1



	z
SN234161	2.013
SN58306	2.187
SN23222	2.231
SN19941	2.357
SN165699	2.364
SN57260	3.028*

Cooke, RSE et al

SNe Ia Summary

• A single parameter (stretch/luminosity) is clearly inadequate as a description of the Ia population

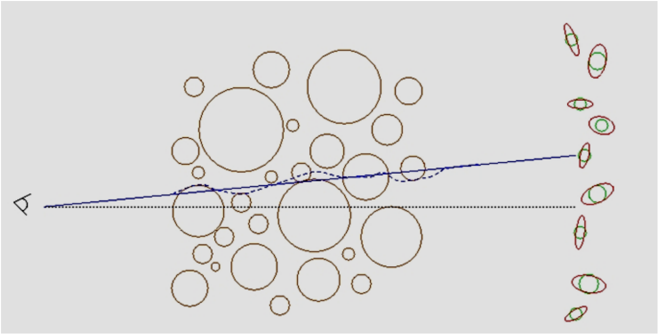
• Host galaxy dependencies are complex. They could signify **more than one progenitor mechanism** whose mix will change with z. The current light curve shape correction may not correct such biases to the 0.02 mag level at $z > 1$

• UV evolution/dispersion results represent **additional complications**. Until understood, these may represent more biases, especially at $z > 1$

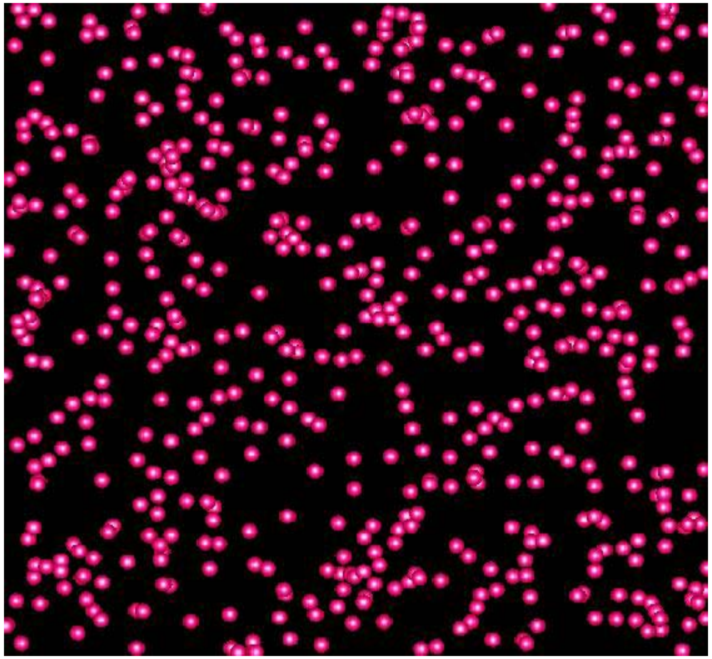
• We should be prepared for a **<u>systematic floor</u>** in precision of using SNe for dark energy studies: probably doesn't affect current usage ($\delta w \sim \pm 0.05$) but suggests more work before investing in precision SNe work with future missions

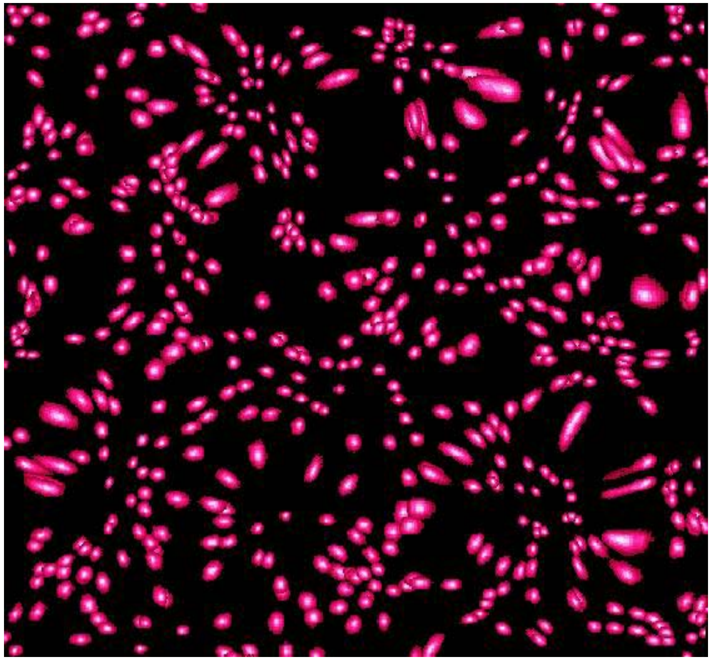
• Improved instrumentation on Subaru offers new opportunities for high z SNe but **<u>spectroscopic follow-up</u>** is always the bottleneck

Method II- Weak Gravitational Lensing



Intervening dark matter distorts the pattern: various probes: shear-shear, g-shear etc





Unlensed

Lensed

Contrasting Distance & Growth-based Methods: I

Friedmann equation gives us epoch-dependent Hubble parameter which defines expansion history:

$$H^2(a) = H_0^2 \left[\Omega_v e^{\int -3(w(a)+1)\, d\ln a} + \Omega_m a^{-3} + \Omega_r a^{-4} - (\Omega - 1) a^{-2} \right]$$

This can be observed in two ways:

(i) geometry via comoving distance-redshift relation (e.g. SNe)

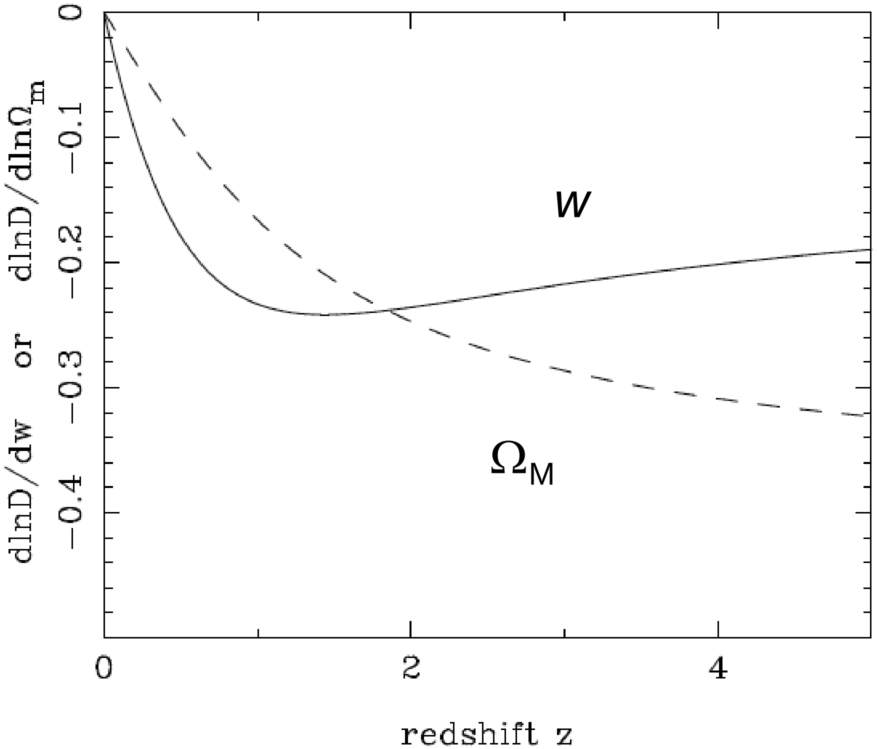
$$dD/dz = c/H(z).$$

(ii) effect on growth of density inhomogeneities (e.g. weak lensing)

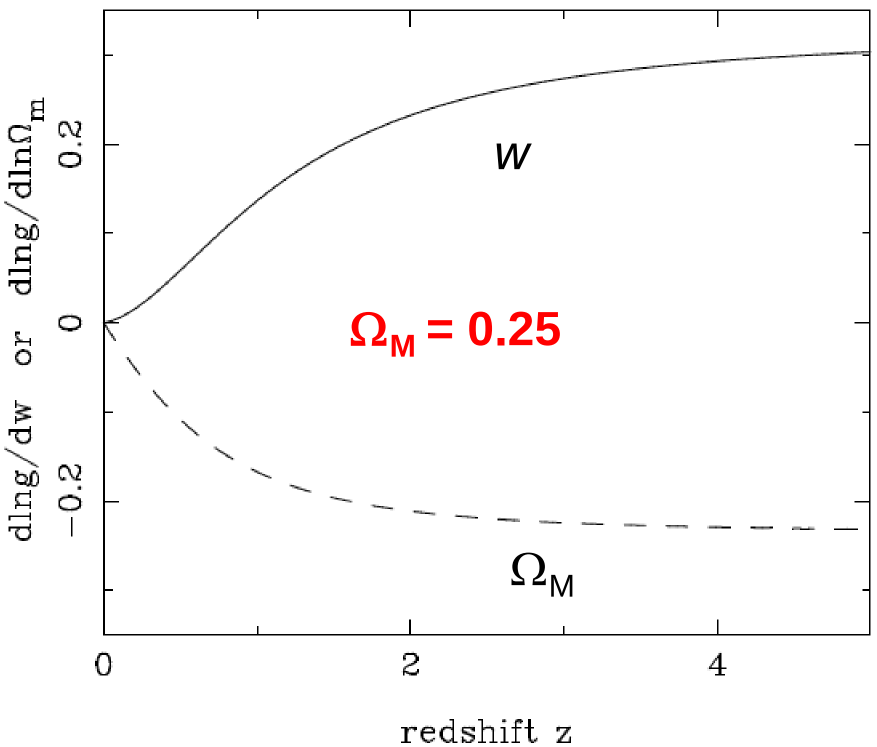
$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = \delta \left(4\pi G \rho_0 - c_s^2 k^2 / a^2 \right)$$

Contrasting Distance & Growth-based Methods: II

dlnD/dw



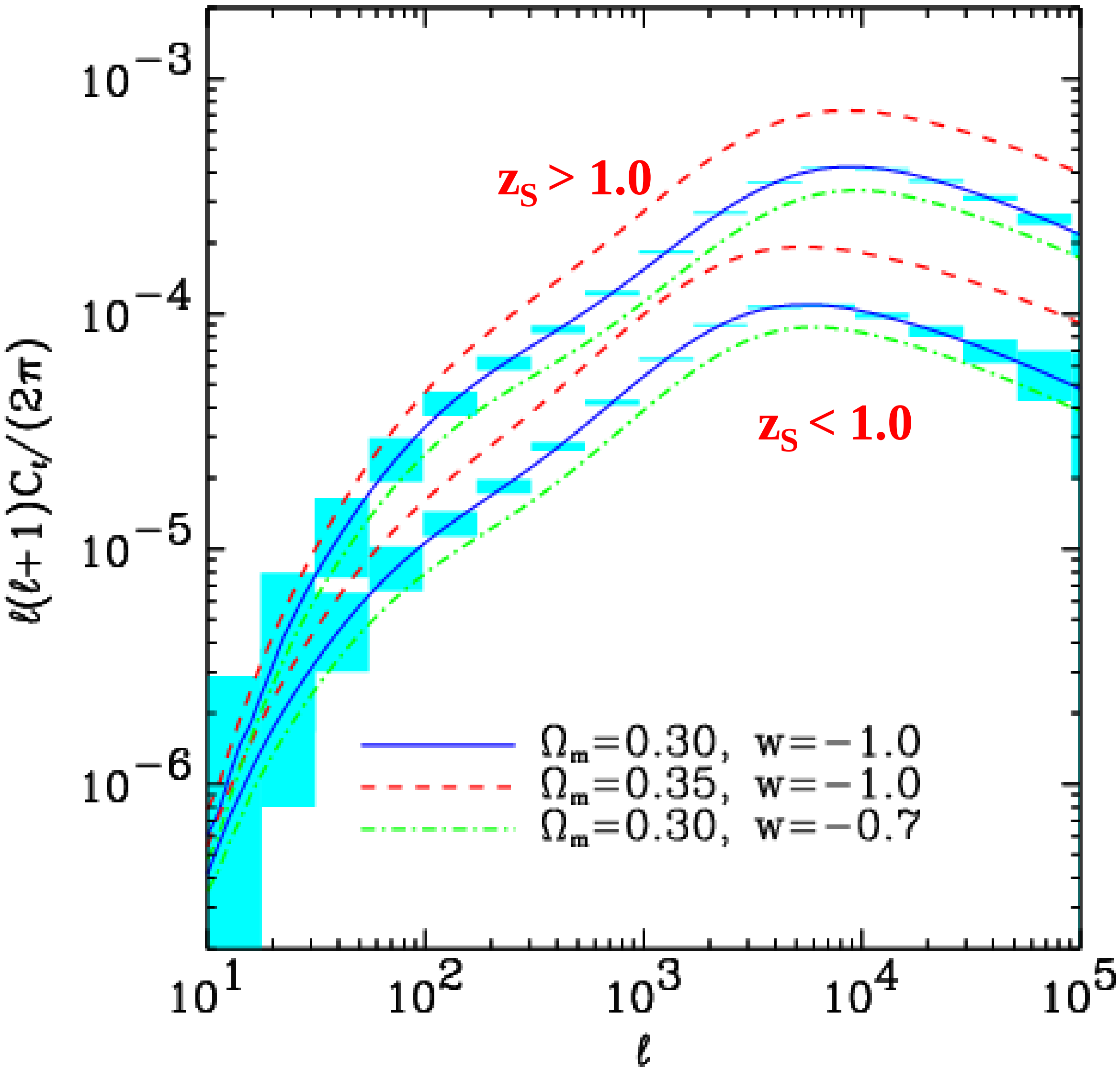
dlng/dw



D(z): not v. sensitive to *w*: 1% precision requires D to 0.2%
also *w* degenerate with changes in Ω_M

