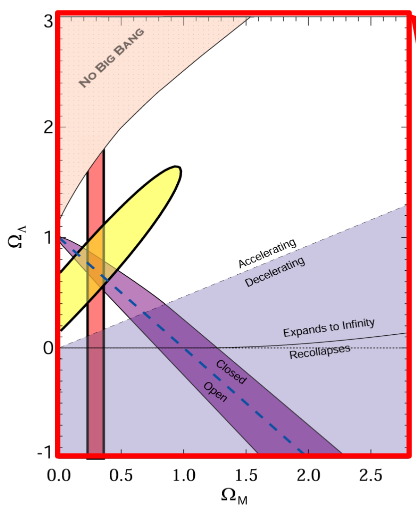
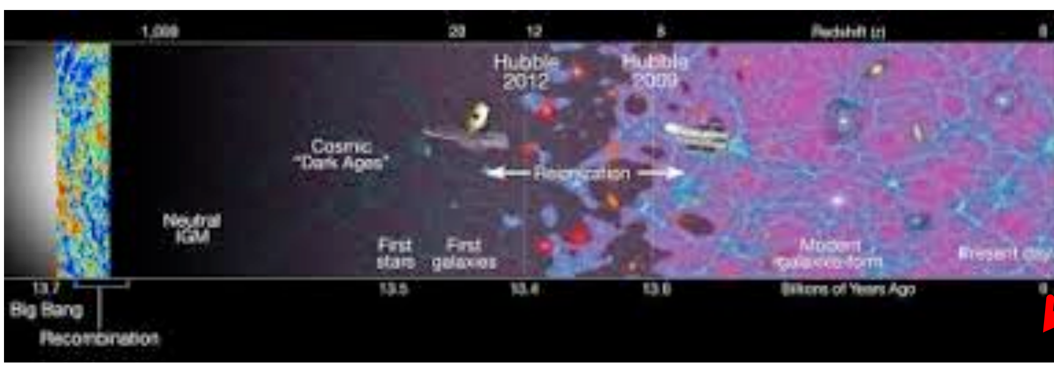
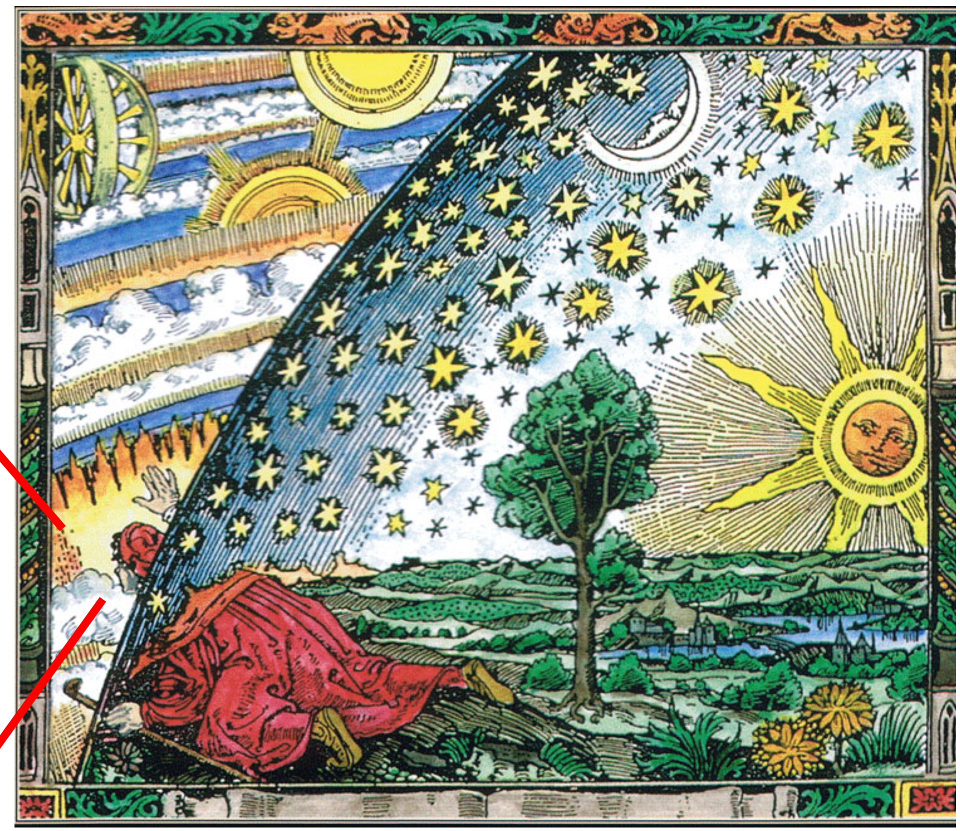
Cosmology & High Redshift Universe: Progress & Challenges

Richard Ellis







Rainbows on the Southern Sky

5th October 2015

Rapidly Developing Situation

- Outstanding scientific questions – nature of the Universe, new physical laws, origin of early galaxies and cosmic reionisation

- Significant growth in astrophysical interest as tracked in recent scientific literature

BUT:

- Ambitious facilities being developed in next decade to address the key issues, e.g. JWST, Euclid, E-ELT/TMT, WFIRST etc

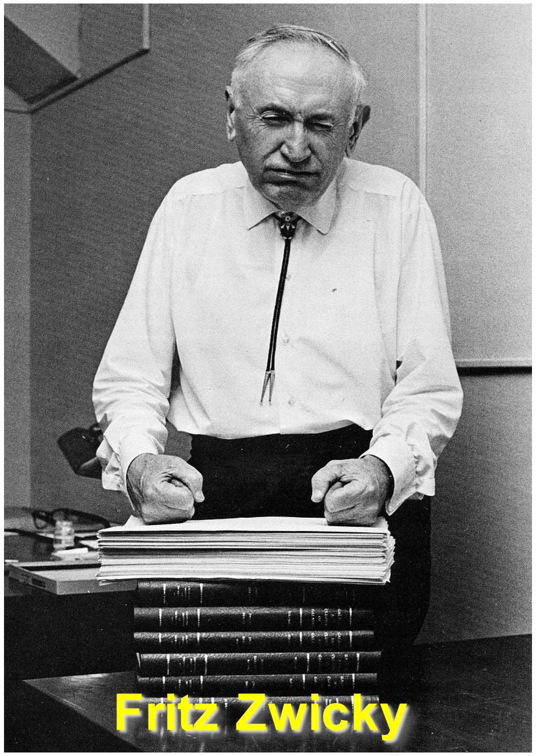
- Rise in dedicated survey facilities e.g. LSST and spectroscopic instruments

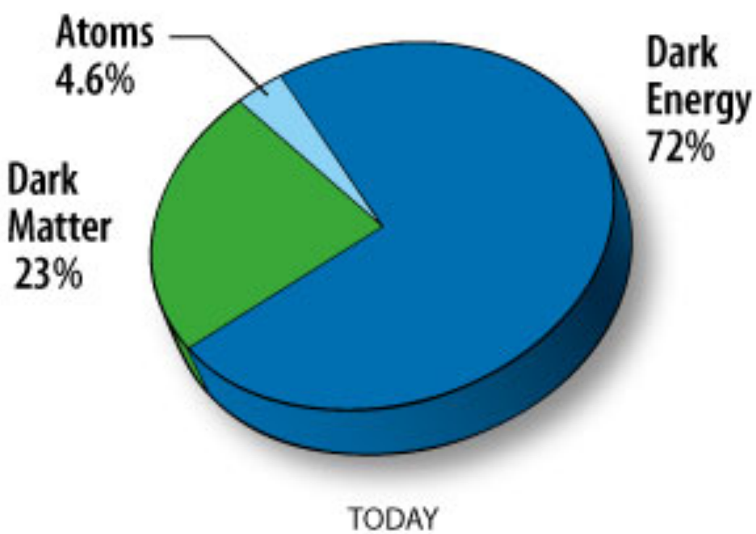
- Realization of key role of non-optical/IR capabilities e.g. ALMA

Must be creative with existing facilities in next 5 years

Cosmology: Two Rogue Ingredients

Dark Matter (1933 -)





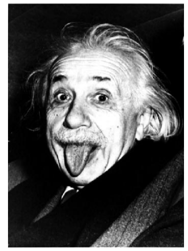
Dark Energy (1998 -)

Precision cosmology is a misnomer:
measurement ≠ understanding.
95% of the Universe is a mystery

Implications of Cosmic Acceleration

Did SN teams re-discover Λ?

$$R_{\mu\nu} - 1/2 g_{\mu\nu} R + g_{\mu\nu}\Lambda = 8\pi G/c^4\, T_{\mu\nu}$$



Two puzzles:

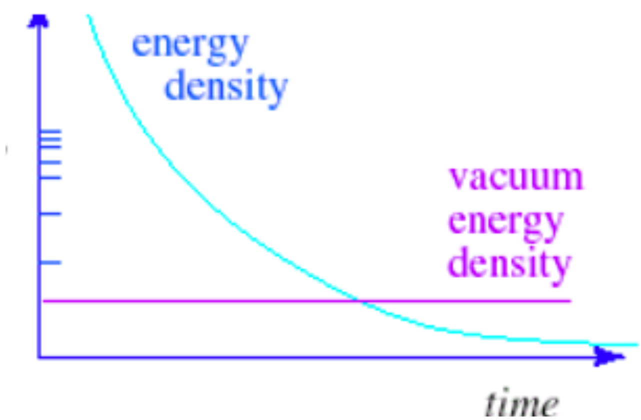
- Quantum field theory $\Lambda = 8\pi G m_P^4$

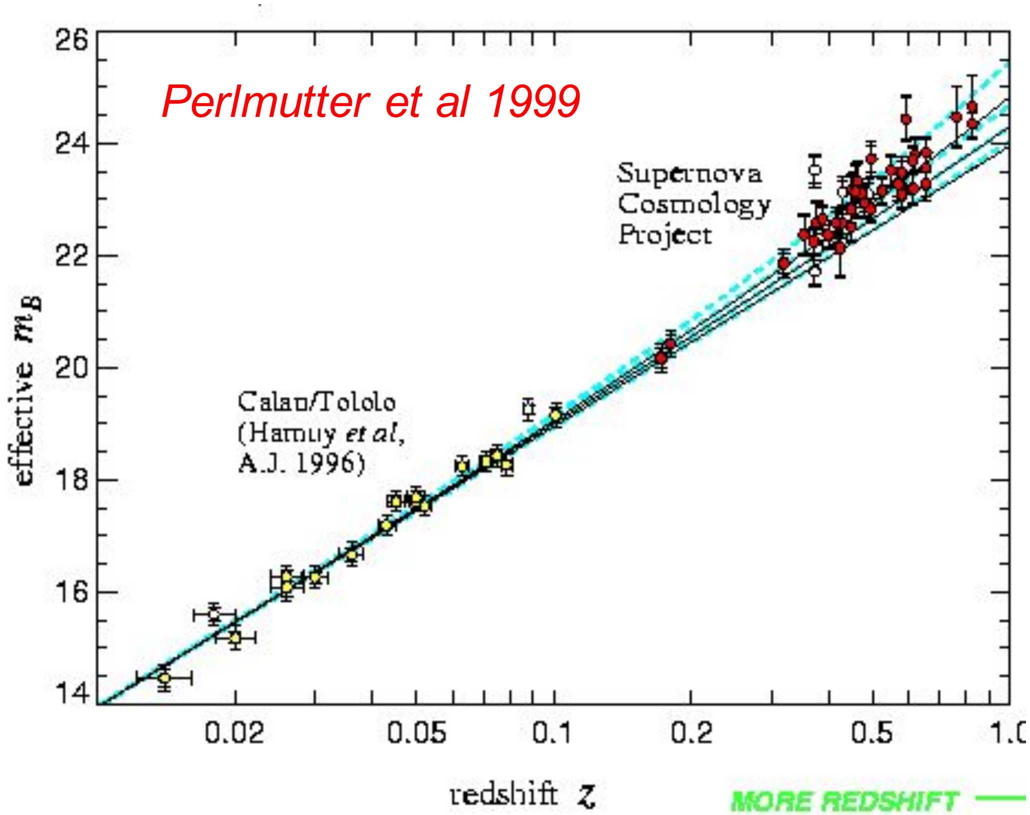
  (10^{120} larger than data)

- Why now?

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

  ρ_{vac} = const (vacuum)



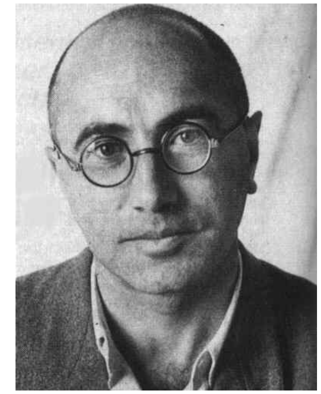


New physics: "dark energy"

- a scalar field: possibly time-dependent

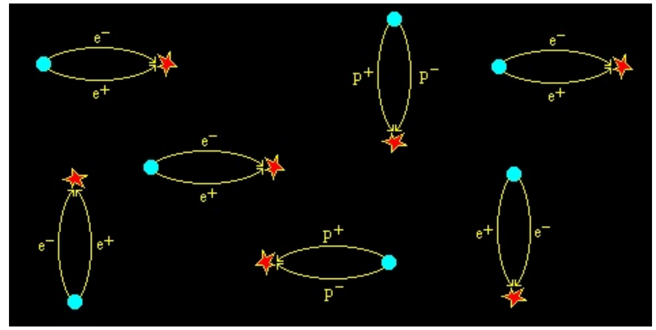
- modification to GR gravity?

Vacuum Energy and a Scalar Field



Zel' dovich (1968)

A vacuum can contain particles and anti-particles in constant creation/annihilation. These exert a *negative pressure* and a repulsion over large distances



Equation of state of the vacuum **$p = f(\rho)$** where ρ is the energy density

w is introduced where **$p / \rho = w$**

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.

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

Modified Gravity?

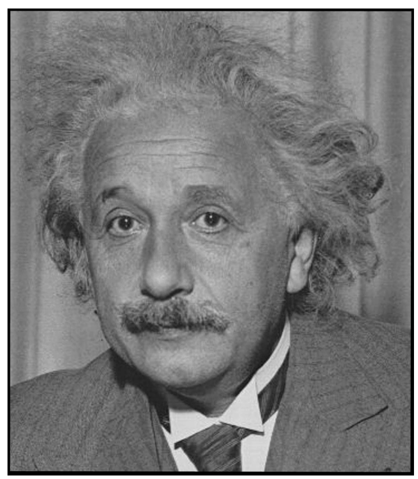
All current measurements relate to expansion rate, assuming H(z) comes from GR Friedmann equation

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

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 is key test

→



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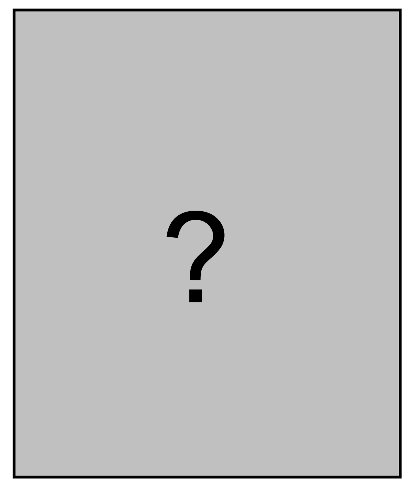


Empirical Approach to Dark Energy

As there is no accepted theory of dark energy, progress is empirical and based on two key questions:

- A new energy component of Universe or breakdown of GR on large scales?

  Need accurate comparison of results on *w* from two independent probes:

  - **geometric measures of the expansion history** (SNe, BAO)

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

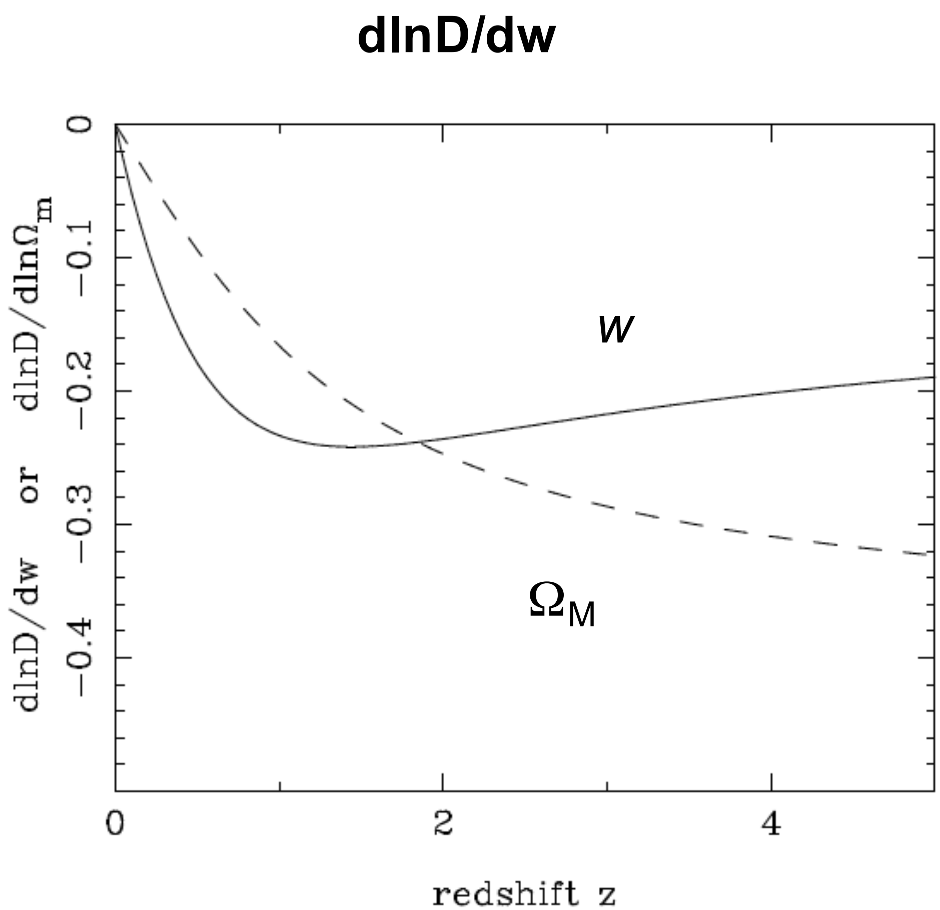
  - **measures of the growth of structure g(t)** (weak lensing, RSD, clusters)

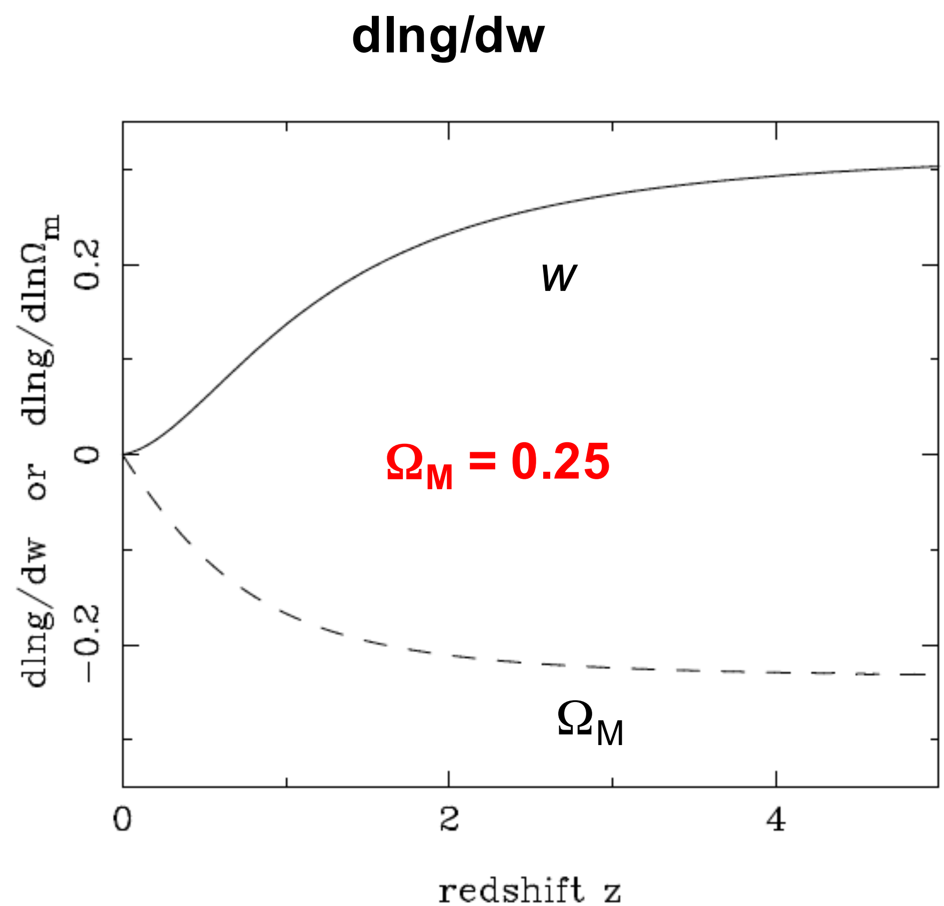
$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = \delta\left(4\pi G\rho_0 - c_s^2 k^2/a^2\right)$$

- If it is a new energy component – is *w* constant with epoch? Is *w = -1* (Λ)?

