Cosmic Accelaration

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IPAC, Caletch

CPAD Instrumentation Frontier 2016, October 8

Outline

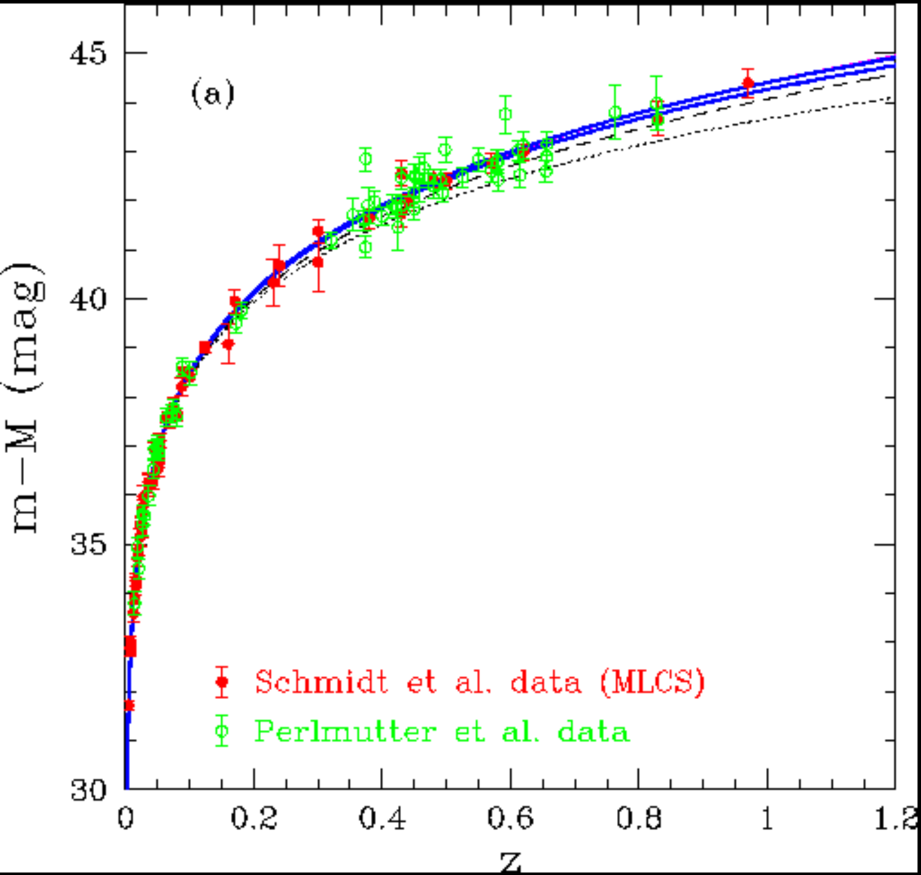
- Observational evidence for cosmic acceleration
- Probing the nature of cosmic acceleration
- Instrumentation for future cosmic acceleration surveys

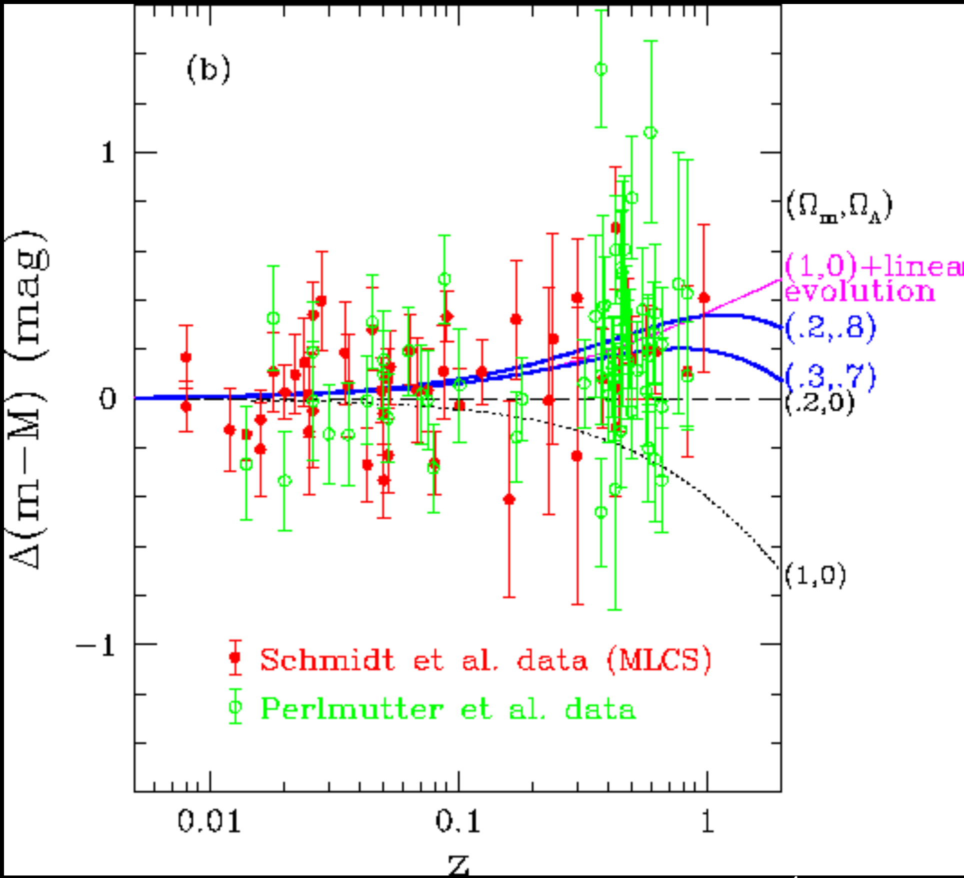
Observational Evidence for Cosmic Acceleration

First Evidence for Cosmic Acceleration
in the Hubble Diagrams of Supernovae [$d_L(z)$]

(Schmidt et al. 1998, Perlmutter et al. 1999)

faint



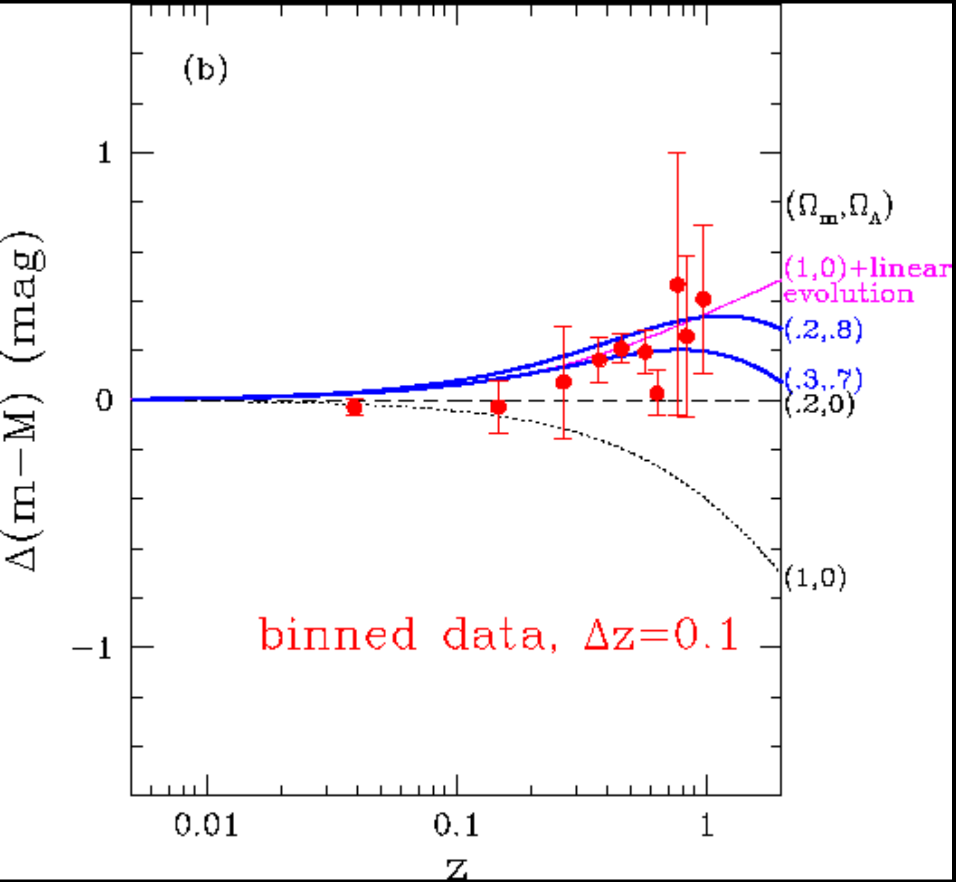


bright

Alternative Analysis of First Evidence

Combined data of 92 SNe Ia from Schmidt et al. (1998) and Perlmutter et al. (1999), flux-averaged to reduce lensing & other non-Gaussian systematics.

[*Wang 2000b, ApJ*]