g(z): *w* has opposite effect to Ω_M
but relevant methods less well-developed

Evolution of the DM Power Spectrum



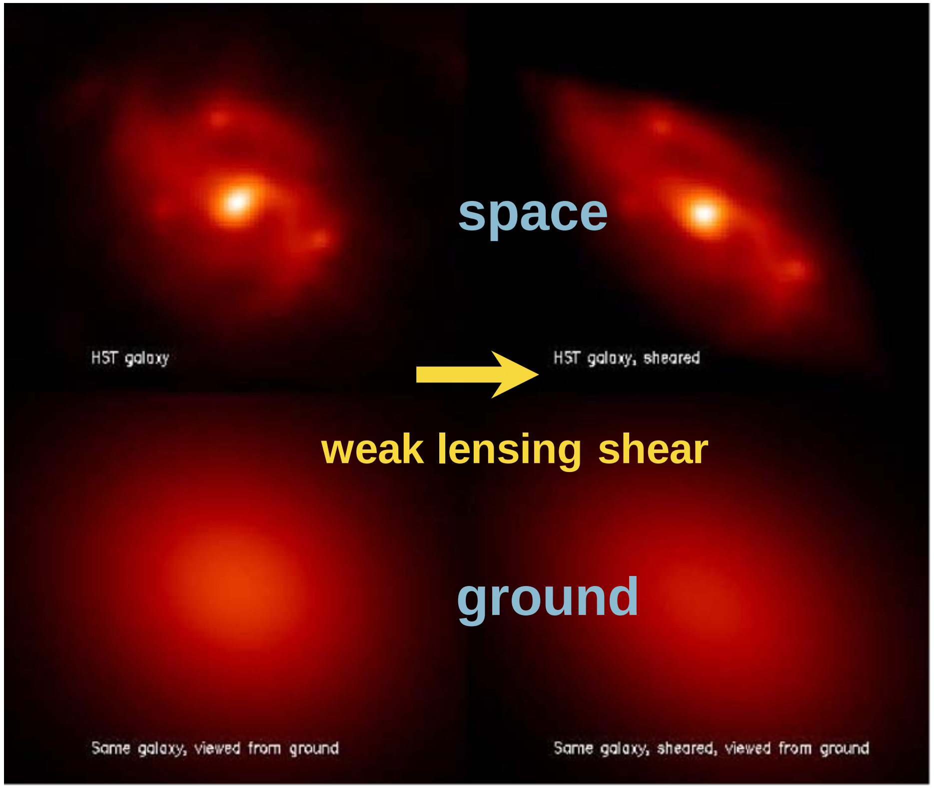
Growth of DM power spectrum is sensitive to dark energy and *w*.

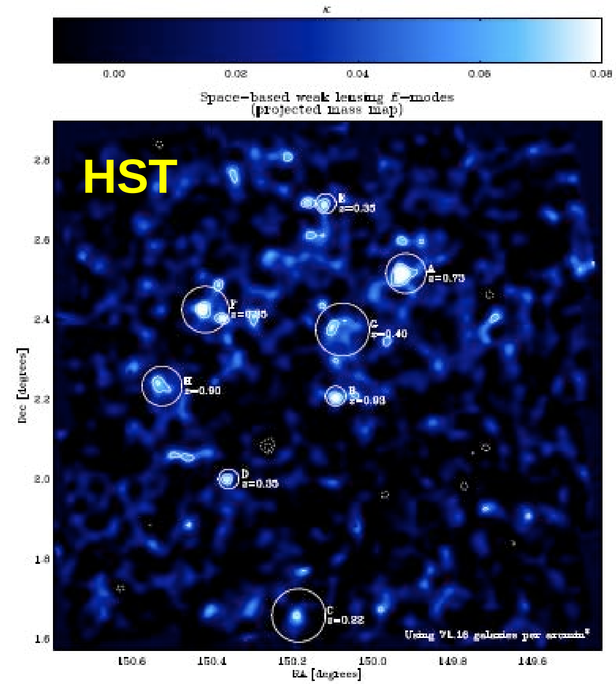
Via redshift binning of background galaxies, can constrain *w* independently of SNe

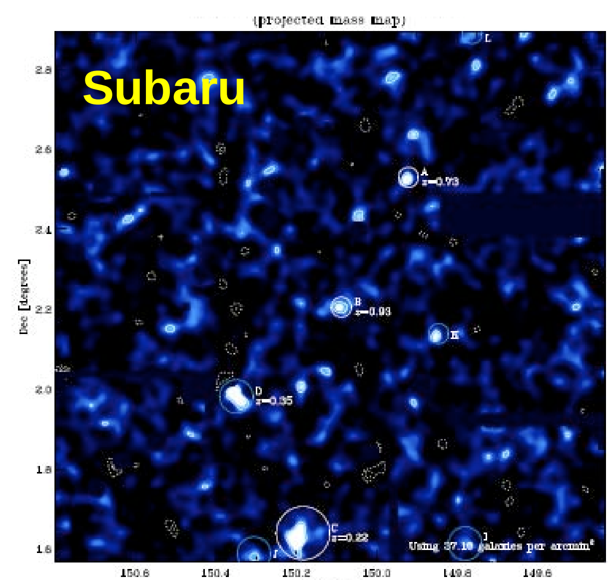
Require:

- **accurate shear measures**
- **large area (1000's deg^2)**
- **photometric redshifts**
- **spectroscopic calibration N(z)**

Ground versus Space





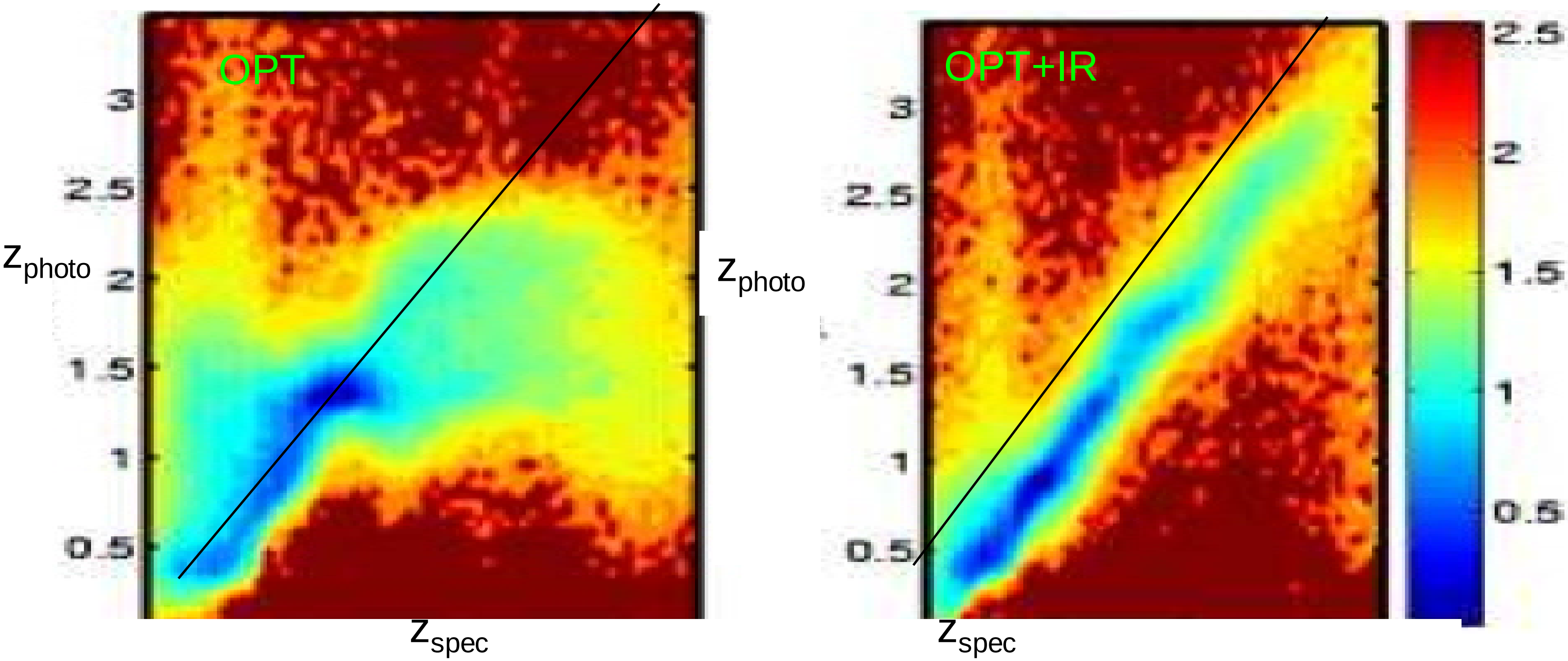


Typical cosmic shear is ~ 1% and must be measured with high accuracy

Space: small and stable PSF:
$\Rightarrow$ larger number of resolved galaxies
$\Rightarrow$ reduced systematics

Kasliwal et al Ap J 684, 34 (2008)

Access to Space for Photometric Redshifts



- Need photometric redshifts for 10^9 galaxies
- But need 1-2 micron infrared data to achieve this precision for z >1 − impossible from ground (sky brightness)
- Additional need $>10^5$ spectroscopic redshifts for calibrating the photo-z's

Weak Lensing Issues

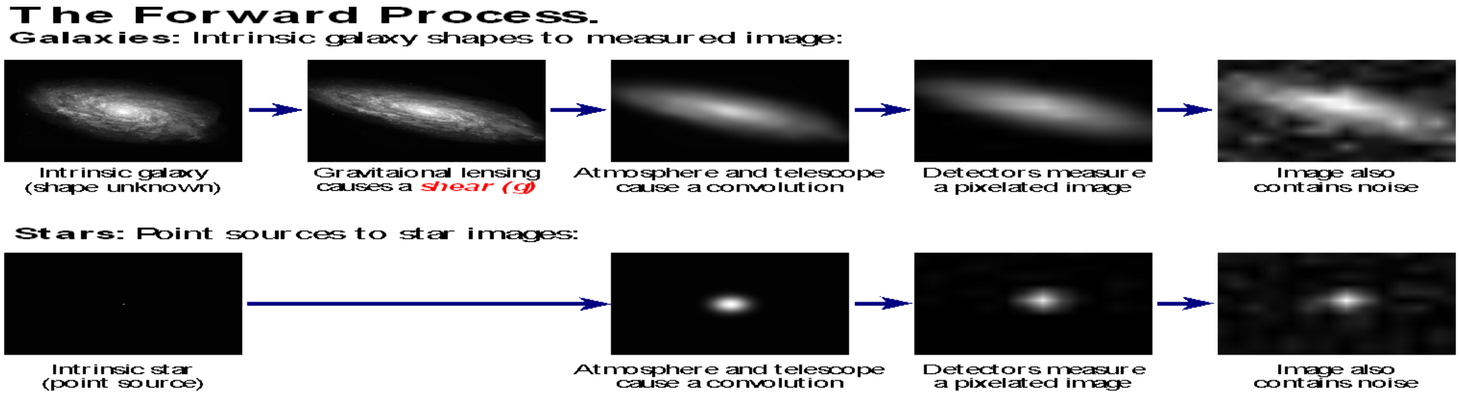
- **Calibration**: Need to measure shear to 10^{-3} & control systematics to $10^{-3.5}$; current methods 10 x worse. Much work needed but good progress (STEP1/2, GREAT08, GREAT10)
- **Point spread function correction:** Both ground (LSST) and space (Euclid) facilities are semi-funded. A space platform will offer superior performance so must be realistic in goals
- **Redshift distributions**: require accurate photometric N(z) for background populations. This means combining optical and infrared data with high precision and calibrating with a large spectroscopic survey