  Requires accurate extension of at least one of the measures to high redshift

Contrasting Distance & Growth-based Methods





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

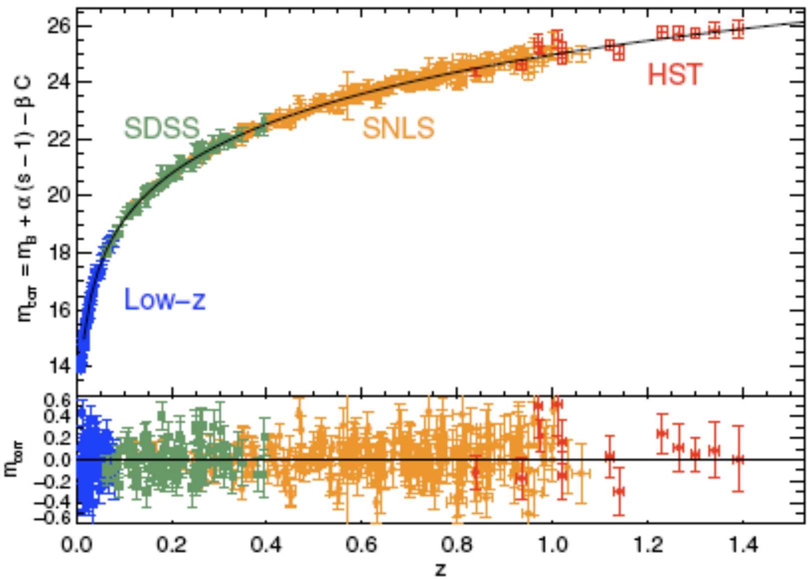
g(z): *w* has opposite effect to Ω_M
but relevant methods less well-developed

Consumer's Guide to Observing Dark Energy

- **Type Ia Supernovae: $d_L(z)$ to $z \sim 2$**
  - Most well-developed and ongoing with rich datasets
  - Key issue is systematics/physics/evol^n: *do we understand SNe Ia?*
- **Weak lensing: g(t) to $z \sim 1.5$**
  - Less well-developed; ground vs space, photo-z calibration
  - Key issues are *fidelity, calibration*
- **Large scale structure (BAO) : $d_A(z)$, H(z) to $z \sim 3$**
  - Late developer: cleanest *requiring huge surveys*
- **Galaxy clustering (clusters, RSD): g(t)**
  - Less favoured by experts, although RSD comes \`for free' with BAO surveys
  - Key issues: *baryonic biases, halo mass calibration*

CFHT SN Legacy Survey 0 < z < 1

$$\Omega_m = 0.269 \pm 0.015 \text{ and } w = -1.061^{+0.069}_{-0.068}$$



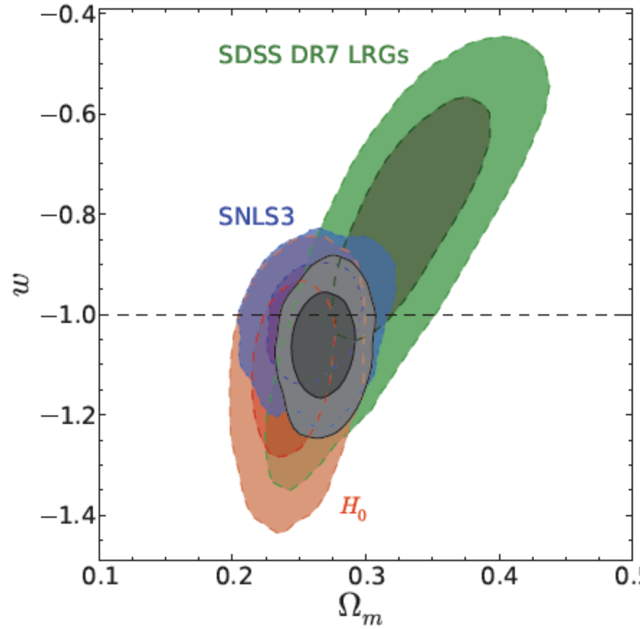


Table 7
Identified Systematic Uncertainties

Description	Ω_m	w	Rel. Area [a]
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85
Calibration	$0.191^{+0.095}_{-0.104}$	$-0.92^{+0.17}_{-0.23}$	1.79
SN model	$0.195^{+0.086}_{-0.101}$	$-0.90^{+0.16}_{-0.20}$	1.02
Peculiar velocities	$0.197^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.03
Malmquist bias	$0.198^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.07
Non-Ia contamination	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1
MW extinction correction	$0.196^{+0.084}_{-0.100}$	$-0.90^{+0.16}_{-0.20}$	1.05
SN evolution	$0.185^{+0.088}_{-0.099}$	$-0.88^{+0.15}_{-0.20}$	1.02
Host relation	$0.198^{+0.085}_{-0.102}$	$-0.91^{+0.16}_{-0.21}$	1.08

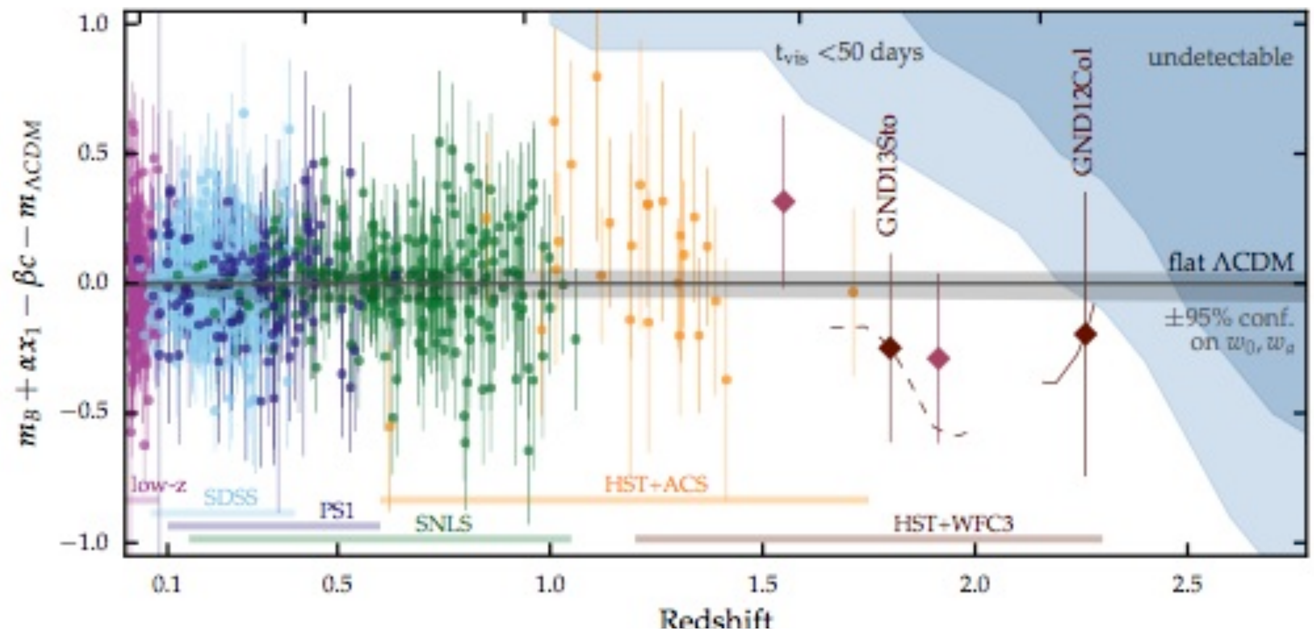
Systematic ≈ statistical, so limiting precision is not number of SNe.

Systematic errors mainly due to photometric calibration; if this could be fixed Δw~2%

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

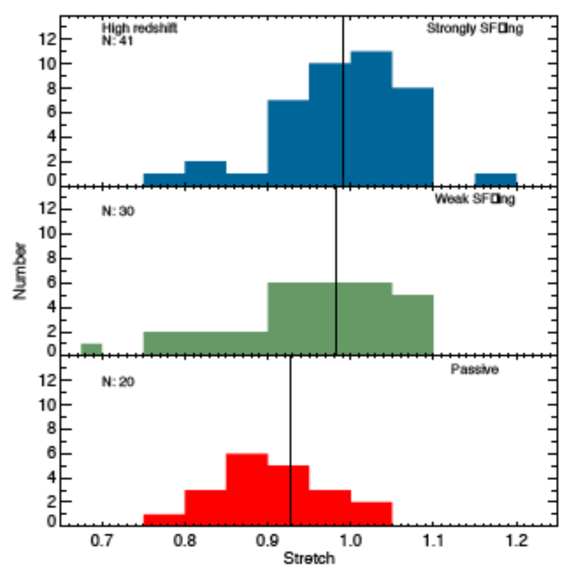
Probing the Deceleration Era

HST-selected z > 1 SNe Ia probe validity of a constant dark energy term which disappears when matter dominates and Universe decelerates; **but do SNe evolve?**



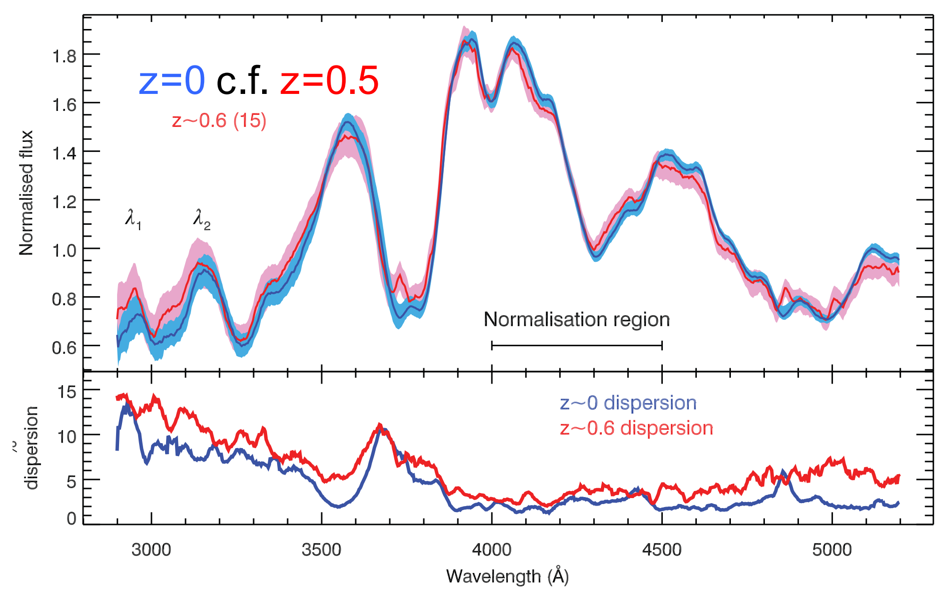
Rodney et al (2015)

light curve stretch & SF rate



Howell et al (2007)

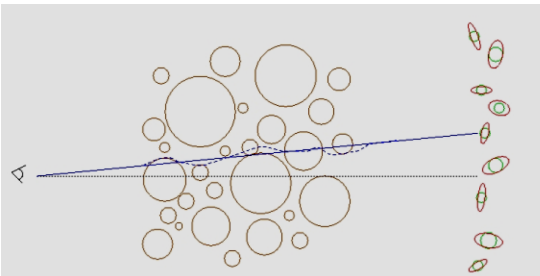
UV spectra: metallicity evolution?



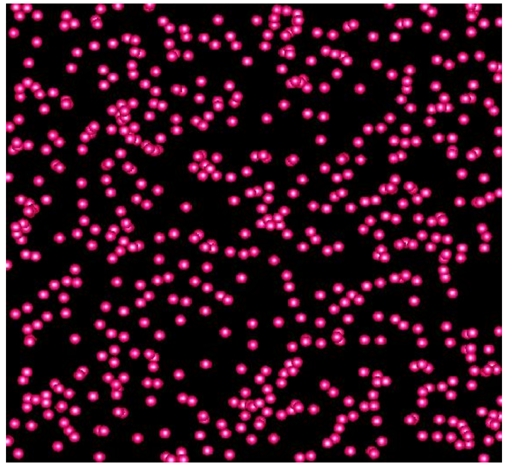
Maguire et al (2012)

Weak Gravitational Lensing

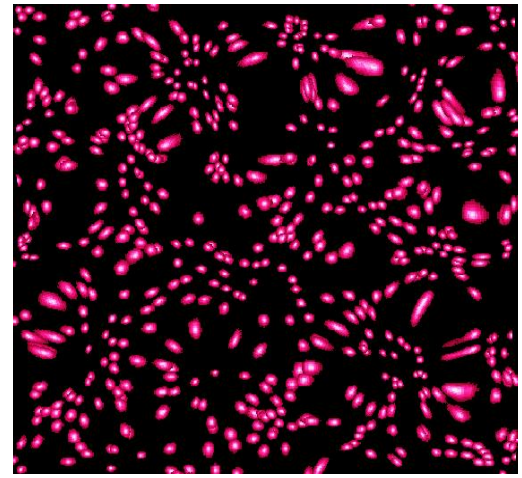
Various probes: shear-shear, galaxy-shear etc



Unlensed



Lensed



Growth of DM power spectrum is sensitive to dark energy. Via redshift binning of background galaxies, can constrain *w*

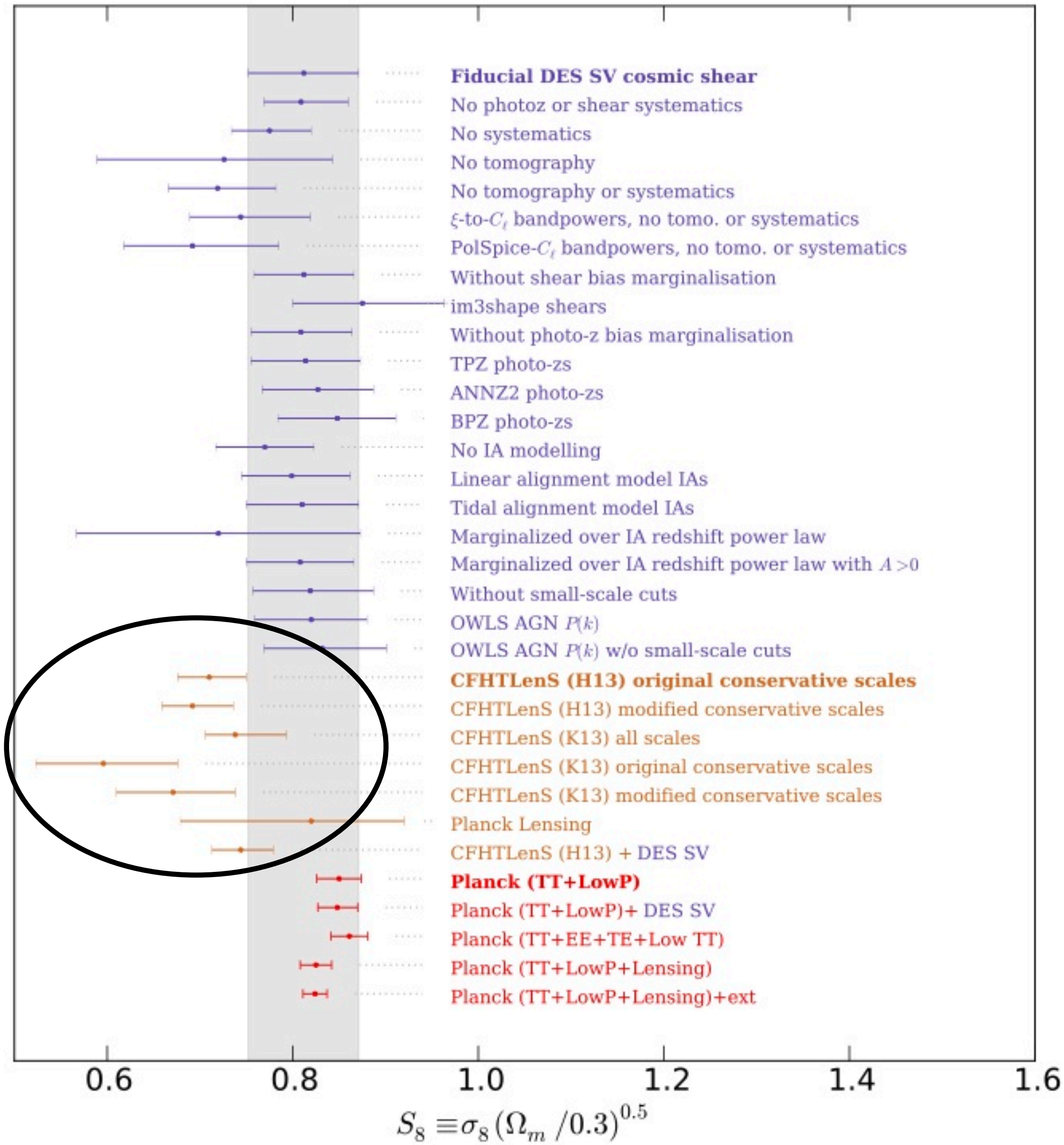
Require:

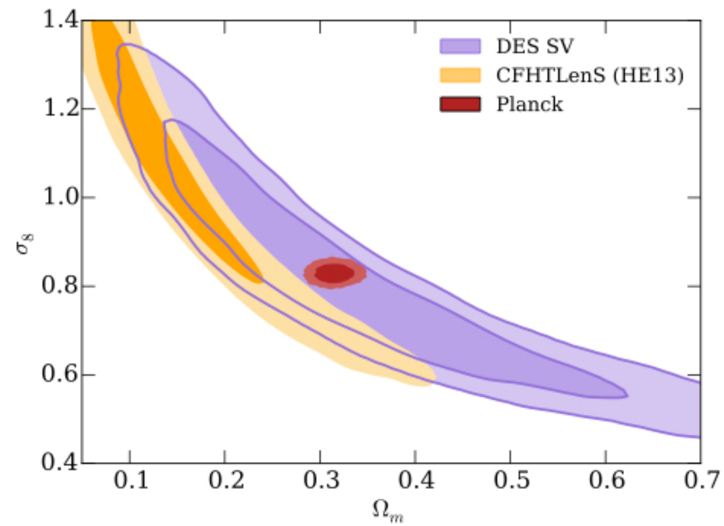
- accurate shear measures
- large area (1000s deg^2)
- photometric redshifts
- spectroscopic calibration N(z)

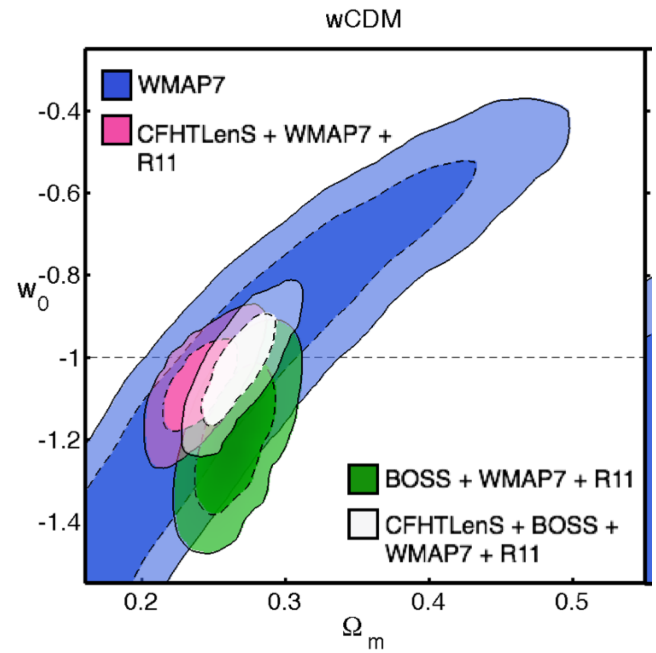
Current/recent ground-based surveys:

CFHTLens (110/154 deg^2, i<25.5)
KIDS (148/1000 deg^2, r<24.9)
DES (139/5000 deg^2, r<24)
Subaru HSC (0/1400 deg^2, r<26)

Planck vs CFHT vs DES: Tensions in σ_8, Ω_M







$$w = -1.02 \pm 0.09$$

Heymans et al (2013), Abbott et al (2015)

