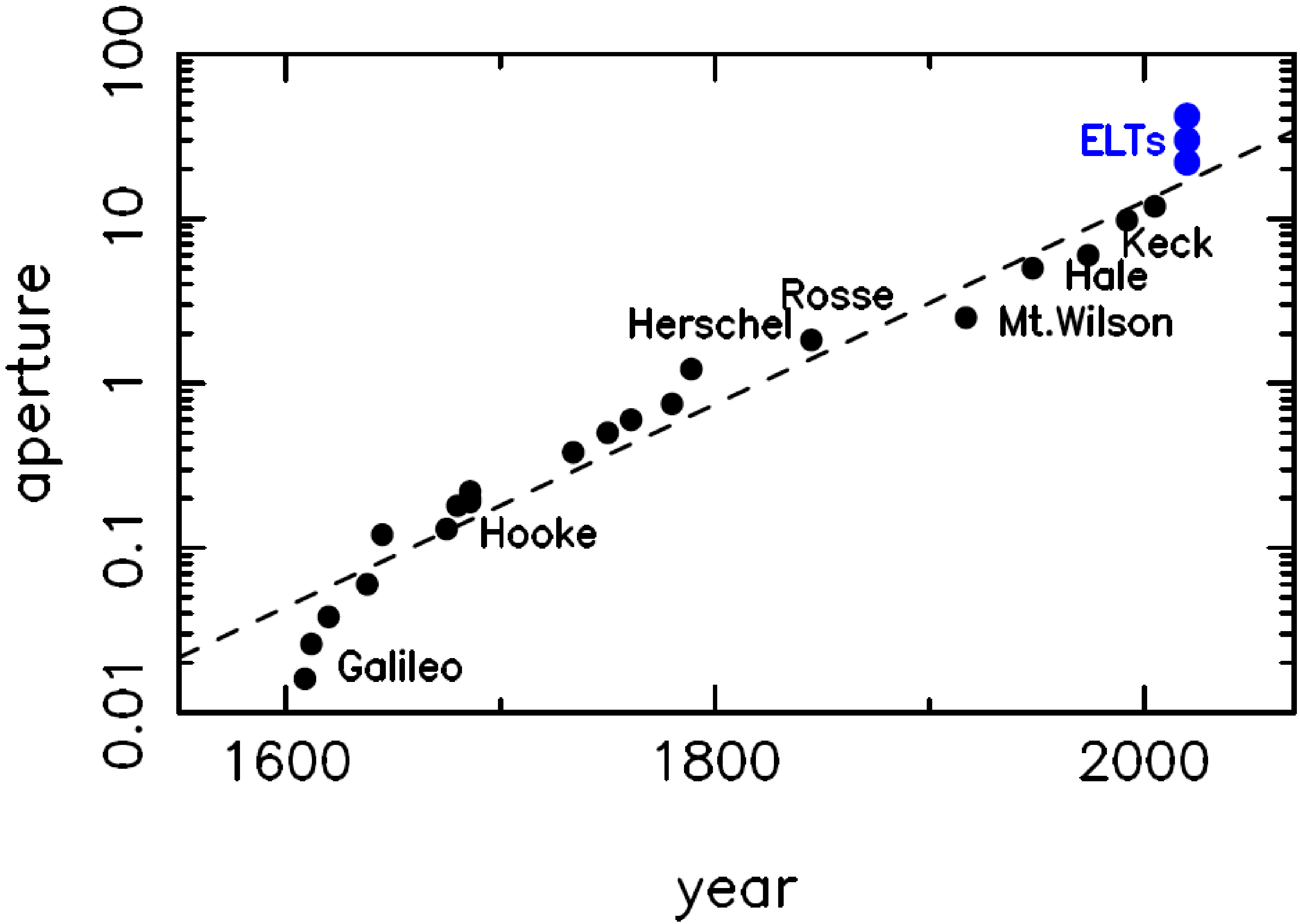
Cosmology, Early Universe and Fundamental Physics
ELT View

Xiaohui Fan

Garching, Mar 25, 2009

Largest Telescopes in the World



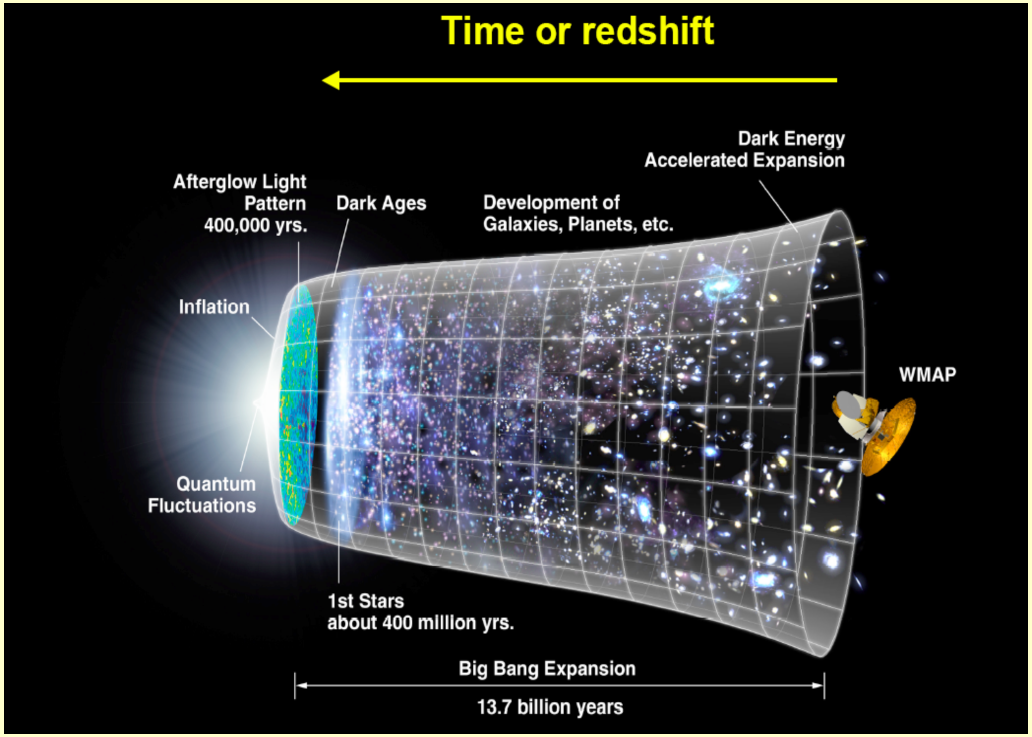
Selected VLT Cosmology Science Cases 1983 - 1986

- Nature of invisible mass
- Large scale structure of the Universe
- Evolution of stellar population with cosmic time
- Determination of deceleration of the universe using SNe 1
- General validity of the laws of physics over cosmic time
- Quasar absorption lines
  - Chemical evolution of the IGM
  - Ly alpha clouds
  - D/H to measure Ω_b
- Deep direct imaging in serendipity mode (Deep Fields)

We are dealing the same set of big *Known-Unknowns*

Big Open Questions

- Cosmological models:
  - Properties of dark energy
  - Nature of dark matter
  - Is LCDM structure formation the correct model
- Physics Laws over Cosmic Time/Cosmic Scale
  - Variability of fundamental constants
  - GR and black hole physics
- Earliest Cosmic Structures
  - Galaxies at z>>6
  - First stars
  - Reionization/IGM enrichment



ELTs for Cosmological Models

- Cosmic Dynamics Test
- Dark Energy Measurements with
  - SNe IA
  - BAO at high-z
  - LISA follow-up
- Dark Matter measurements with
  - Dwarf galaxies
  - Cluster dynamics
  - Gravitational lensing

ELTs for Cosmological Models

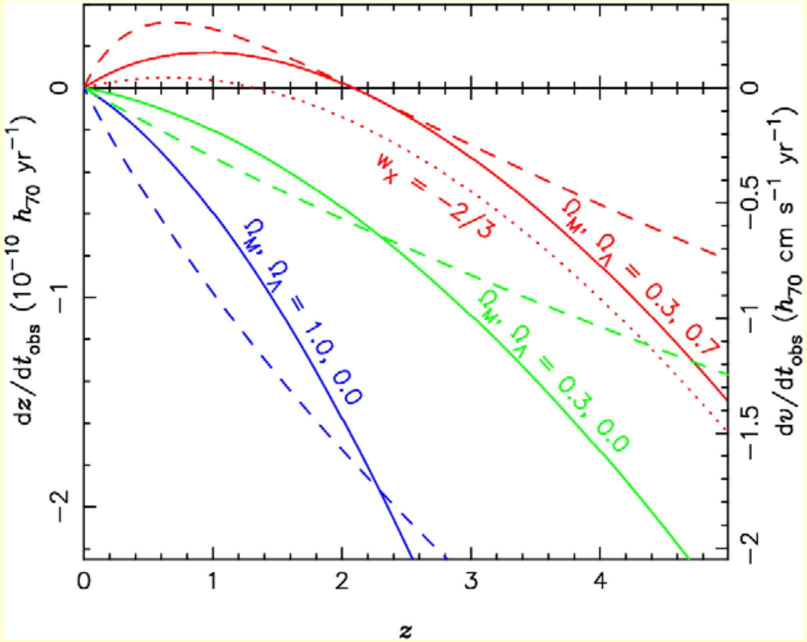
- **Cosmic Dynamics Test**
- Dark Energy Measurements with
  - **SNe IA**
  - BAO at high-z
  - LISA follow-up
- Dark Matter measurements with
  - **Dwarf galaxies**
  - Cluster dynamics
  - Gravitational lensing