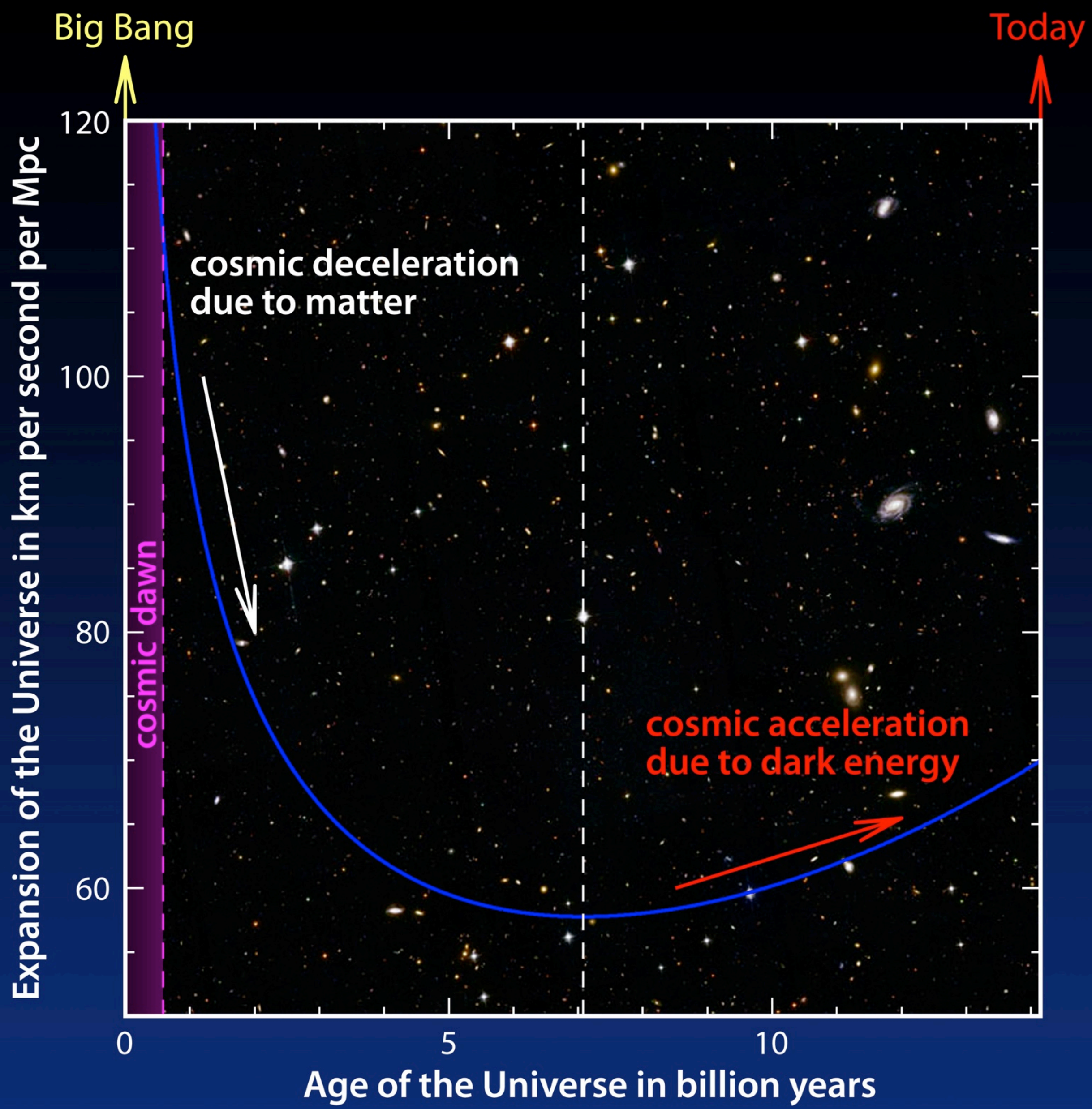


Deceleration parameter

$$q_0 = \Omega_m/2 - \Omega_\Lambda$$

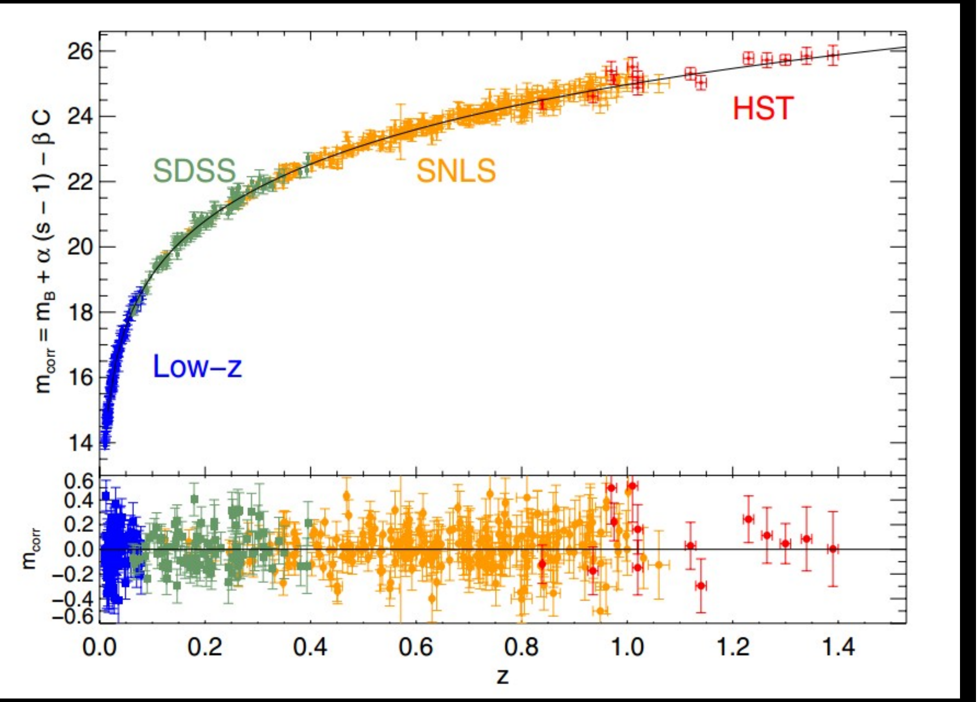
Data favor $q_0 < 0$:
<u>cosmic acceleration</u>

(a.k.a. "dark energy")

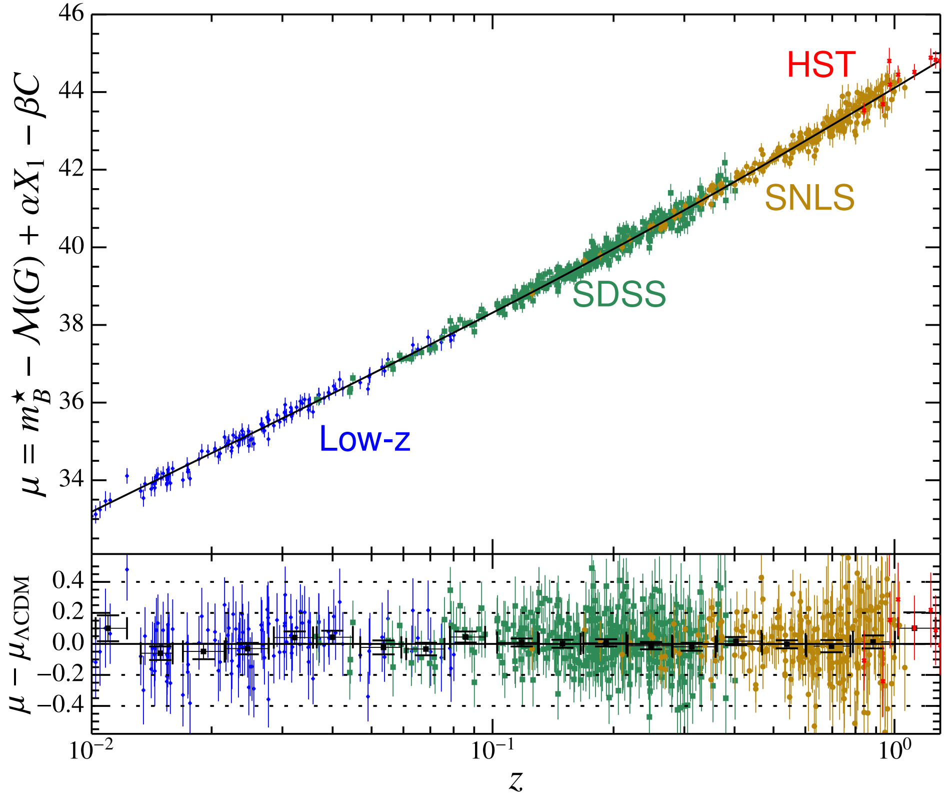

Big Bang
Today
Expansion of the Universe in km per second per Mpc
120
100
80
60
cosmic dawn
cosmic deceleration
due to matter
cosmic acceleration
due to dark energy
0
5
10
Age of the Universe in billion years

Evidence for Cosmic Acceleration Has Strengthened With Time

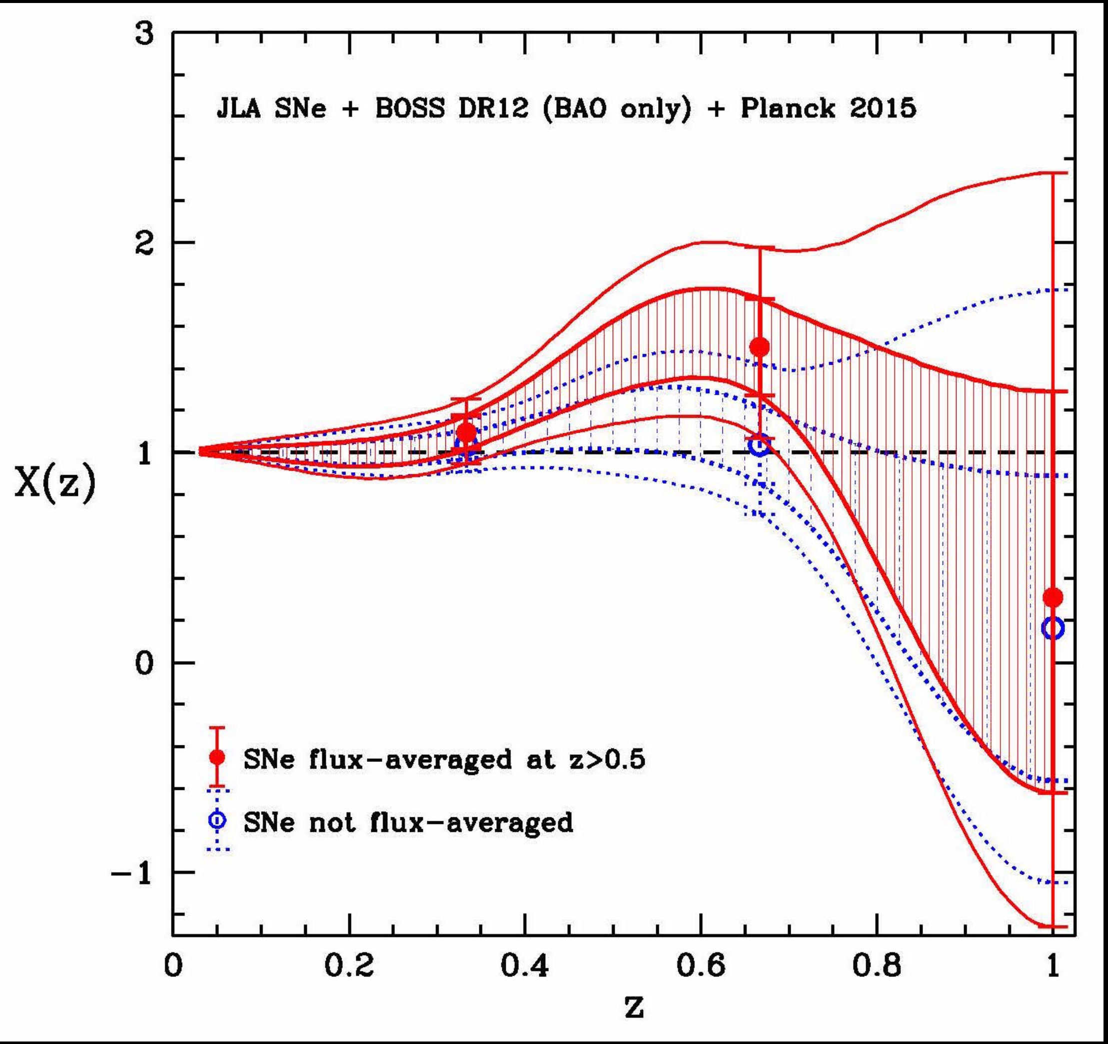
Hubble diagram of 472 SNe Ia compiled by Conley et al. (2011)



Hubble diagram of 740 SNe Ia compiled by Betoule et al. (2014) [JLA set]