Testing Shear Algorithms

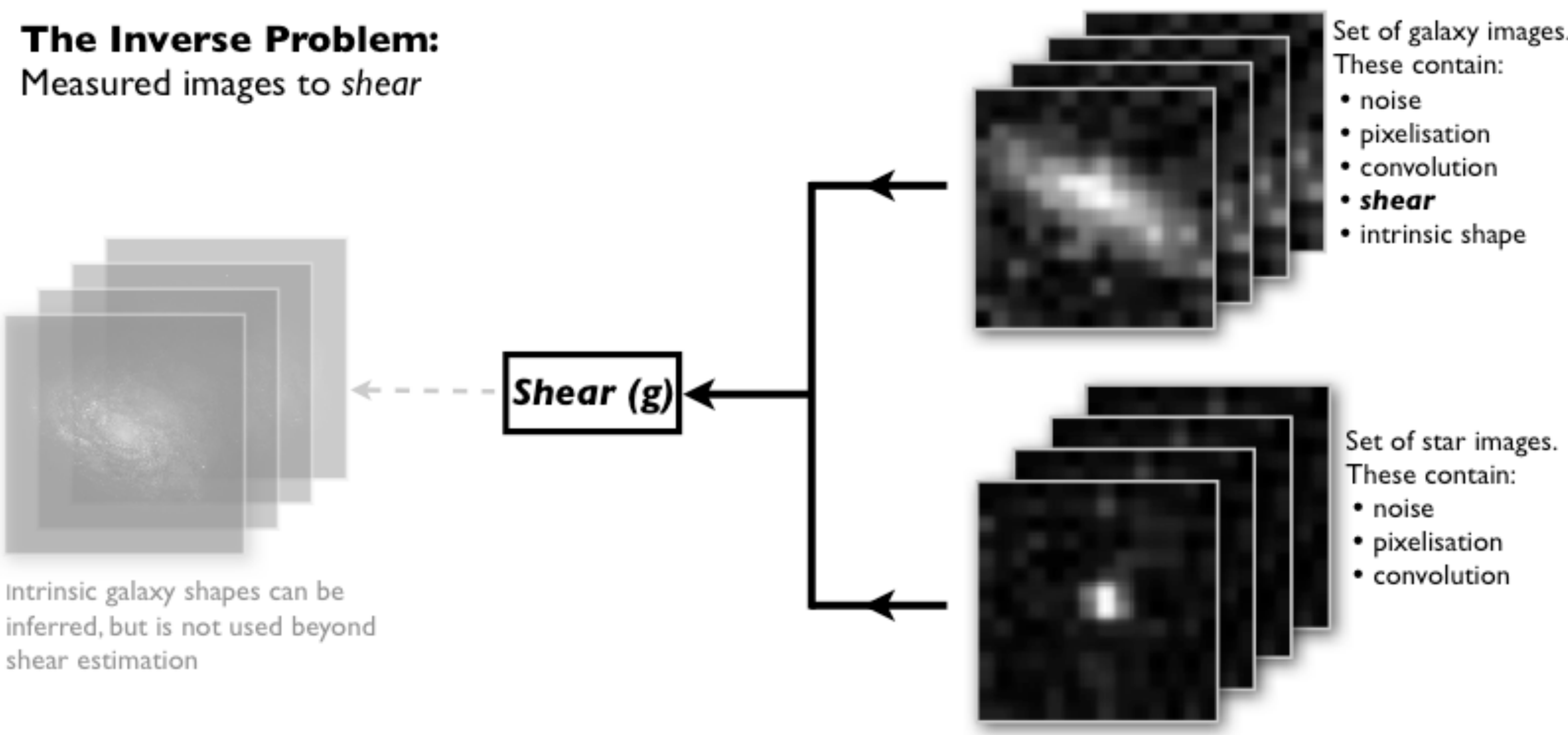
The Forward Process

Galaxies: Intrinsic galaxy shapes to measured image:

Intrinsic galaxy (shape unknown) → Gravitaional lensing causes a ***shear (g)*** → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

The Inverse Problem:

Measured images to *shear*

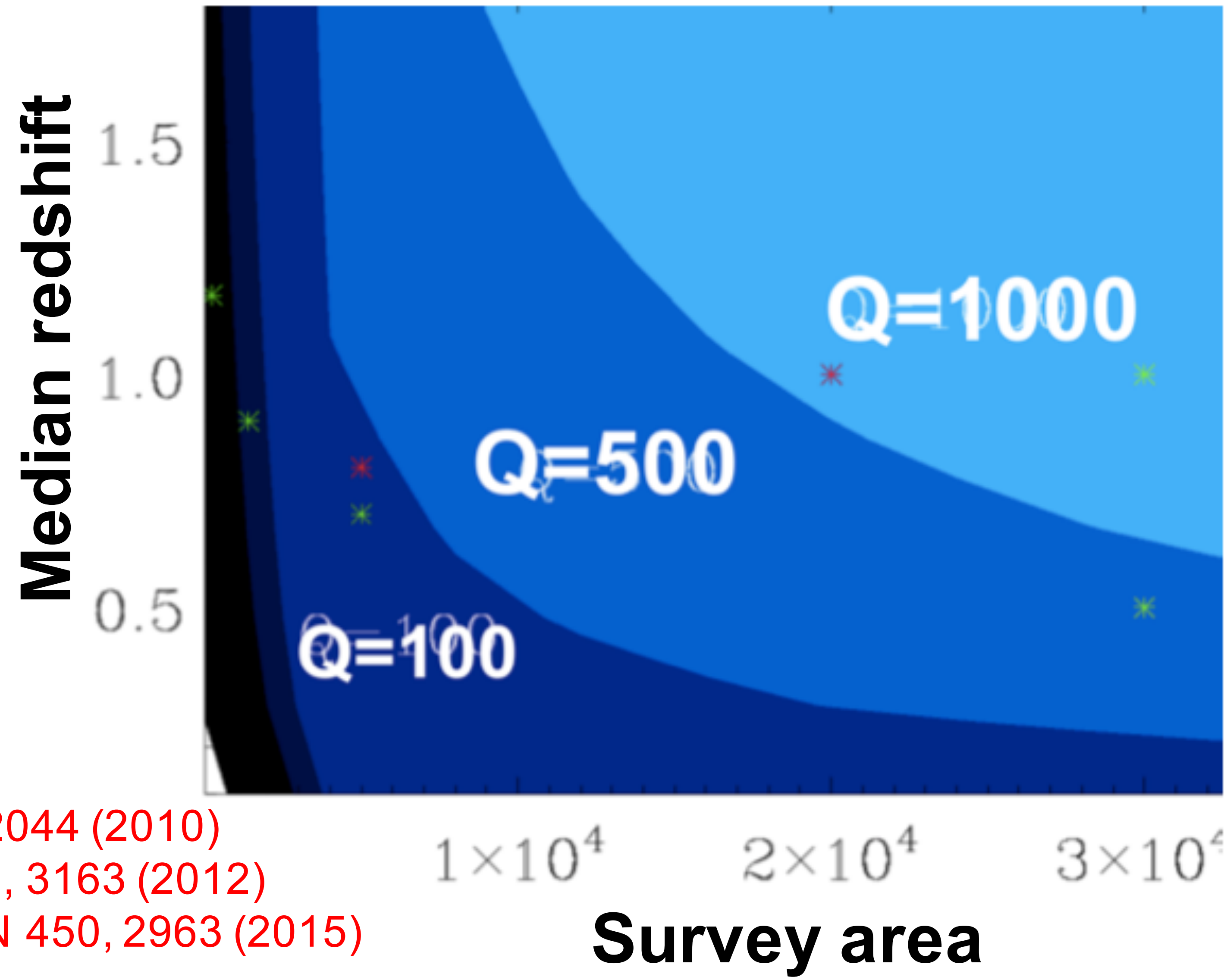


GREAT08 → GREAT10 → GREAT 3 Challenges

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

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



Bridle et al MN 405, 2044 (2010)
Kitching et al MN 423, 3163 (2012)
Mandelbaum et al MN 450, 2963 (2015)

Requirement for Euclid: Q=1000

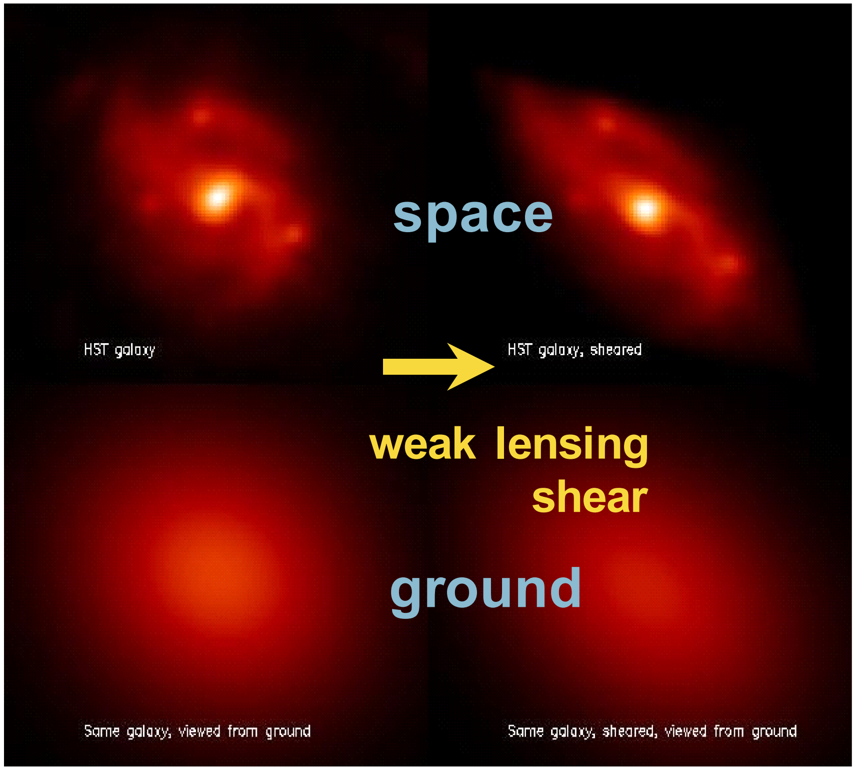
GREAT3
The third GRavitational lEnsing Accuracy Testing challenge

Substantial progress in 2014: Many algorithms achieve Q>800

Leaderboard	Space-based	Varying shear	Winning team	Winning score	Winning entry	Number entries
control-ground-constant	N	N	CEA-EPFL	1211.4	gfit_sf_12_CGC	250
control-ground-variable	N	Y	CEA-EPFL	1068.0	gfit_sf_8_CGV_pca_s40-0.2-0.6	160
control-space-constant	Y	N	Amalgam@IAP	1516.2	A_SP_12.8	110
control-space-variable	Y	Y	Amalgam@IAP	1198.8	A_SP_v3.4	96
full-ground-constant	N	N	sFIT	800.2	basic_cal_fgc6	11
full-ground-variable	N	Y	sFIT	379.1	basic_cal_fgv7	17
full-space-constant	Y	N	sFIT	1184.3	basic_cal_fsc9	17
full-space-variable	Y	Y	sFIT	856.2	basic_cal_fsv11	25
multiepoch-ground-constant	N	N	sFIT	1017.1	basic_cal_mgc7	71
multiepoch-ground-variable	N	Y	MegaLUT	1131.3	Bonn_MegaLUT_MGV_v4_hn_gcircp7_prior_flag13gmp8	53
multiepoch-space-constant	Y	N	sFIT	841.4	basic_cal_msc9	48
multiepoch-space-variable	Y	Y	CEA-EPFL	1605.0	gfit_sf_5_MSV	45
real_galaxy-ground-constant	N	N	Amalgam@IAP	1121.0	A_SP_10.2	195
real_galaxy-ground-variable	N	Y	CEA-EPFL	790.9	gfit_RGV_pca_s55_0.6_0.0	93
real_galaxy-space-constant	Y	N	Fourier_Quad	1918.5	Fourier_Quad_S6	92
real_galaxy-space-variable	Y	Y	MegaLUT	1667.2	Bonn_MegaLUT_RSV_v4_hn_lowcx3	83
variable_psf-ground-constant	N	N	sFIT	883.5	basic_cal_vgc4	60
variable_psf-ground-variable	N	Y	Amalgam@IAP	229.8	A_SPvp_0_7v	60
variable_psf-space-constant	Y	N	Amalgam@IAP	1182.6	A_SPvp_1_1	25
variable_psf-space-variable	Y	Y	sFIT	1275.6	basic_cal_vsv	17

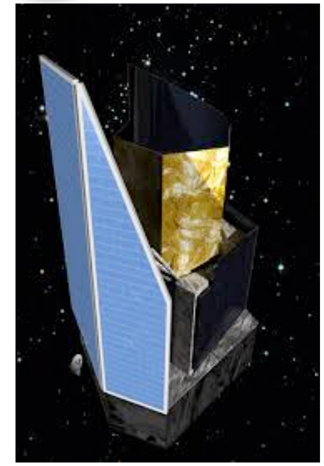
Courtesy: Rachel Mandelbaum & Barney Rowe (GREAT3 workshop 2014)

Ground vs Space: Euclid approaches..



ESA Cosmic Vision call 2007
Final approval 2012
Projected launch 2020+

- WL r<24 15000 deg^2
- BAO survey of 50M galaxies



Team of ~1000 scientists

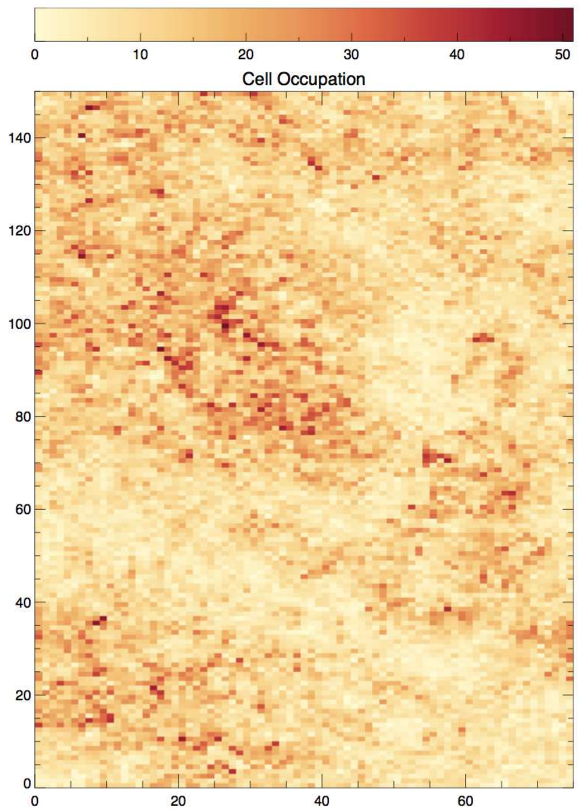
Typical cosmic shear is ~ 1% and must be measured with high accuracy

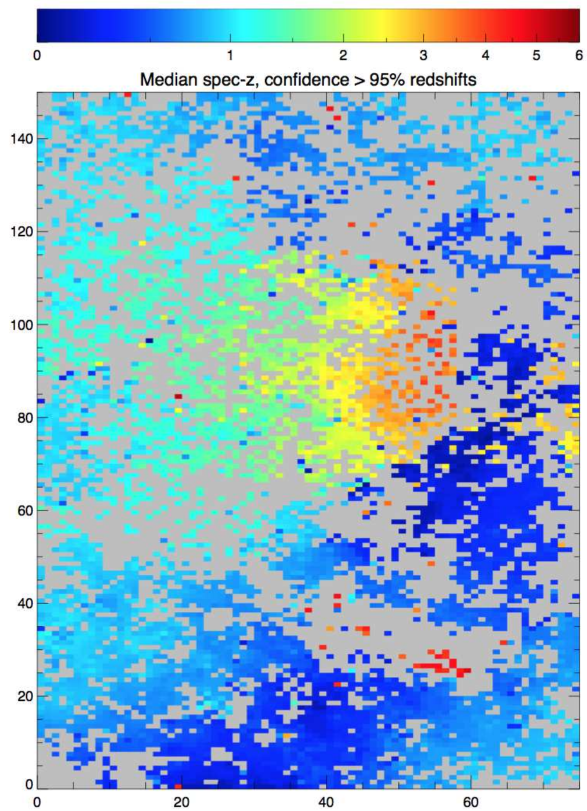
Space: small and stable PSF:
⇒ larger number of resolved galaxies
⇒ reduced systematics

Ground-based Requirements for Euclid

Spectroscopic redshifts for a representative subset required for two purposes:
- to account for intrinsic alignments between associated galaxies: $\sigma(z) < 0.05\text{-}0.10$
- to calibrate the mean redshifts of 10-20 photo-z bins for g(t) to 2% precision

Brute force approach not feasible: ~100,000 redshifts with >99.5% completeness!
Proposed solutions: X-correlation of photo-z & spectroscopic samples (Newman et al)
optimized targeting of areas in photo-z space (Masters et al)
Empirical map in N-dimension colour space coded by density of objects (constructed with non-linear PCA method) enables optimal targeting for a spectroscopic survey.



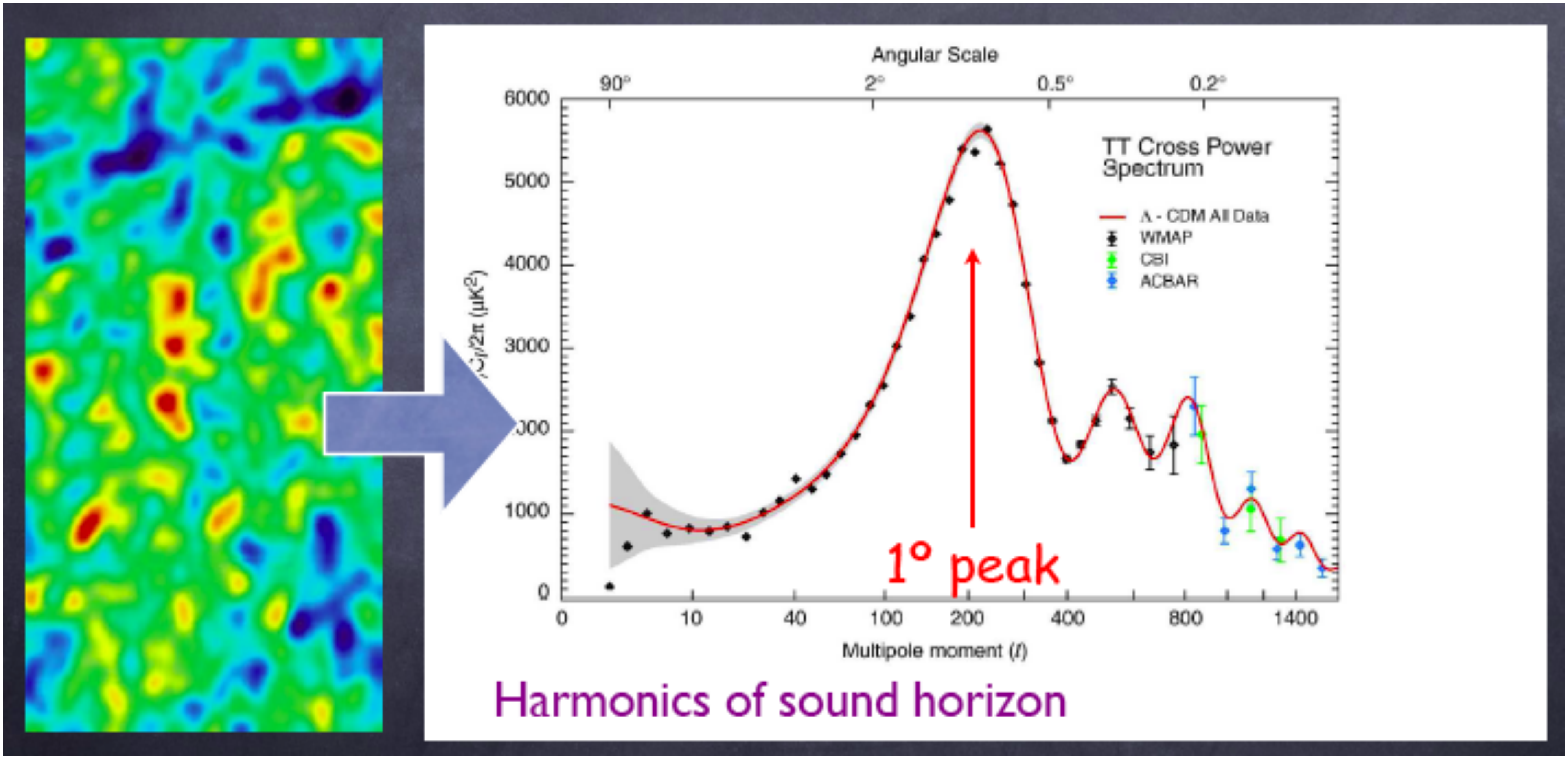


For a Euclid r<24 ugrizYJH WL survey, using COSMOS spectroscopic data, estimate targeted approach requires 10,000 redshifts.

Noting current surveys, require additional ~50 Keck/VLT nights with optical and NIR spectrographs

Masters et al arXiv 1509.03318

Baryonic Acoustic Oscillations



Residual of acoustic horizon at last scattering in galaxy distribution.

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

Peebles & Yu 1970;
Sunyaev &
Zel'dovich 1970

3-4σ detection by 2dF (Cole et al 2005) & SDSS (Eisenstein et al 2005)

How it works – lots of redshifts and big volumes!