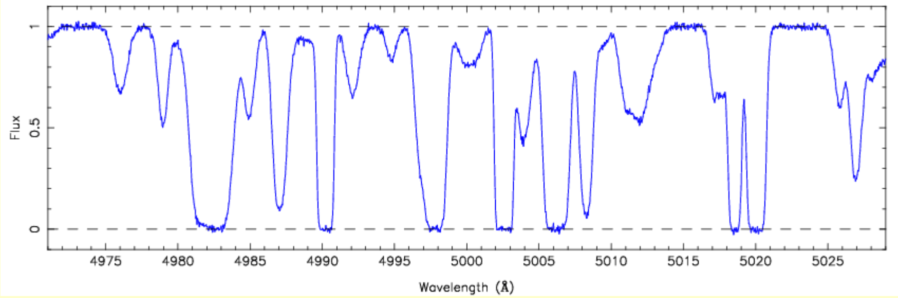
Cosmic Dynamics Test

- Acceleration or Deceleration of the universe causes **observed redshift** of an object to be a function of time:

$$\dot{z} = (1+z)H_0 - H(z)$$

- Measuring $\dot{z}(z)$:
  – Most direct and model-independent test of the expansion history
  – Independent measurement of accelerated expansion.
- Measuring redshift drift:
  – Ly alpha forest of luminous quasars
  – High S/N
  – High resolution Echelle
  – Ultra stable: **laser frequency comb**
  – Long (~20 year) baseline



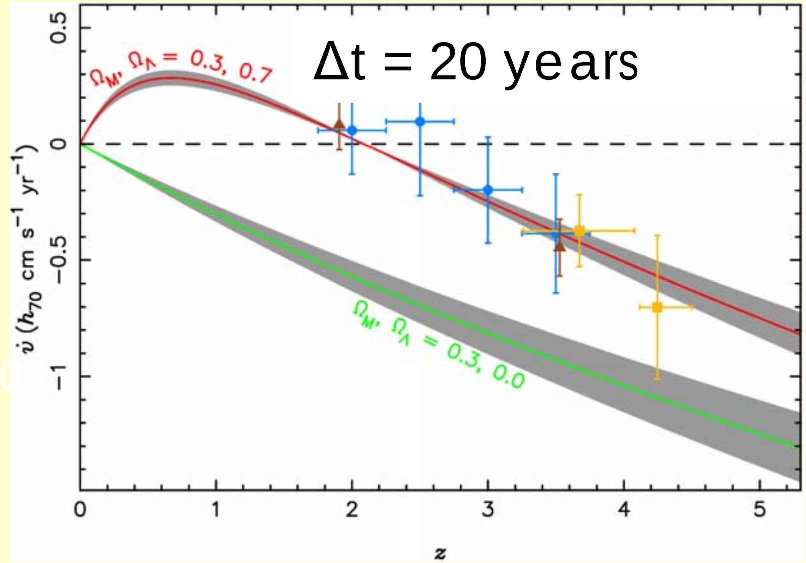


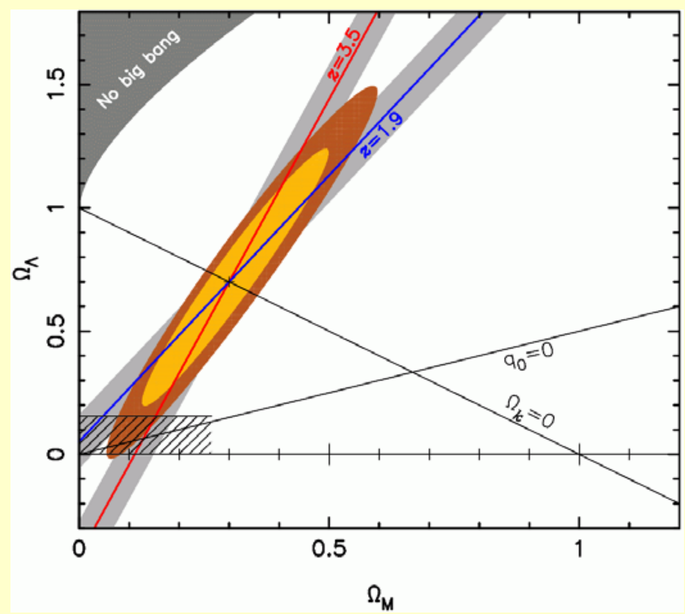
Liske et al. 2008

Cosmic Dynamics Test

- Simulations by Liske et al. 2008
  - 4000 hours of E-ELT over 20 years (one set of points)
  - Accurate and model-independent measurement of dark energy
- Legacy dataset
  - Extremely exciting
  - Is the price too steep?

Liske et al. (200

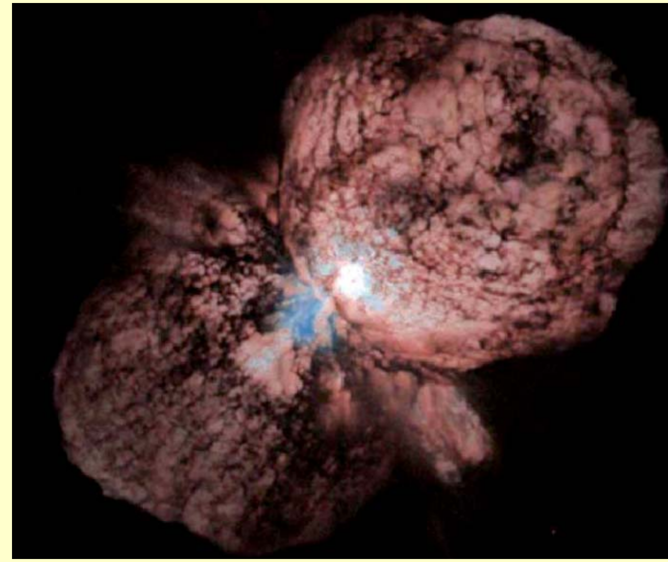


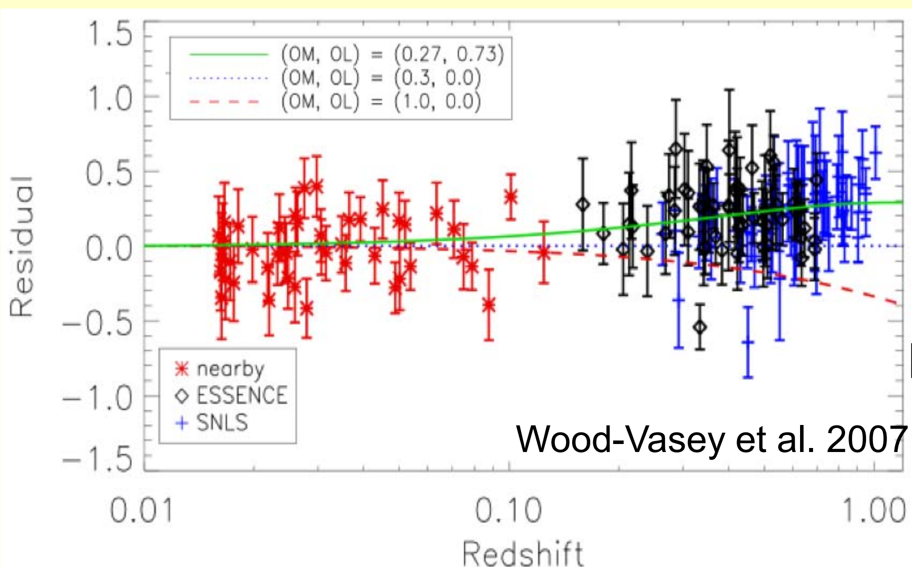


(2008)

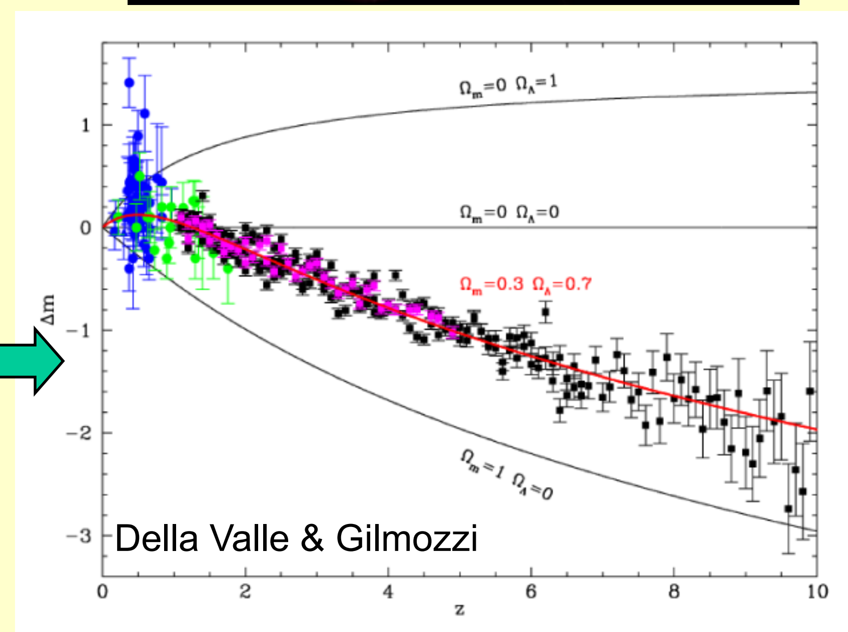
Dark energy with SNe IA

- The equation of state of dark energy can be measured at high z using SNe as standard candles