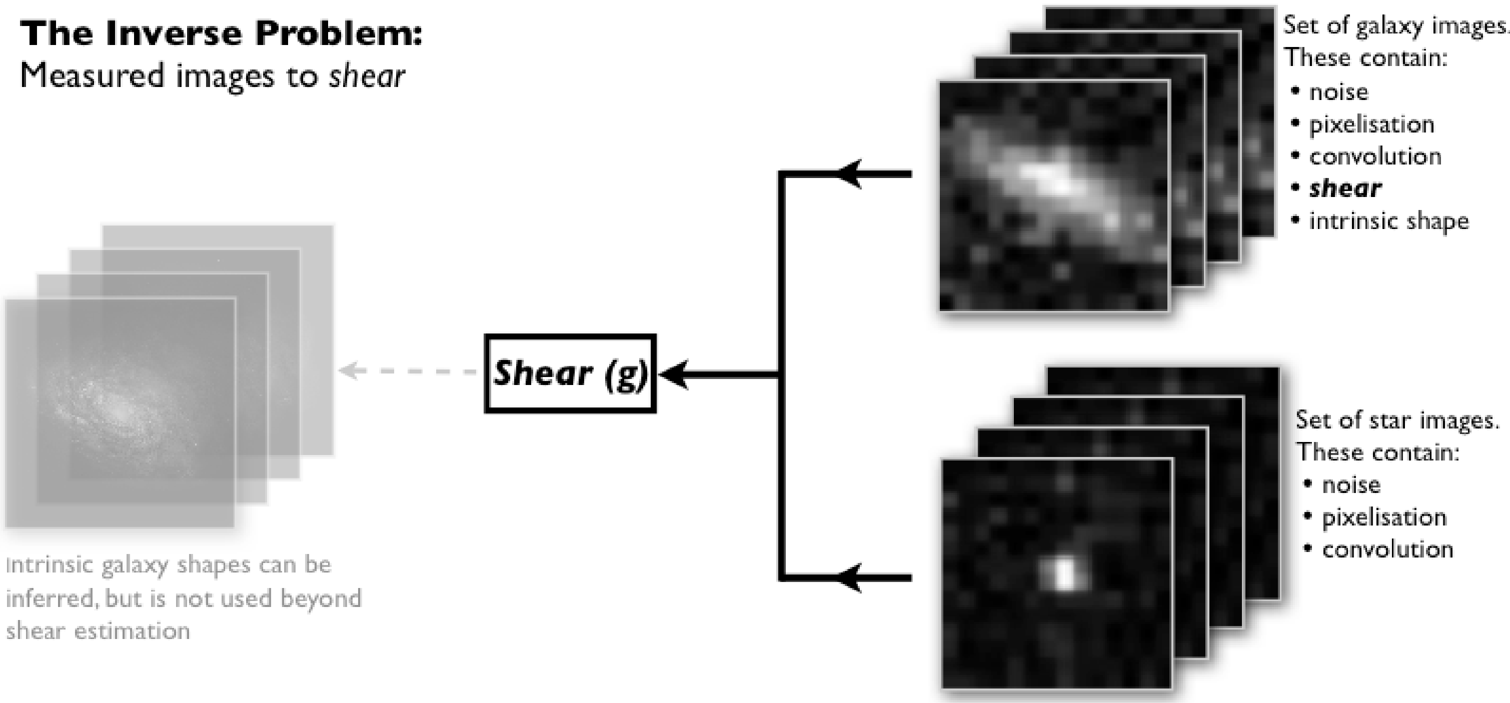
Provocative remark!

The lensing community is very enthusiastic and hard-working but outside this community there is a lot of skepticism! Euclid and LSST will be drivers and HSC has to establish its place

Testing Lensing Algorithms

The Forward Process





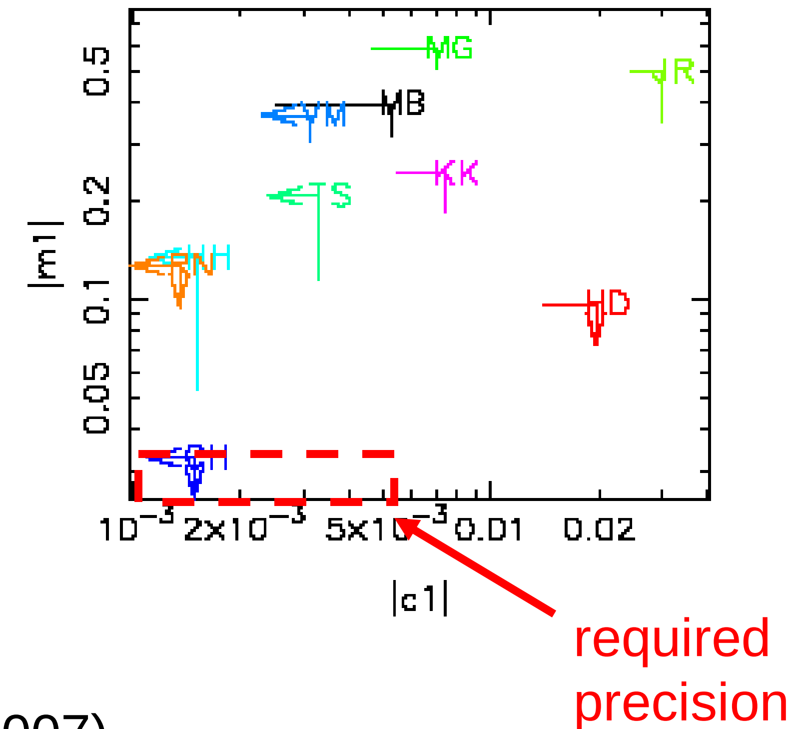
STEP: Correctly Extracting the Weak Signal

STEP project: blind comparisons on simulated datasets

The contestants

Author	Key	Method
Bergé	JB	Shapelets (Massey & Refregier 2005)
Clowe	C1	KSB+ (same PSF model used for all galaxies)
Clowe	C2	KSB+ (PSF weight size matched to galaxies')
Hetterscheidt	MH	KSB+
Hoekstra	HH	KSB+
Jarvis	MJ	Bernstein & Jarvis (2002)
Jarvis	MJ2	Bernstein & Jarvis (2002) (new weighting scheme)
Kuijken	KK	Shapelets (Kuijken 2006)
Mandelbaum	RM	Reglens (Hirata & Seljak 2003)
Nakajima	RN	Bernstein & Jarvis (2002) (deconvolution fitting)
Paulin-Henriksson	SP	KSB+
Schirmer	MS1	KSB+ (scalar shear susceptibility)
Schirmer	MS2	KSB+ (tensor shear susceptibility)
Schrabback	TS	KSB+
Semboloni	ES1	KSB+ (shear susceptibility fitted from population)
Semboloni	ES2	KSB+ (shear susceptibility for individual galaxies)

$$\Delta\gamma = m_1\gamma + c_1$$



Heymans et al (2006), Massey et al (2007)

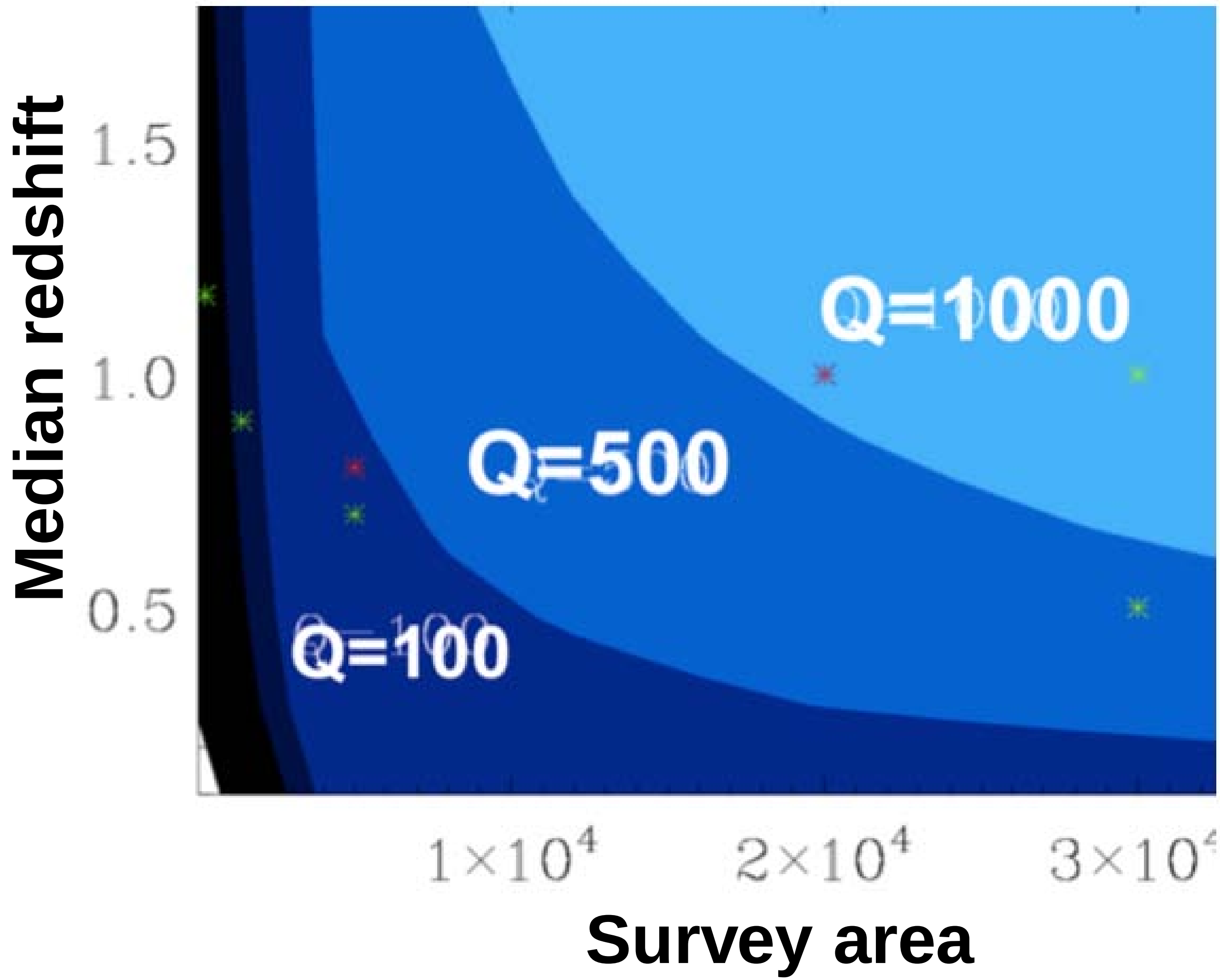
Most algorithms don't yet recover shear at the necessary precision (in terms of linearity m_1 or calibration c_1)

GREAT08 + GREAT10 Challenge

$$\sigma_i^2 = \frac{1}{2\pi}\int_{\ell_{\min}}^{\ell_{\max}} \ell(\ell+1)|C^{\rm input}(\ell) - C^{\rm submitted}(\ell)|d\ln\ell. \qquad Q_{\rm GREAT10} \equiv \frac{\mathcal{N}}{\langle\sigma^2\rangle}$$

Figure of merit Q (high is good) derived from comparing submitted and input power spectrum C(l)

For a particular survey, for systematic errors to match statistical ones, you get a target Q



Requirement for Euclid: Q=1000

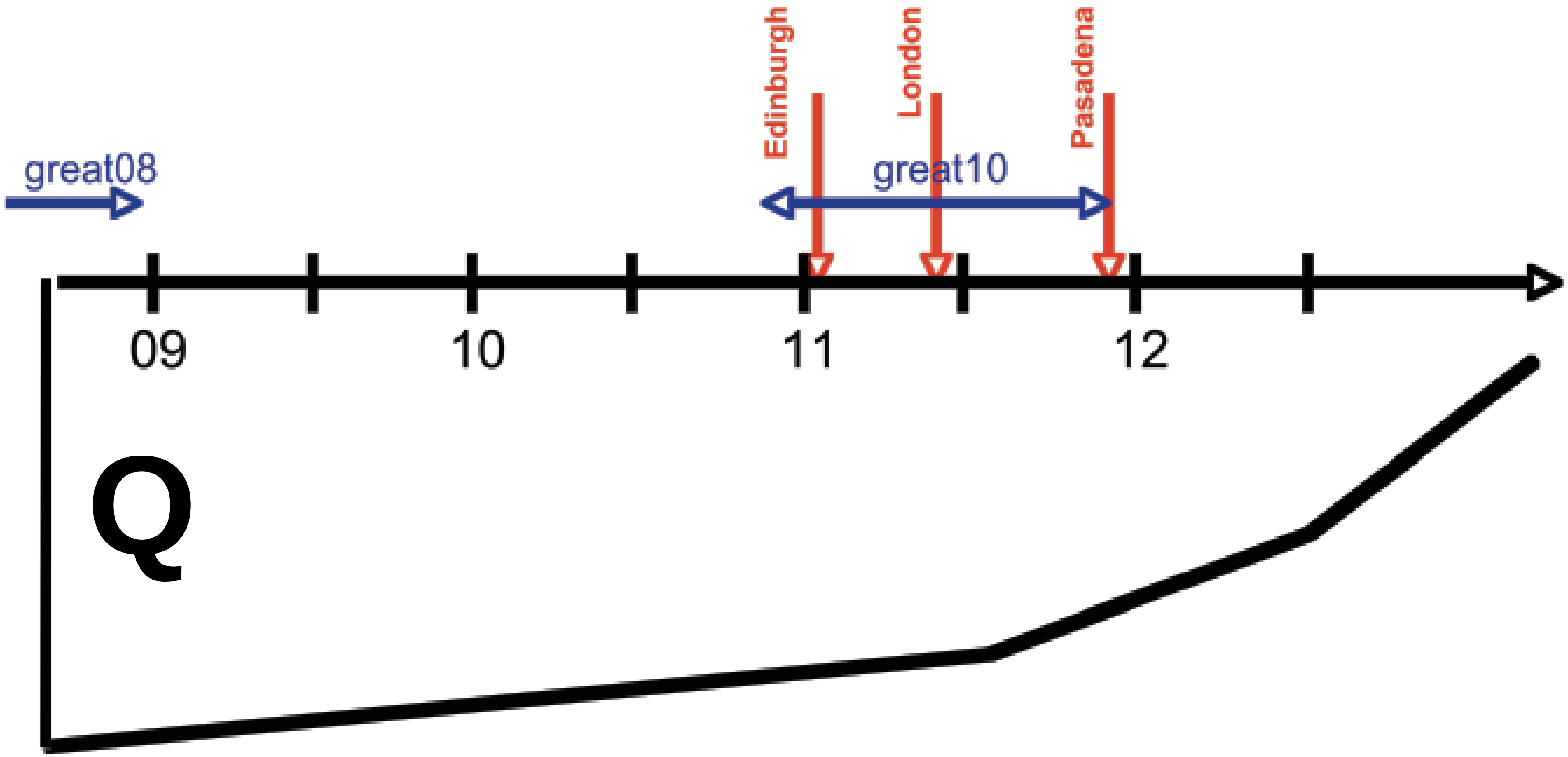
GREAT10
GRavitational lEnsing Accuracy Testing