Typical simulation:

z=1 survey

N= 2. 10^6 galaxies

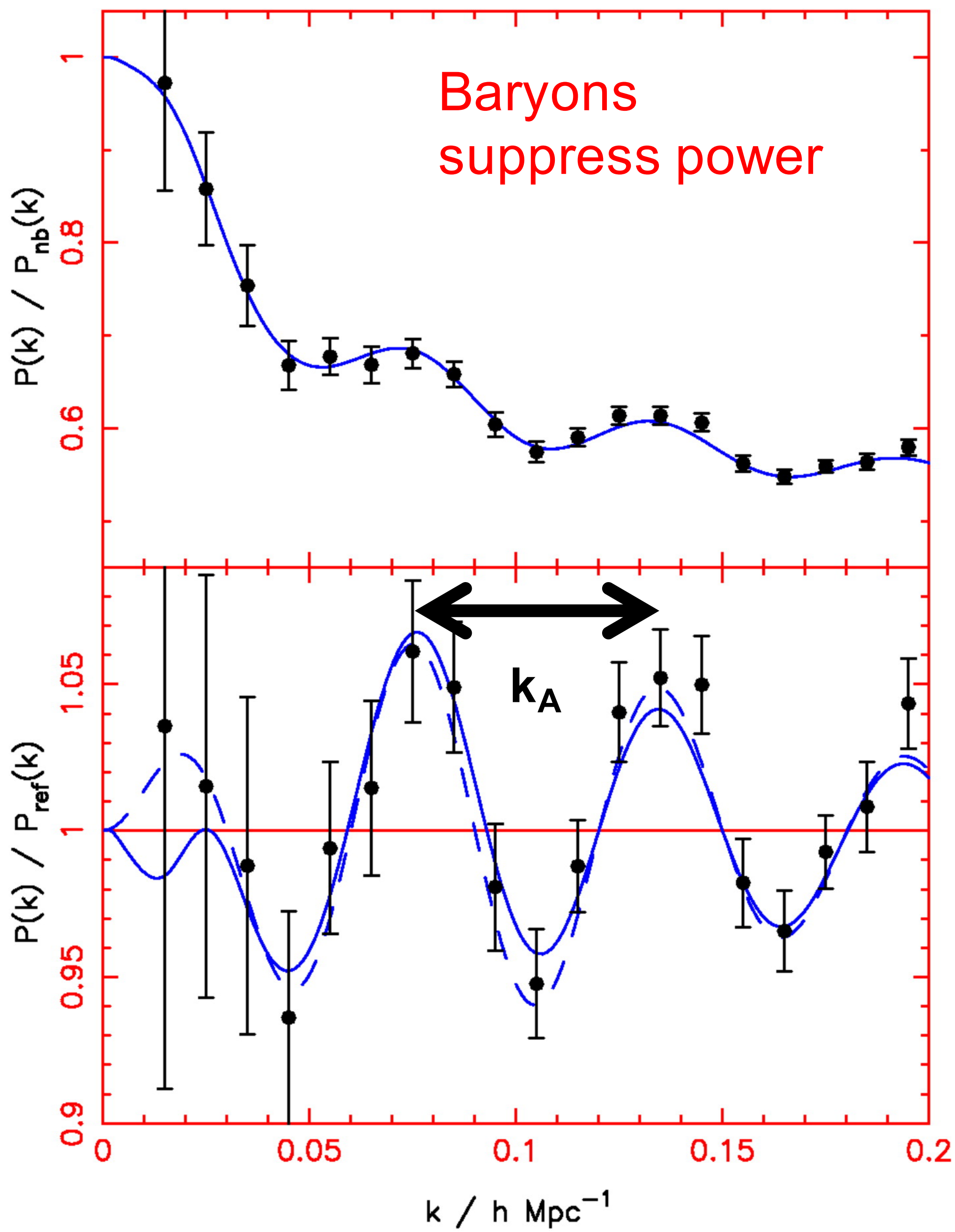
600 deg^2

V = $6 \times V_{SDSS}$ (1 Gpc^3)

bias = 1

Truth

Fit



Power spectrum ratio P(k)/P_{nb}(k)

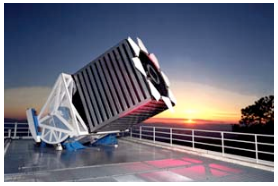
Divided by smooth fit

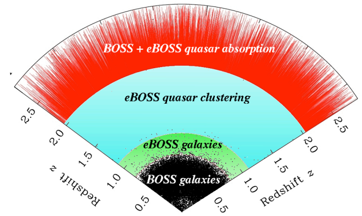
k_A is the "standard ruler"

Must measure its redshift dependence

The BAO Race is On..

1. eBOSS





2.5m APO, 3.0 deg dia, 1000 fibres
λλ0.36-1.04μm, R<5000
Survey ongoing: July 2014 – 2019

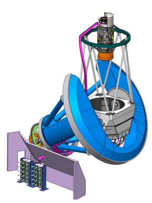
2. HETDEX

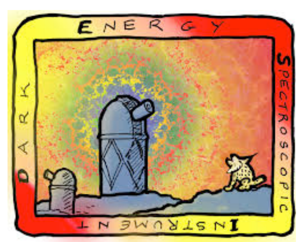
8.2m 0.4 deg dia, 150 IFUs
λλ0.35-0.55μm; R~800
Funded; survey yet to begin

3. PFS

8.2m 1.5 deg dia, 2400 fibres
λλ0.35-1.3μm; R~<5000
Funded; 2019-2024?

4. DESI

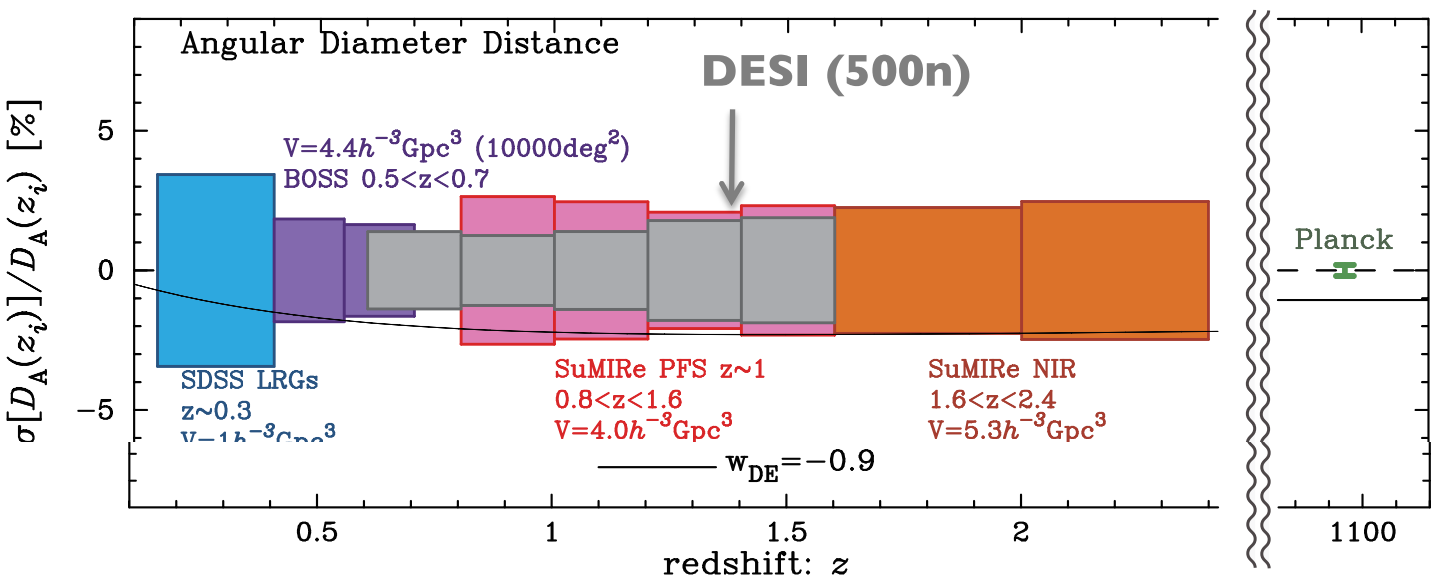




4.0m, 3.0 deg dia, 5000 fibers
λλ0.36-0.98μm, R<5000
Mostly funded; 2019-2024?

Plus 4MOST, WEAVE & ultimately Euclid and WFIRST/AFTA

Subaru PFS Predictions

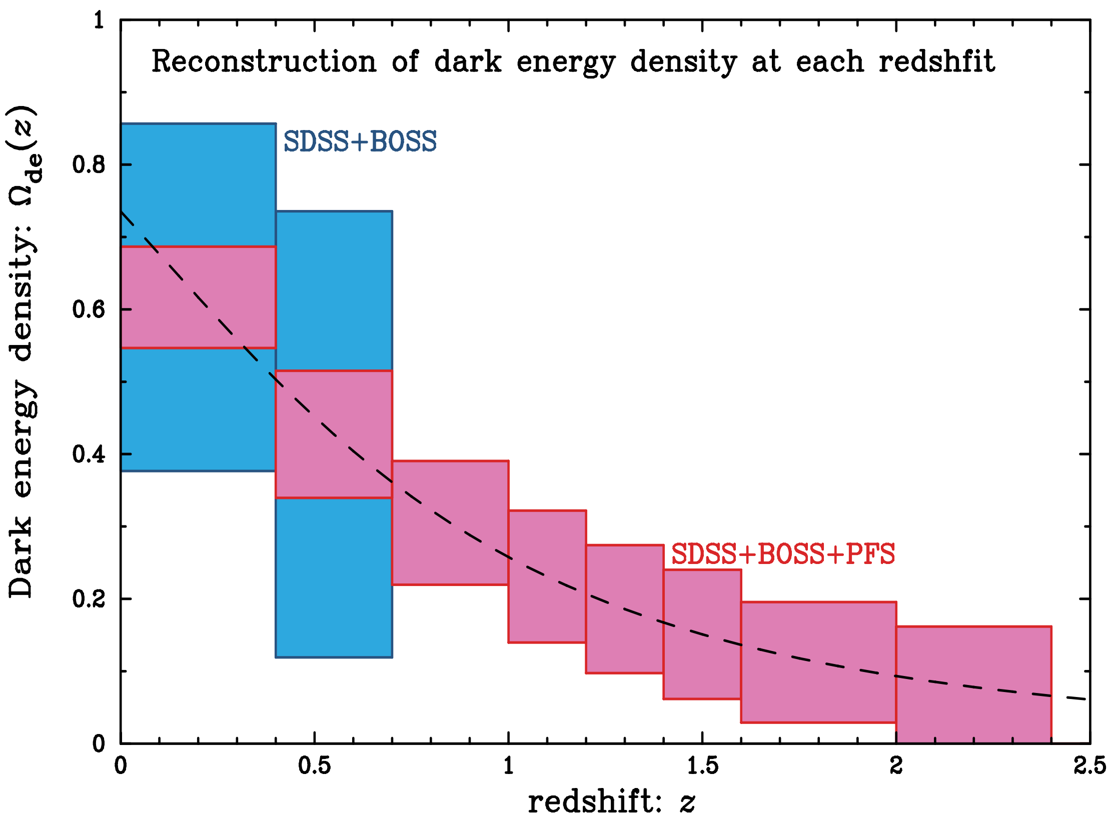


The PFS survey claims a *3%* accuracy of measuring $D_A(z)$ and $H(z)$ in each of 6 redshift bins, over $0.8<z<2.4$

Comparable to BOSS but extending to higher redshift

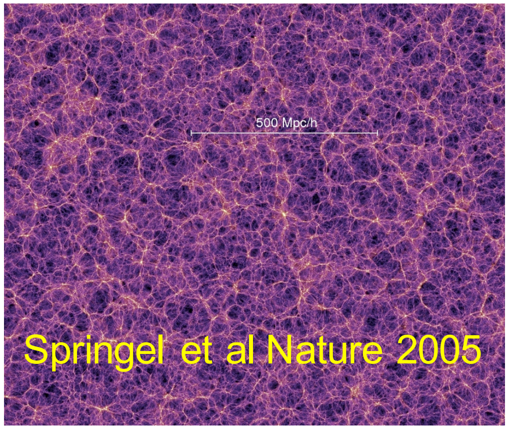
Efficient given competitive situation

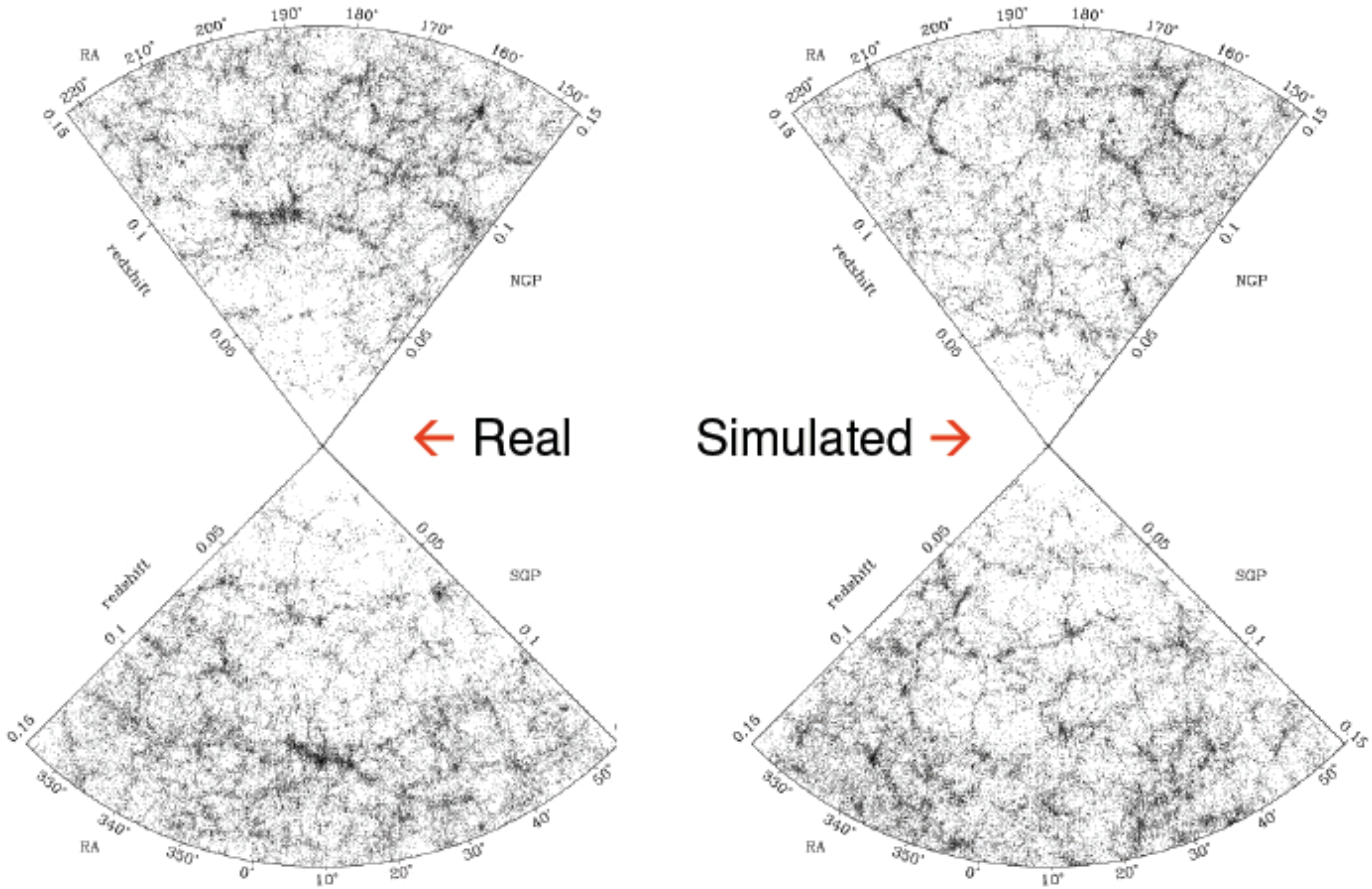
BOSS (2.5m): 5 yrs
PFS (8.2m): 100 nights



Empirical reconstruction of $\Omega_{de}(z)$ to 7% accuracy of in each bin to z~2.4

Cold Dark Matter: The `Standard Model'





2dF redshift survey: Colless et al (2001)

- As important as `Dark Energy' problem given DM's role in structure formation
- CDM popular because no shortage of WIMP candidates
- Successful on large scales, several puzzles on small scales

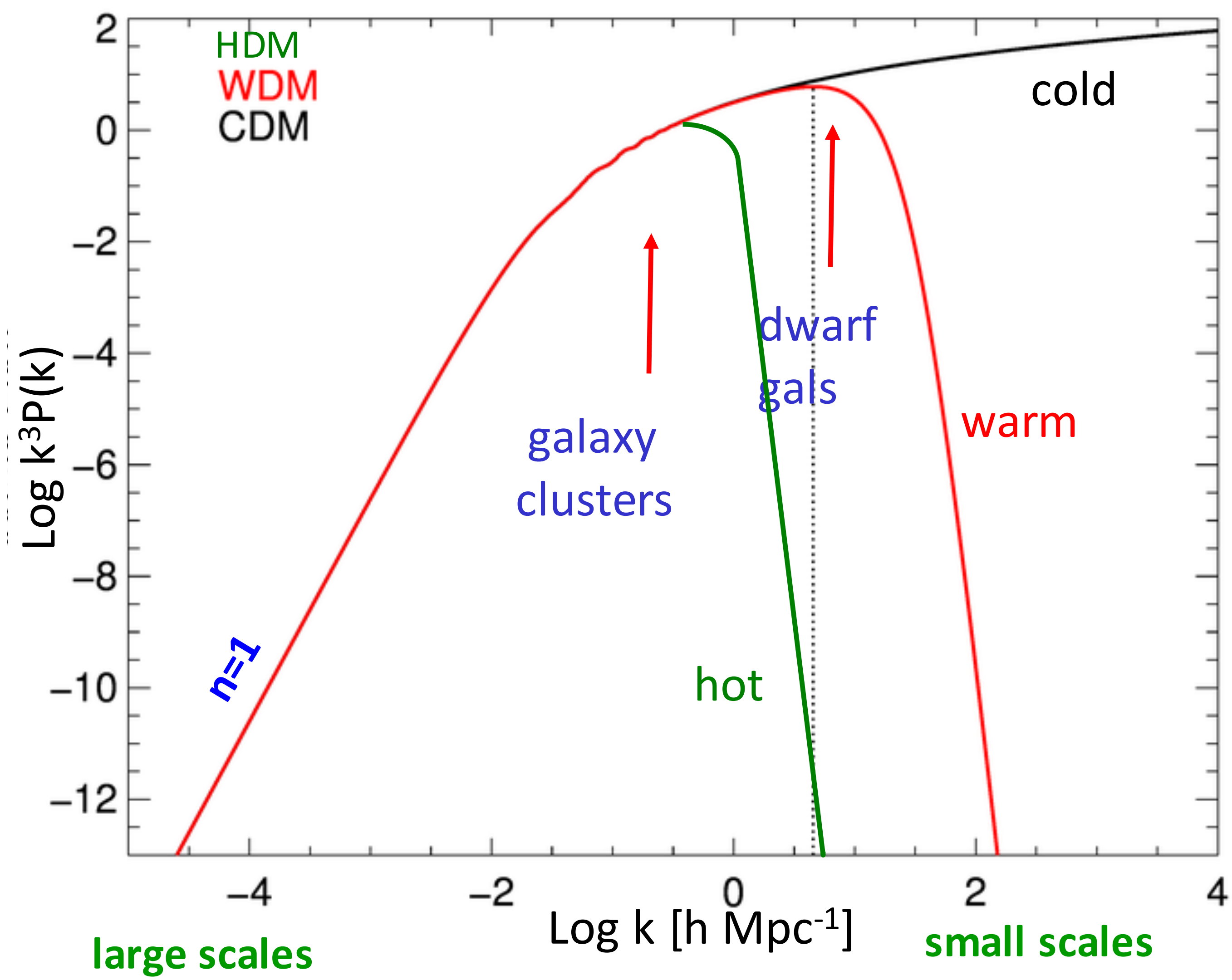
Testing CDM on Smaller Scales

DM affects the growth of structure in the Universe according to when it becomes non-relativistic which defines its *free-streaming length*

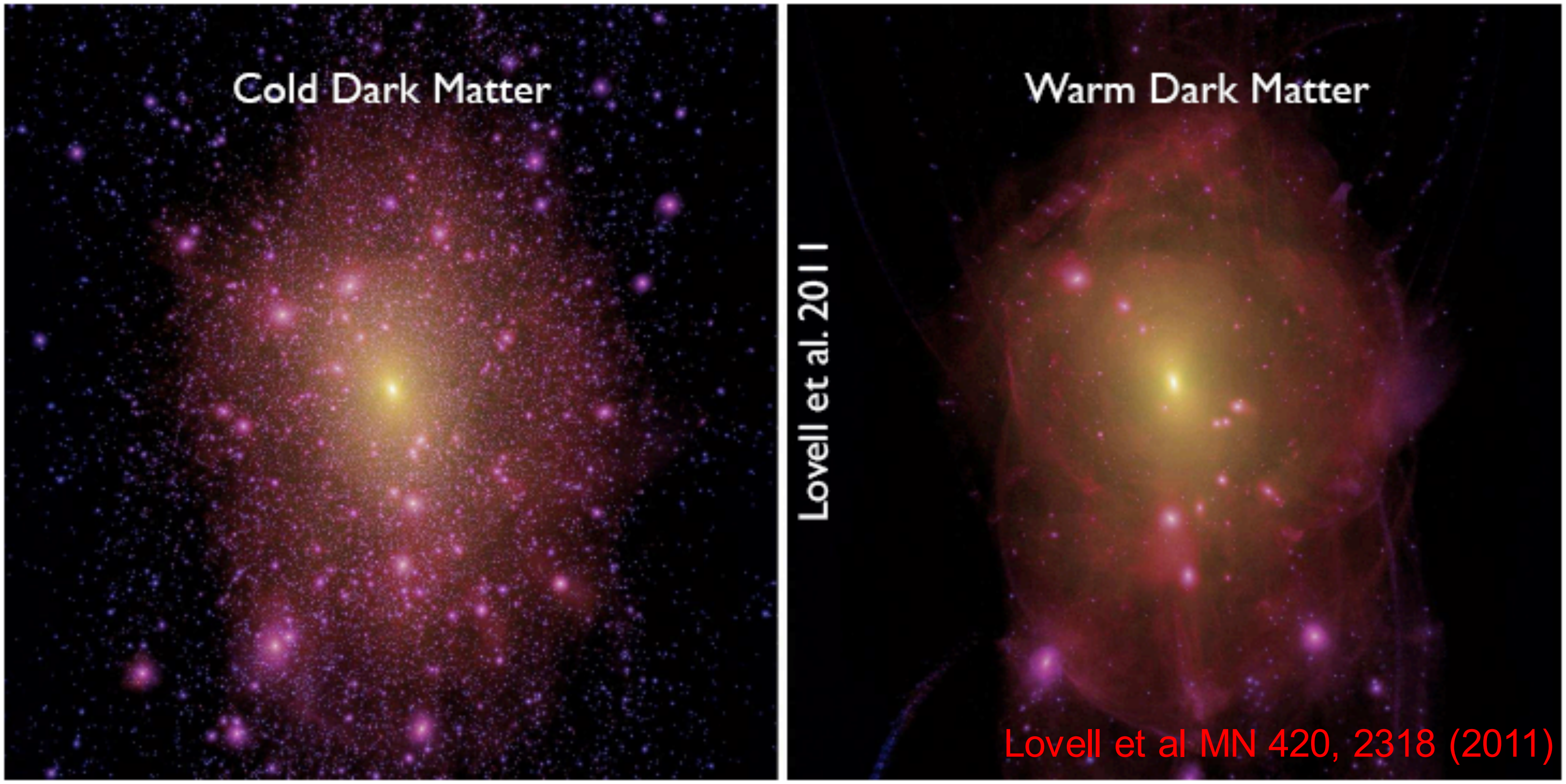
Cold DM (e.g. neutralino, axion): leads to lots of structure on sub-galactic scales