Wood-Vasey et al. 2007



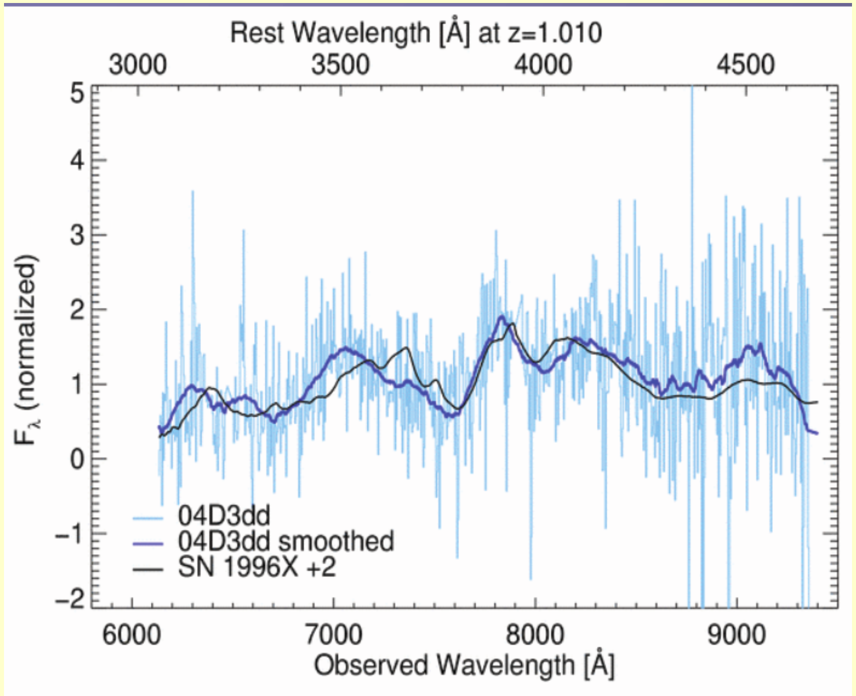
Della Valle & Gilmozzi

Dark Energy with SNe IA

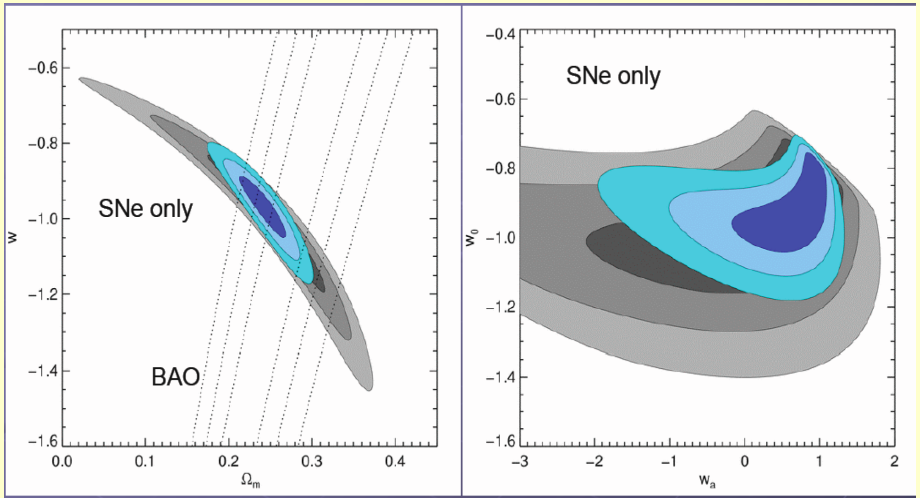
- Sweet spot is at z=1-2
- Efficient single object far-optical/near-IR spectrograph

Redshift	Peak magnitude (AB)	Spectroscopic exposure time (hrs) – assumes NFIRAOS, S/N=5	
		30m	42m
1.7	J =25.3	0.16	0.07
2.8	H=26.1	1.7	0.9
4.0	K=26.8	6.1	3.2