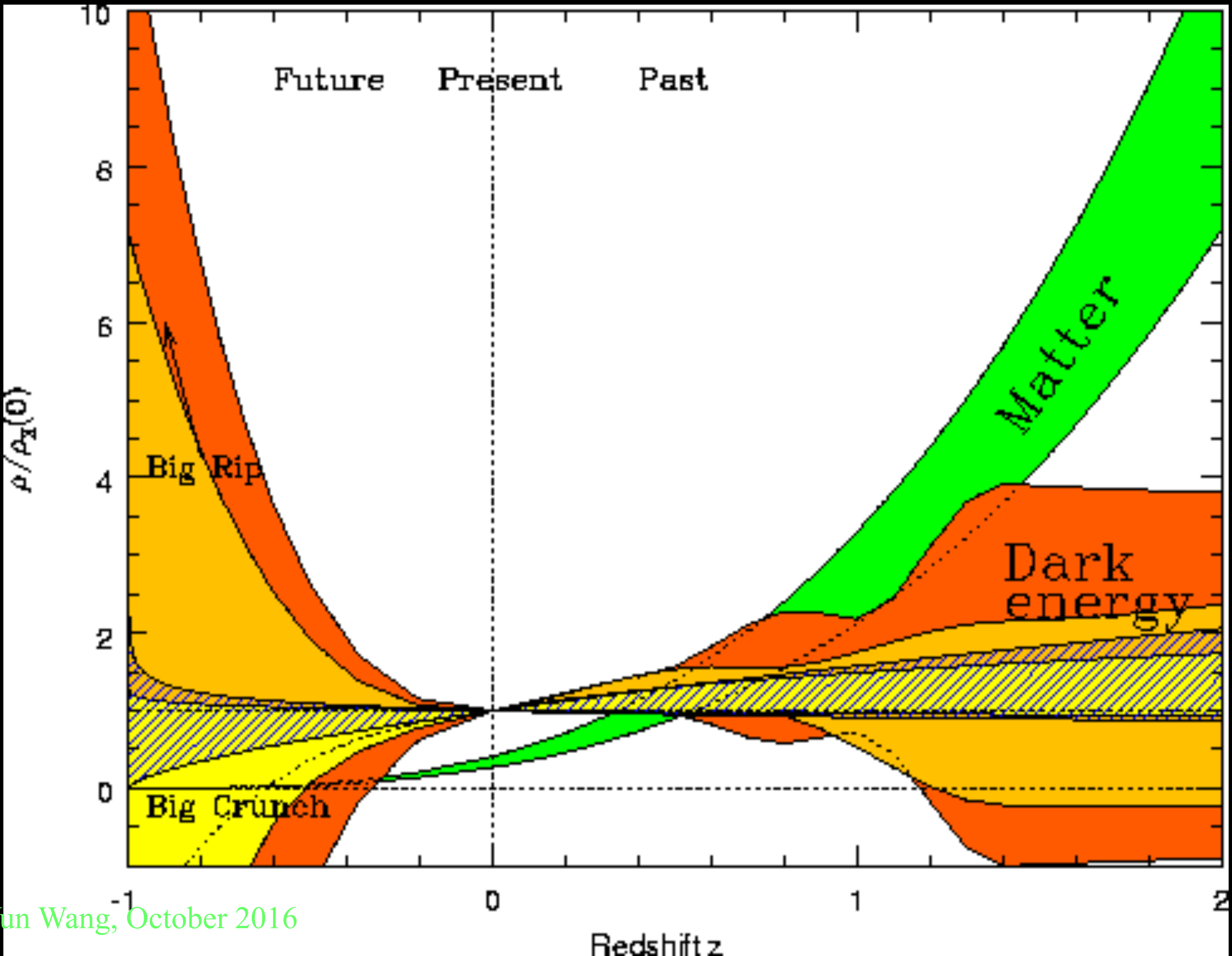
Model-Independent Constraints on Dark Energy



$X(z)=\rho_X(z)/\rho_X(0)$ *Wang, PRD (2016)*

What is the Fate of the Universe?

Wang & Tegmark, PRL (2004)



Probing the Nature of Cosmic Acceleration

Incorporating Cosmic Acceleration Into the Cosmological Model

- **Einstein's Equation:**

$$R_{\mu\nu} - g_{\mu\nu}R/2 = 8\pi G T_{\mu\nu}$$

- **Modify the Einstein Equation:**
  - **Add a new energy component to the RHS:** **dark energy models**
  - **Change the LHS by modifying the metric:** **modified gravity models**

Some Candidate Models for Cosmic Acceleration

- **Cosmological Constant** *(Einstein 1917)*
- **Quintessence** *(Freese, Adams, Frieman, Mottola 1987; Linde 1987; Peebles & Ratra 1988; Frieman et al. 1995; Caldwell, Dave, & Steinhardt 1998; Dodelson, Kaplinghat, & Stewart 2000)*
- **K-essence:** *(Armendariz-Picon, Mukhanov, & Steinhardt 2000)*
- **Modified Gravity**

  Vacuum Metamorphosis *(Sahni & Habib 1998; Parker & Raval 1999)*
  Modified Friedmann Equation *(Freese & Lewis 2002)*
  Phantom DE from Quantum Effects *(Onemli & Woodard 2004)*
  Backreaction of Cosmo. Perturbations *(Kolb, Matarrese, & Riotto 2005)*
  Emergent Gravity (*Padmanabhan 2009*)

How to Probe the Nature of Cosmic Acceleration

- ***Cosmic expansion history $H(z)$ or DE density $\rho_X(z)$***
  tells us whether DE is a cosmological constant

  $$H^2(z) = 8\pi\, G[\rho_m(z) + \rho_r(z) + \rho_X(z)]/3 - k/a^2$$

- ***Growth history of cosmic large scale structure [growth rate $f_g(z)$ or growth factor $G(z)$]***
  tells us whether general relativity is modified, given *H*(*z*)

Observational Probes of Dark Energy

- **SNe Ia (Standard Candles):** method used in DE discovery, independent of clustering of matter, probes $\boldsymbol{H(z)}$.

- **Galaxy Clustering (including Baryon Acoustic Oscillations as Standard Ruler):** BAO is calibrated by CMB, probes $\boldsymbol{H(z)}$; redshift-space distortions probe $\boldsymbol{f_g(z)}$.

- **Weak Lensing Tomography and Cross-Correlation Cosmography:** probe a combination of $\boldsymbol{G(z)}$ and $\boldsymbol{H(z)}$.

- **Galaxy Cluster Statistics:** probes a combination of $\boldsymbol{H(z)}$ **and** $\boldsymbol{G(z)}$

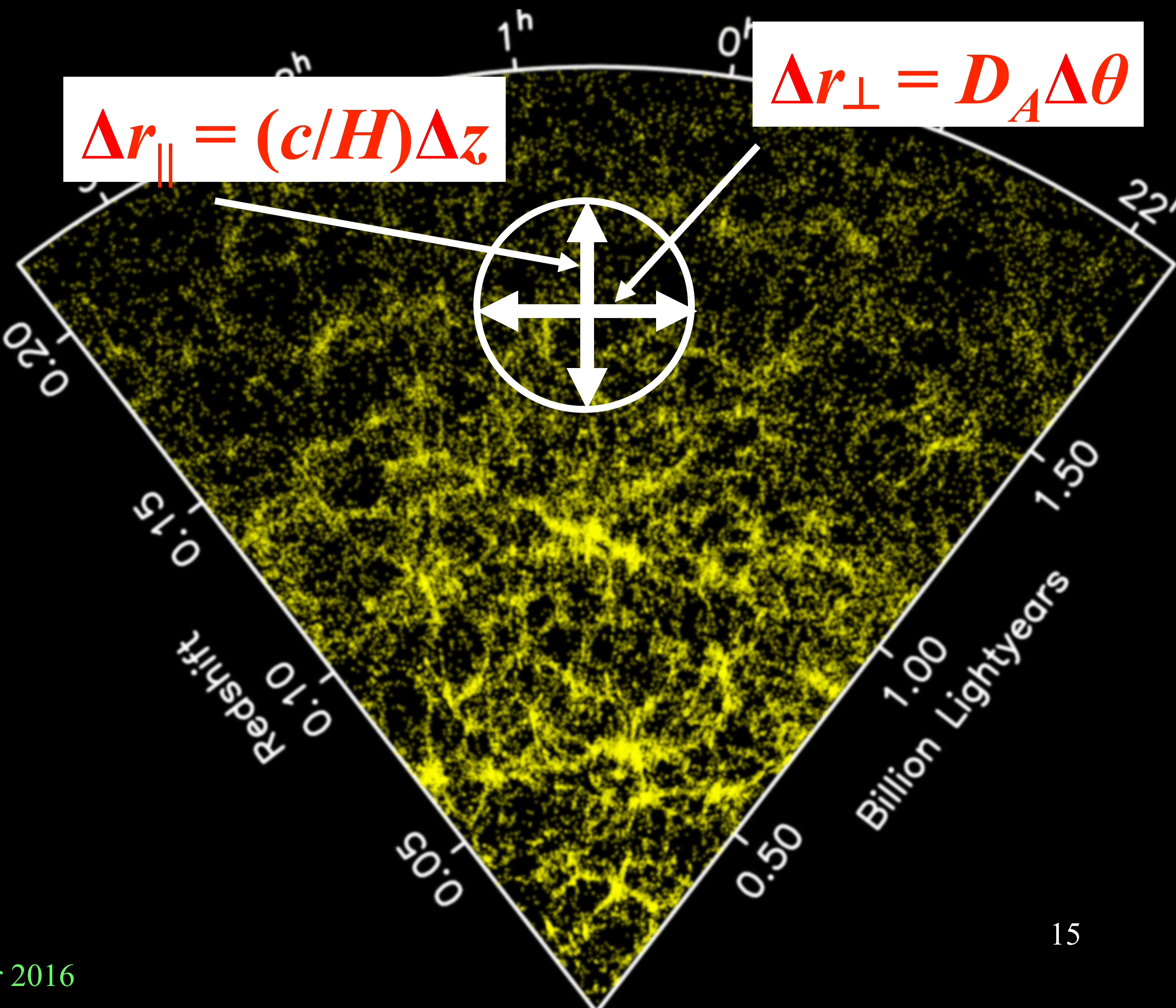
BAO as a Standard Ruler

Blake & Glazebrook 2003
Seo & Eisenstein 2003

BAO "wavelength" in radial direction in slices of z : $H(z)$

BAO "wavelength" in transverse direction in slices of z : $D_A(z)$

BAO systematics:
➔Bias
➔Redshift-space distortions (can be used to measure $f_g(z)$ if properly modeled)
➔Nonlinear effects



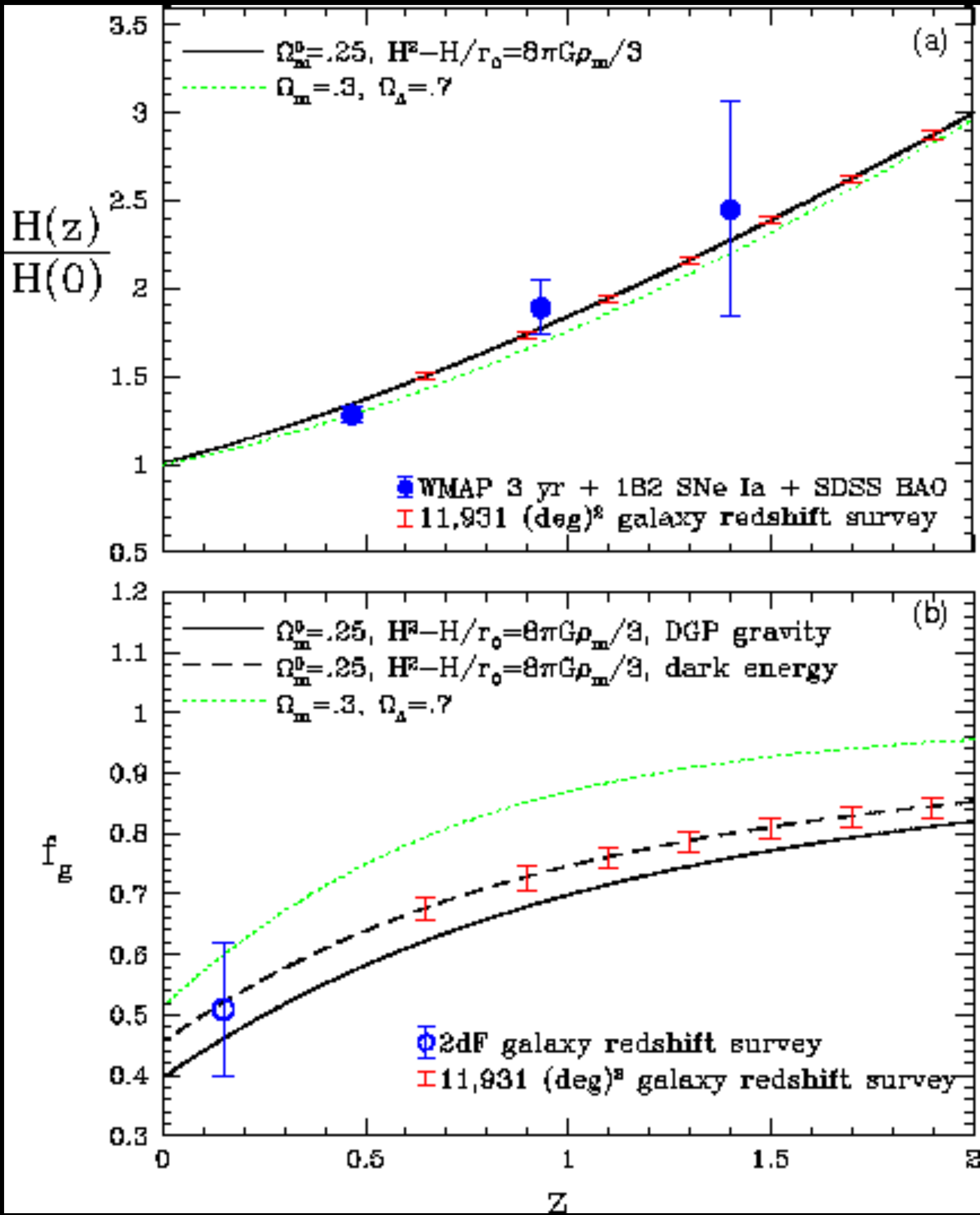
The Use of Galaxy Clustering to Differentiate Dark Energy & Modified Gravity