Warm DM (e.g. sterile neutrinos): produces much less structure on sub-galactic scales

DM power spectrum ("power per octave")



Local Group Structure



Distribution of present and disrupted satellite galaxies around Milky Way is a sensitive probe of DM and its role in galaxy formation

Cold DM predicts too many Milky Way satellites (Klypin+ 1999)

Could be resolved via baryonic effects

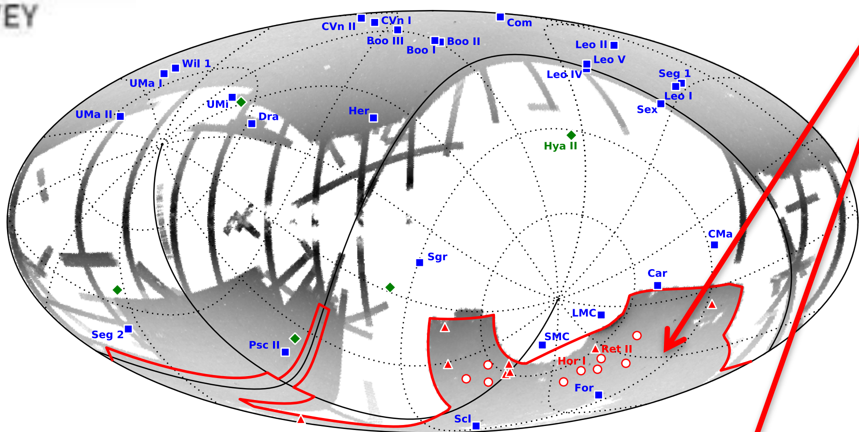
- reionization/SN feedback (still expect dark satellites)
- survey biases (e.g. surface brightness & sky coverage issues)

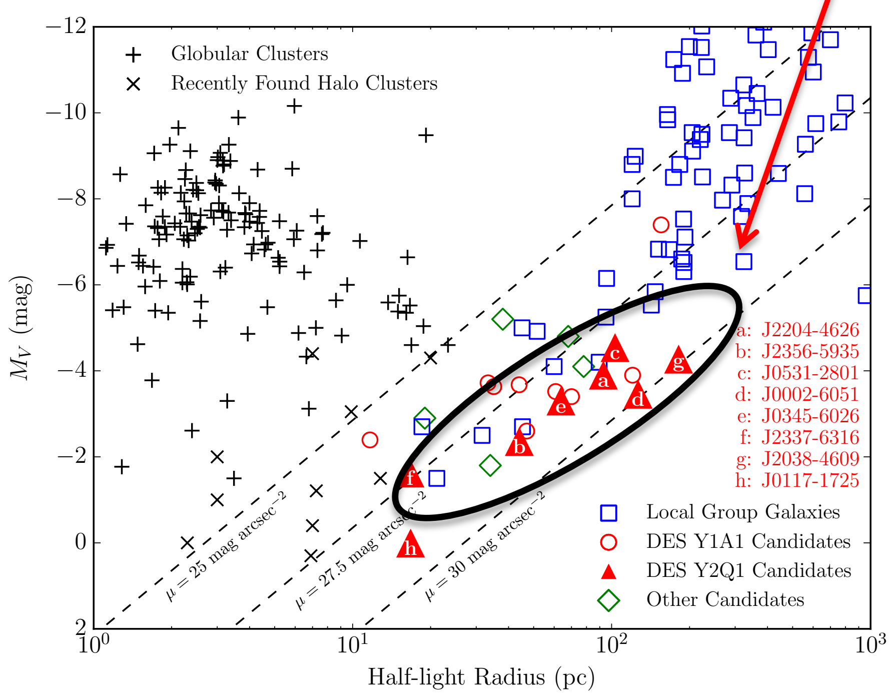
The challenge is no longer `counting visible dwarfs' but finding the dark ones.

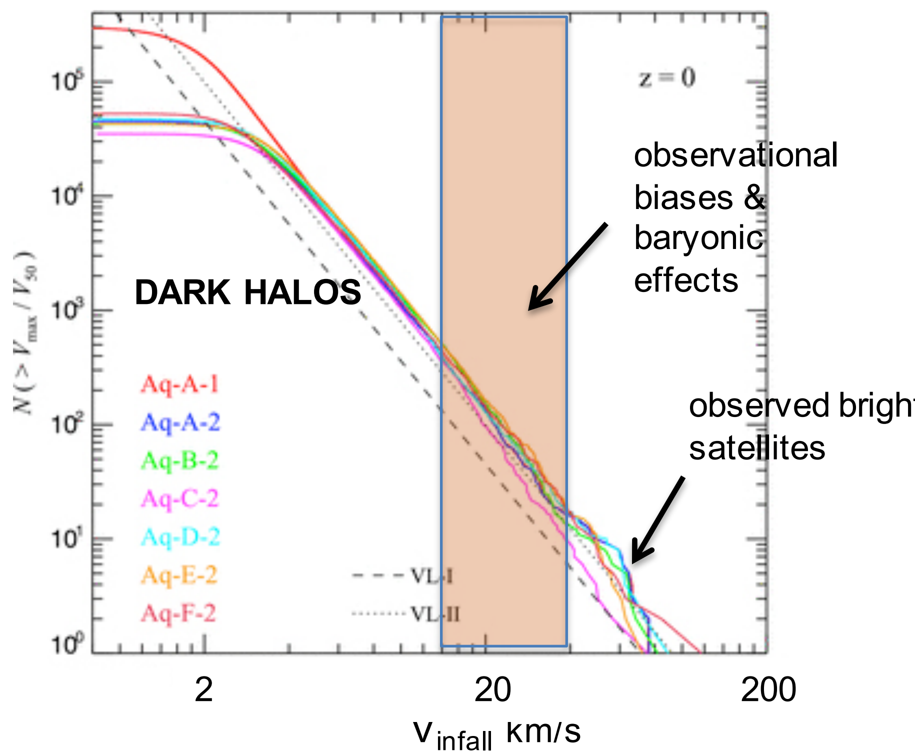
Many More LG Dwarfs Being Found...

DARK ENERGY SURVEY

15-17 new dwarfs found in first 2 years of DES survey data (Drlica-Wagner et al 2015) but discovery rate is consistent with prediction from SDSS statistics given lower surface brightness limit of DES (Tollerud et al 2008) – so no real change **– challenge is to find dark ones!**

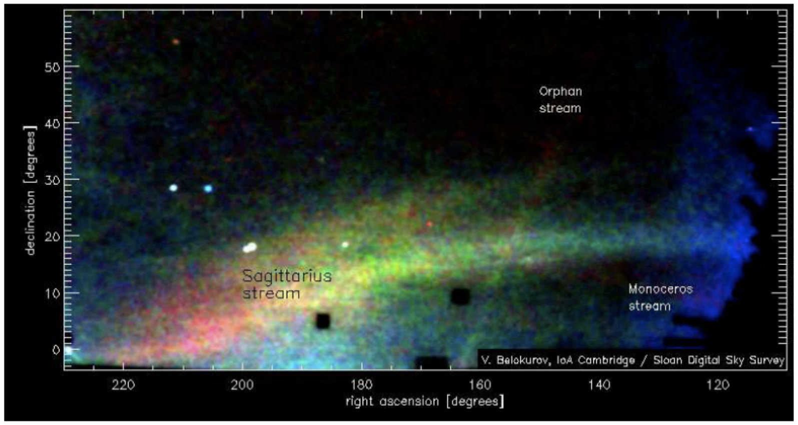


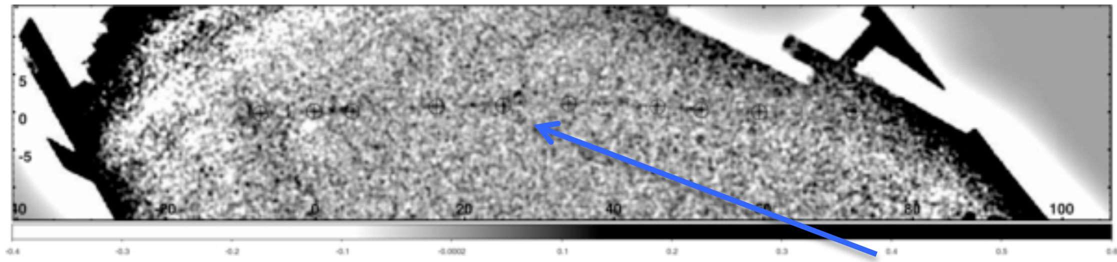




Springel et al (2008)

Counting Dark Halos: Gaps in Stellar Streams?



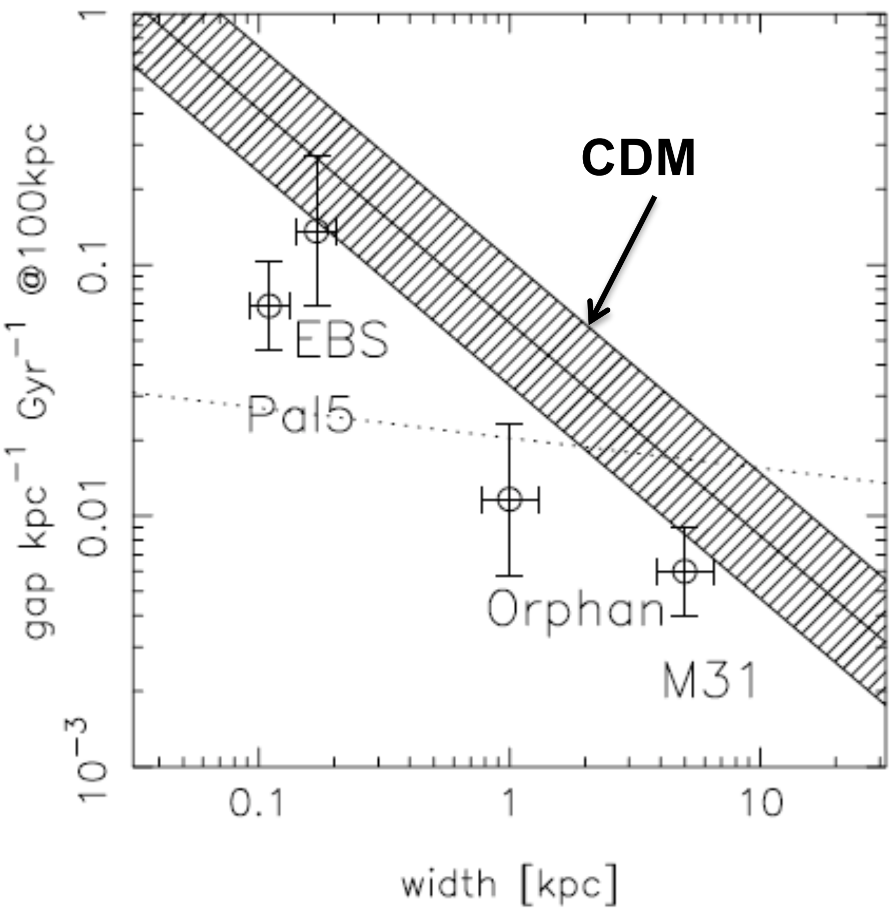


Structure in the streams is caused by DM sub-halos with masses > $10^6 M_\odot$

Number density of gaps in streams quantifies the abundance of dark sub-halos above this minimum mass.

With uncertainty, the abundance of gaps scaled to a fixed distance is consistent with CDM but the age of the stream needs to be assumed

Kinematic constraints would be more powerful but requires a wide field facility

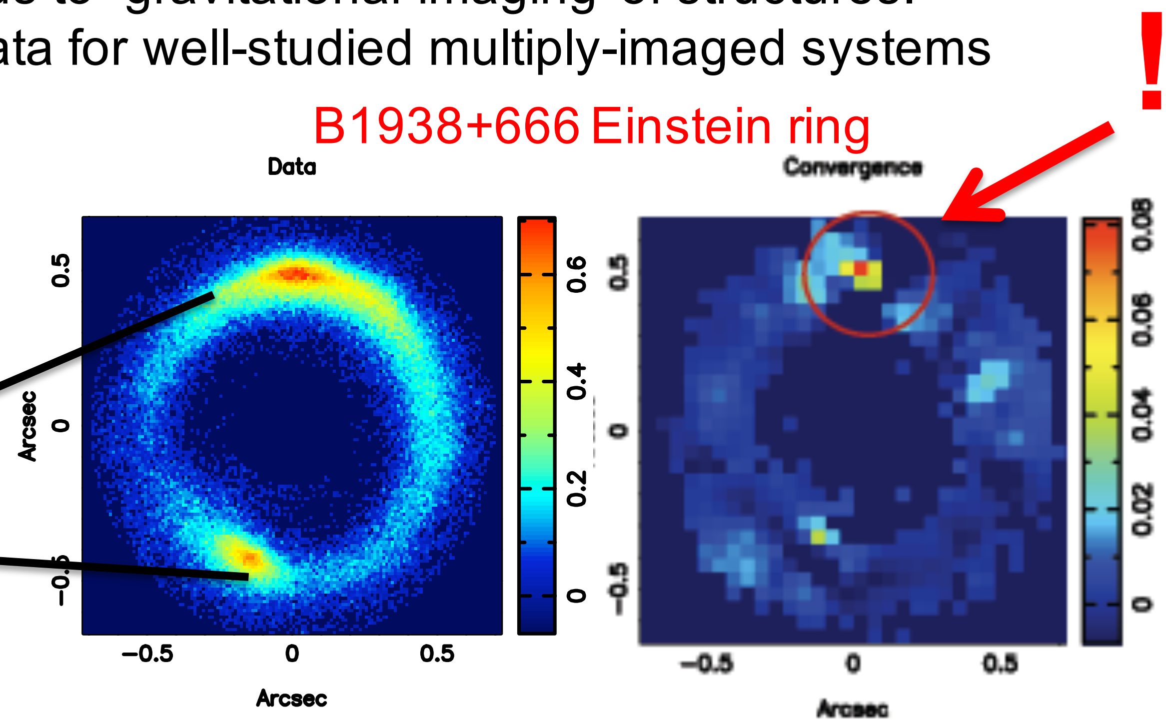


Carlberg et al (2012,2013)

Counting Dark Halos: Lensing Anomalies

Flux/positional anomalies leads to `gravitational imaging' of structures.
Requires exquisite imaging data for well-studied multiply-imaged systems

B1938+666 Einstein ring



Early demonstration of ability to gravitationally image a halo of inferred mass ~ 3.10^8 $M_\odot$ and hence, with sufficient data the DM fraction and mass function slope α

$$dN/dm \propto m^{-\alpha}$$

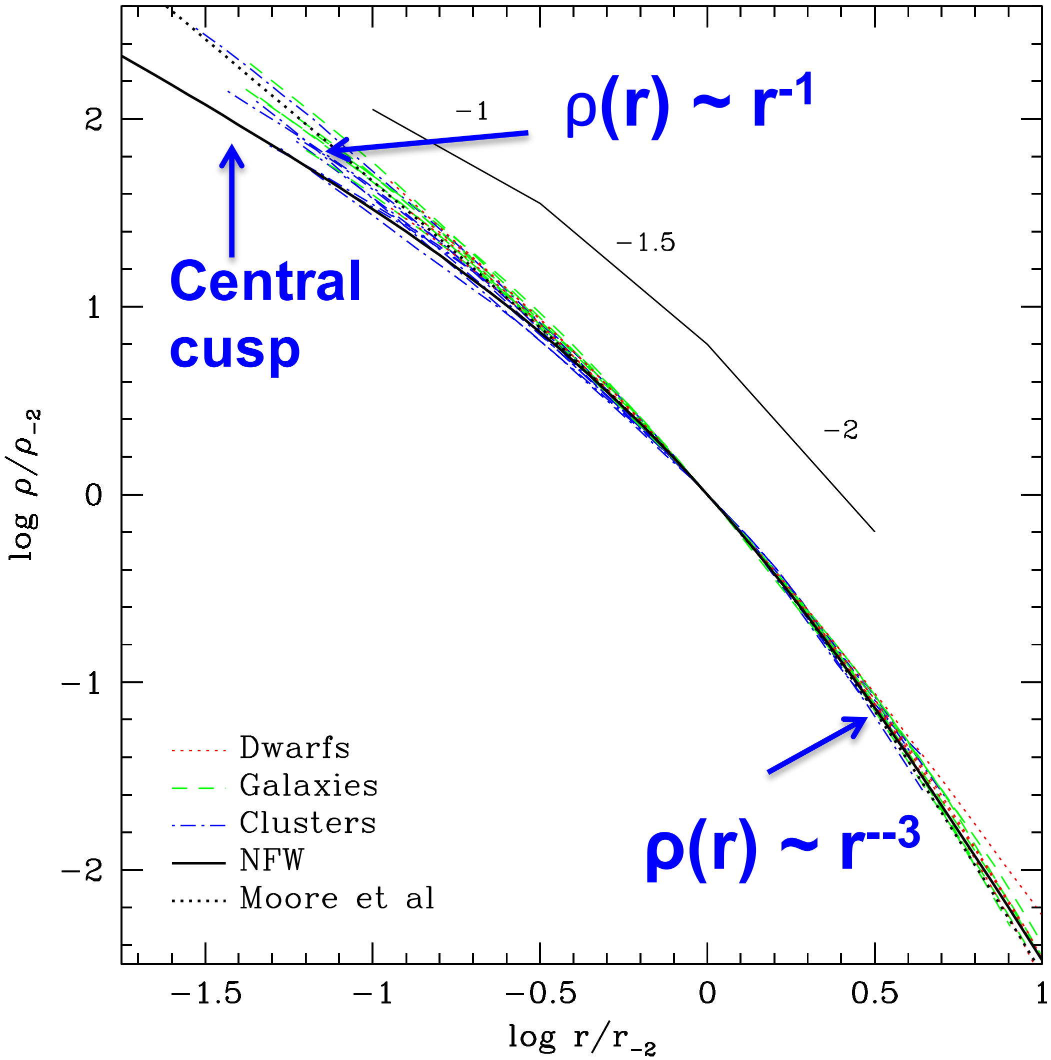
Need lots of lenses, accurate PSF
Limitations: 3-D position of substructure in host, projection effects

Vegetti et al (2012)

Universal DM Density Profiles?