Courtesy: I. Hook



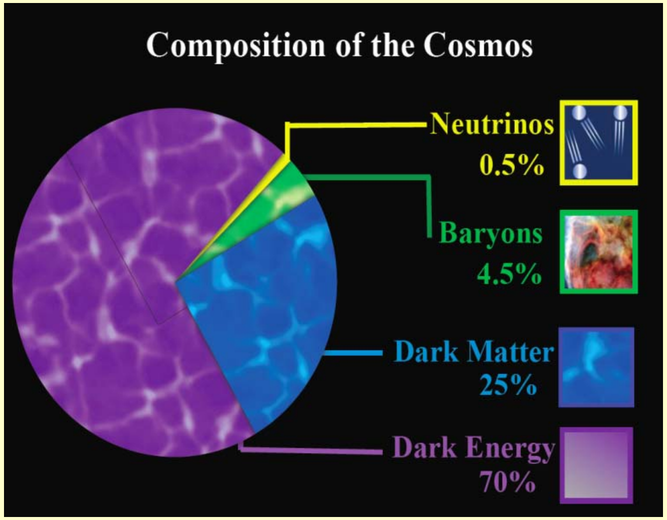
2 hours on 8-m

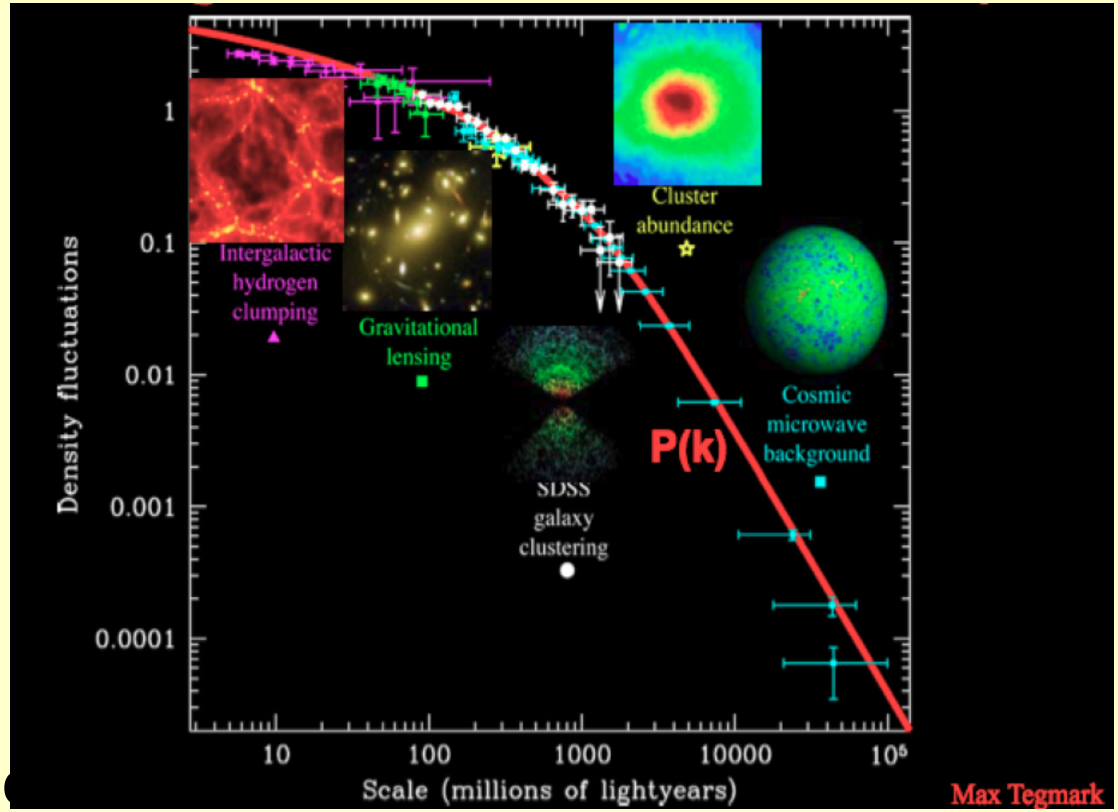


Only SNe + flat Universe assumed. No prior on Ω_M

500 low-z + 1500 from 0.1<z<1.1 + 250 JWST/TMT 1<z<3

Small Scale Structure



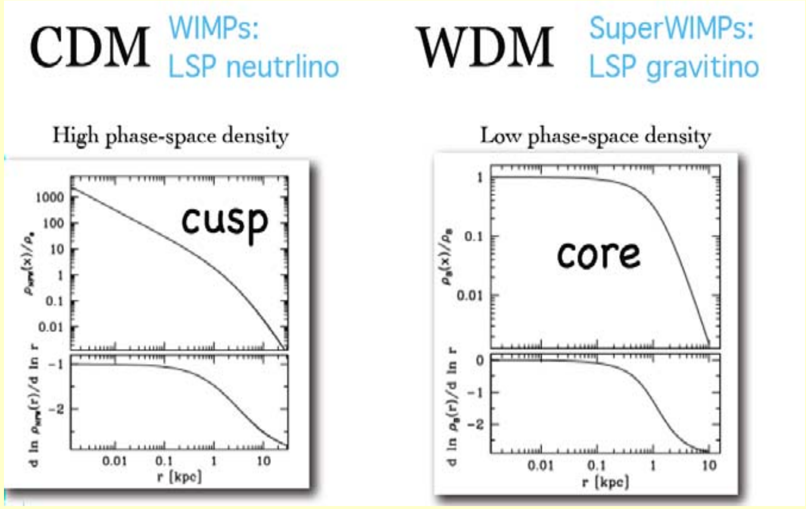


LCDM cosmology

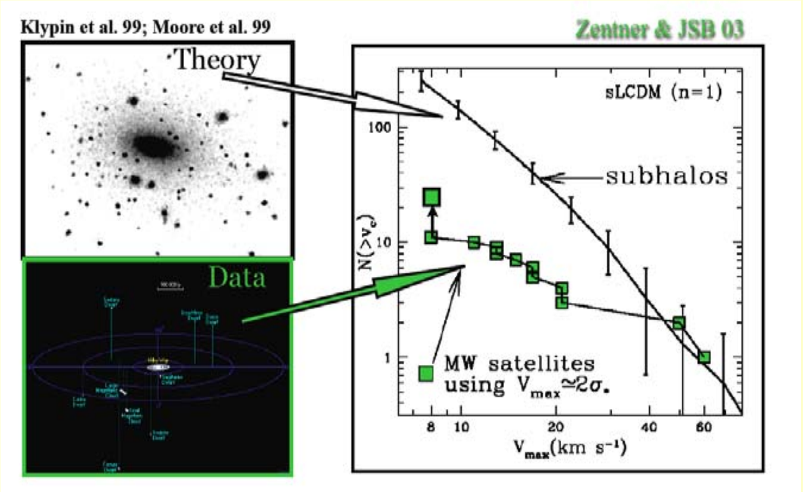
- Large scale: fits well
- Problem with small scale
  - satellite problem
  - rotation curve inconsistent with CDM prediction
  - disk galaxies hard to make/keep thin
- Answer: Near-field Cosmology

Near Field Cosmology with ELTs

- Dwarf Spheroidal velocity profiles:
  - Constrain nature of dark matter
  - Understanding the missing satellite problem
- Resolved stellar populations:
  - Test hierarchical galaxy formation on small scales
  - Constrain merger histories
- Needs:
  - **optical multi-object Echelle on ELTs**
    - Similar to MIKE on Magellan or Hectoechelle on MMT
    - MANIFEST on GMT?



Bullock et al.



ELTs for Cosmological Models

- Cosmic Dynamics Test:
    - ***Single-object Optical Echelle, D^2, laser frequency comb***
- Dark Energy Measurements with
    - SNe IA
        - ***Single-object optical/IR spectrograph, $D^{2\text{-}4}$, LTAO***
    - BAO at high-z
        - ***Optical MOS, $D^2\Omega$***
- Dark Matter measurements with
    - Dwarf galaxie dynamics
        - ***Multi-object optical Echelle, $D^2\Omega$***
    - Cluster dynamics
        - ***Multi-object optical Echelle, $D^2\Omega$***
    - Gravitational lensing
        - ***Optical/IR IFU, $D^{2\text{-}4}$, LTAO***

ELTs for Fundamental Physics

- Variability of fundamental constants
  - Fine structure constants $\alpha = \frac{e^2}{\hbar c}$.
  - Proton/electron ratio $\mu = m_p/m_e$
- BH physics
  - Galactic center

Varying Fundamental Constants?

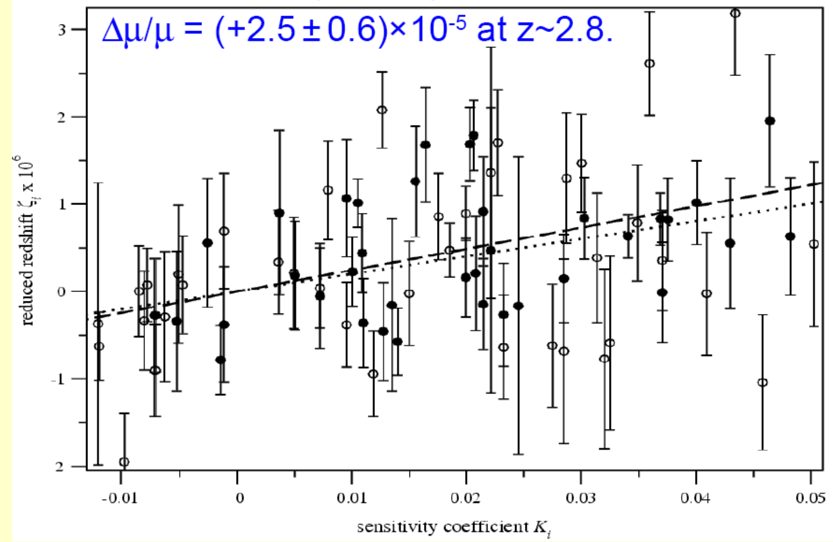
- α and μ are constants in standard model
  - Modern unified theories which invoke extra-dimensions suggest that these constants might vary with cosmic time
  - laboratory constraints:

$$d\alpha/dt/\alpha=(-3.1\pm3.0)\times10^{-16}\ yr^{-1}$$
$$d\mu/dt/\mu=(1.5\pm1.7)\times10^{-15}\ yr^{-1}$$

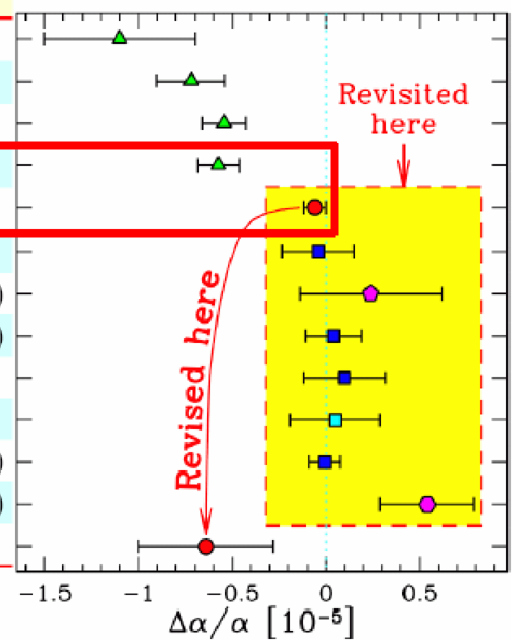
  - Cosmological tests can be few orders of mag more sensitive.
- α and μ variability can tested through quasar absorption lines
  - Fine structure constant is tied to wavelength ratios of multiples
  - Proton/electron ratio is tied to rotational/vibrational energy of molecules
  - Old idea: first proposed by Dircac in 1930s, and first test on high-z sources in 1970s.