Q(max) = 319.5

Rank	Group Name	User Name	Method Name	Submission Date	Q	Sigma Sys
1	DeepZot	David Kirkby	fit2-unfold (ps)	Sept. 1, 2011, 4:53 p.m.	319.5	3.12987E-0
2	DeepZot	David Kirkby	fit1-unfold (ps)	Sept. 1, 2011, 4:51 p.m.	291.5	3.4304E-06
3	Ohio State University	OSU KSB	KSB	Aug. 29, 2011, 10:58 p.m.	119.6	8.36359E-0
4	EPFL LASTRO	nurbaeva	gfit_den_cs	Sept. 2, 2011, 10:05 a.m.	118.8	8.4204E-06
5	Ohio State University	pmelchior	ARES	Sept. 2, 2011, 6:22 a.m.	115.5	8.6578E-06
6	Ohio State University	pmelchior	ARES2	Sept. 2, 2011, 4:36 p.m.	114.0	8.76837E-0
7	mpi-is	mpi-is	method04 (set21)	Sept. 2, 2011, 11:16 a.m.	109.7	9.11972E-0
8	mpi-is	mpi-is	method04	Sept. 1, 2011, 2:25 p.m.	109.3	9.15092E-0
9	mpi-is	mpi-is	method04 (set_21 corrected)	Sept. 1, 2011, 5:53 p.m.	109.3	9.15092E-0
10	mpi-is	mpi-is	method05 (set21)	Sept. 2, 2011, 1:33 p.m.	96.4	1.03681E-0
11	mpi-is	mpi-is	method05	Sept. 2, 2011, 10:18 a.m.	95.0	1.05228E-0
12	Ohio State University	kh	KSB_BSA (ps)	Sept. 1, 2011, 11:38 a.m.	92.0	1.08703E-0
13	UCL CoGS	browe	Im3shape NBC0	Aug. 31, 2011, 12:54 p.m.	89.1	1.12279E-0
14	UCL CoGS	browe	Im3shape NBC1	Sept. 2, 2011, 1:37 a.m.	88.9	1.12478E-0
15	UCL CoGS	browe	Im3shape NBC0XS	Sept. 2, 2011, 3:12 p.m.	88.6	1.12827E-0
16	UCL CoGS	ucl	Im3shape Uncalibrated	Aug. 30, 2011, 11:57 p.m.	87.6	1.14111E-0
17	UCL CoGS	browe	Im3shape Uncalibrated XS	Sept. 2, 2011, 4:11 p.m.	87.2	1.14683E-0

Courtesy: Tom Kitching (Image Analysis in Cosmology, Pasadena Sep 2011)

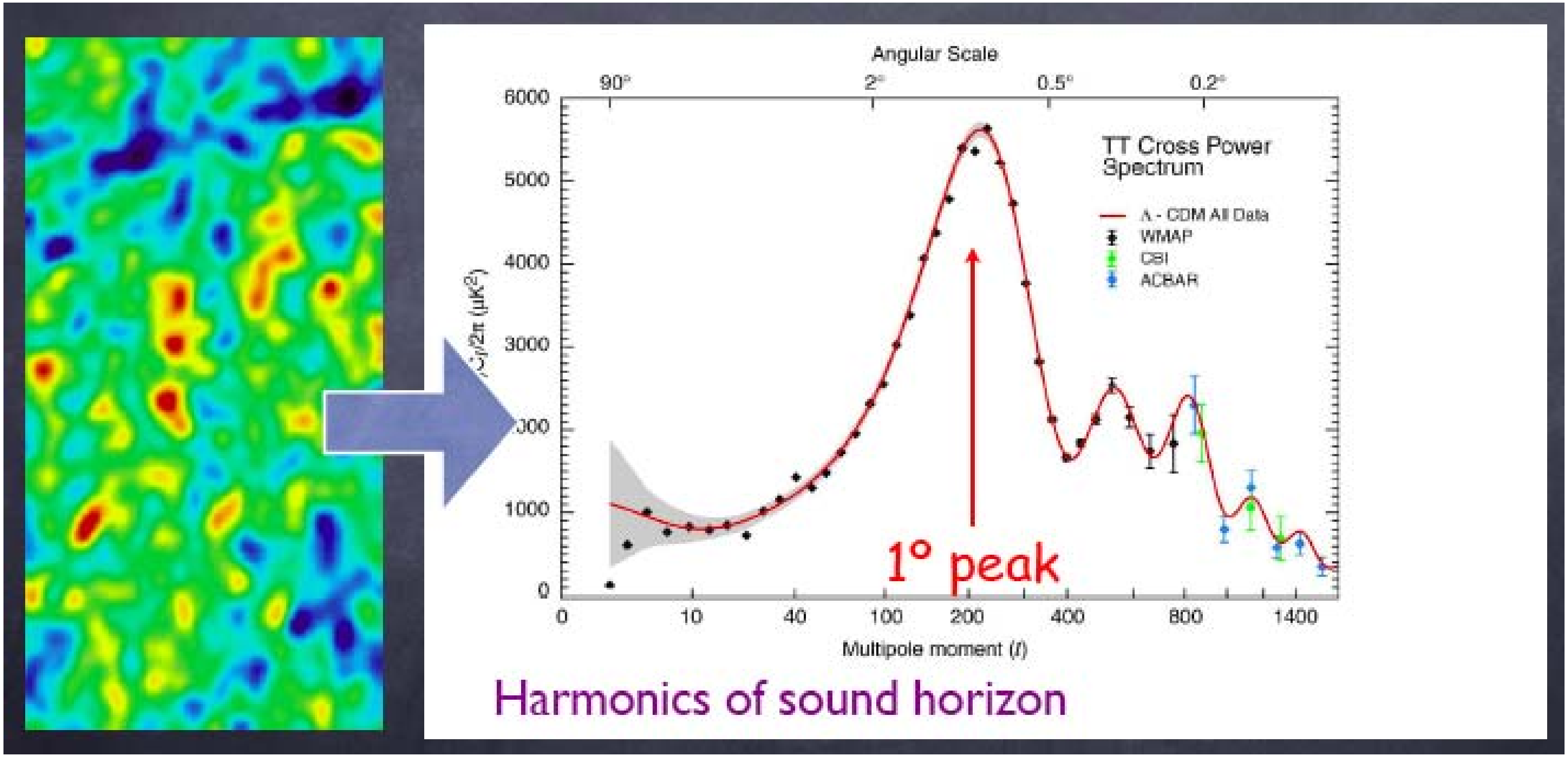
Here's hoping for the best..



~ 3 more challenge cycles before 2020 (Euclid, WFIRST, LSST)

Courtesy: Tom Kitching (Image Analysis in Cosmology, Pasadena Sep 2011)

Method III – Large Scale Structure



Residual of acoustic horizon at last scattering in galaxy distribution.

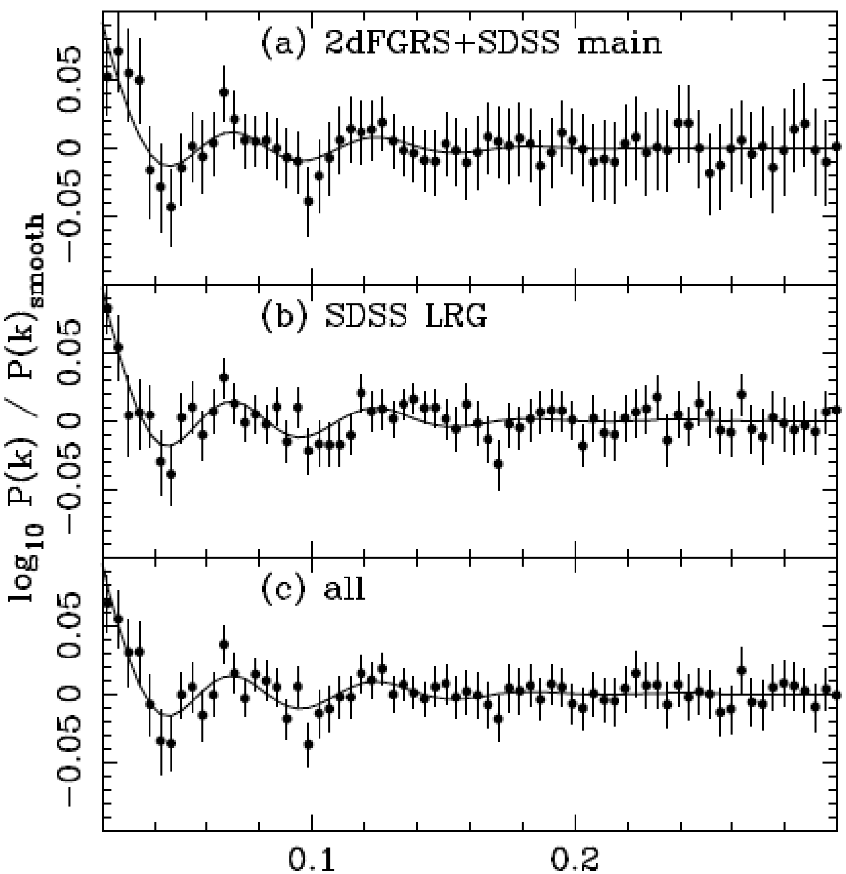
$$D_{\rm LS} \simeq 147\,(\Omega_m h^2/0.13)^{-0.25}(\Omega_b h^2/0.023)^{-0.08}\ \mathrm{Mpc}$$

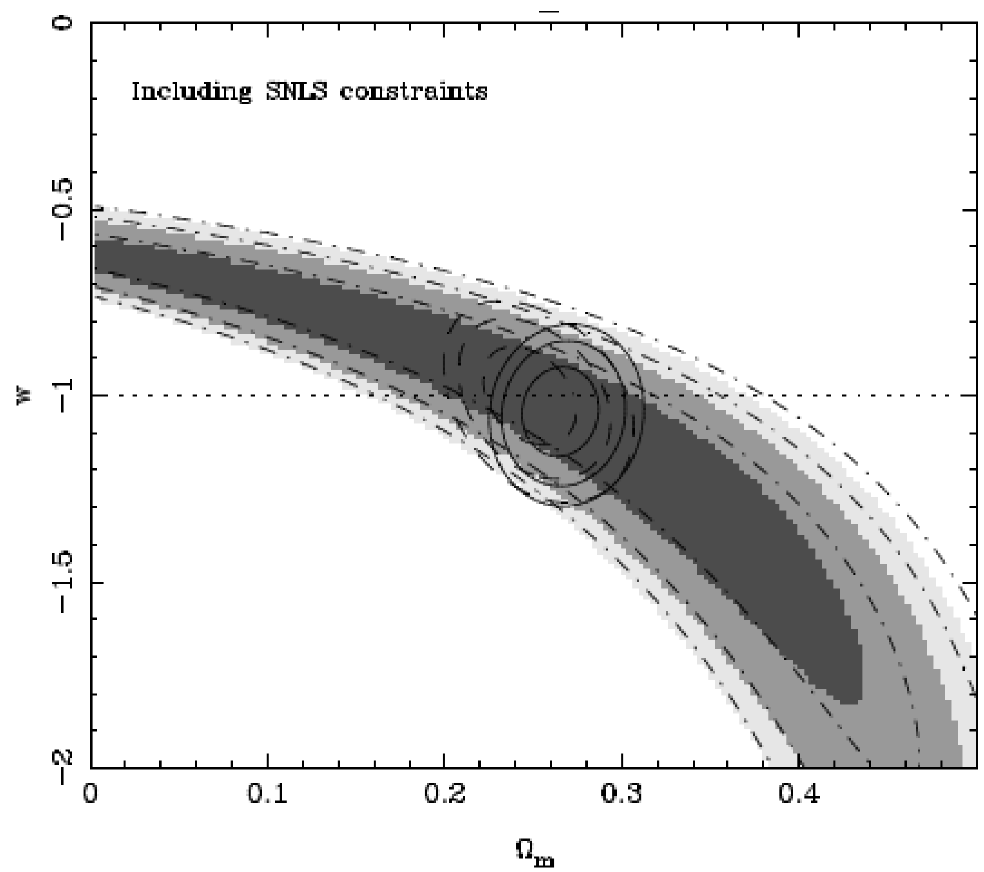
Peebles & Yu 1970; Sunyaev & Zel'dovich 1970