Across a wide range of scales, from dwarfs to clusters, the 3D DM radial profile ρ(r) in N-body simulations is found to be self-similar with a central cusp, $\rho(r) \sim r^{1}$

Adiabatic contraction (collapse of baryons) would make the observed profile steeper



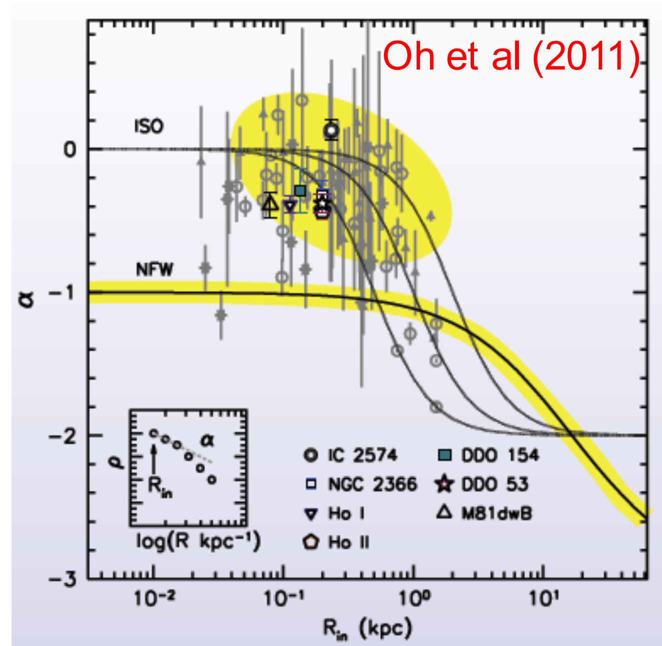
The NFW

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

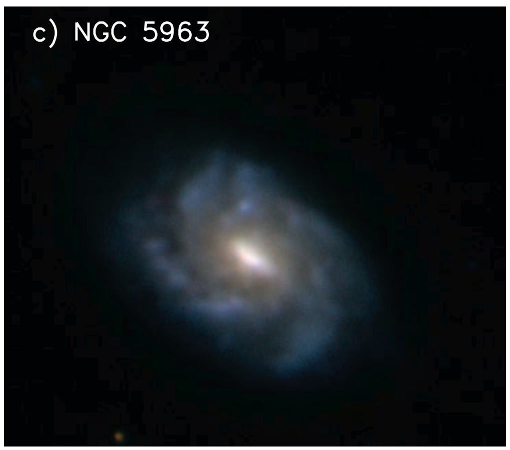
Navarro, Frenk & White (1996)
Springel et al (2008)
Gao et al (2012)

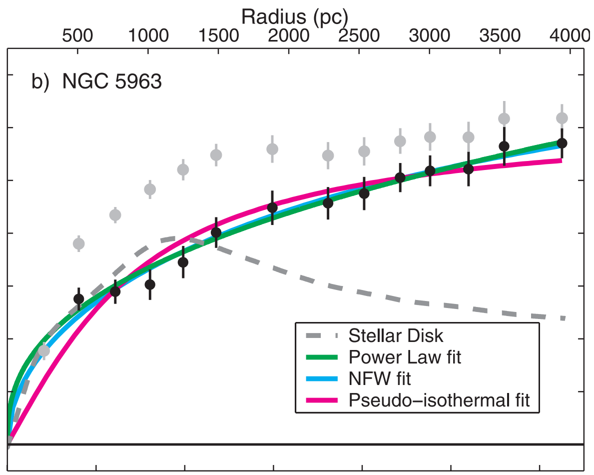
Core-Cusp Problem in Field Dwarfs

Low mass disks offer best constraints since 2D HI and Hα measures enable detailed modeling of projection and other complications. Nearly all show flat cores (ρ~const) rejecting the NFW profile.



However, some dwarfs <u>are</u> consistent with NFW arguing against a generic problem with CDM (e.g. NGC5963, Simon et al 2005).





Outflows from supernova explosions can flatten the cusp. Best option is multiple short SN bursts which temporarily evacuate the gas from the core leading to irreversible K.E. gains for the DM (Pontzen & Governato 2012)

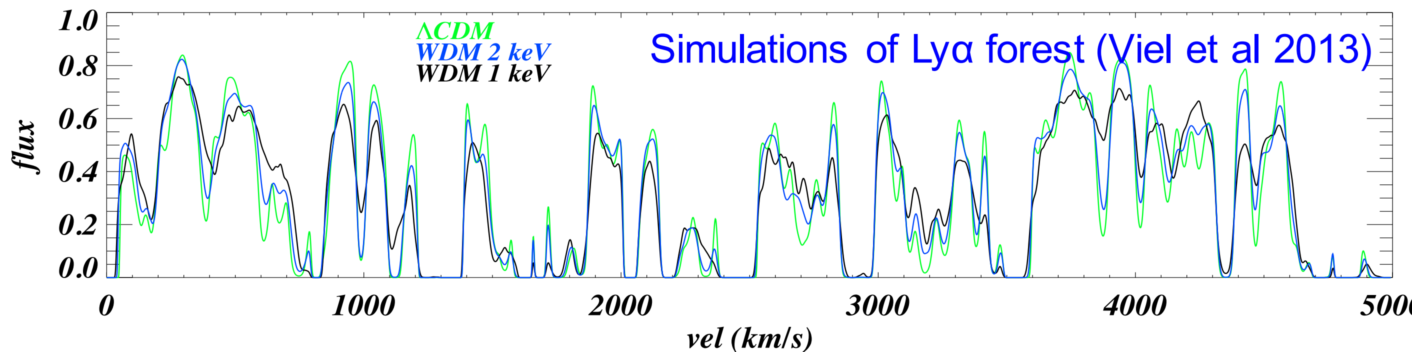
Next step: correlate DM profiles with past SF history

CDM Astrophysical Scorecard

- Missing satellite problem: ok if there are tidally-stripped objects & dark halos whose gas was expelled or consumed during reionization ➔ **find dark halos**
- Boylan-Kolchin effect (expect many dense massive satellites): no convincing explanation except cosmic variance ➔ **external halo mass functions**
- Flat DM profiles in low mass galaxies: Can resolve with continued SN feedback but contrived ➔ **is there evidence of bursts?**

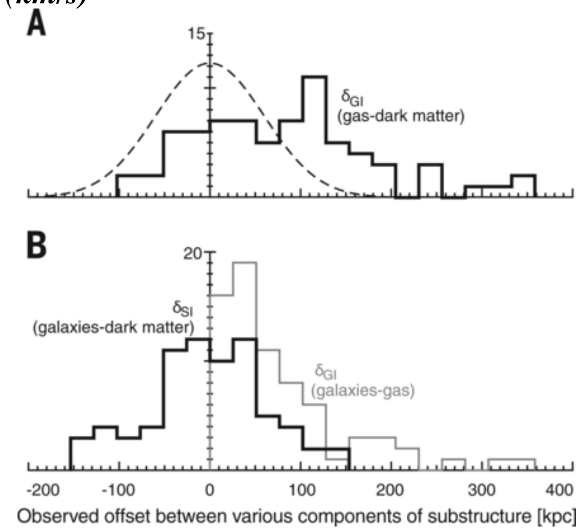
Warm DM (e.g. sterile neutrino): washes out cusps but has difficulty in explaining Lyα forest data and suppresses formation of galaxies at high redshift

Self-interacting DM: non-zero scattering coefficient only affects dense cores. Some limits from ``Bullet clusters''

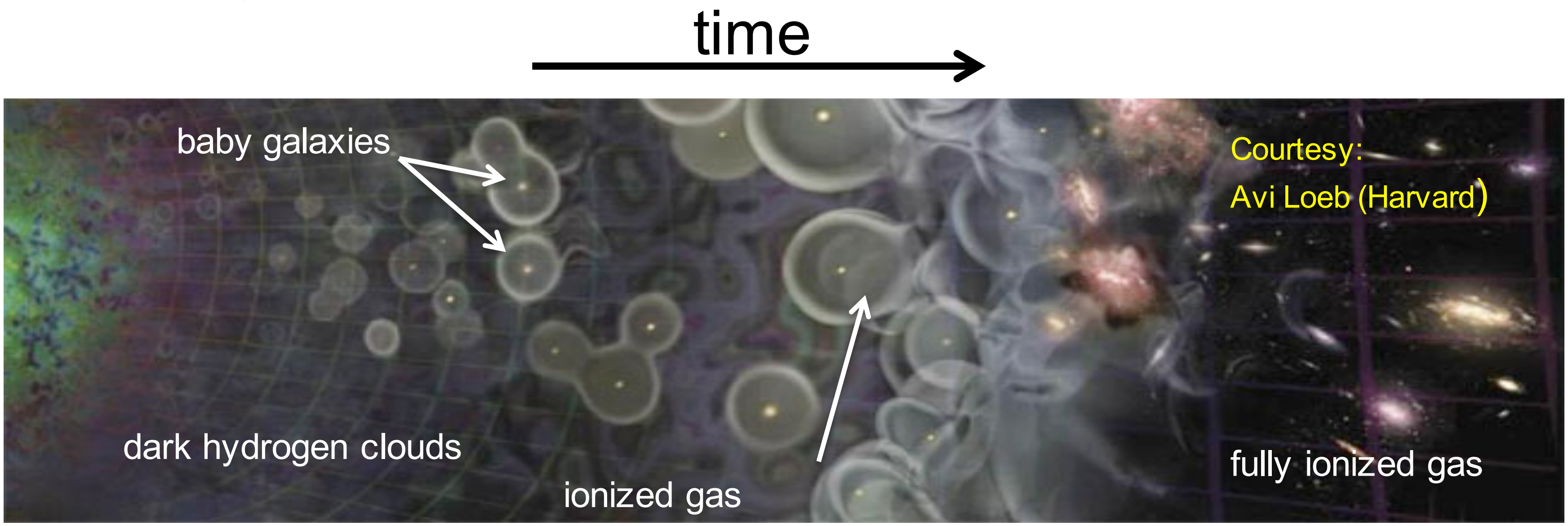


Simulations of Lyα forest (Viel et al 2013)

Positional offsets of DM, gas and galaxies for 72 interacting systems places upper limit on σ_{DM} (Harvey et al 2015)



High Redshift Galaxies & Reionization



Big Questions:

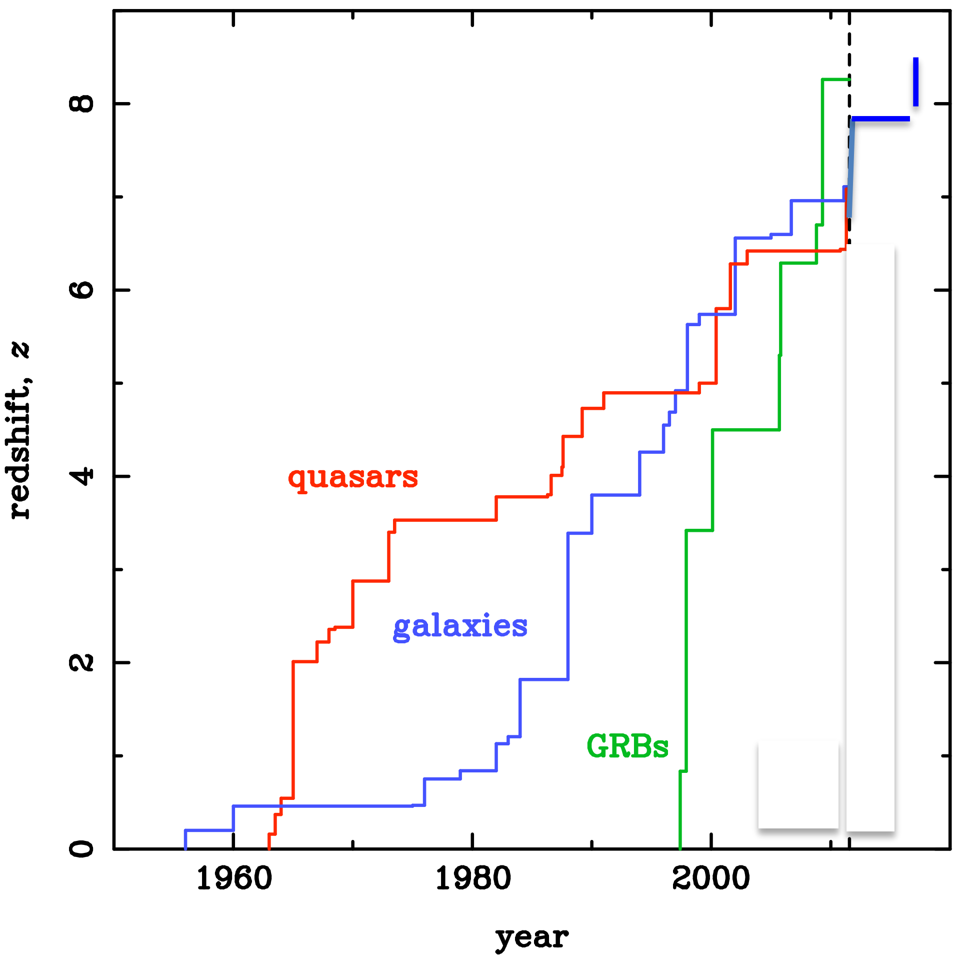
1. When did reionization occur?
2. Were star forming galaxies responsible?

Issues, prospects and challenges:

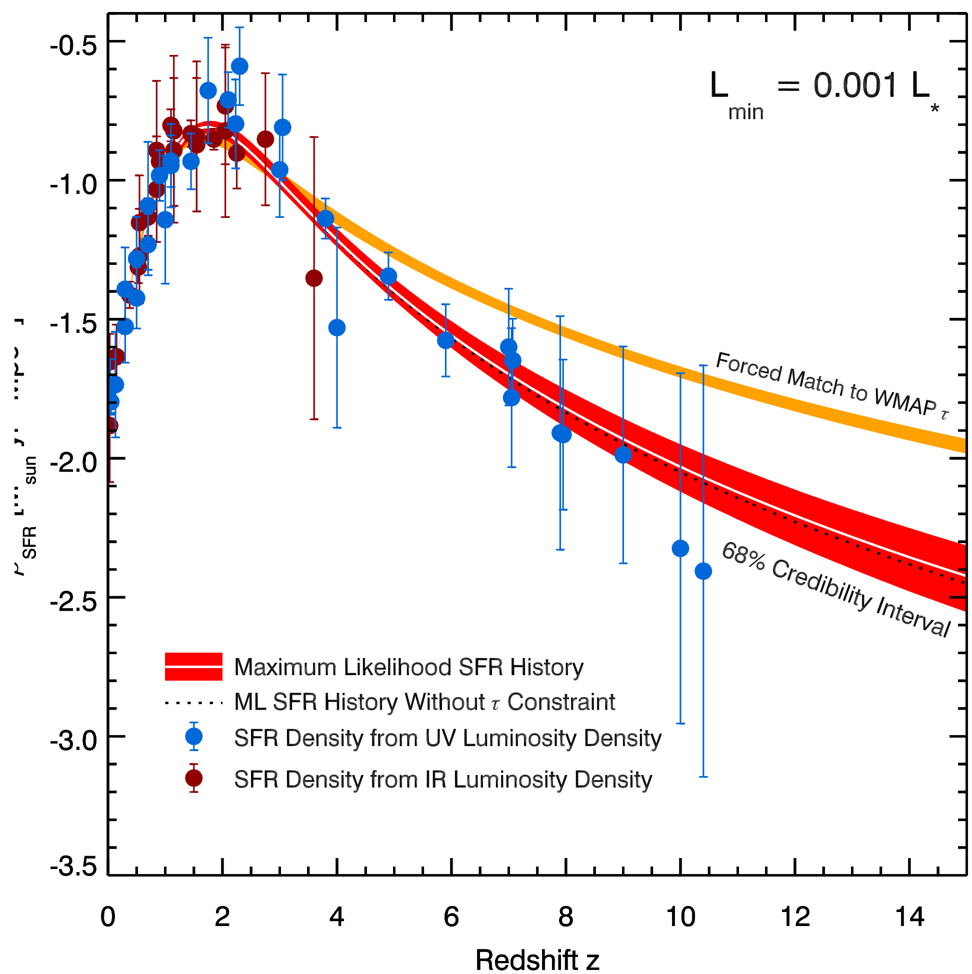
- Lyman alpha as tracer of IGM neutrality?
- **Ionizing output from star-forming galaxies?**
- Is the census of star forming galaxies complete?
- **Early dust**
- Role of AGN and early black holes

Receding Horizons: Star Formation History

Most distant object



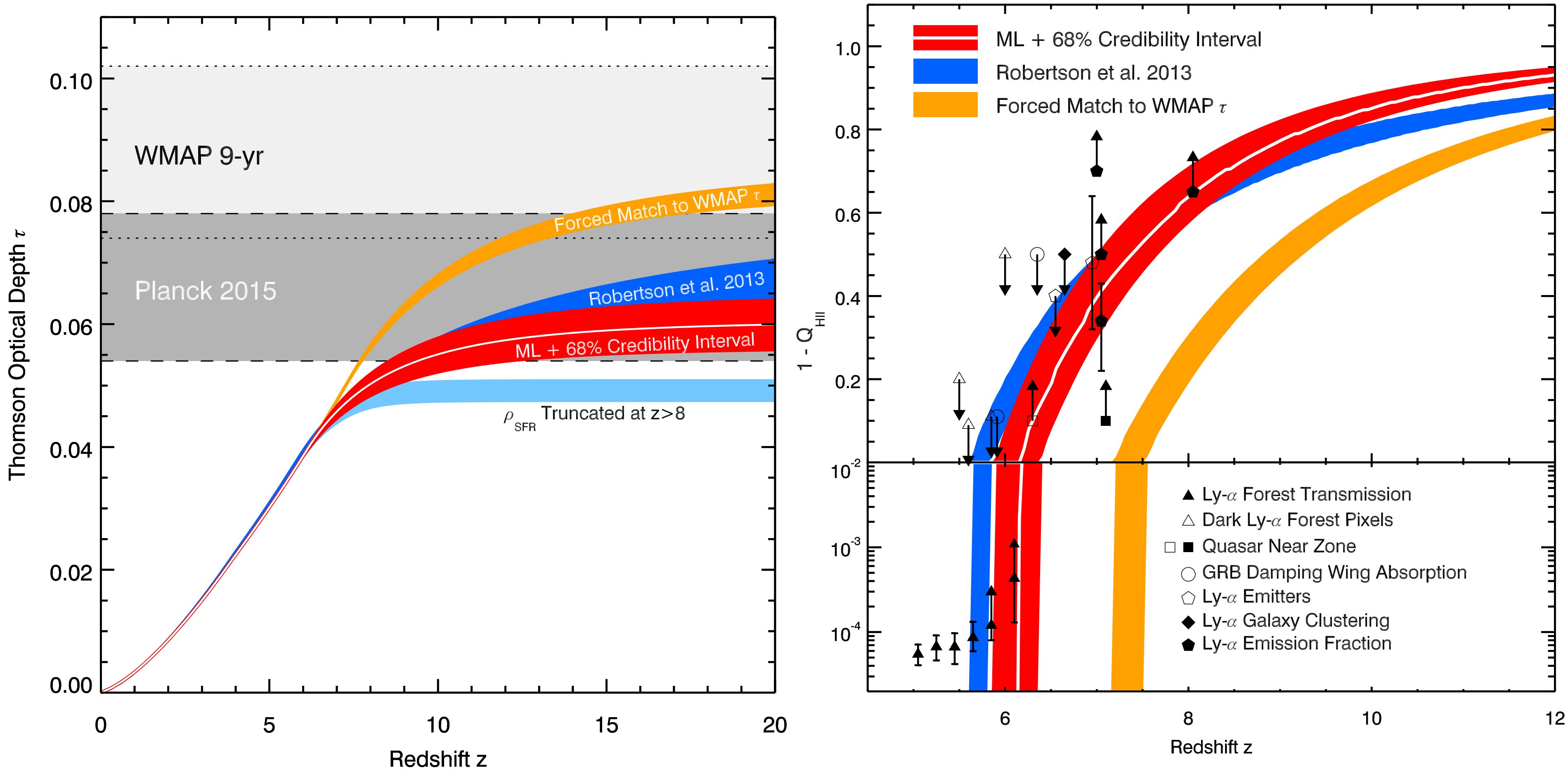
Galaxy census reaches to z~10 utilizing both blank fields and lensed surveys.