Current constrains: Intriguing but controversial

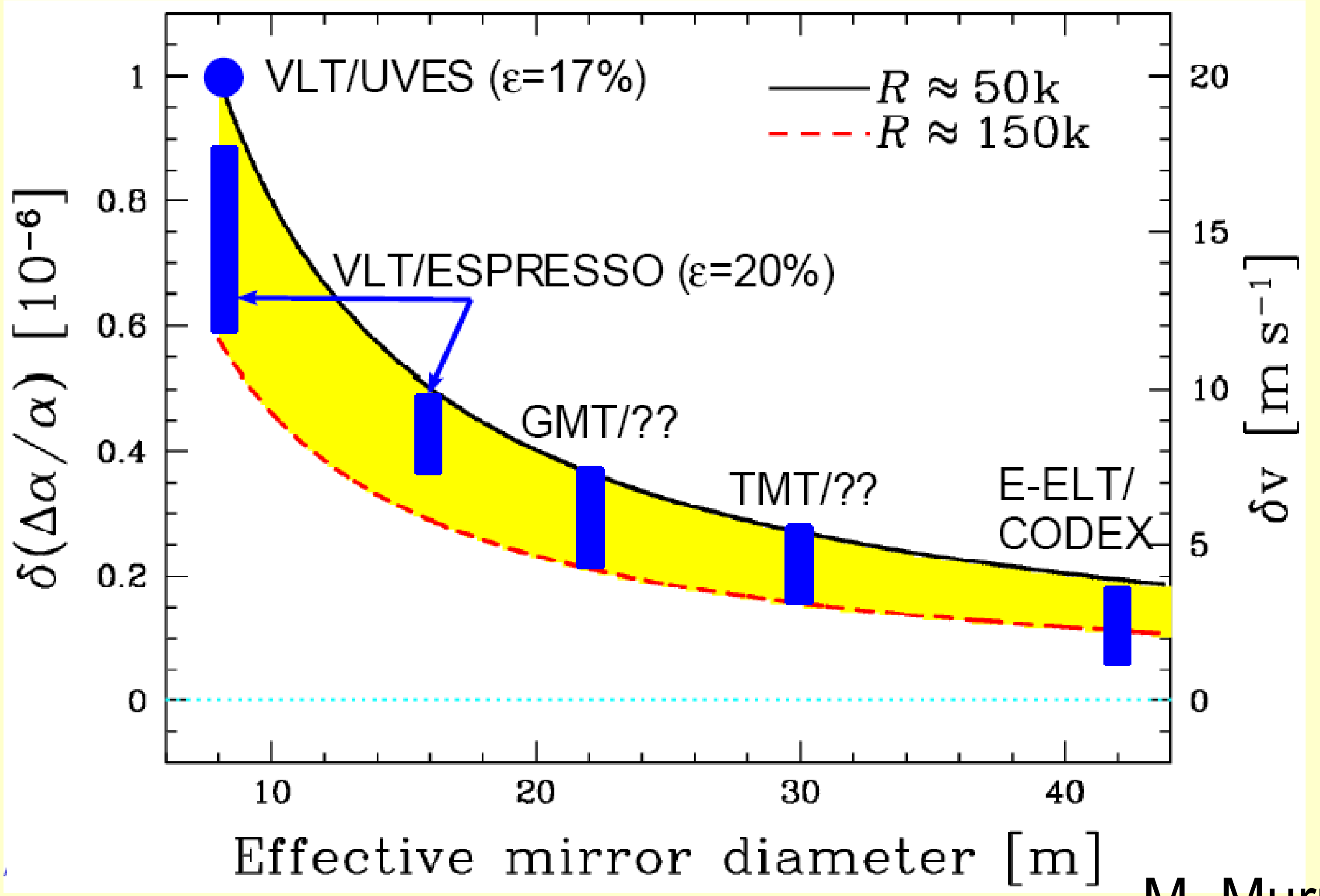
Ubachs et al. (2007):



Instrument	N_{abs}	z_{abs}	$\Delta\alpha/\alpha$ [10^{-5}]	Reference
HIRES	30	0.5–1.6	−1.100 ± 0.400	Webb et al. (1999)
HIRES	49	0.5–3.5	−0.720 ± 0.180	Murphy et al. (2001a)
HIRES	128	0.2–3.7	−0.543 ± 0.116	Murphy et al. (2003)
HIRES	143	0.2–4.2	−0.573 ± 0.113	Murphy et al. (2004)
UVES	23	0.4–2.3	−0.060 ± 0.060	Chand et al. (2004)
UVES	1	1.151	−0.040 ± 0.190 ± 0.270	Quast et al. (2004)
UVES	1	1.839	+0.240 ± 0.380	Levshakov et al. (2005)
UVES	1	1.151	+0.040 ± 0.150	Levshakov et al. (2005)
UVES	1	1.151	+0.100 ± 0.220	Chand et al. (2006)
HARPS	1	1.151	+0.050 ± 0.240	Chand et al. (2006)
UVES	1	1.151	−0.007 ± 0.084 (± 0.100)	Levshakov et al. (2006)
UVES	1	1.839	+0.540 ± 0.250	Levshakov et al. (2007)
UVES	23	0.4–2.3	−0.640 ± 0.360	This work



How much will measurement improve?



M. Murphy

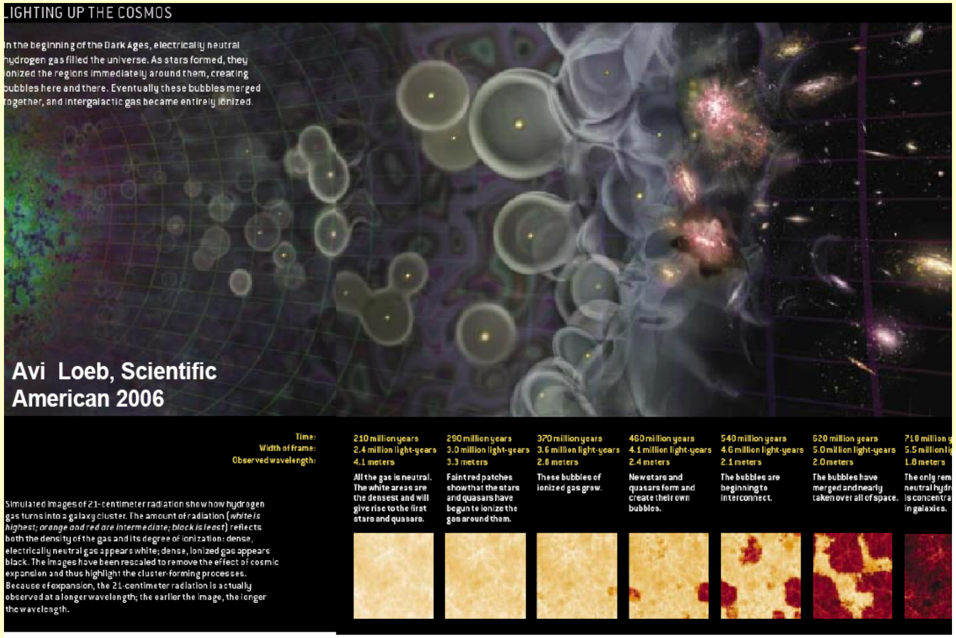
ELTs for Fundamental Physics

- Variability of fundamental constants
  - Fine structure constants
    - ***Single-object optical Echelle, D^2***
  - Proton/electron ratio
    - ***Single-object optical Echelle, D^2, UV sensitive***
  - Requirements on spectrograph
    - 1m/s wavelength calibration
    - 1m/s stability over night
    - R>50k-100k
    - **Frequency comb technology for wavelength calibration**
- BH physics
  - Galactic center
    - ***Near-IR Imager/IFU, D^4, LTAO/MCAO***

ELTs for First Light

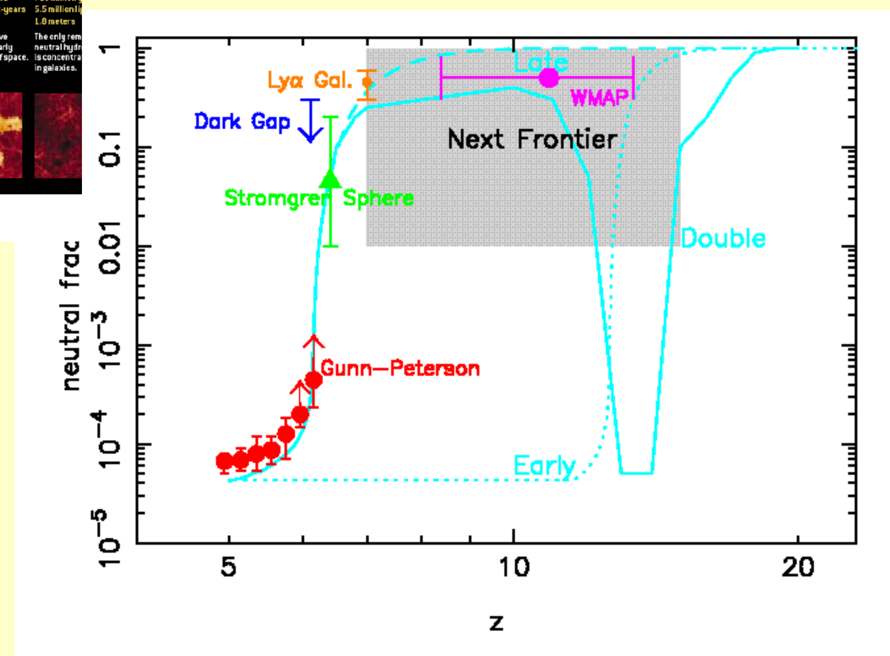
- Highest redshift galaxies through Ly alpha
- Reionization history
  - Ly alpha galaxy mapping
  - GRBs and quasars
  - First metals in the IGM
- First stars
  - HeII, signature of Pop.III
  - Extremely metal poor stars in the Galaxy

Probing Reionization History



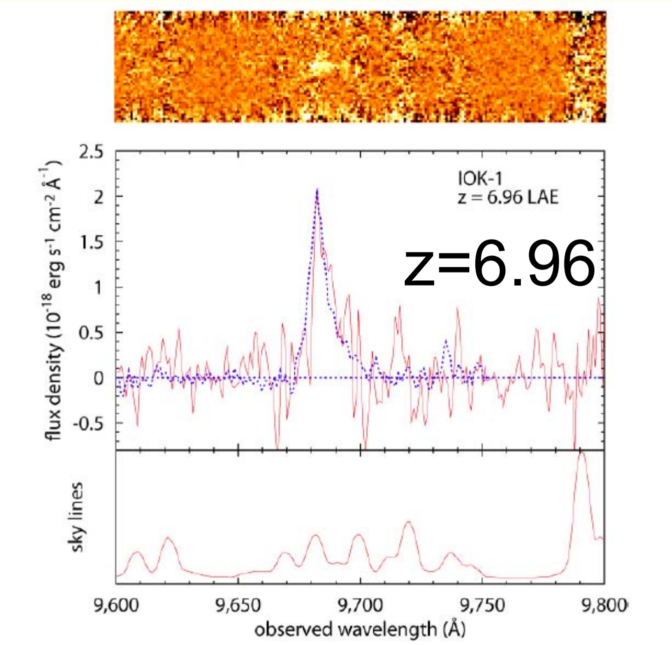
But did it really happen like this..?