Measuring redshift-space distortions $\beta(z)$ and bias $b(z)$ allows us to measure $f_g(z)=\beta(z)b(z)$

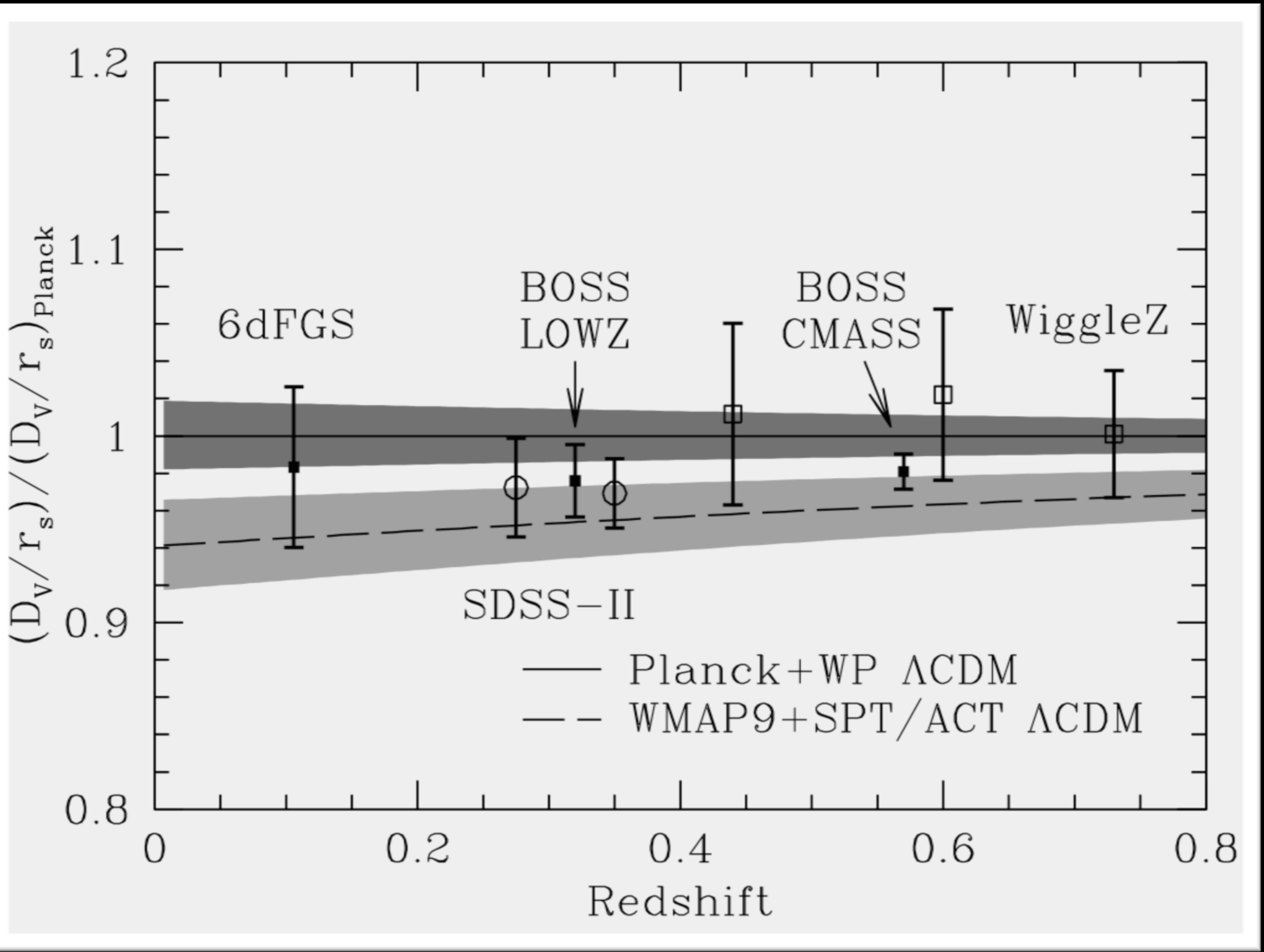
$[f_g=\mathrm{dln}\delta/\mathrm{dln}a]$

$H(z)$ and $f_g(z)$ allow us to differentiate dark energy and modified gravity.

Wang (2008)



Inconsistencies of Current data: BOSS DR11 vs. CMB



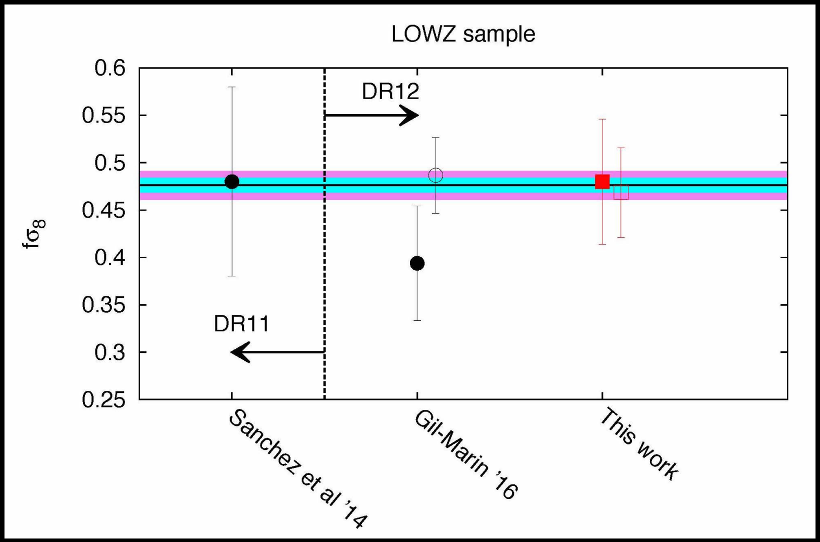
Tension between BOSS DR11 BAO distance measurements and constraints from CMB data.

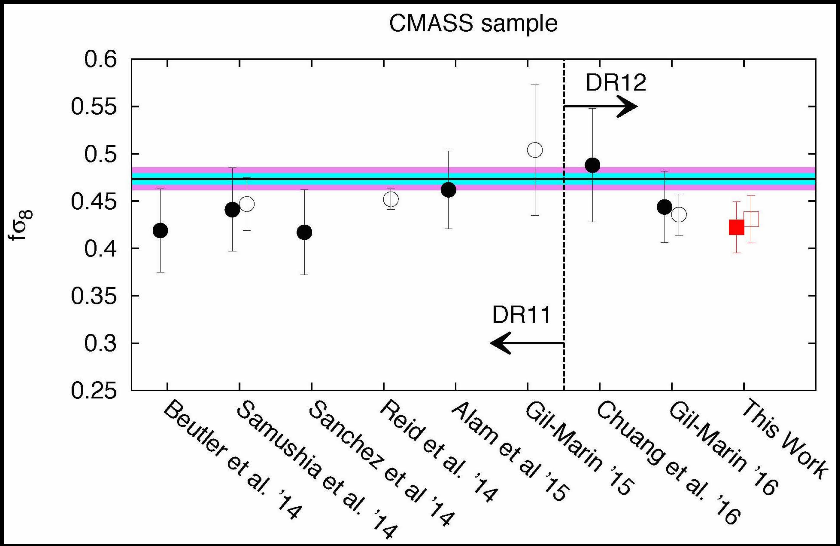
Anderson et al. (2014)

This trend has continued in the BOSS DR12 data.

BOSS DR12

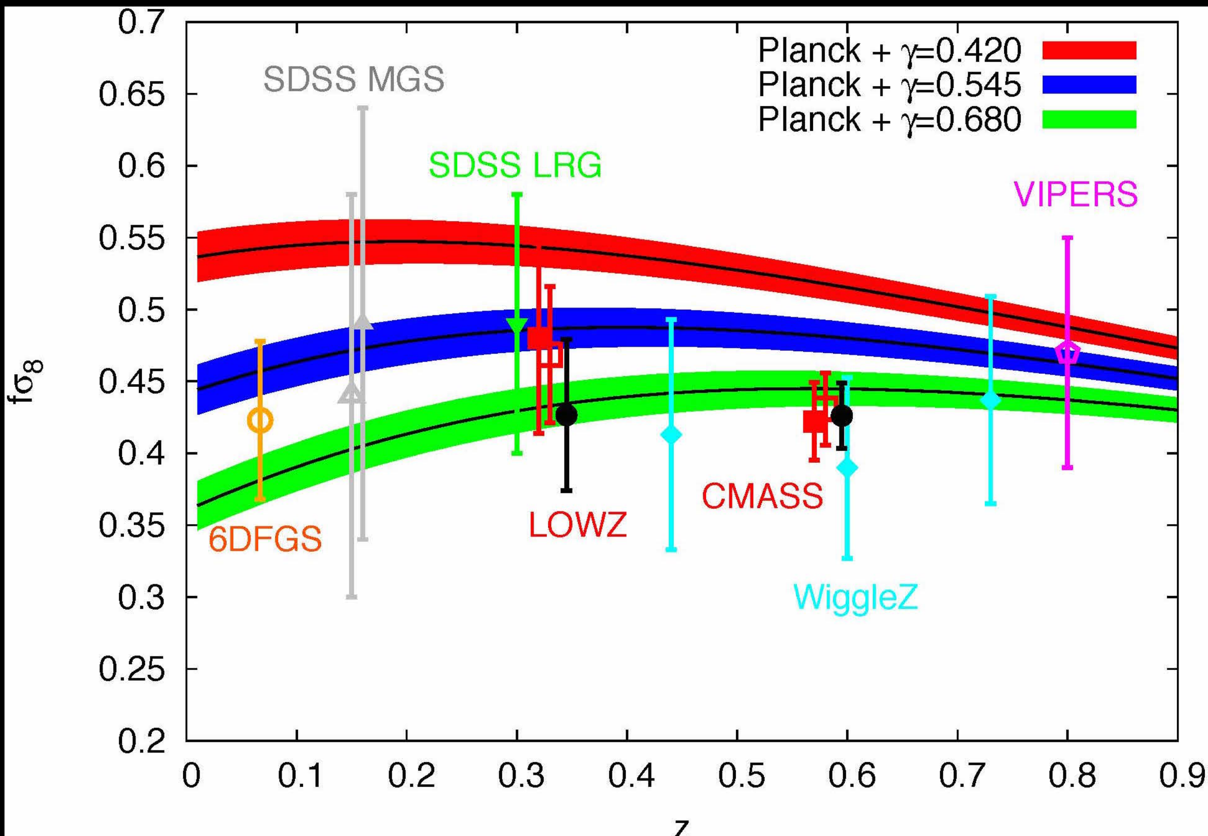
- The BOSS team is working on their official paper for DR12, Anderson et al. (2016)
- Four papers have been published by subsets of the BOSS team
  - The H(z) and $D_A(z)$ measurements at z=0.32 and z=0.57 are consistent with DR11 results
  - The growth rate measurements at z=0.32 and z=0.57 appear sensitive to model assumptions





Gil-Marin et al. (2016), 1606.00439

BOSS DR12 and CMB: the Tension Continues



The growth rate as a function of redshift. The central blue band is the prediction from Planck assuming GR (γ=0.545). The red squares are results from BOSS DR 12 (the empty squares differ in modeling assumption and are slightly displaced for clarity).