Courtesy: Dan Mortlock

Robertson et al (2015)

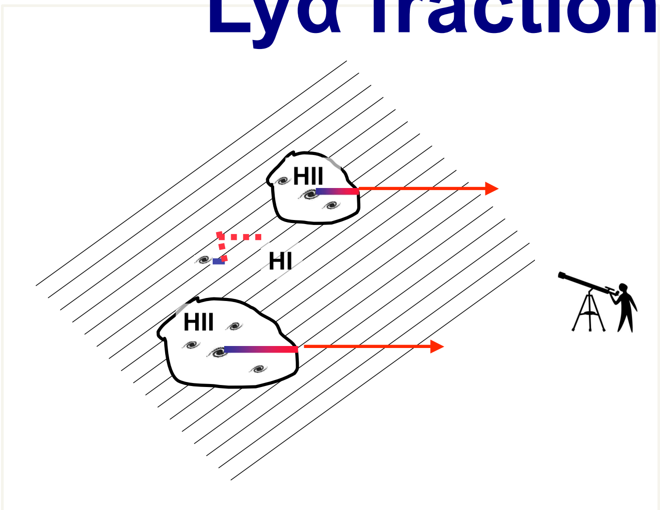
Planck & HST: Reionization over 6 < z < 12



Adopting f_{esc} = 0.2, ξ_{ion} consistent with β= -2, a LF extending to M_{UV}=-13 can match Planck data with reionization largely contained with 10 < z < 6

Robertson et al (2015), see also Bouwens+(2015), Mitra+(2015)

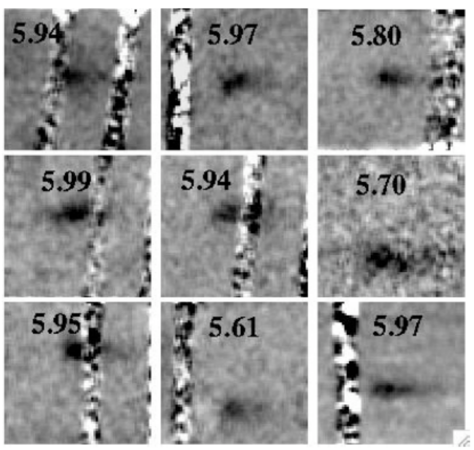
Lyα fraction declines sharply to z~8



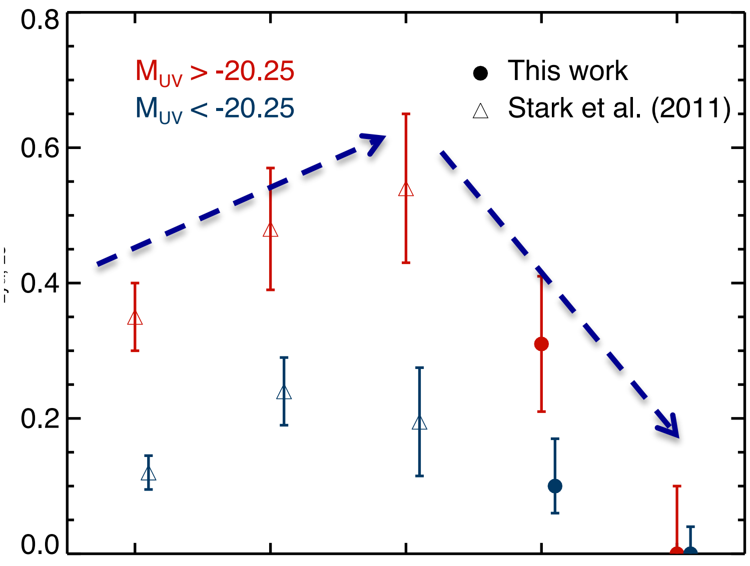
Via resonant scattering, Lyα visiblity is reduced when a galaxy lies in a partially-neutral IGM (Miralda-Escude 1998, Santos 2004)

First applications Fontana+ (2010), Stark+(2010)

z~6 emitters



Fraction of galaxies showing Lyman α



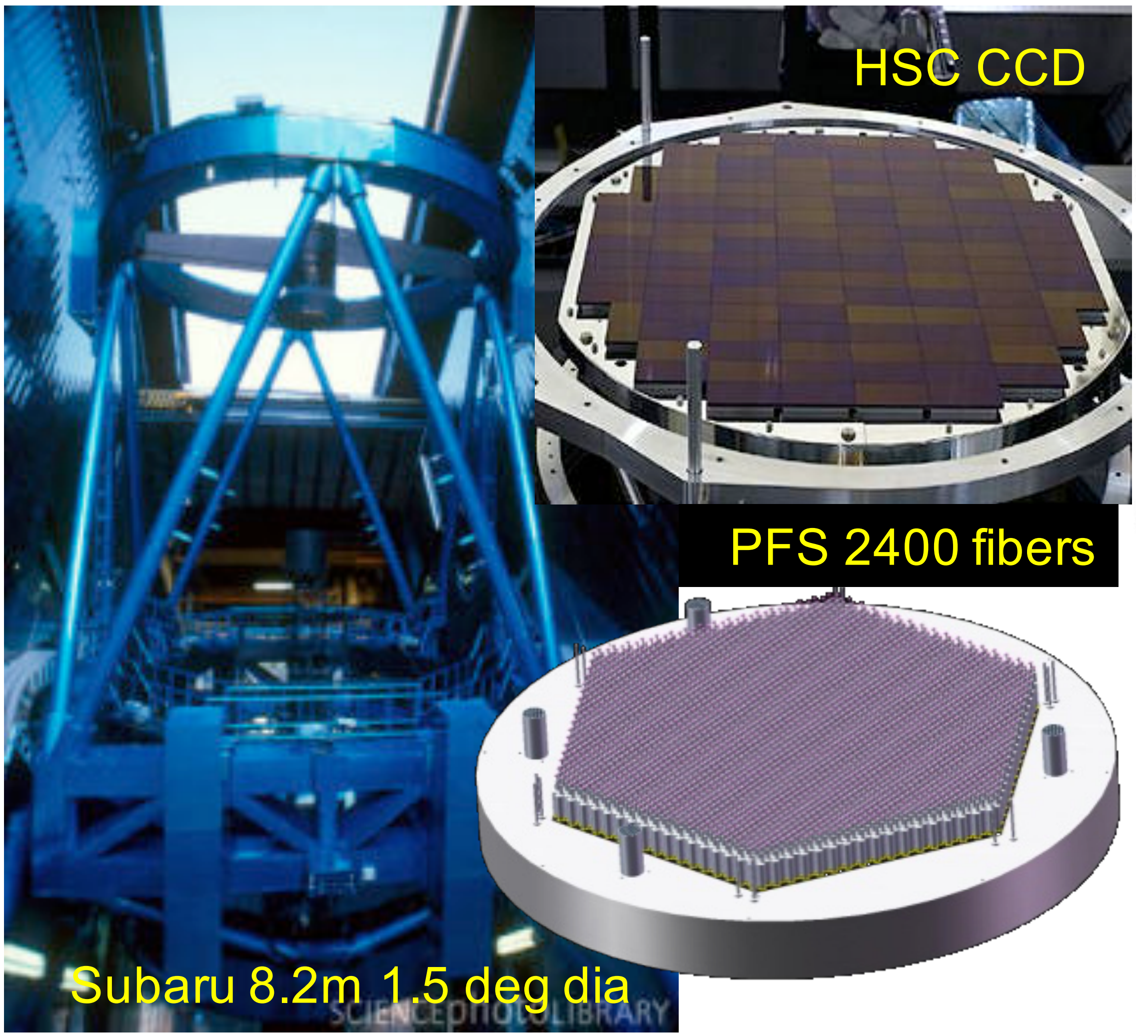
redshift

Schenker et al (2014) – Keck MOSFIRE + UDF, CLASH 7<z<8.2
Treu et al (2013) – Keck MOSFIRE + BoRG z~8
Finkelstein et al (2013) – Keck MOSFIRE + CANDELS z > 7
Pentericci et al (2014) – VLT FORS 6<z<7.3

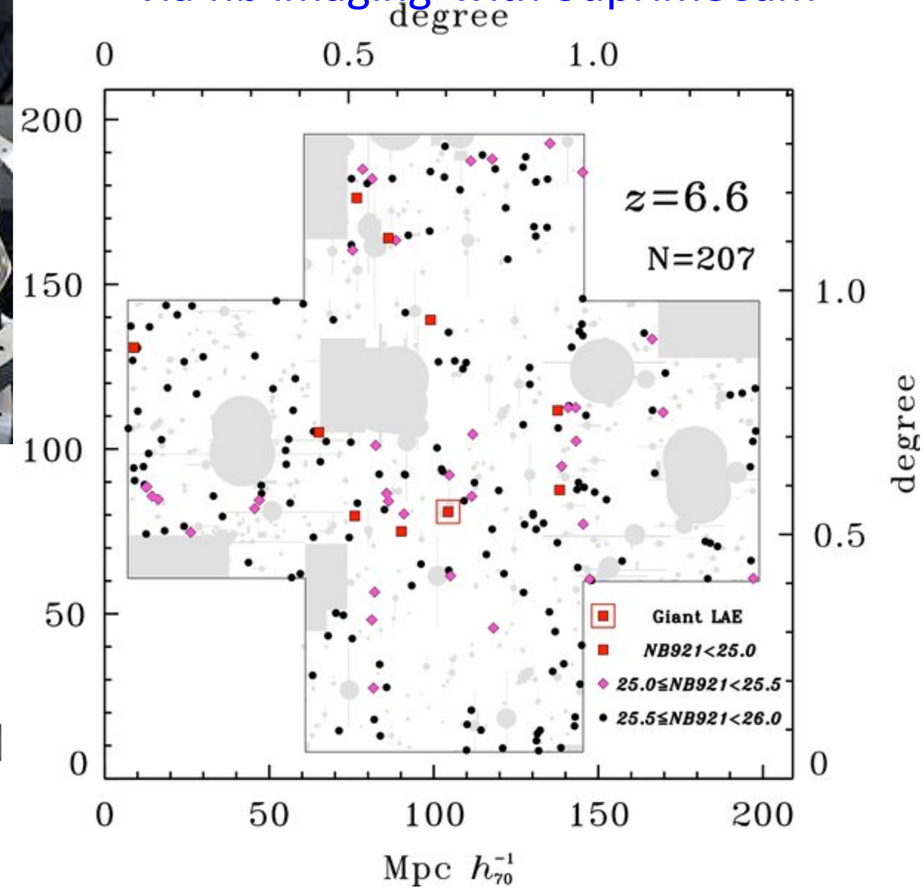
Spatial Distribution of Lyα Emitters

Subaru HSC/PFS will chart distribution of Lyα emitters at end of reionization (5.7<z<7.1) in possible coordination with LOFAR

Constrains evolving sizes of ionized bubbles & longevity of ionizing sources.



Angular distribution of z~6.6 LAEs via nb imaging with SuprimeCam

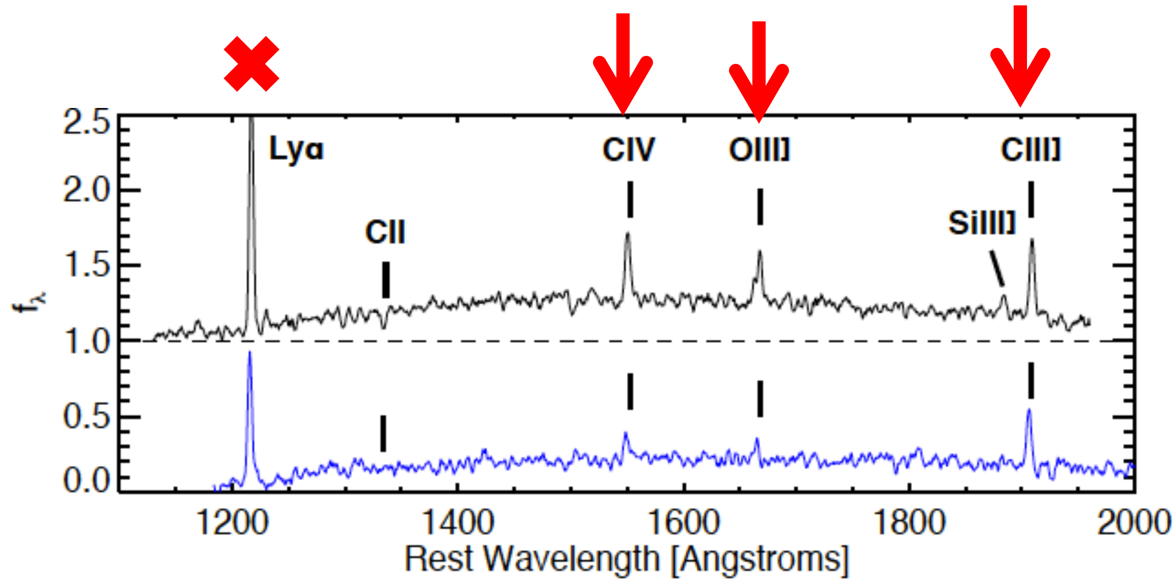


Ouchi et al 2010

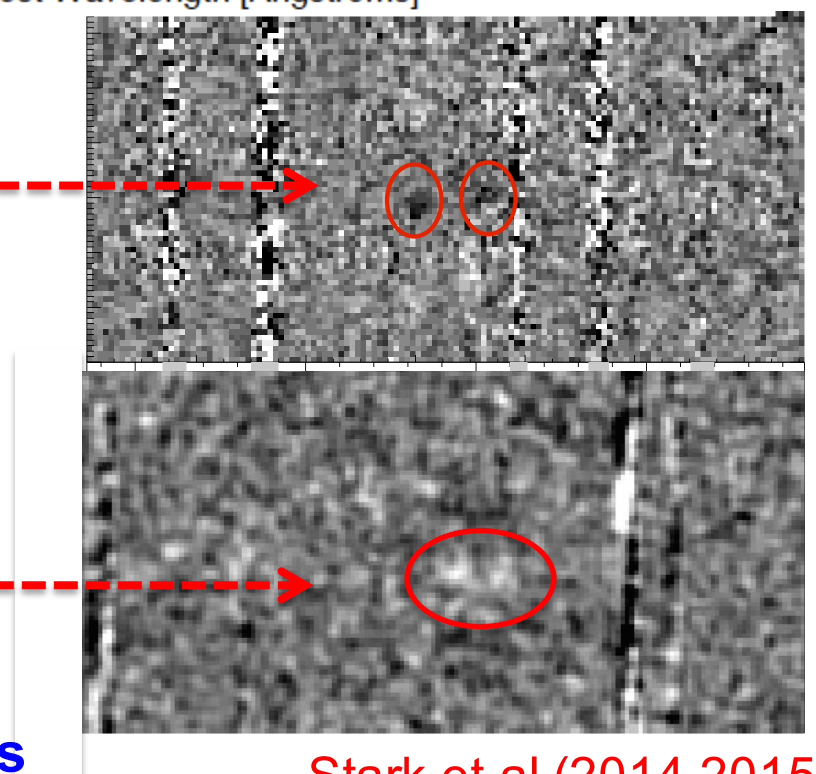
Diagnosing Ionizing Radiation via UV Metal Lines

- CIV 1548 Å 48 eV
- O III] 1664 Å 35 eV
- CIII] 1909 Å 29 eV

Valuable indicators of early hot stellar populations and their ionizing capability



CIV 1548/1550 Å doublet at z=7.05

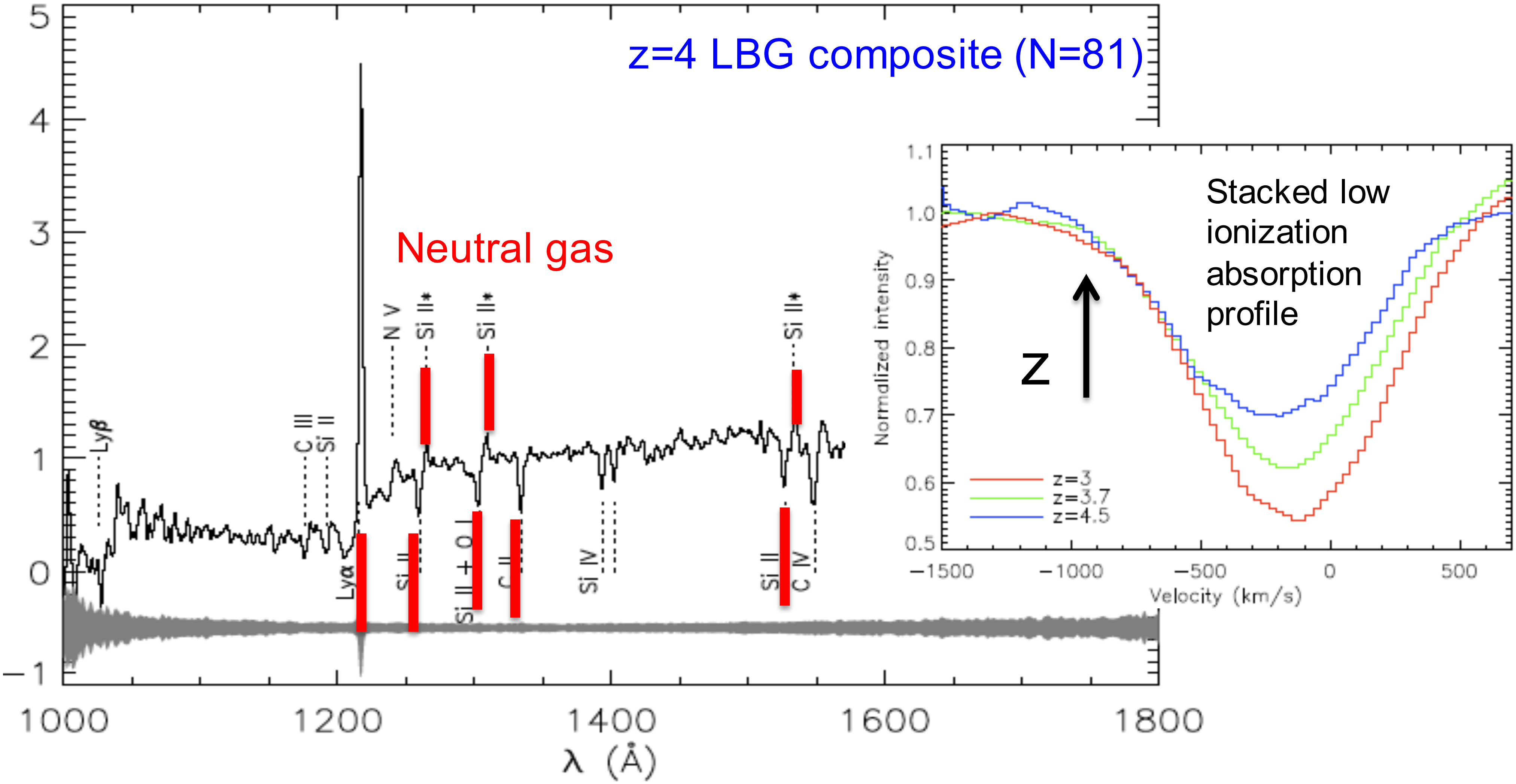


CIII] 1905/1909 Å doublet at z=7.73

Long integrations with NIR spectrographs

Stark et al (2014,2015)

Rising Escape Fraction with Redshift?



Reduced covering fraction of low ionization gas consistent with smaller galaxies, more energetic SF and higher escape fraction

Requires high dispersion stacks of z > 5 targets

Jones et al (2012, 2013)

Dust at High z?

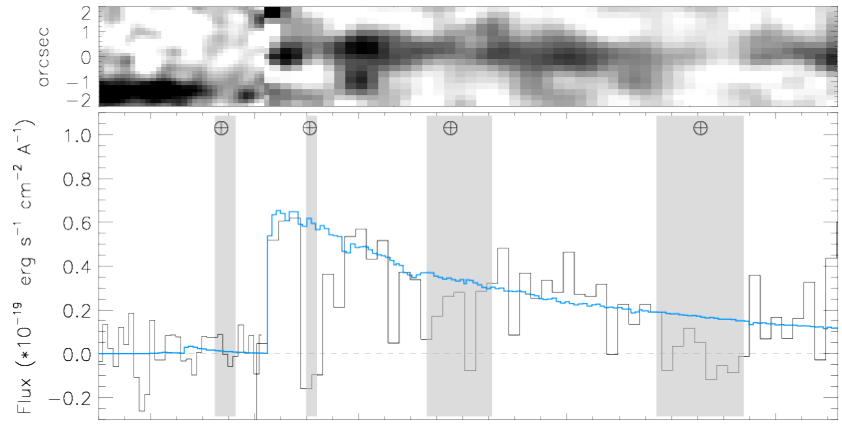
- Lensed z~7.5 galaxy A1689_zD1 in Abell 1689 (Bradley et al 2008); magnification ~×9

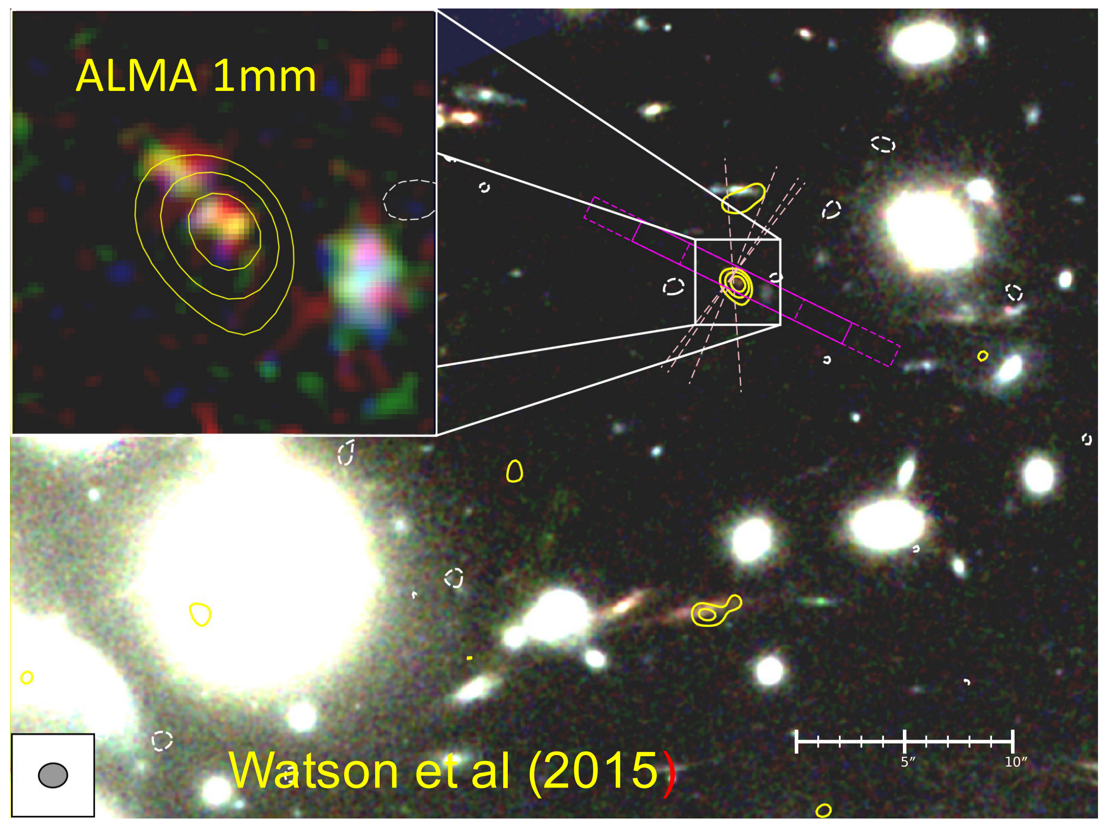
- Low mass (log M*~9.2) with blue UV slope

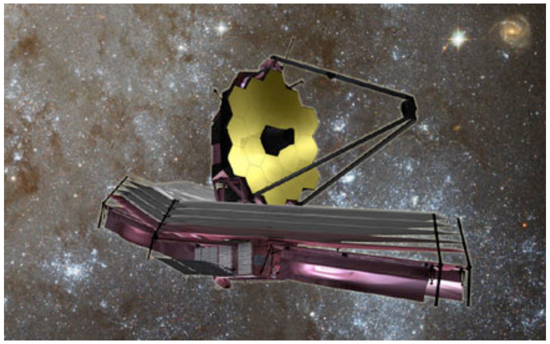
- ALMA band 6 (1mm) detection confirmed via 3 independent exposures (log M_{dust} ~8)

More ALMA data on z > 7 LBGs!