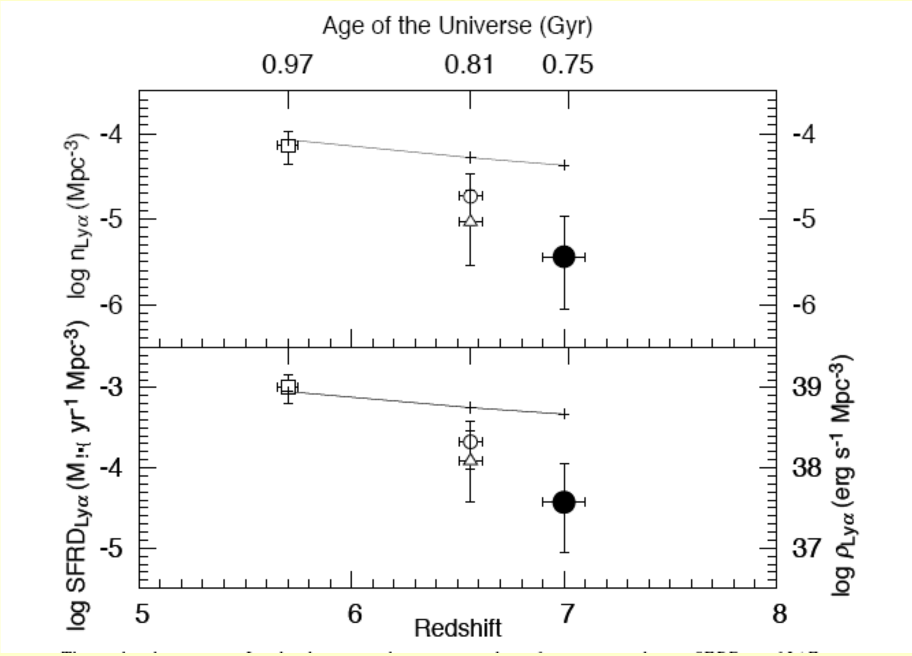
Key Questions:
When? - reionization redshift
How? - uniform/patchy? topology
What? - galaxies, AGN, other?



Fan, Carilli & Keating 2006

Ly α Galaxy LF at z>6



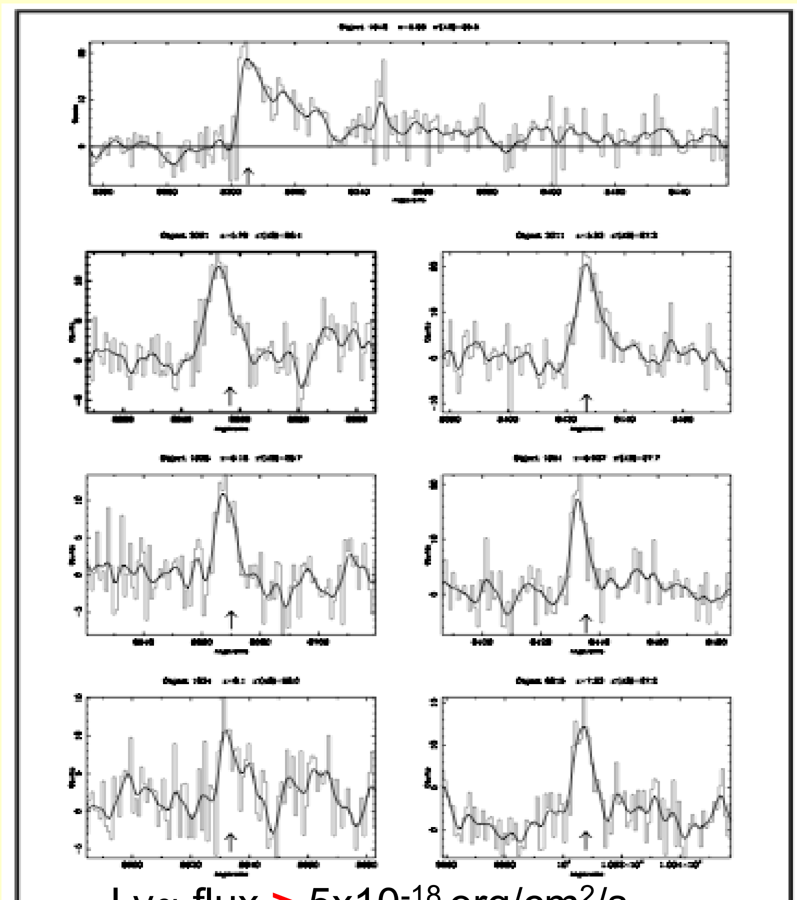


Iye et al. 2006
Kashikawa et al. 2006
Ota et al. 2007

- Neutral IGM has extended GP damping wing → attenuates Ly α emission line
- Detectability of Ly α galaxies as markers of IGM optical depth
  - Reionization not completed by z~6.5
  - **f_{HI} ~ 0.3 - 0.6 at z~7**
  - **Overlapping at z=6-7?**

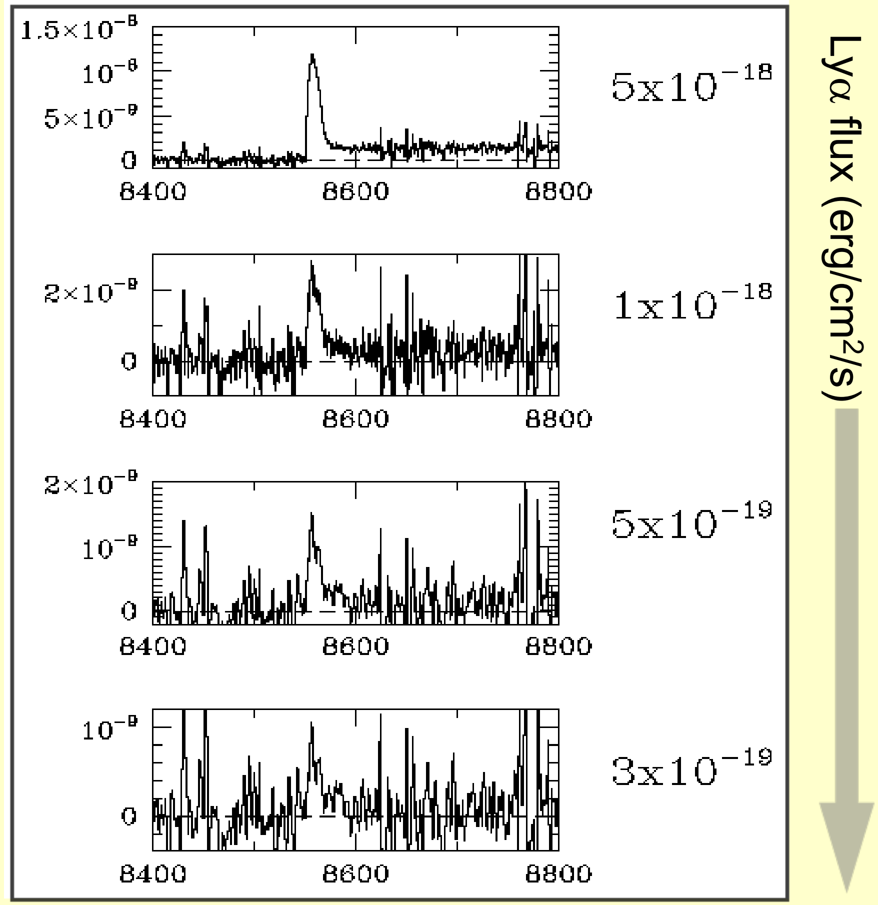
Ly-α in high-z galaxies

- GLARE survey of high-z Lyα galaxies; 36hr integration with Gemini+GMOS[Stanway et al 2006]