Gil-Marin et al. (2016), 1606.00439

Future Cosmic Accleration Surveys *(an incomplete list)*

Galaxy Redshift Surveys:

- BOSS (2011-2014): 10,000 sq deg GRS for LRGs, 0.1<z<0.7
- HETDEX(2014-?): 420 sq deg GRS, 1.9 < z < 3.5
- eBOSS (2014-2020): GRS over 7,500 sq deg for LRGs (0.6<z<0.8), and over 1500 sq deg for [OII] ELGs (0.6<z<1)
- PFS (2018?-): GRS of ELGs over 1400 sq deg (0.6<z<2.4)
- DESI (2018?-2022): GRS over 14,000 sq deg for LRGs (0.1<z<1.1) and [OII] ELGs (0.1<z<1.8?)
- Euclid (2020-): GRS over 15,000 sq deg of ELGs (0.7<z<2)
- WFIRST (2024?-): GRS over ~2200 sq deg of ELGs (1<z<3)

Weak Lensing Imaging Surveys:

- DES (2013-?): optical WL over 5000 sq deg (i=24)
- Euclid (2020-): NIR WL over 15,000 sq deg (R+I+Z=24.5, H=24)
- LSST (2023-?): optical WL over 18,000 sq deg (r=24.5)
- WFIRST (2024?-): NIR WL over 2200 sq deg (H~26.5)

Instrumentation for Future Cosmic Acceleration Surveys

"Future Cosmic Surveys"
(2016, Chicago)

Five potential future projects, outlined in "Cosmic Visions Dark Energy: Science" (DOE), were discussed at this meeting:

1. **Southern Spectroscopic Instrument:** wide-field, highly multiplexed spectroscopy on intermediate-to-large aperture telescope in the southern hemisphere
2. **DESI-2:** beyond DESI, aims to obtain spectra of 100M galaxies using [OII] to z=2.5
3. **Low Resolution Spectroscopy:** dz/(1+z)>0.003, high galaxy number density
4. **21 cm:** probes reionization, heating, the dark ages, and LSS
5. **Billion Object Apparatus (BOA):** 1 billion optical spectra in the radio (SKA2 HI survey), or in the optical (most powerful cosmic acceleration science)

Massively Multiplexed Spectroscopy: the Next Frontier

- 100M-1 billion galaxy spectra
- High galaxy density, which enables
  - multi-tracer studies of cosmic acceleration via BAO/RSD, to evade the cosmic variance and boost statistical power
  - higher order statistics, to enable tighter and more robust cosmological constaints

BOA Survey Design

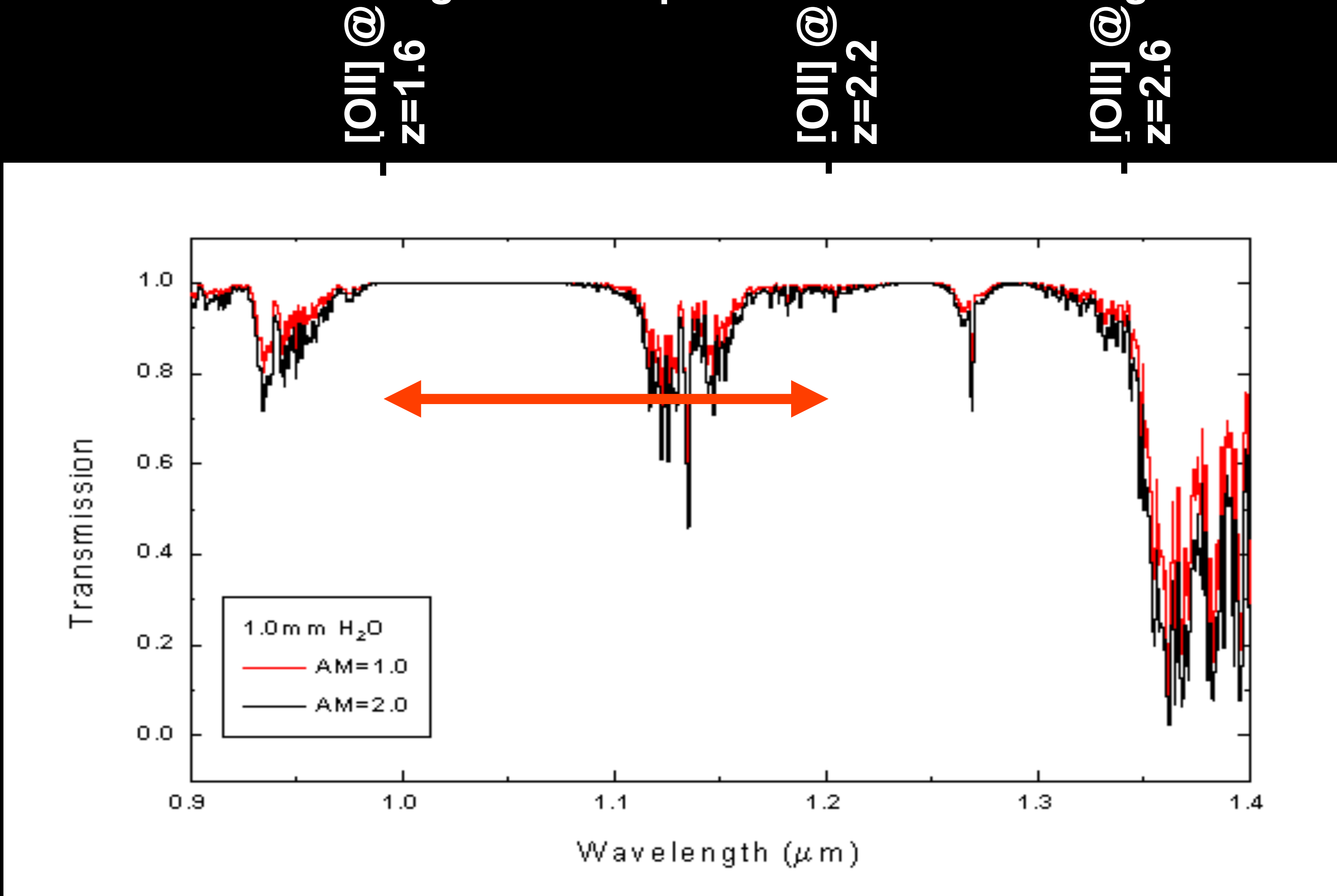
(from Kyle Dawson's presentation at "Future Cosmic Surveys")

- 35k targets per sqdeg, 14k sqdeg
  - Magnitude limited sample to z<1.5
  - UGR selection for 1.5<z<3.25
  - 500M spectra
  - 15X DESI
- 350M Fourier modes
  - 30X DESI
- 10m telescope
  - 6X DESI collecting area
- 1 hr exposures for ?90%? redshift success
  - 2.4X DESI exposure times
- Overall ~4X better [OII] sensitivity than DESI for low z sample
- 3600-13,000 \AA
  - Includes IR channel for [OII] detection to z=2.5
  - R~4000 for sky subtraction and [OII] identification

Beyond DESI: instrument upgrade

From David Schlegel's presentation at "Future Cosmic Surveys

λ = 980 - 1200 nm is a good atmospheric window from the ground



BOA Survey Characteristics

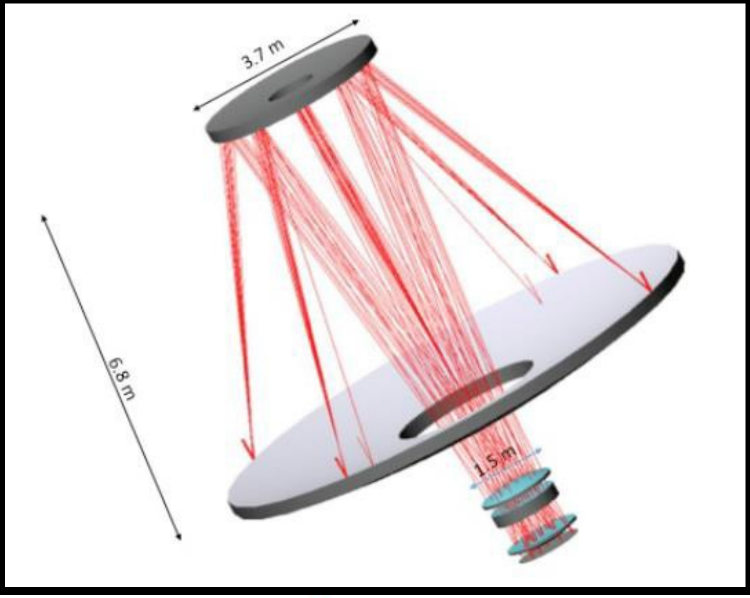
(from Kyle Dawson's presentation at "Future Cosmic Surveys")

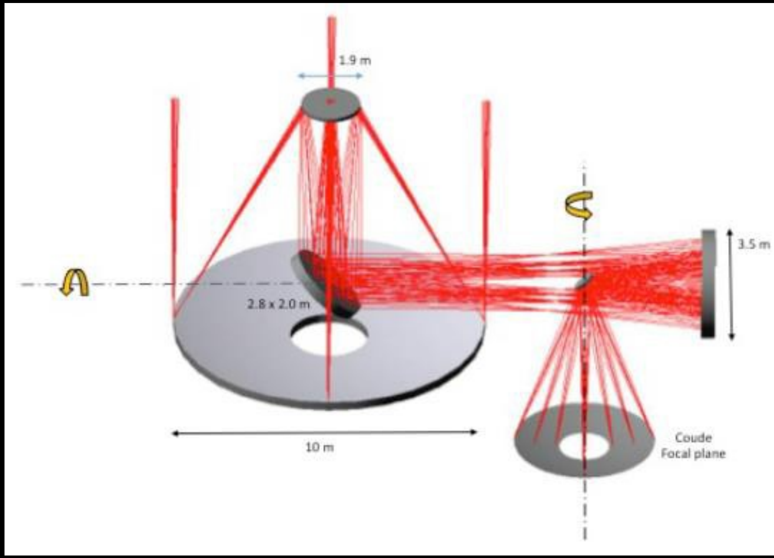
- Conservative Assumptions
  - 1000 hours open shutter per year
  - 1 hr/exposure
  - 10 yr program
- 10,000 unique pointings
  - 2.5 degree FOV (4.9 sqdeg per field)
  - Three passes per coordinate (3hrs with repeat visits to lyman-alpha forest tomography targets)
- Assume 80% fiber efficiency
  - 13k fibers per sqdeg
  - 65k fibers for instrument
- Increase fiber density 2X to reach 1B spectra

BOA: Possible Telescope Design

(from Kyle Dawson's presentation at "Future Cosmic Surveys")

- Two designs for massively multiplexed spectrographs on 10-m class telescope
  - Pasquini et al., 2016
- Fiber design
  - 2.5 degree diameter (4.9 sqdeg)
  - 1.3 meter focal plane diameter (Cass focus)
- Ring design
  - 1.5 degree diameter (1.0 sqdeg)
  - 4.6 meter focal plane diameter (Coude focus)
- Bigger spectrograph on bigger telescope:
  - Cass versus Coude
  - FOV considerations