Confirmed at 3-4σ by 2dF (Cole et al) and SDSS (Eisenstein et al)

Combining SDSS and 2dF

P(k) / P(k)$_{smooth}$





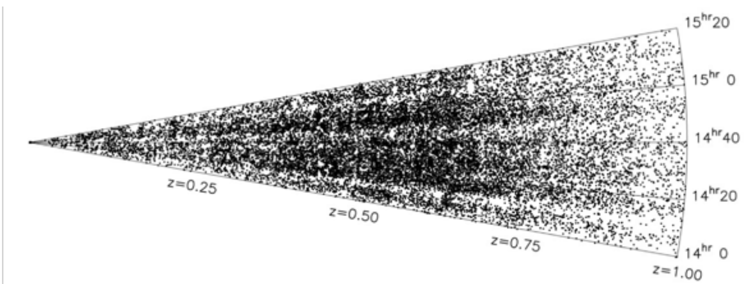
Combining with WMAP, SNLS in flat case:

$$\Omega = 0.249 \pm 0.018; \; w = -1.004 \pm 0.088$$

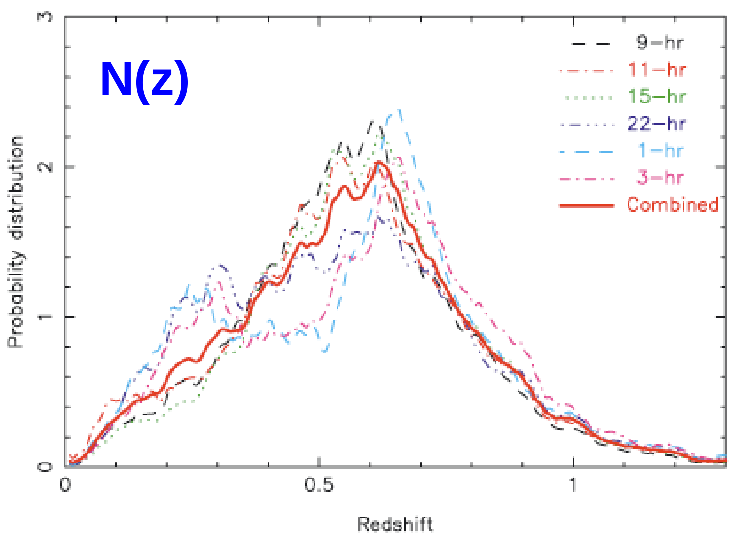
Percival et al MNRAS 381, 1053 (2007)

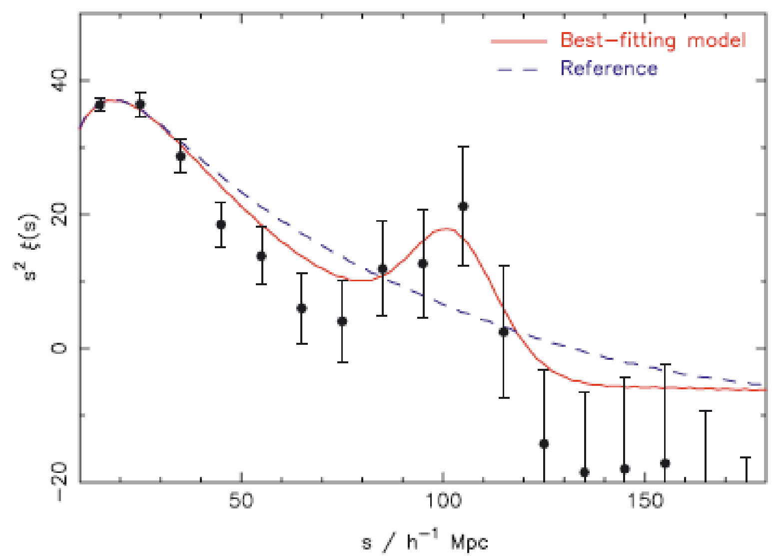
`WiggleZ' Project (PI: Glazebrook)

- 240,000 redshifts with AAΩ spectrograph
- Emission line g z>0.5 from GALEX+SDSS
- 10^3 deg^2, 220 nights z_P~0.6
- First results from 132,500 redshifts
-



Projected result: Δw~8%

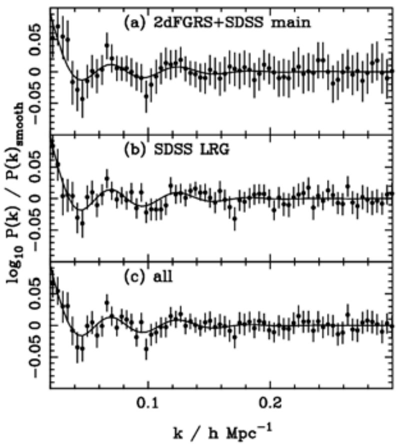




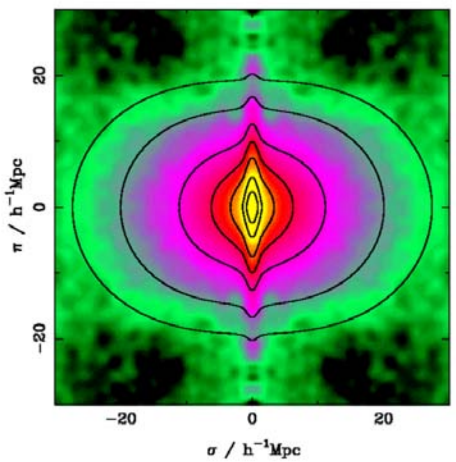
Blake et al (2011) 3.2σ detection

Cosmology with PFS

Baryonic Acoustic Oscillations



Redshift Space Distortions



[O II] redshift survey: $0.6<z<1.6$ $R<22.9$; 4×10^6 galaxies; **80 clear nights**

- BAO yielding *w* to 3% (valuable test of $w \neq -1.0$)
- RSD yielding f_g to 1.5% (first test of modified GR as sol^n to DE)
- large scale structure and galaxy evolution in clusters and field

Synergy with HyperSuprimeCam (targets, colors, weak lensing)

PFS would be the first survey to probe z > 1 complementing BOSS with similar precision, offering the potential of a breakthrough in understanding Dark Energy

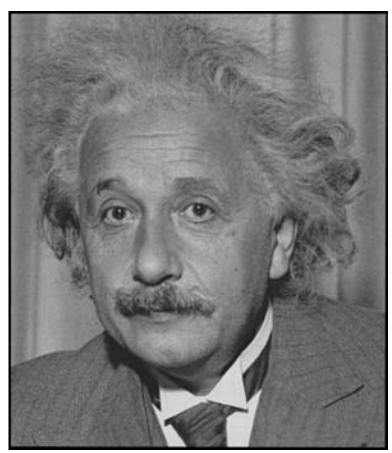
Modified Gravity?

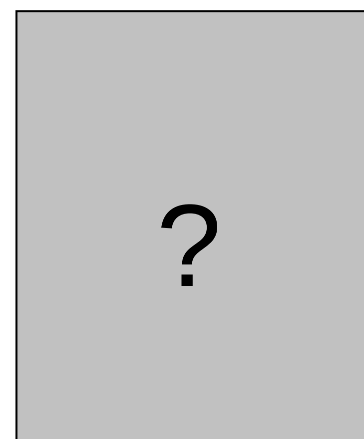
All current measurements relate to expansion rate, assuming H(z) comes from GR Friedmann equation

$$H^2(z) = H^2_0 \; [\, (1-\Omega)\,(1+z)^{2} + \Omega_M\,(1+z)^{3} + \Omega_R\,(1+z)^{4} + \Omega_{DE}\,(1+z)^{3\,(1+w)} \,]$$

Curvature — matter — radiation — extra term from non-GR?

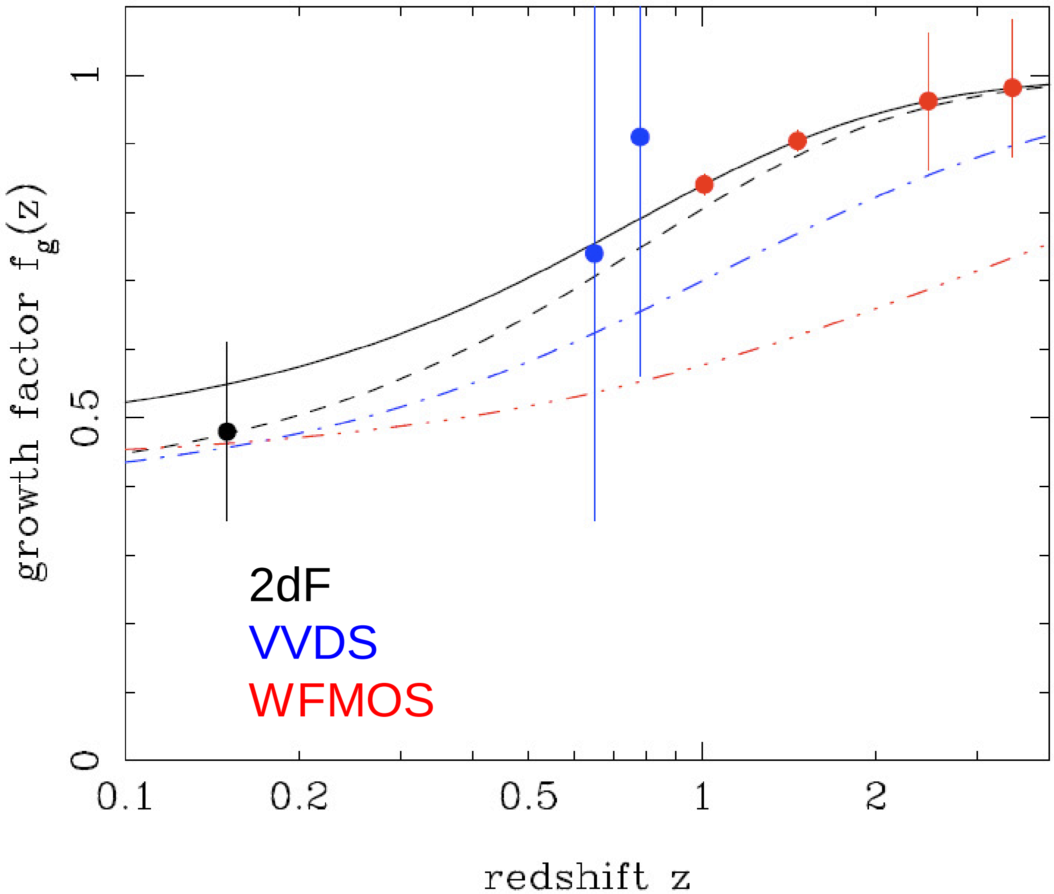
Suppose *DE is an illusion*, indicating failure of Einstein gravity on large scales. Density fluctuations perform differently to global expansion history as valuable probe