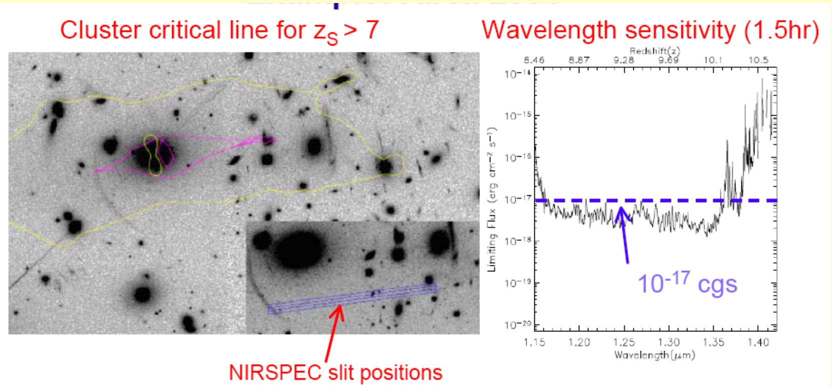
Lyα flux > 5×10^{-18} erg/cm^2/s

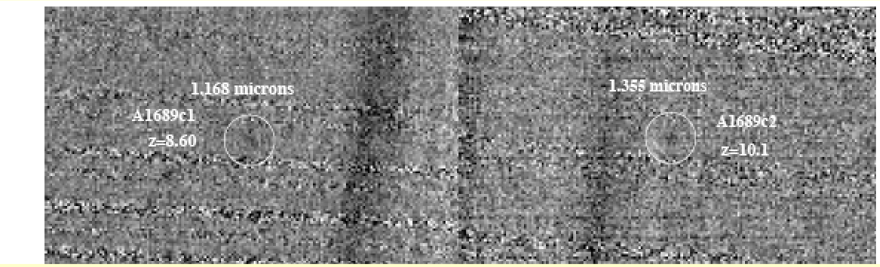
- Simulated observation of z=6 Lyα galaxy; 30hr with GMT+GMACS [McCarthy 2007]



Ground-based Ly α surveys

- DAZEL - **The Dark Age Z(redshift) Lyman-α Explorer** on VLT:
  - dedicated Ly α narrow band survey instrument for z=7 - 10
  - ~ 1 object per 10 hour field
- Keck blind spectroscopic survey along critical lines of high-z clusters
  - Six promising Lyα emitter candidates at z=8.7 - 10.2
  - Large abundance of low-L galaxies; providing sufficient reionization photons
  - Limit of current search;
- New generation of OH suppression technique and AO:
  - Ground-based surveys could find Ly α emitters at z<12





Stark et al.

Telescope JWST 6.5m	Diameter	X(Temperate)		
Magellan	6.5	0.32	0.16	0.06
Gemini, Subaru, VLT	8.2	0.50	0.25	0.10
Grantecan, Keck, SALT	10.1	0.76	0.38	0.15
ELT	30	6.7	3.4	1.4

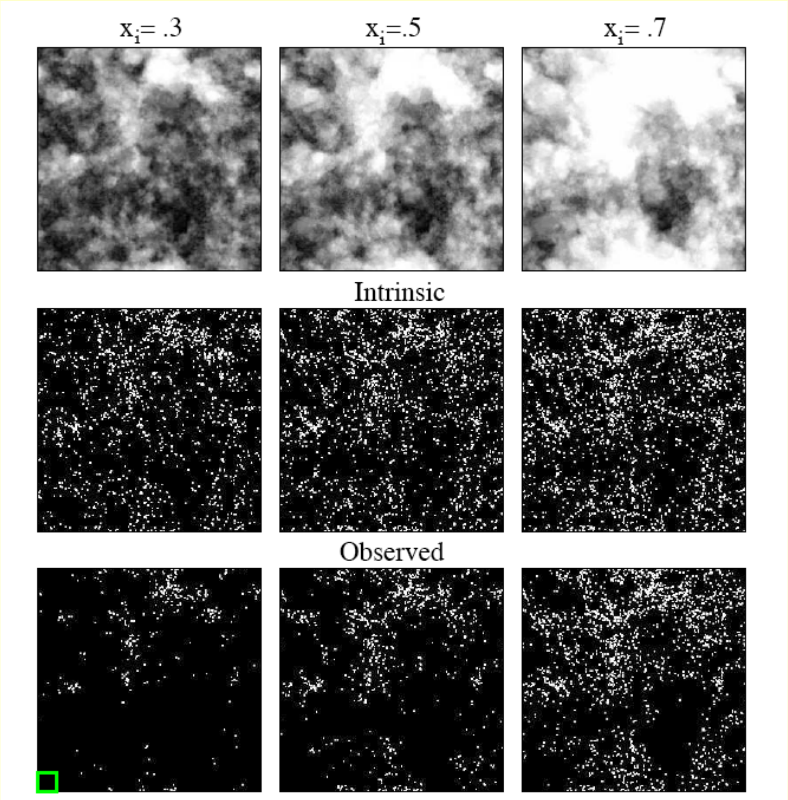
J H K

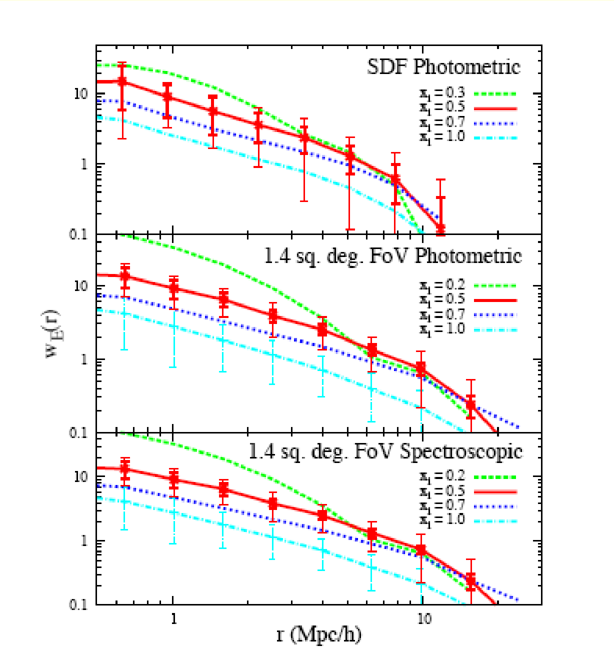
Bland-Hawthorn

Reionization Topology with Lyα Emitters

- Ly α emitter could provide sensitive probe to reionization history, especially during overlapping
  - Evolution of LF (constrain f_{HI})
  - Clustering

Distribution of Lyα emitters over 3' FOV



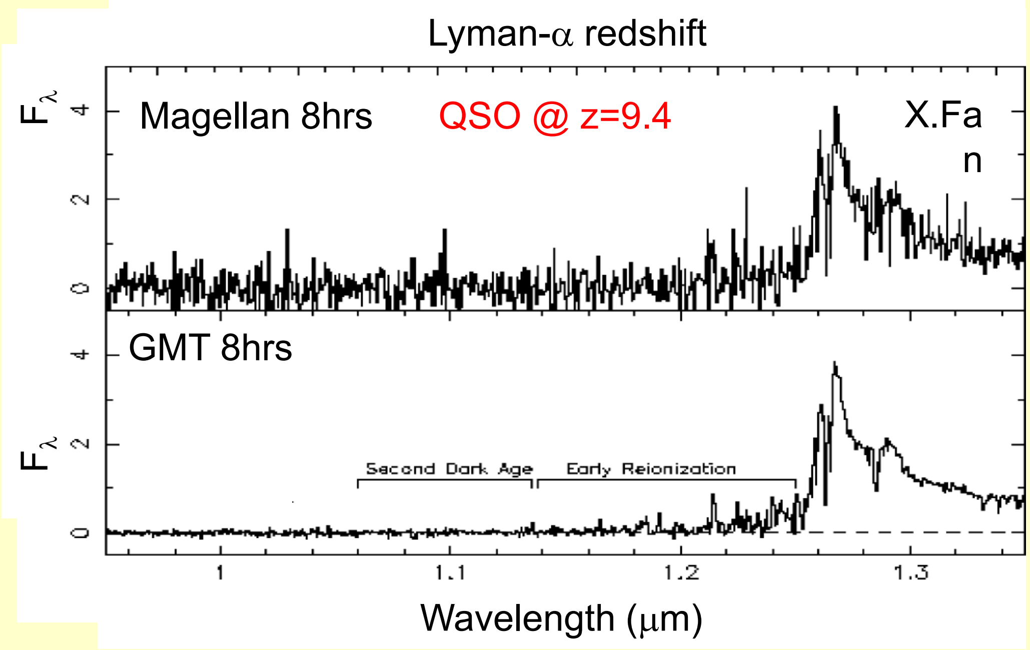


Angular correlation of Lyα emitters

Neutral $\rightarrow$ Ionized

McQuinn et al.