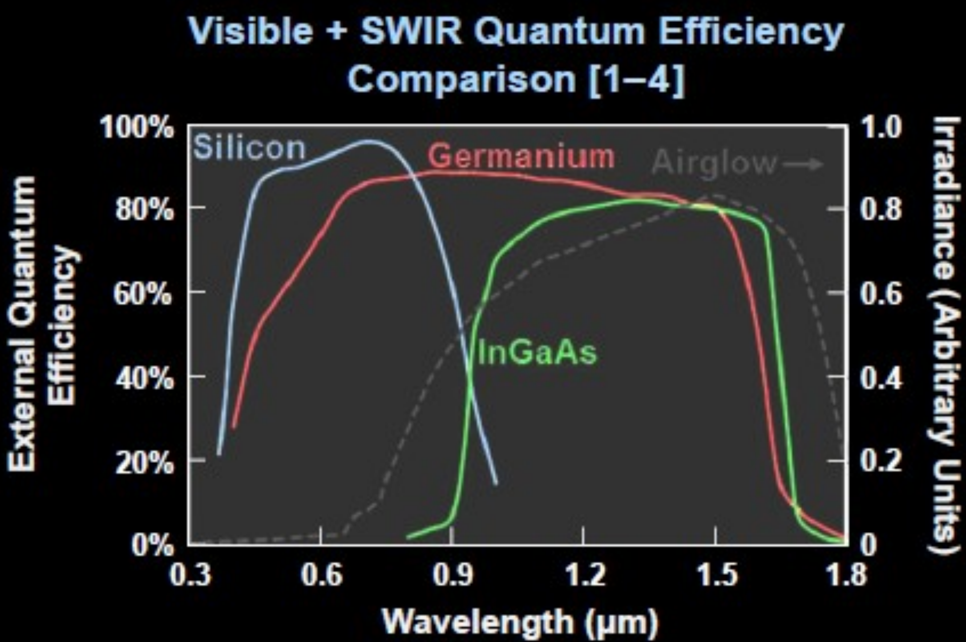


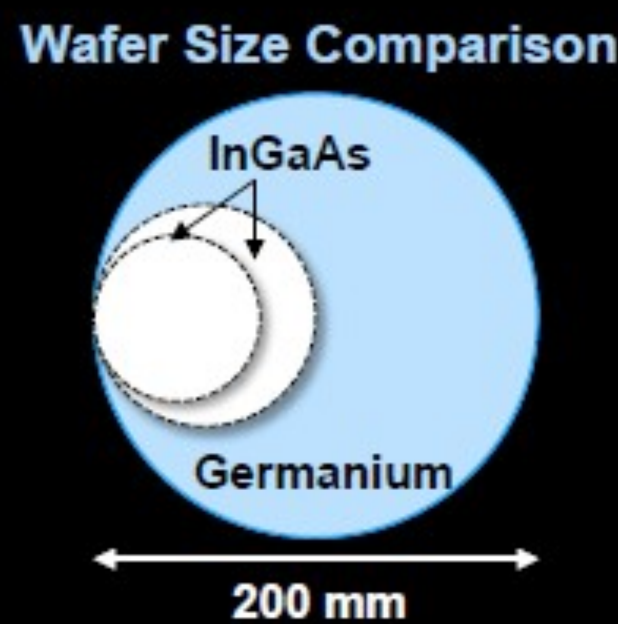
BOA: Spectrographs

(from Kyle Dawson's presentation at "Future Cosmic Surveys")

- DESI design with 4th channel
- Silicon + Germanium CCDs
- Si for two channels, 3500<lambda<8000 \AA
  - Well-known technology
- Ge for two channels, 8000<lambda<13,000 \AA
  - New CCD's being developed at Lincoln Labs/LBNL

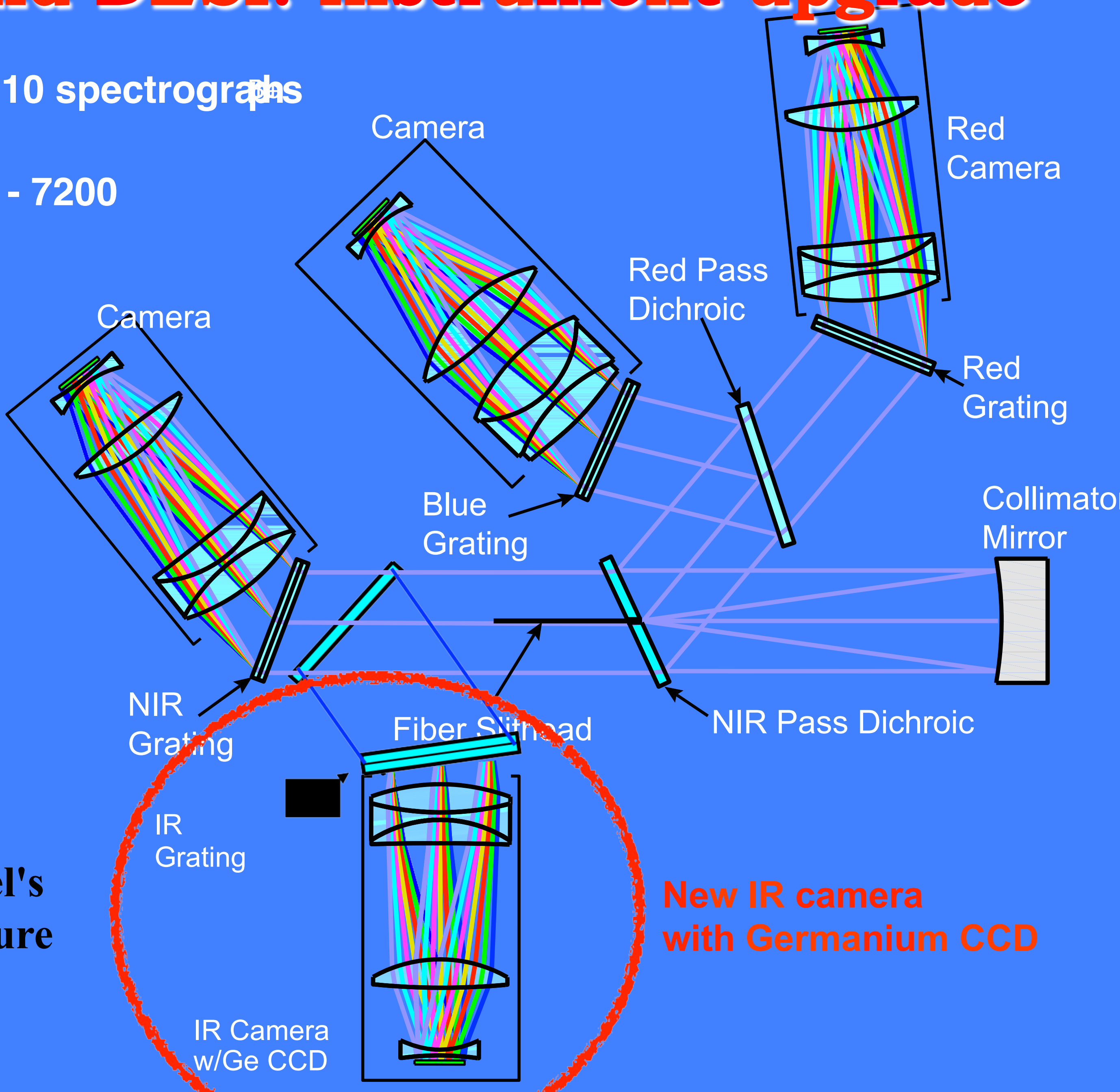
From Christopher Leitz (MIT LL)





Beyond DESI: instrument upgrade

Add 4th arm to all 10 spectrographs
λ = 980 - 1200 nm
Resolution = 6000 - 7200
Germanium CCDs
NIR

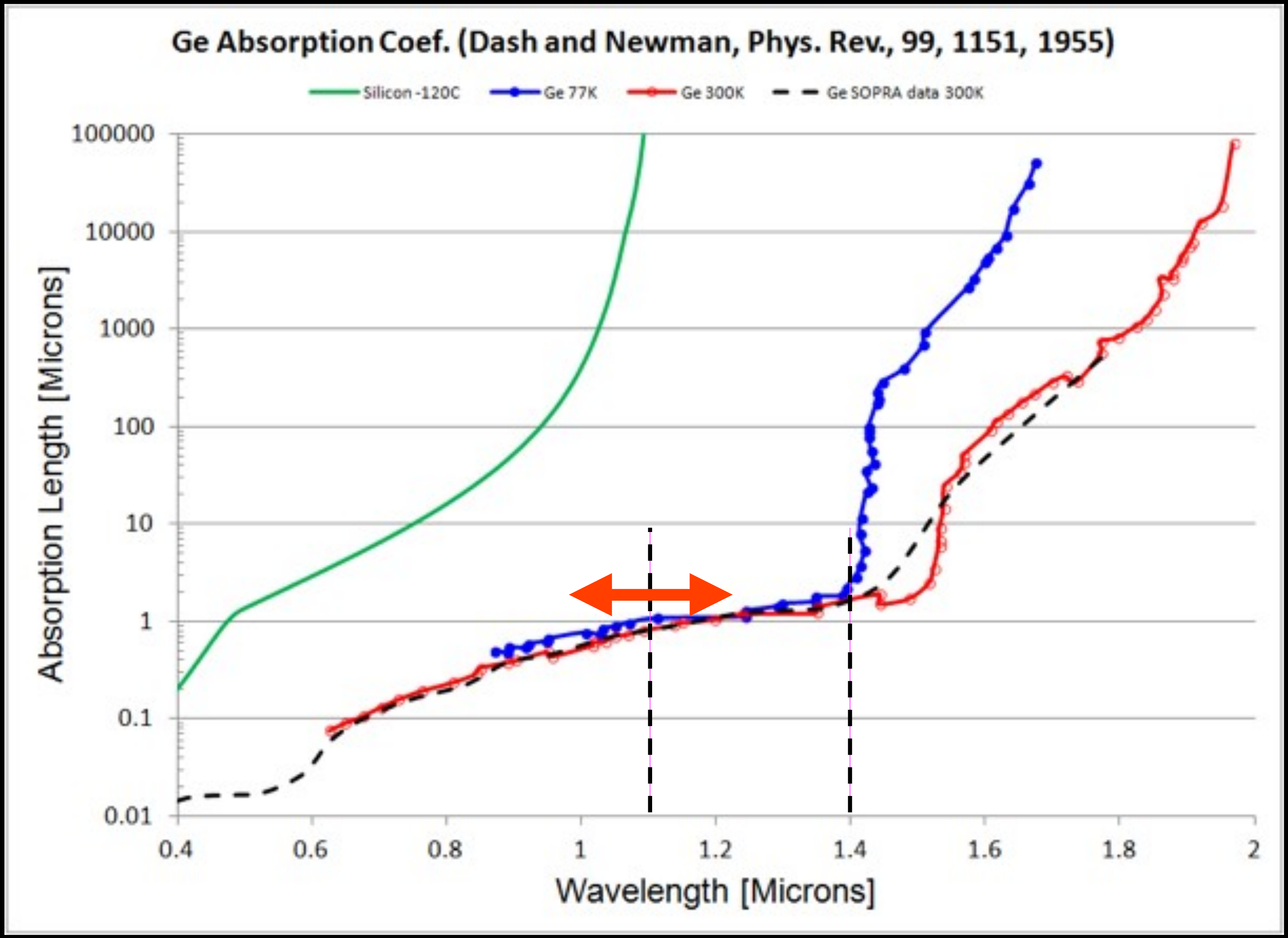


(From David Schlegel's presentation at "Future Cosmic Surveys)

Beyond DESI: instrument upgrade

(From David Schlegel's presentation at "Future Cosmic Surveys")