VLT X-shooter spectrum

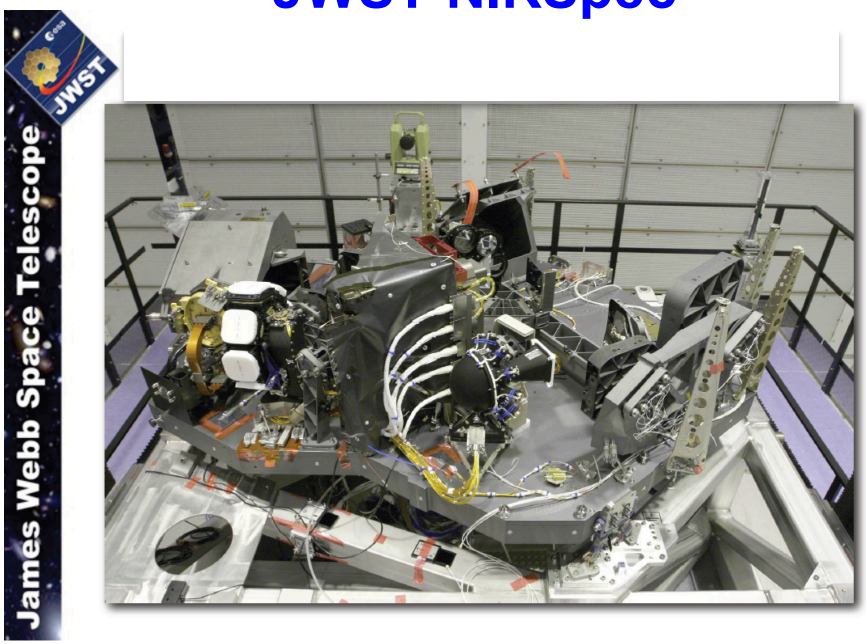




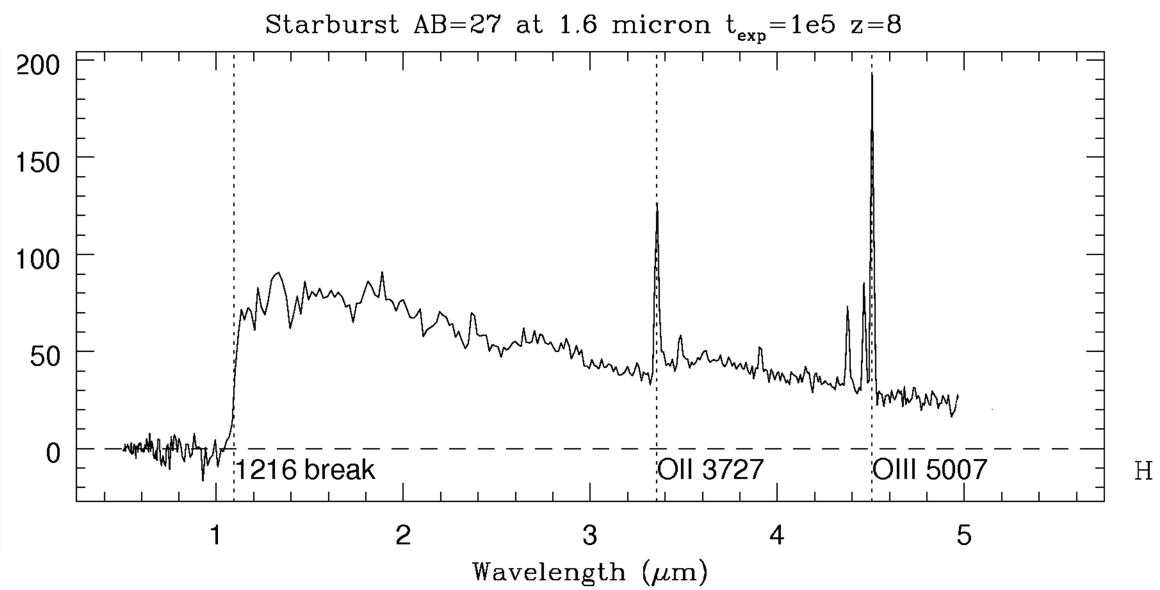


Chemical Evolution: The Next Diagnostic

JWST NIRSpec



z=8 UDF galaxy; 25 hour exposure



JWST will detect starlight and provide access to rest-frame optical nebular lines ([O II], [O III], [N II], Hα) of great utility in tracing gas phase enrichment

Summary Points

- Main dark energy probes (weak lensing, large scale structure) now the province of dedicated experiments although some are being carried out on general purpose telescopes (e.g. Subaru)

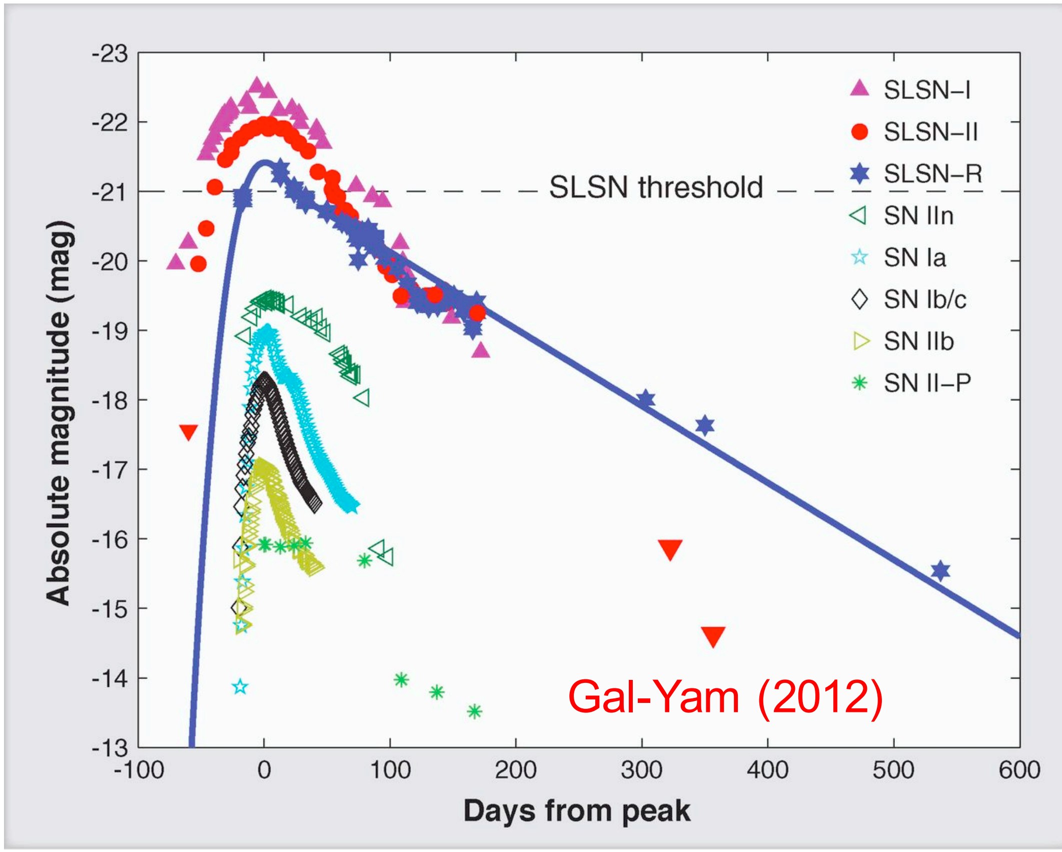
- Window of opportunity ahead of Euclid very limited in all areas; better to complement Euclid e.g. higher sampling in BAO, spectroscopic calibration of photometric redshifts

- Many opportunities in dark matter investigations: Galactic searches for dark halos, lensing anomalies, impact of baryonic events on DM distribution: evidence for departures from standard model remains slim, however.

- High redshift studies and questions regarding reionization require major investment in challenging spectroscopy ahead of JWST: UV metal lines probe nature of early hot stars and high dispersion spectra probes escape of ionizing radiation: major effort to increase number of high z lensed targets

[redacted]

More Interesting Use of High z SNe?



Explosion (literally!) in study of superluminous SNe which offer

- new trace of early chemical enrichment
- beacons for identifying early galaxies
- probes of cosmic reionisation, feedback & rapid mini-halo enrichment
- nucleosynthesis products in local dwarf galaxies

Requirement for Euclid: Q=1000

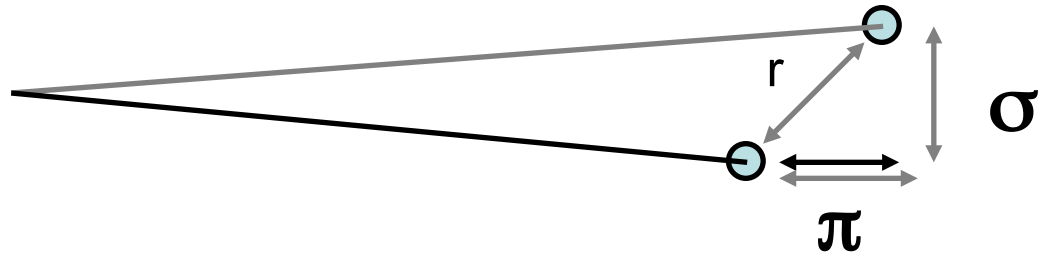
GREAT10
GRavitational lEnsing Accuracy Testing

Q(max) = 319.5 in 2011

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-06
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-06
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-06
7	mpi-is	mpi-is	method04 (set21)	Sept. 2, 2011, 11:16 a.m.	109.7	9.11972E-06
8	mpi-is	mpi-is	method04	Sept. 1, 2011, 2:25 p.m	109.3	9.15092E-06
9	mpi-is	mpi-is	method04 (set_21 corrected)	Sept. 1, 2011, 5:53 p.m	109.3	9.15092E-06
10	mpi-is	mpi-is	method05 (set21)	Sept. 2, 2011, 1:33 p.m	96.4	1.03681E-05
11	mpi-is	mpi-is	method05	Sept. 2, 2011, 10:18 a.m.	95.0	1.05228E-05
12	Ohio State University	kh	KSB_BSA (ps)	Sept. 1, 2011, 11:38 a.m.	92.0	1.08703E-05
13	UCL CoGS	browe	Im3shape NBC0	Aug. 31, 2011, 12:54 p.m.	89.1	1.12279E-05
14	UCL CoGS	browe	Im3shape NBC1	Sept. 2, 2011, 1:37 a.m	88.9	1.12478E-05
15	UCL CoGS	browe	Im3shape NBC0XS	Sept. 2, 2011, 3:12 p.m	88.6	1.12827E-05
16	UCL CoGS	ucl	Im3shape Uncalibrated	Aug. 30, 2011, 11:57 p.m.	87.6	1.14111E-05
17	UCL CoGS	browe	Im3shape Uncalibrated XS	Sept. 2, 2011, 4:11 p.m	87.2	1.14683E-05

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

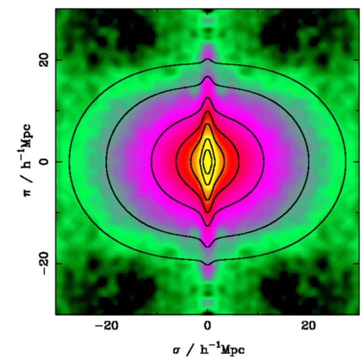
Redshift Space Distortions for free..



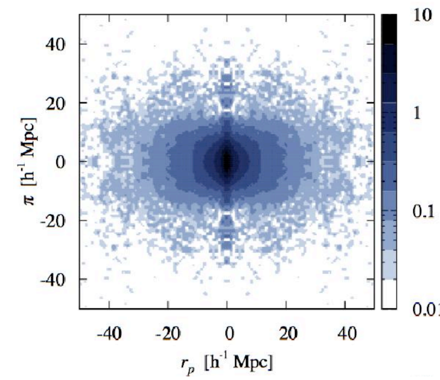
- Peculiar velocities quantified by asymmetrical correlation fn $\xi(\sigma,\pi)$
- Small separations: 'Finger-of-God'
- Large separations: l.o.s. flattening

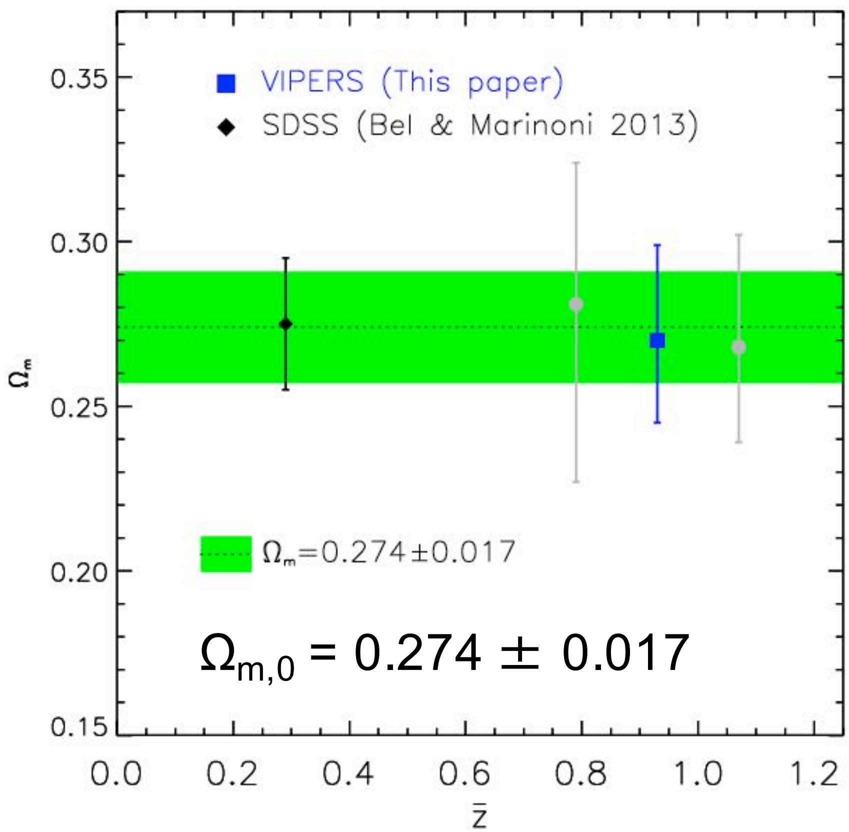
Yields $\Omega_M^{0.6}/b$ thus require bias factor b

2dF:
Peacock et al (2001)



VIPERS:
Bel et al (2014)



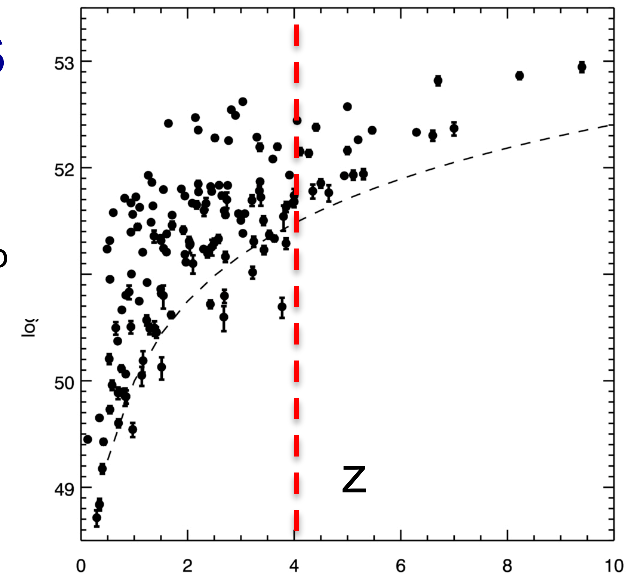


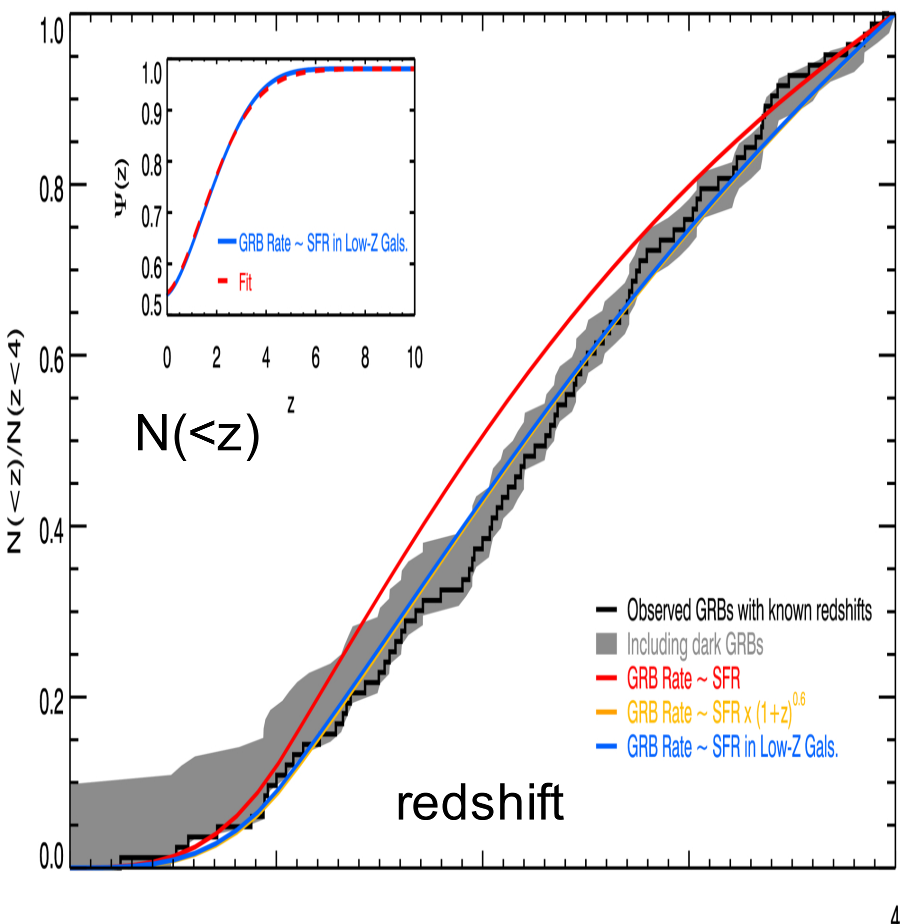
Constraints on early SF from GRBs

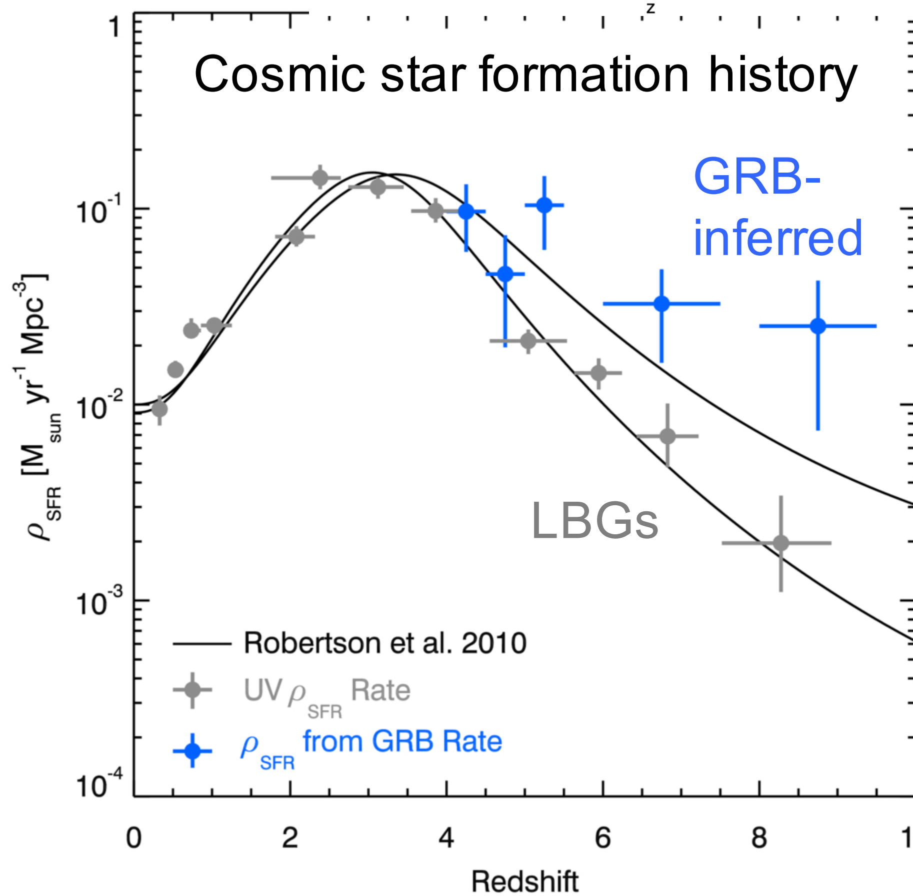
N(< z) for 152 long duration GRBs matches integral of SFH 0<z<4. This enables us to deduce early SFH from rate of z>6 GRBs

.

Major discrepancy! Missing star formation?







Robertson & Ellis (2012)