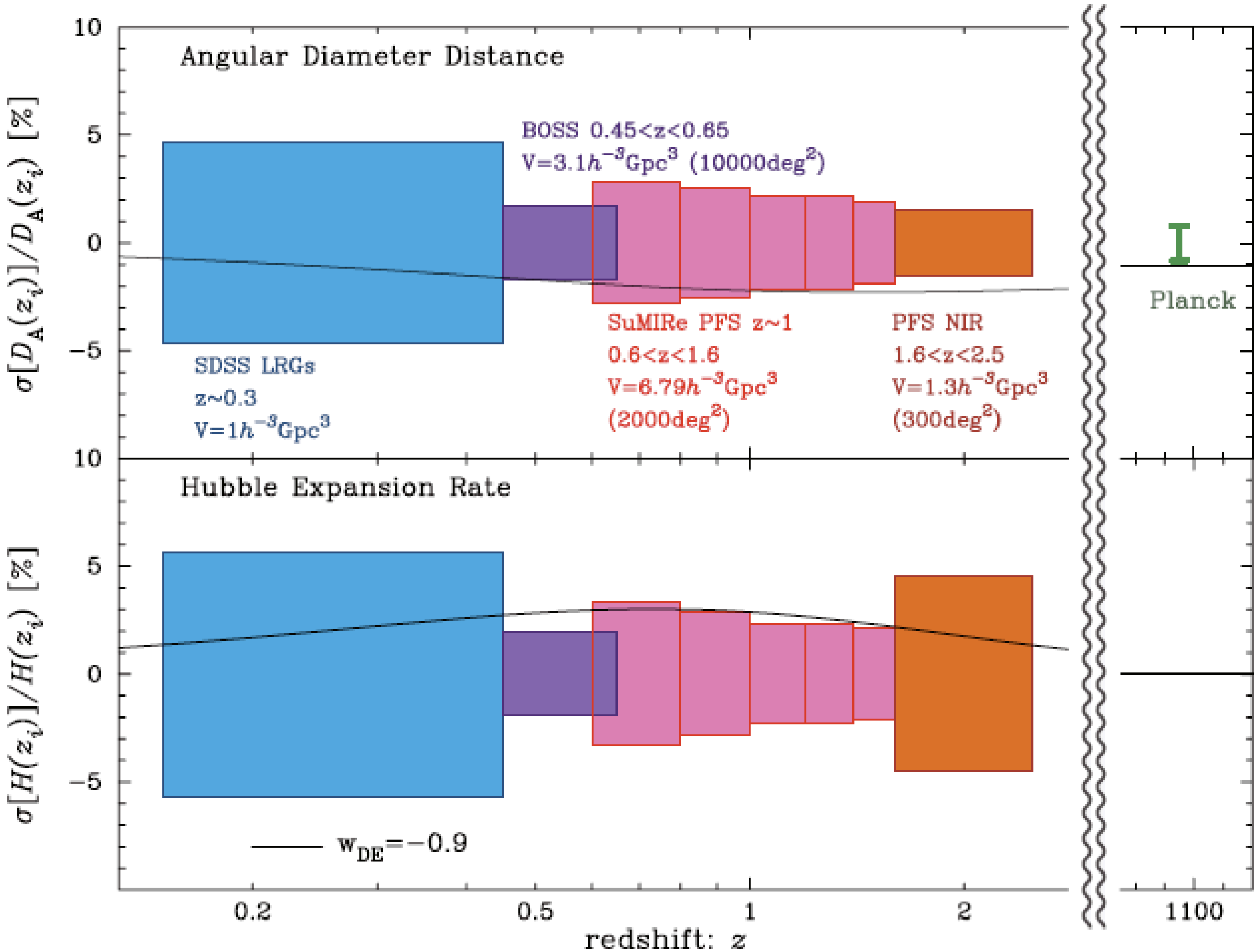
Redshift Space Distortions

- Acts as measure of gravitationally-induced peculiar velocities
- Growth $f_g = d \ln \delta / d \ln a$ and expect $f_g \approx \Omega_m^{0.55}$
- Independent of Λ & w
- Suppose *DE is an illusion*, indicating failure of Einstein gravity. Density fluctuations perform differently to global a(t) as valuable probe
- So measure $f_g \approx \Omega_m^{\gamma}$ Is $\gamma =$ 0.55??
- Quickest potential breakthrough for DE!



PFS offers best opportunity after BOSS!

PFS Science White Paper (Takada & Silverman)



DE Figure of Merit Forecasts

	BOSS	PFS(+BOSS)	SuMIRe (BOSS+PFS+HSC)
Redshift	$0.2 < z < 0.65$	$0.6 < z < 1.6$	$0 \lesssim z \lesssim 1.6$
Sky Coverage	10000 deg^2	2000 deg^2	2000 deg^2
$\sigma(w_{\rm pivot})$	0.083	0.046	0.017
DE FoM	13	33	345
Growth: $\sigma(\gamma)$	-	-	0.032
$\sigma(\sum m_\nu)$ [eV]	-	-	0.06 eV
$\sigma(f_{\rm NL})$	-	-	$\sim$5

Working group needs to discuss many issues:

- non-linear effects (clustering and redshift-space distortion)
- scale dependent bias for RSD (combining HSC DM and PFS)
- merits of the IR BAO component (much harder)
- target selection and survey optimization (80, 100, 120 nights?)

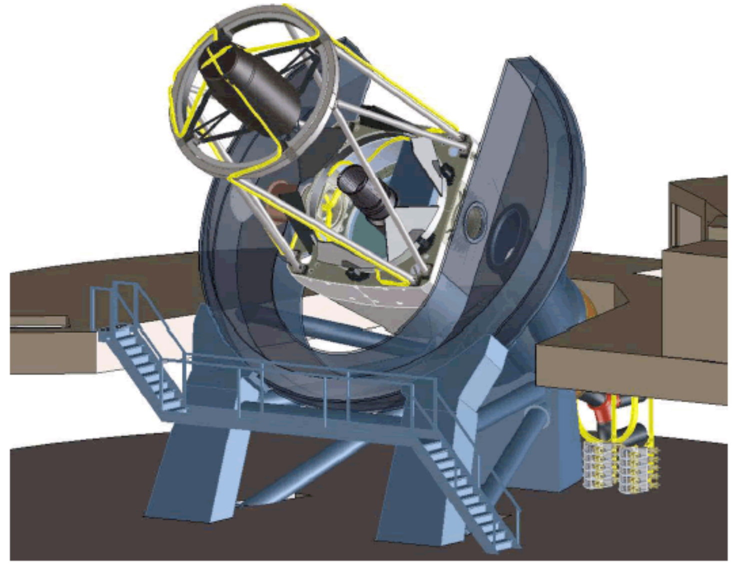
Competitive Landscape - I

4MOST

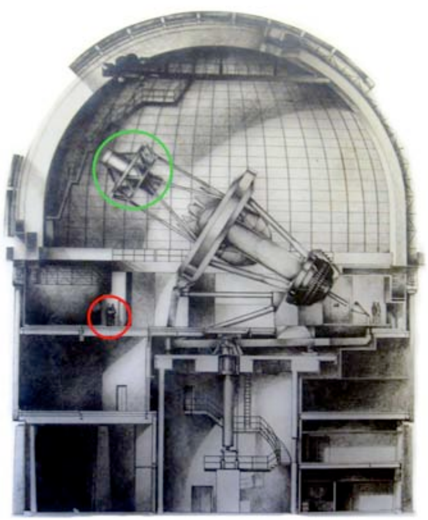
4-meter Multi Object Spectroscopic Telescope

Proposal for a Conceptual Design Study for ESO

BigBOSS



DESpec



Competitive Landscape - II

Funded projects:

SDSS 3 (BOSS): BAO	1.3 10^6 LRGs $0.2 < z < 0.8$ ~10,000 deg^2
LSS	160,000 QSOs $2.3<z<2.8$
SDSS 3 (APOGEE): GA	10^5 red giant spectra in dust-obscured disk/spheroid
	H<13 R~20,000 $1.5<\lambda<1.7$ μm
SDSS 3 (SEGUE-2): GA	~10^5 SDSS spectra at 10<R<60 kpc to g=19
	velocities, types, abundances
	rare (e.g. metal-poor) stars
HERMES (AAT): GA	chemical tagging for assembly history
	R~28,000 to V~14
HETDEX: BAO	8.10^5 Ly α emitters $1.9<z<3.5$ over 420 deg^2 (175 nights!)

Unfunded projects:

BigBOSS: BAO	3.0 deg field on Mayall 4m; 14,000 deg^2, (500 nights)
DESpec: BAO	2.2 deg field on Blanco 4m; strategy TBD
ngCFHT: BAO/GA	TBD: various versions with 4-10m aperture!
4MOST: BAO/GA	>3.0 deg field on VISTA, R~5000 7-25 10^6 spectra
	5 year public survey; entering feasibility study

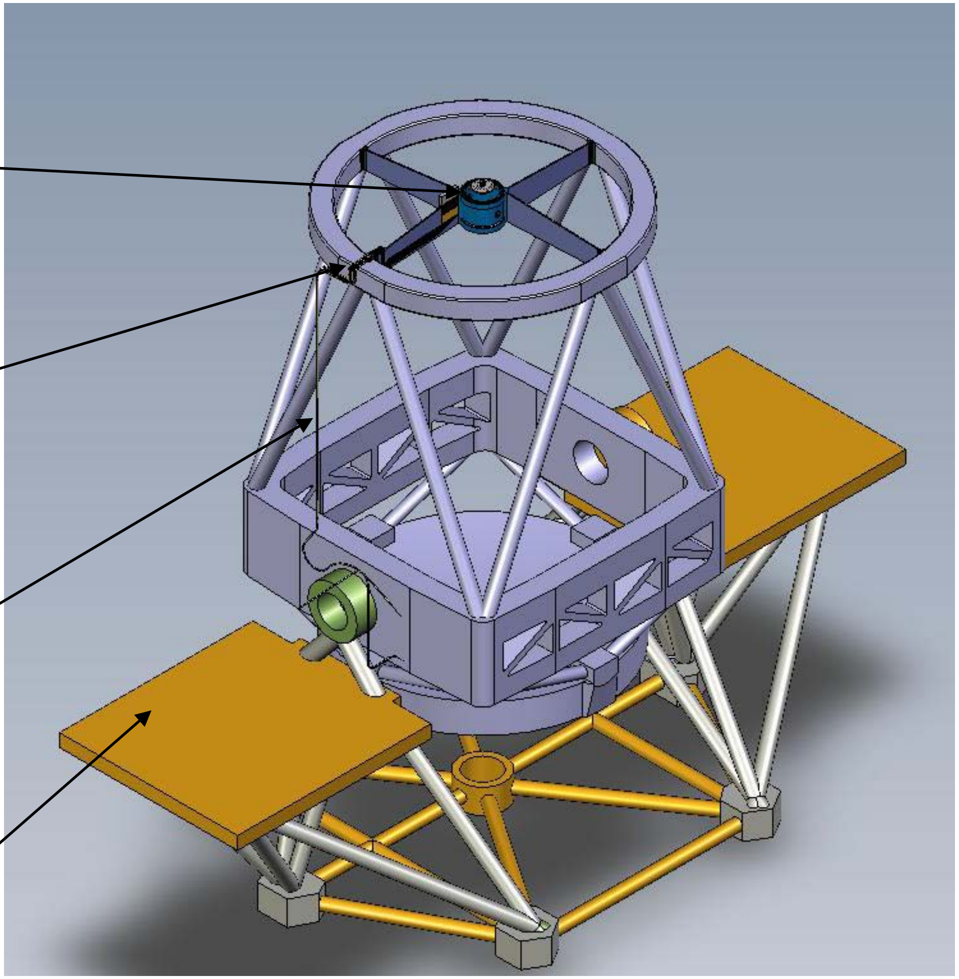
PFS on Subaru 8m telescope

Prime Focus Unit includes Wide Field Corrector (WFC) and Fiber Positioner

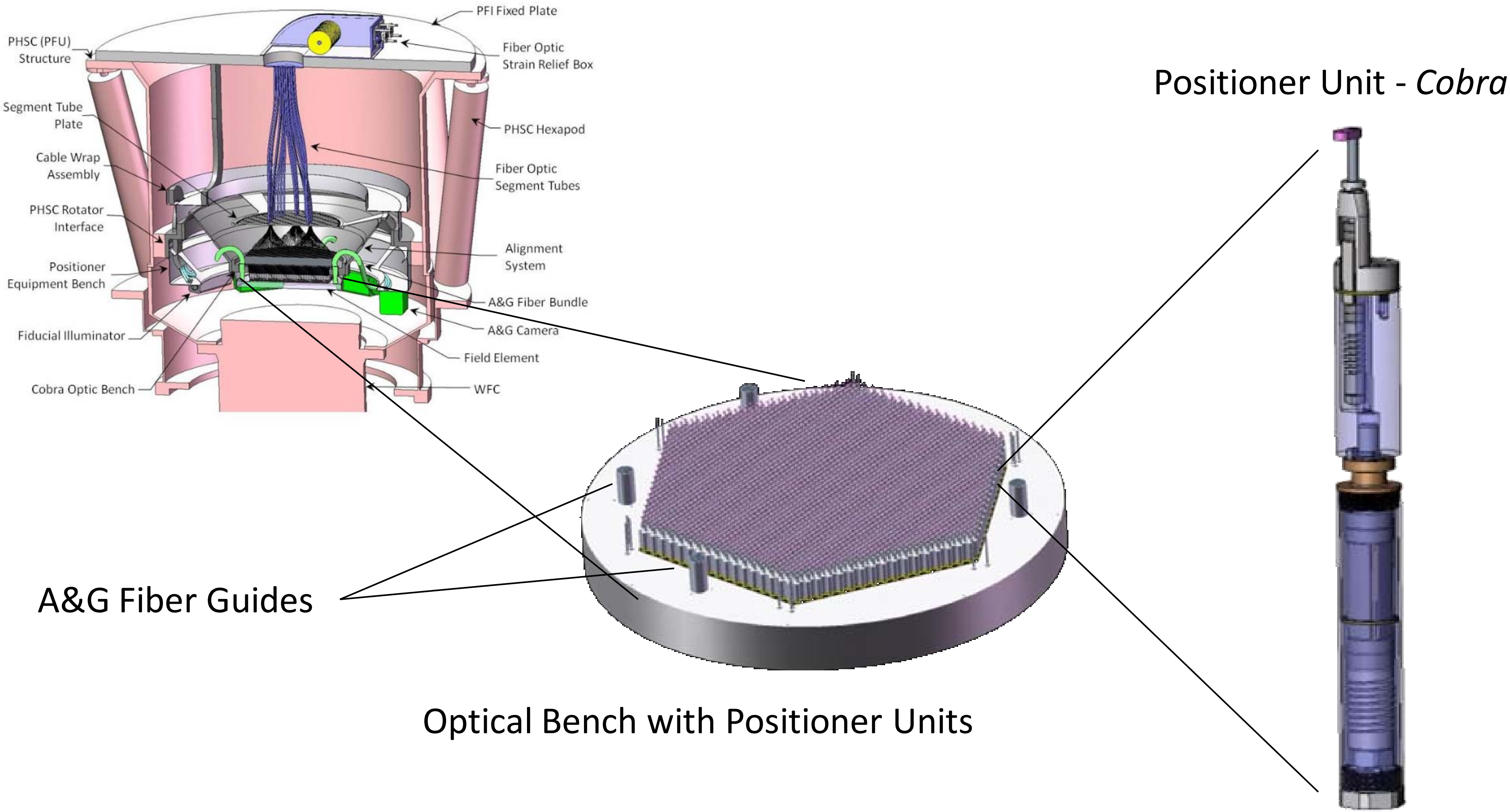
Fiber connector mounted on top end structure