λ = 980 - 1200 nm is also well-matched to Ge CCD detectors

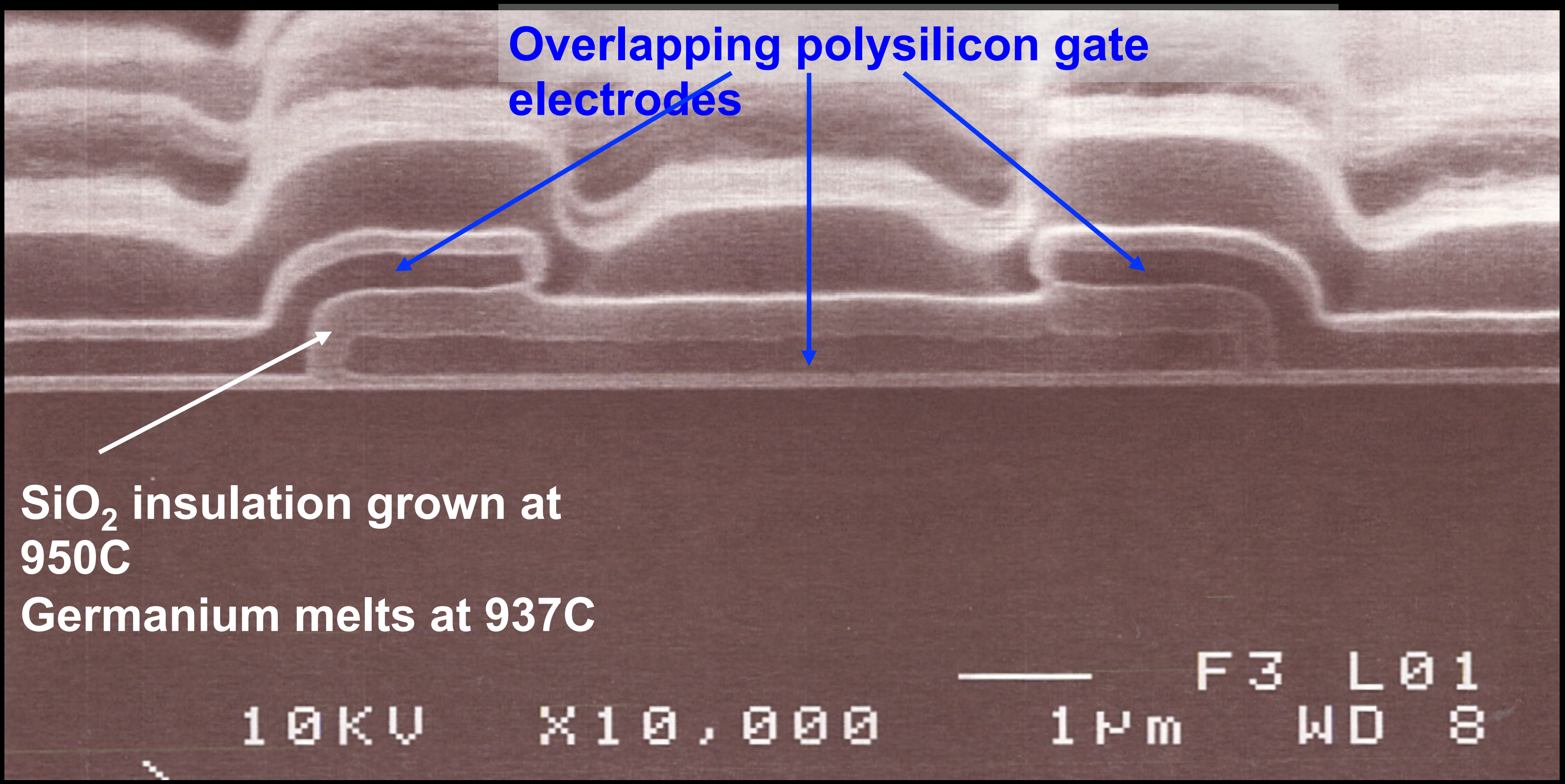


Beyond DESI: instrument upgrade

(From David Schlegel's presentation at "Future Cosmic Surveys")

Ge CCD detectors are in development

- Most fabrication steps identical to silicon CCDs
- Final processing would be at labs
- Readout systems would be identical to CCDs
- Better than HgCd detectors because thermal photons rejected



BOA: Technical Challenges

(from Kyle Dawson's presentation at "Future Cosmic Surveys")

- Details of target selection and exposure depth
  - What is optimal number density for $z<1.5$ and $z>1.5$?
  - What is the expected redshift success rate versus exposure time?
  - What are requirements for spectroscopic completeness?
  - What are maximal allowable uncertainties in the selection function?
- Fiber placement
  - How to fill focal plane with ~100,000 fibers?
- Spectrographs
  - DESI design with 4th channel possible
  - How to scale production to accommodate ~100,000 fibers?

Promising Technology: Digital Micromirror Devices (DMDs)

- Commercial product by Texas Instrument
- Alternative slit selector studied in 2002 for JWST
- DMD-based multi-object spectrographs (MOS) have been built for ground-based telescopes: RITMOS (Mees Observatory 24 inch, 2003) and IRMOS (0.8-2.5 microns on KPNO 4m, 2004), both with 848x600 TI DMD
- NSF has funded a $1.5M project (9/2016-8/2018) to build a MOS for SOAR (4.1m), with 2048x1080 TI DMD
- Gemini funded a study in 2015 for a $15M Gemini MOS, with 2048x1080 TI DMDs

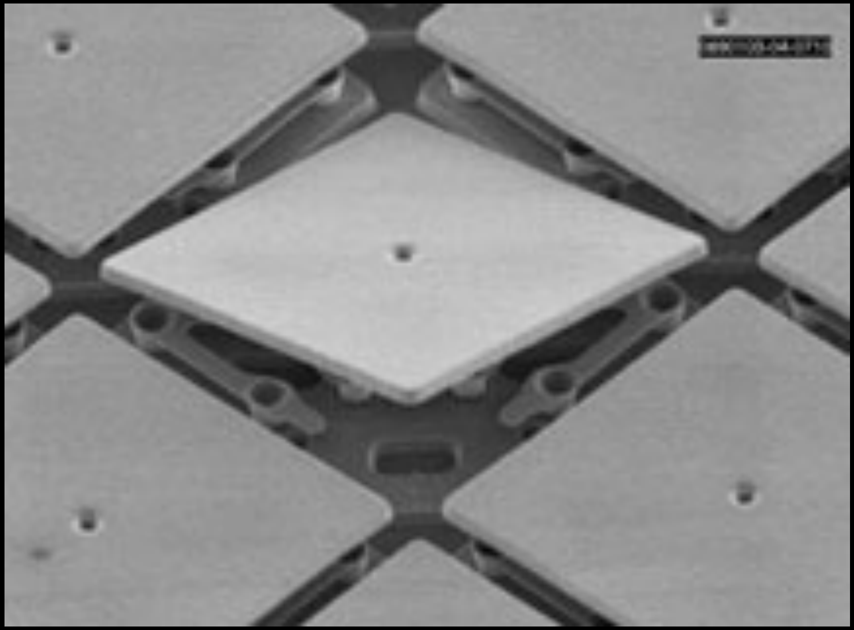
Texas Instrument DMDs

(Slide from Massimo Robberto)

- A DMD is a microelectrical mechanical system (MEMS) built on top of a memory array.

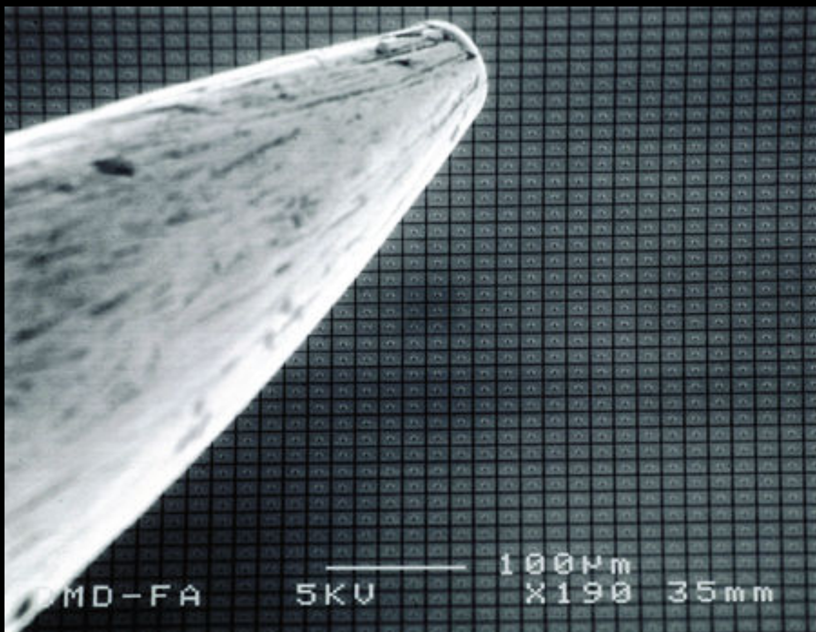
- It primary purpose is a spatial light modulator (SLM).

- The mirrors tip about the diagonal ±12°



Digital Micromirror Devices

(Slide from Massimo Robberto)

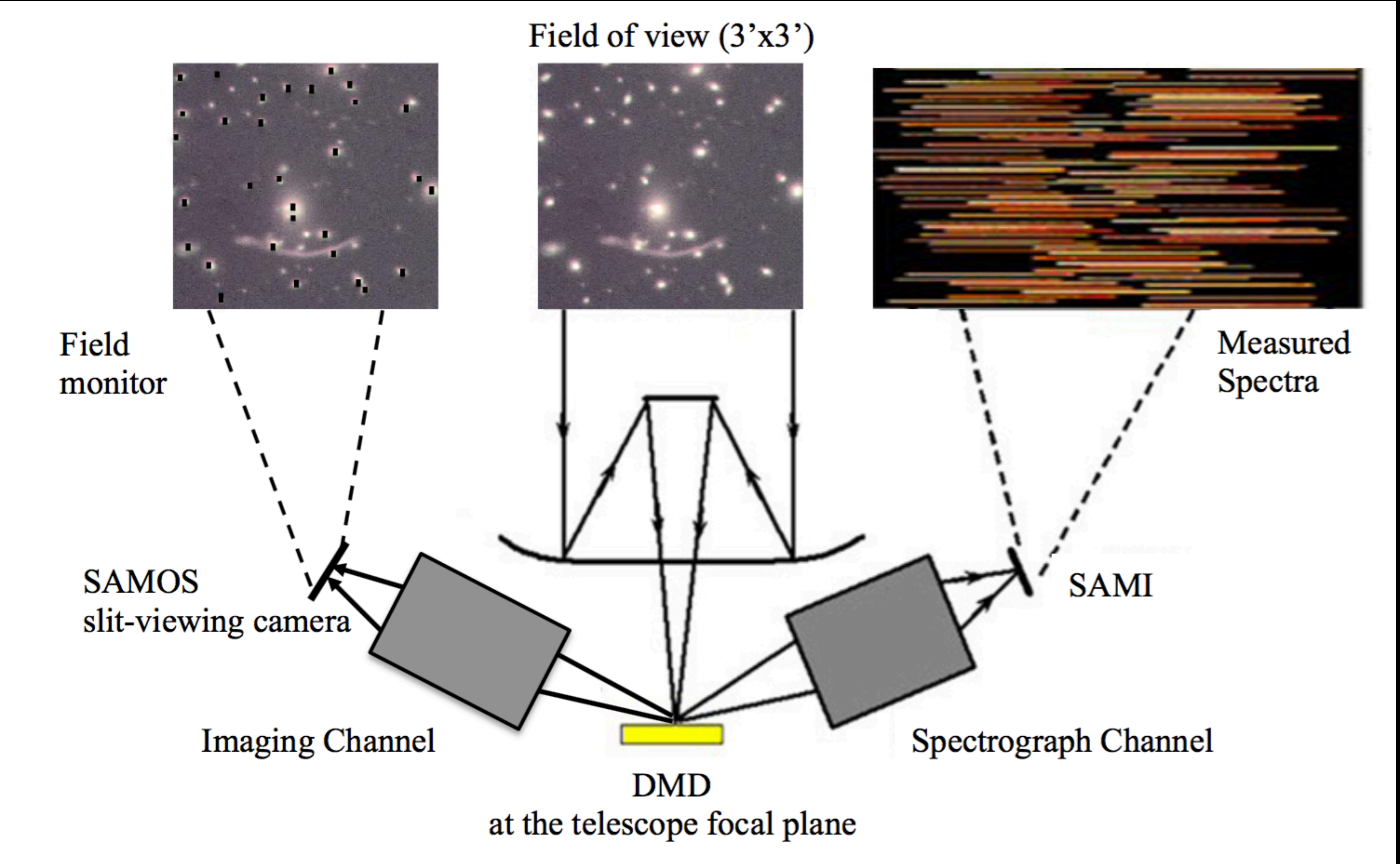


DMDs come in different format;
Tens of million pieces have been produced for consumer market

Cinema 2K model
2048×1080 elements
Square mirrors, 13.8µm side
92% filling factor

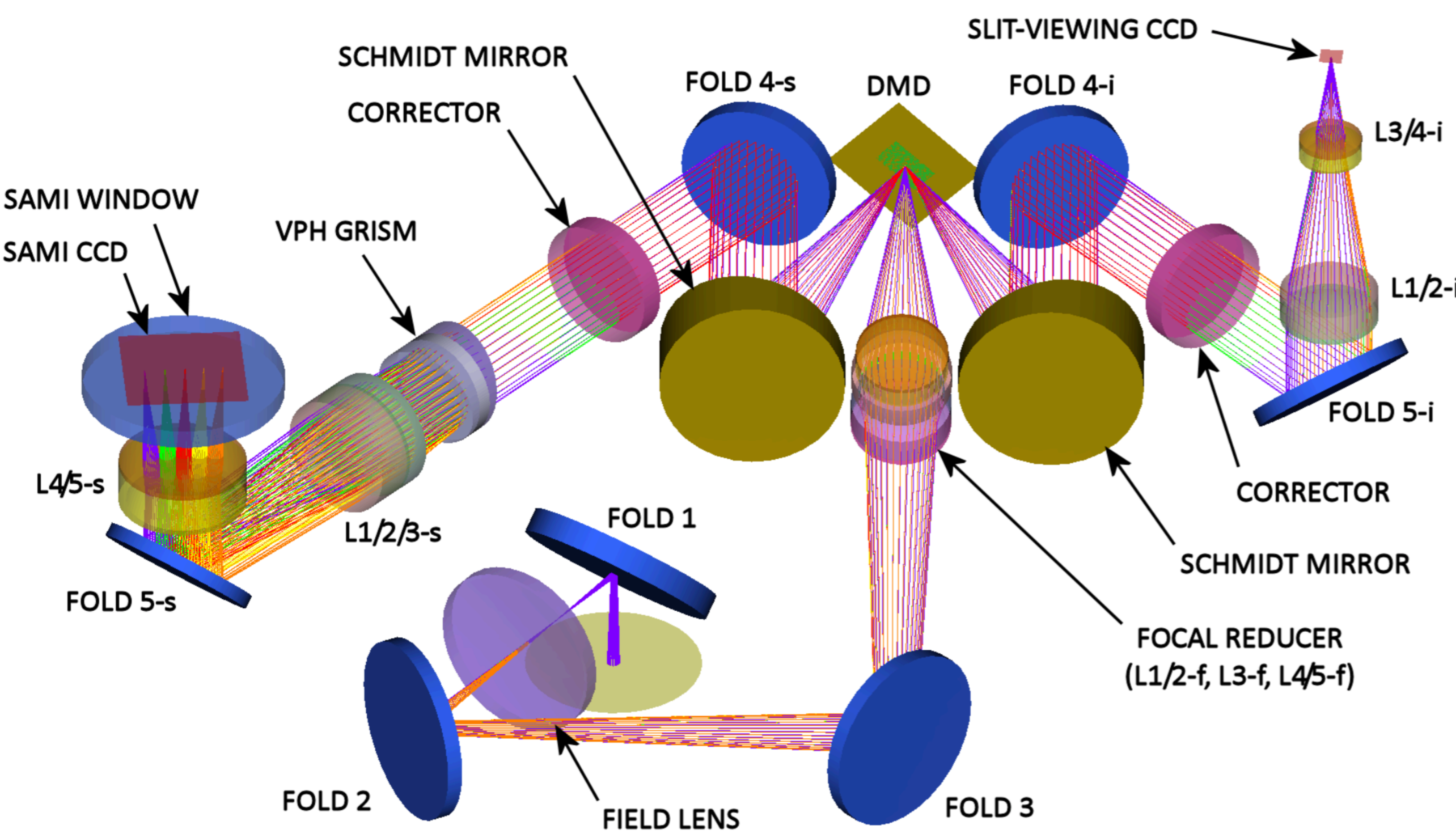
DMD-based MOS on SOAR

(Slide from Massimo Robberto)



Optical Layout for SOAR

(Slide from Massimo Robberto)



DMD Wishlist

- Many more micro-mirrors per DMD, with each micro-mirror at least 13.8μm on the side (2048x1040 TI Cinema DMD) to allow simplicity in optical design. Could very large format DMDs be used (instead of 100k fibers) for BOA?
- Longer wavelength cutoff (limited by the operating temperature of the controlling electronics), to allow NIR and IR observations.

Cosmic Acceleration Parallel Session at CPAD 2016

Conveners: Elisabeth Krause & Eduardo Rozo

- Aaron Roodman: Summary of the Cosmic Visions Report
- Jeff Newman: Physics with future Spectroscopic Surveys
- Blake Sherwin: Physics with future CMB Surveys
- Dragan Huterer: Constraining Inflation with CMB and LSS
- Laura Newburgh: Physics with future Intensity Mapping Surveys
- Salvatore Vitale: Cosmology with Gravitational Wave Events
- Oliver Dore: Enhancing WFIRST Science with Ground-Based Surveys

✪ There are mysteries in the Universe in addition to cosmic acceleration.

✪ Surveys optimized for probing cosmic acceleration also lead to spectacular data for probing early Universe physics.

Back-up Slides

Weak Lensing Tomography and Cross-Correlation Cosmography

Gravitational Lens in Abell 2218 HST · WFPC2

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA

- **Weak Lensing Tomography:** compare observed cosmic shear correlations with theoretical/numerical predictions to measure cosmic large scale structure growth history $G(z)$ and $H(z)$ *[Wittman et al. 2000]*

- **WL Cross-Correlation Cosmography** measure the relative shear signals of galaxies at different distances for the same foreground mass distribution: gives distance ratios $d_A(z_i)/d_A(z_j)$ that can be used to obtain cosmic expansion history $H(z)$ *[Jain & Taylor 2003]*

Clusters as DE probe

1) Use the cluster number density and its redshift distribution, as well as cluster distribution on large scales.

2) Use clusters as standard candles by assuming a constant cluster baryon fraction, or use combined X-ray and SZ measurements for absolute distance measurements.

- ***Large, well-defined and statistically complete samples of galaxy clusters are prerequisites.***

Testing Gravity: Measuring the Metric

In the conformal Newtonian gauge (the longitudinal gauge), the perturbed Robertson-Walker metric is given by

$$\mathbf{ds^2 = a^2(\tau)[-(1+2\phi)d\tau^2 + (1-2\psi)\gamma_{ij}dx_i dx_j]}$$

•Applicable only for scalar mode of the metric perturbations

•ϕ: the gravitational potential in the Newtonian limit

•γ_{ij}: the three-metric for a space of constant spatial curvature

WL: probe $\phi+\psi$

GC/RSD: probes ϕ (peculiar velocities follow gradients of the Newtonian potential)

How Many Methods Should We Use?

- The challenge to solving the DE mystery will not be the statistics of the data obtained, but the tight control of systematic effects inherent in the data.
- A combination of the three most promising methods (SNe, GC/BAO, WL), each optimized by having its systematics minimized by design, provides the tightest control of systematics.

Dark Energy Equation of State

- Equation of state $w = p/\rho$
  - Matter: $p = 0$ ($w = 0$)
  - Radiation: $p = \rho/3$ ($w = 1/3$)
  - Dark energy: $p = w_X(z)\,\rho$

    Cosmological constant: $p = -\rho$ ($w = -1$)

DMD-based MOS on SOAR: Main Parameters

(Slide from Massimo Robberto)

Telescope aperture	410 cm
SAM corrected FoV	$3' \times 3'$
DMD type	Cinema 2K, 2048×1080 mirrors
DMD mirror scale	$0.167''$/mirror $3' \times 3'$ over 1080×1080 mirrors
SAMI CCD	E2V 4096×4112 pixels
SAMI pixel scale	$0.133'' \times 0.133''$ $3' \times 3'$ over 1350×1350 pixels
Slit width	$0.33''$, 2.5 CCD pixels/slit (2 DMD mirrors) $0.50''$, 3.7 CCD pixels/slit (3 DMD mirrors) $0.67''$, 5 CCD pixels/slit (4 DMD mirrors), etc.
Spectral coverage and resolutions (for 2 DMD = $0.33''$ slits)	3500-5500Å, $R \simeq 2500$ (blue channel, $R\theta = 833$) 5500-9500Å, $R \simeq 2000$ (red channel, $R\theta = 667$) 8300-9100Å, $R \simeq 10,000$ (Ca triplet, $R\theta = 3332$)
Length of the spectra	4090-1350 = 2740 pixels
Max nr. of spectra	$\simeq 200$, assuming 7 CCD pixel separation between spectra.
Slit-viewing camera	SBIG STT-3200ME with KAF-3200ME ($2184 \times 1472 \times 6.8\ \mu$m) 1.36 pixels per DMD mirror

GMOX baseline parameters

(Slide from Massimo Robberto)

Nr. of Channels	**3 (Blue, Red, NIR arm)**

GMOX Arms/Channels	• Blue arm: 3,300 - 5,890Å
	• Red arm: 5,890 – 9,700Å
	• NIR arm:
	    • YJ-channel: 0.97 - 1.37μm (1.45μm dichroic)
	    • H-channel: 1.50 - 1.80μm (1.9μm dichroic)
	    • K-channel: 2.01 - 2.42μm

Field of view	171" x 90" @ f/16 (Gemini N+S+ALTAIR) 83" x 44" @ f/32 (GEMS)
DMD type	Cinema 2K, 2048 x 1080 mirrors 13.0μm side, 13.7μm center-to-center
Mirror scale	83.3 mas/mirror @ f/16 40.0 mas/mirror @ f/33.2
Nominal resolving power	R = 5,000

GMOX Baseline Parameters

(Slide from Massimo Robberto)

Nominal slit-width & sampling	Blue: 0.41” (5 DMD mirrors) - 3 CCD pixels/slit Red: 0.33” (4 DMD mirrors) - 3 CCD pixels/slit NIR: 0.25” (3 DMD mirrors) - 2.75 FPA pixels/slit
Detectors	Blue, Red: CCD E2V290-99, 9,216 x 9,232 pixels (baseline) or CCD STA1600, 10,560 x 10,560 pixels NIR: 3 FPAs, model HI4RG, 4,096x 4,096 pixels
Nr. of spectra	~ 400, assuming 5 mirrors/target
Acquision + Slit-viewing + Tip-tilt control camera	Present on • Blue Channel • Red Channel • IR Channel