Fiber cable routed around elevation axis and brings light from 2400 fibers to 3 identical spectrographs

Spectrograph room located above Naysmith platform



PFS Positioner



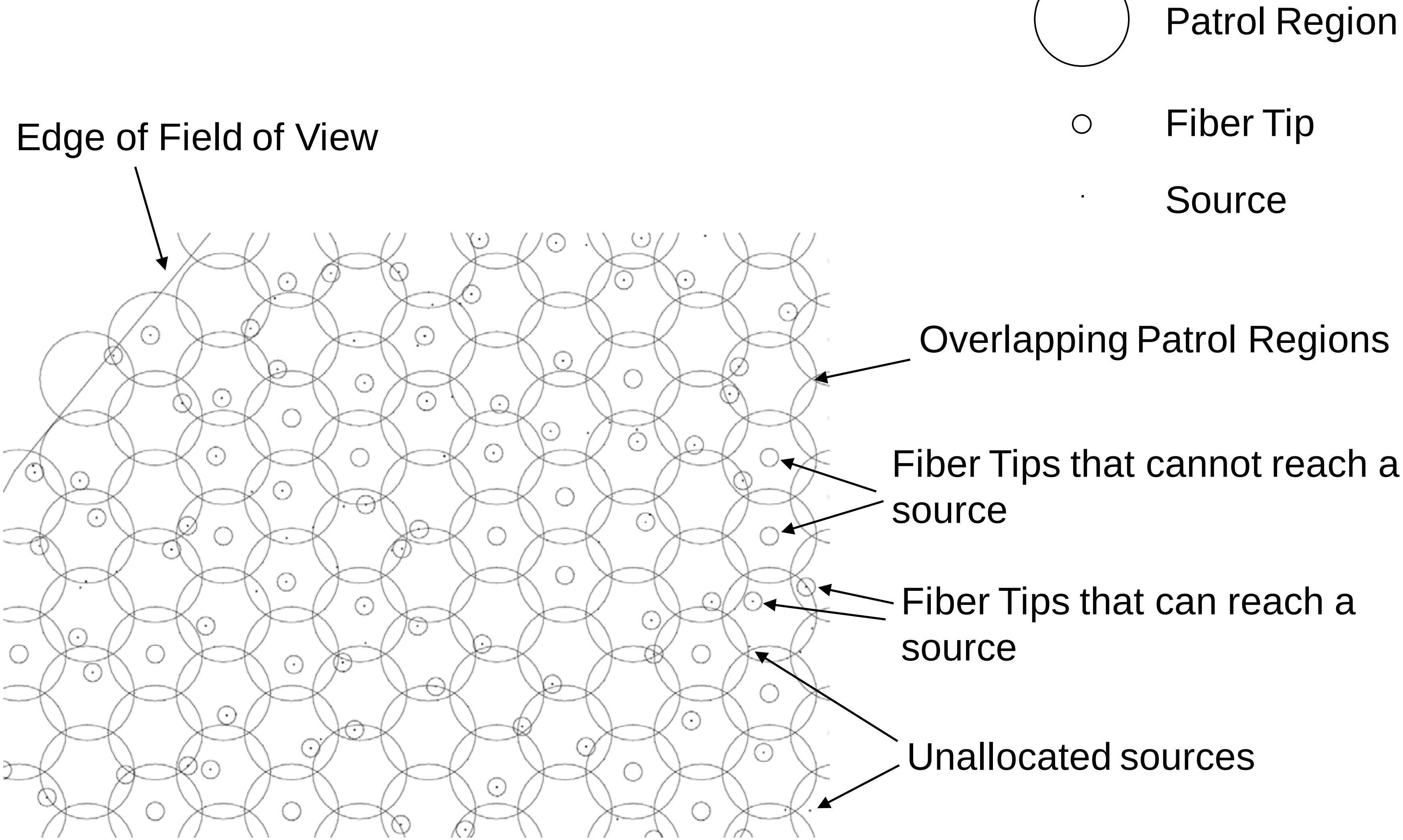
Cobra system tested at JPL in partnership with New Scale Technologies

Designed to achieve 5μm accuracy in < 8 iterations (40 sec)

Up to 4000 positioners 8mm apart in hexagonal pattern to enable field tiling

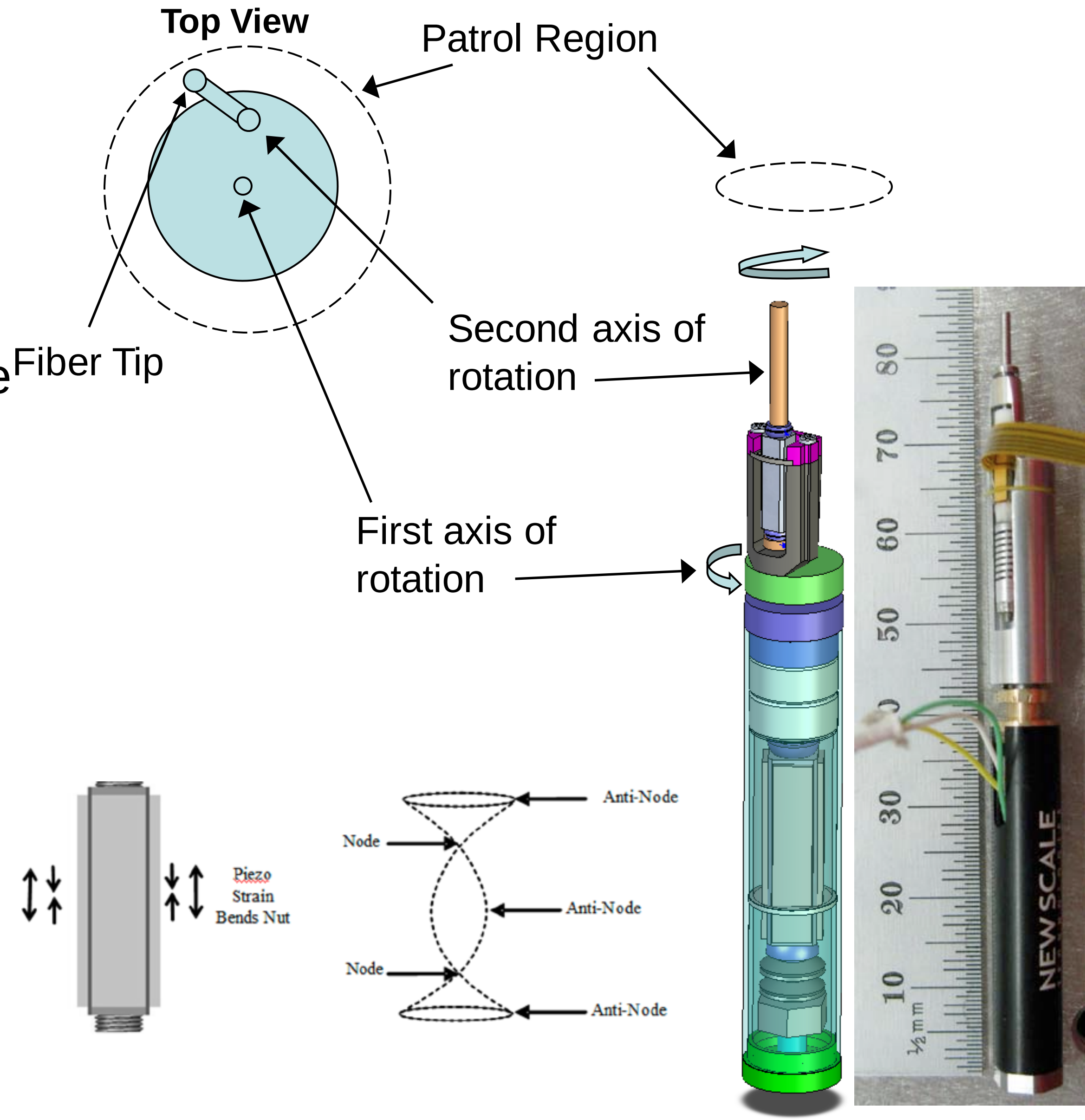
Positioner and Source Allocation

Subsection of Instrument Focal Plane

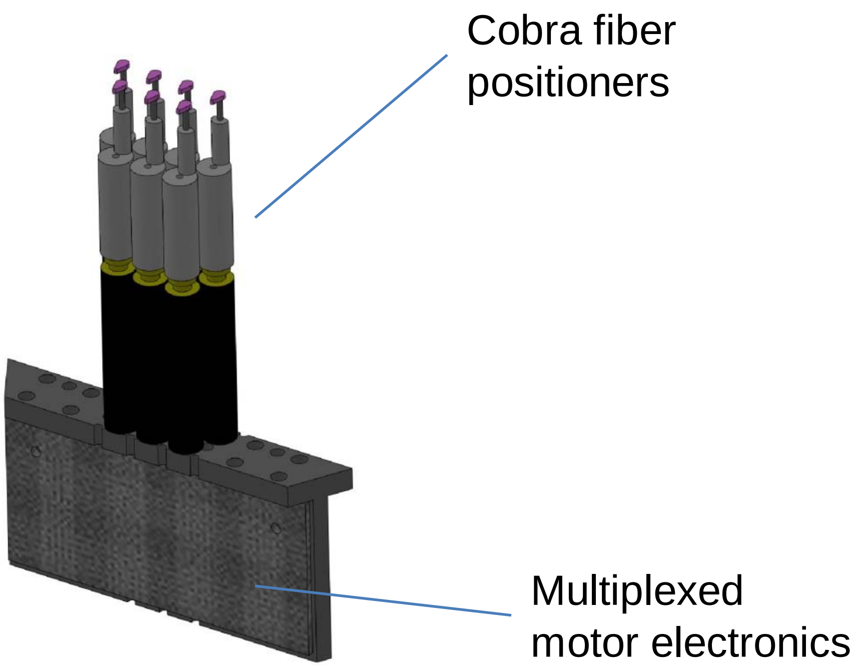


Positioner Element – “Cobra”

- Each Positioner element uses 2 “rotary squiggle” motors (2.4mm) with 5µm resolution and ~instantaneous response
- Each motor rotates to provide complete coverage of the patrol region.
- Optical fibers mounted in “fiber arm” which attaches to upper positioner axis
- Fiber runs through the center of the positioner
- Prototyped and tested in through JPL and New Scale Technologies



Next Step: Cobra 7-element Prototype



Proposed 7-element prototype to demonstrate mechanical integration, tolerances, & integrated electronics

Prototype array of positioners is an essential precursor to proposing for a ~2400-4000 element system

Following Japanese community approval of PFS (Jan 2011), Caltech/JPL is now developing prototype as working system ($400K award Sep 2011)

Verify scalability using prototype module of 7 units by summer 2012

Retire risks on
- assembly & integration
- multiplexed electronics
- performance variability
- collision avoidance
- metrology imaging
- closed loop behavior

Unit 3-arm Spectrograph

f/2.5 Schmidt collimator with 250mm beam & VPH gratings

λλ 3800 Å – 1.3 μm in 3 f/1.0 cameras:

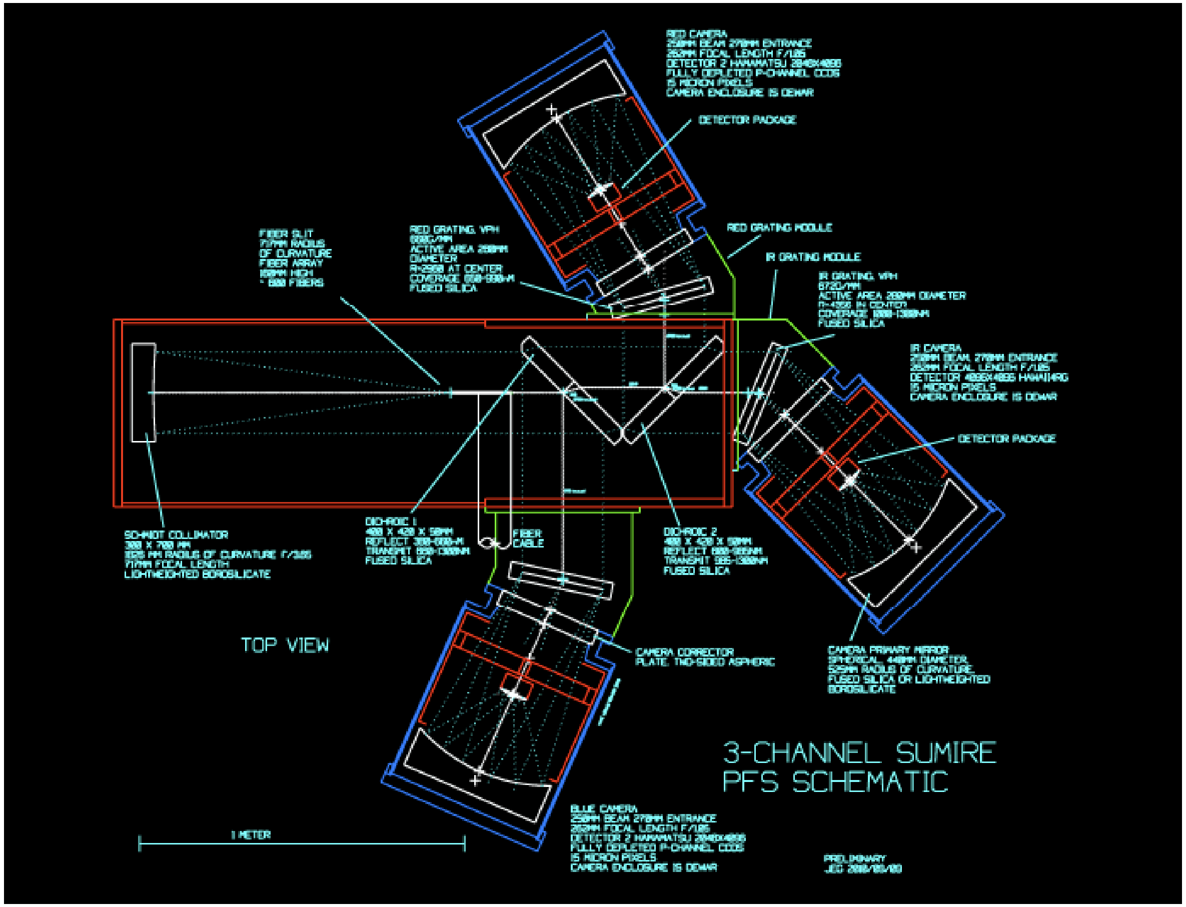
3800-6700 Å R~2000

6550-10000 Å R~4000

97000-13000Å R~4000

Optical arms: Two 2K × 4K Hamamatsu CCDs

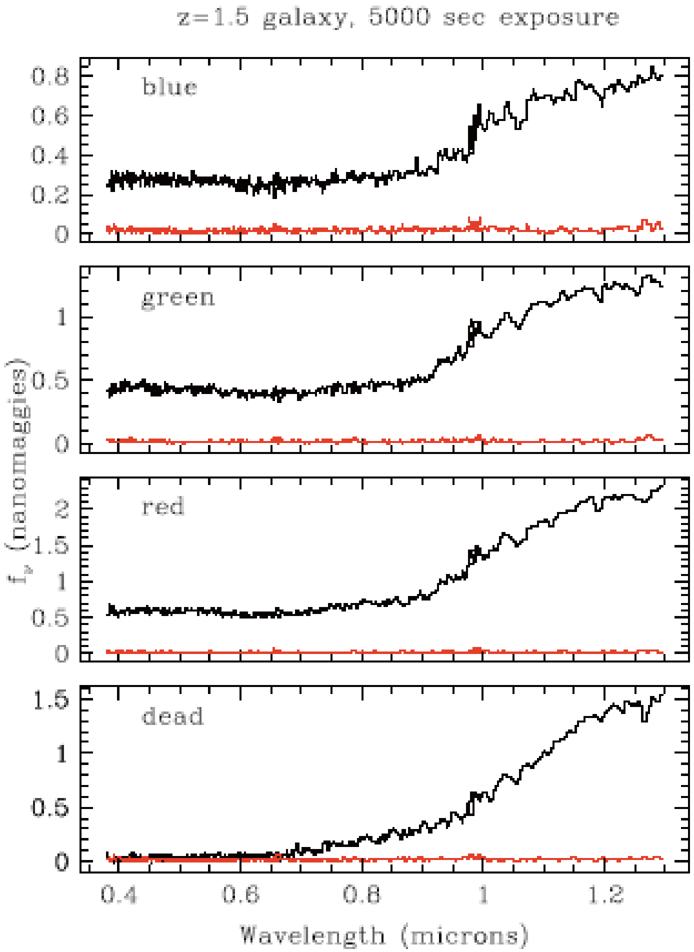
IR arm: Teledyne 4K × 4K HgCdTe 1.7 μm cutoff array



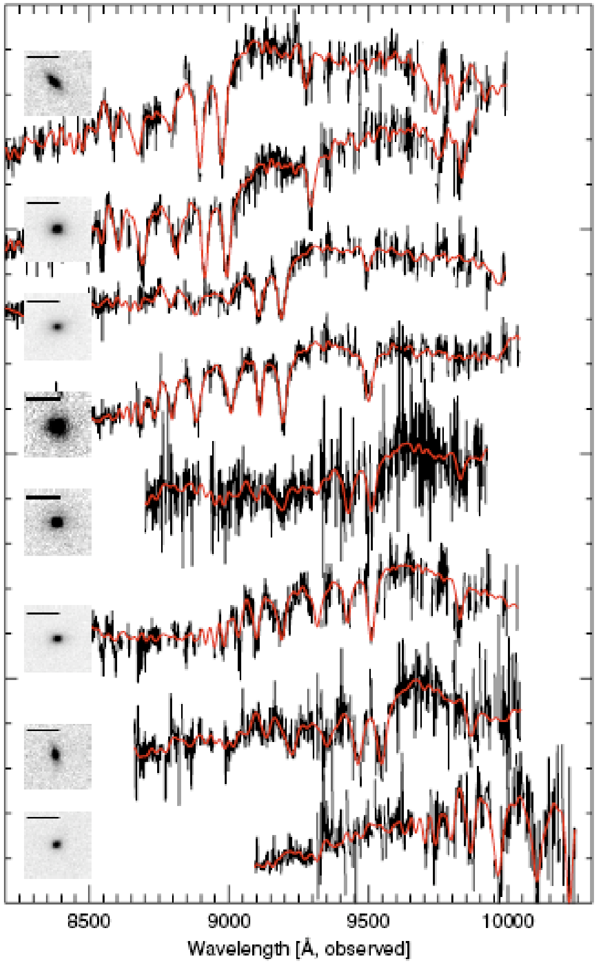
Design: Jim Gunn (Princeton)

Quality of Spectra Required

White Paper Simulation (5000sec)



Keck LRIS 1.3<z<1.6 (12 hours!)



Emission line surveys practical, but stellar continuum measures very hard

Science Planning…

• Scientific scope and priorities of a SSP is an important precursor to a functioning PFS partnership

• The combination of the WFMOS science case and the PFS White Paper provides an excellent starting point but Working Groups in the key areas need to define requirements and perhaps undertake more realistic simulations

- Cosmology
- Galactic Archeology
- Galaxy Evolution
- AGN/QSOs

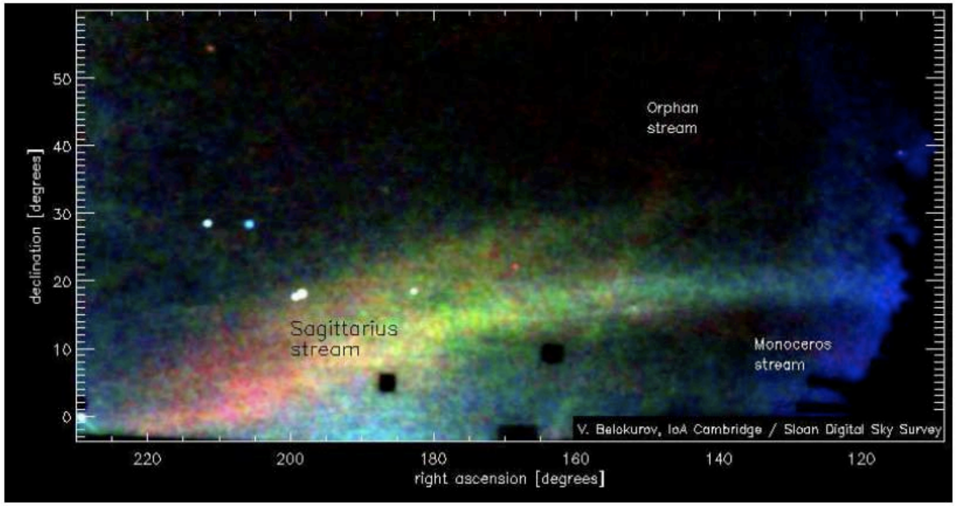
• Recognize other multi-object programs (BOSS, HERMES, 4MOST…)

• Possibility of sharing PFS time across programs (e.g. galaxies and cosmology)

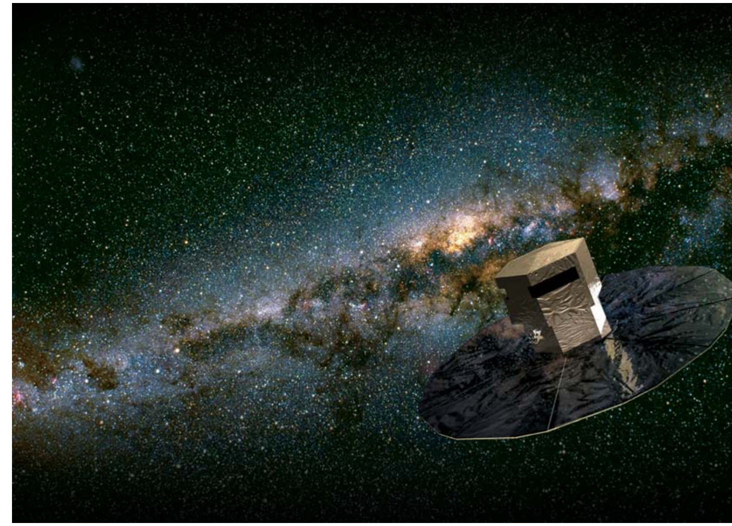
• How do we account for unforeseen opportunities in the era of TMT/LSST?

Galactic Archeology

Galactic Streams



GAIA 3-D revolution

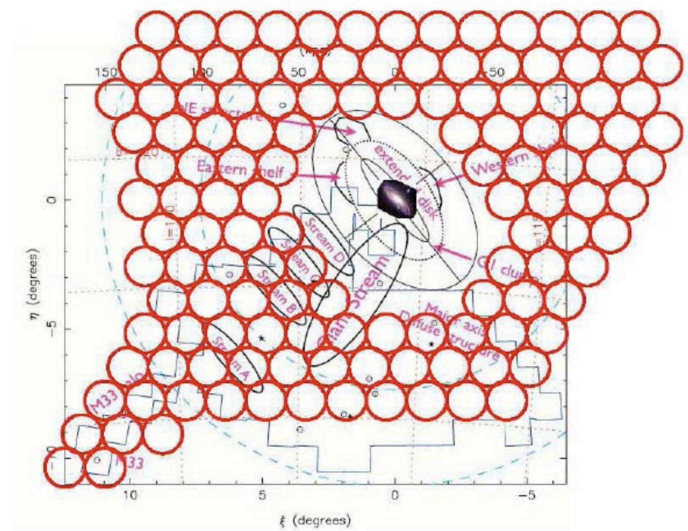


Galactic Structure <u>is</u> Near-Field Cosmology!

Stellar kinematics and abundances offer a huge potential in synergy with GAIA – a revolution in our understanding of DM halo & how Milky Way & M31 assembled.

But now competitive as GAIA approaches!
How can PFS complement other surveys?

M31 Halo



Galactic Programs

• Original WFMOS GA program was ambitious (by Gemini design)

LowRes (dynamics) R ~5000 V < 20; 3 × 10^6 stars; 76 nights
~~HiRes (chemistry) R~20,000 V < 17; 10^6 stars; 110 nights~~

NB: R~20,000 capability would have been unique to 8m aperture but no longer a first light capability (although White Paper recommends later upgrade)

• PFS White Paper offers several individual programs
  • Milky Way halo: R~3000 10^6 stars V<20.5 + GAIA (50 nights)
  • Studies of M31 halo (30 nights)
  • Local Group dwarfs (8 nights)

• Key issues:

  • Which are competitive with 4m programs and 8-10m M31 campaigns?
  • Are there useful collaborative synergies with other programs?
  • Which GA programs fit well into a SSP?

Distant Galaxies

The basic case is well-posed in the PFS White Paper in two components:

- **Galaxy & AGN evolution to z~2 through a wide area survey**
  30 deg^2 z_{AB}<22.5 10^6 galaxies 100 nights

  • multi-facetted approach involving detailed of mass assembly, chemical evolution, QSOs, clusters (X-ray, SZ) etc.

- **Lyman alpha emission in various HSC samples in the range 2<z<7**
  30 deg^2 i'_{AB}<24 30,000 LBGs and 8,000 LAEs 40 clear nights

  • large scale structure (LAEs), stacked LBG spectra, feeding Keck/VLT and TMT for more detailed studies

Both programs well suited to Subaru and beyond reach of competitor instruments (except HETDEX for LAEs @ z~2-3)

Key issue: optimal survey areas (e.g. to combat cosmic variance)
practicality of securing suitable spectra at these very faint limits
balance of effort between 1<z<2 and higher z

Future Synergies Important