Probing the Neutral Era with ELT Quasar/GRB Spectroscopy

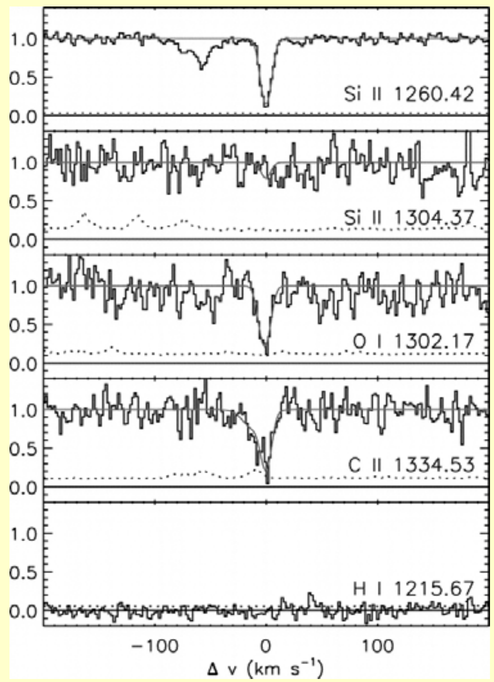


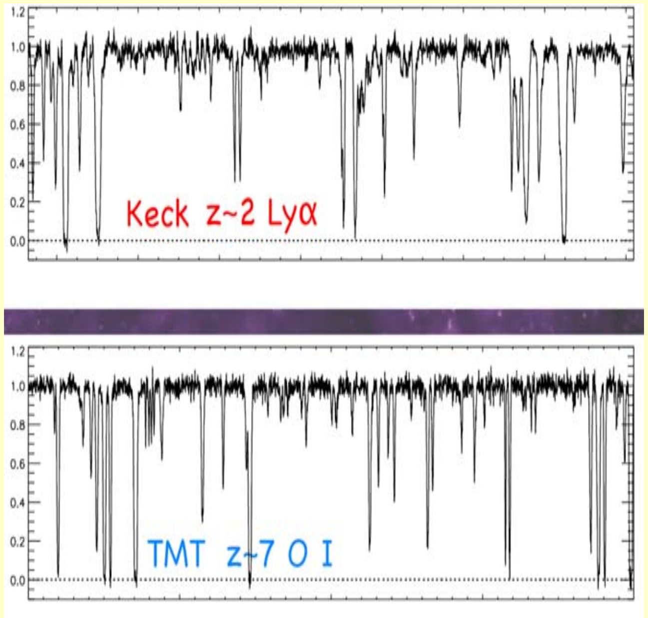
- High resolution, moderate (R~5000) resolution spectroscopy of bright quasars/GRBs will allow determination of reionization, using
  - optical depth measurements
  - distribution of dark absorption troughs
  - sizes of quasar HII regions

Reionization with OI Absorption

- OI Forest (Oh 2002)
  - OI and H have almost identical ionization potentials
  - In charge exchange equilibrium with H but much lower abundance
  - **Fluctuating OI forest during neutral era to probe ionization topology and metal pollution in the IGM**

OI system at z=6.26



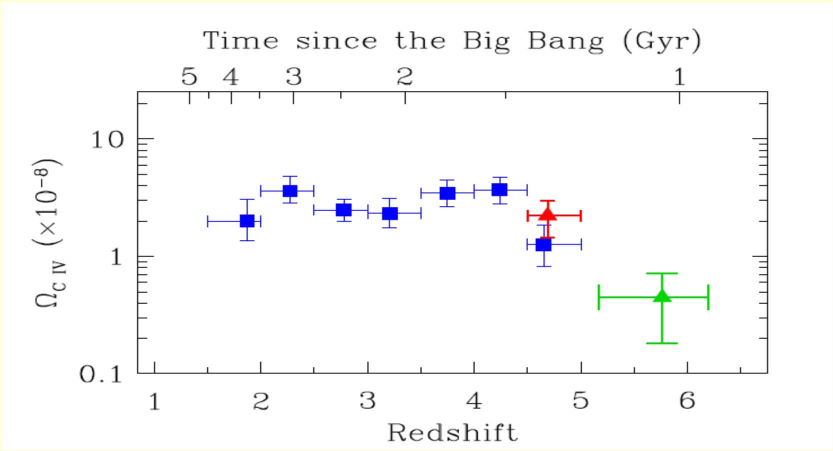


Becker et al. 2006

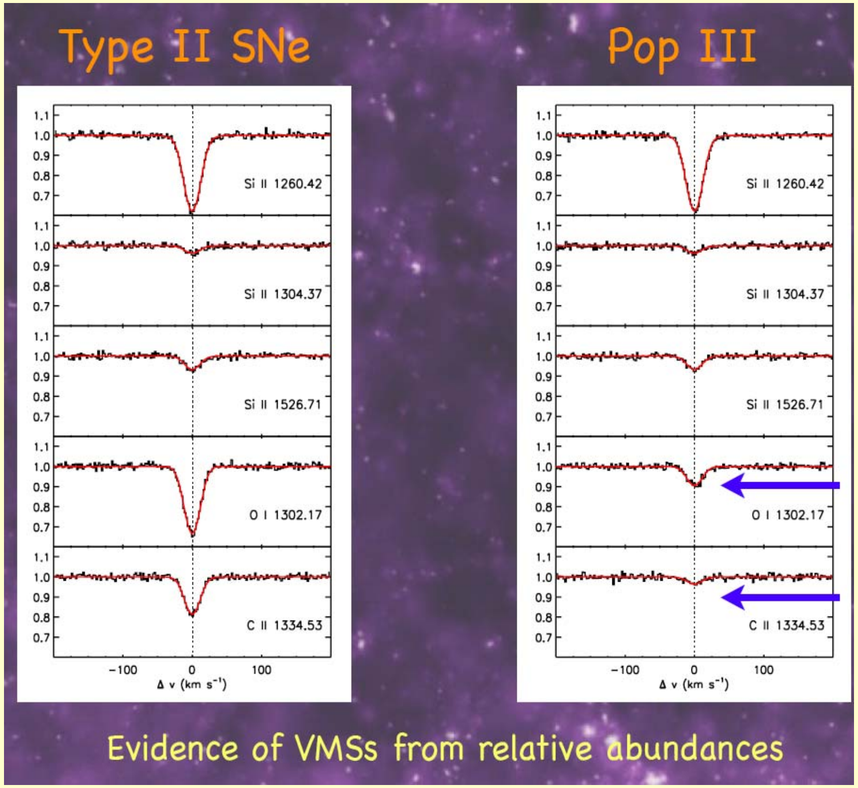
Evolution of IGM Metals

- Early Enrichment of the IGM by First stars
  - First sign of rapid evolution at z~6

Evolution of CIV systems



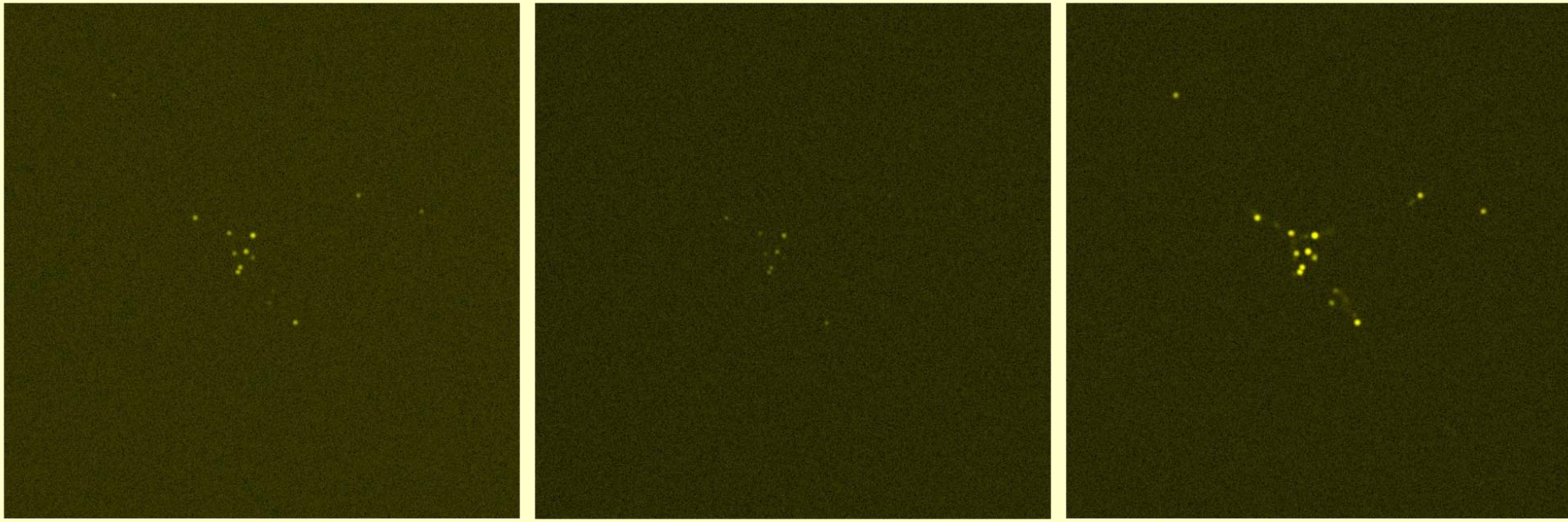
Ryan-Weber et al.



- IGM enrichment
  - •Signature of first stars
  - •Chemical feedback of earliest galaxies

G. Becker

Star-formation at z~10



Star-forming region, z~10, GMT+GLAO, R=3000 filter, 8 hours

- Lyman α 1216Å
- 20% escape fraction

- He II 1640Å
- Salpeter IMF (ext. to 500$M_\odot$)
- Zero metals

- He II 1640Å
- Top-heavy IMF (300-1000$M_\odot$)
- Zero metals

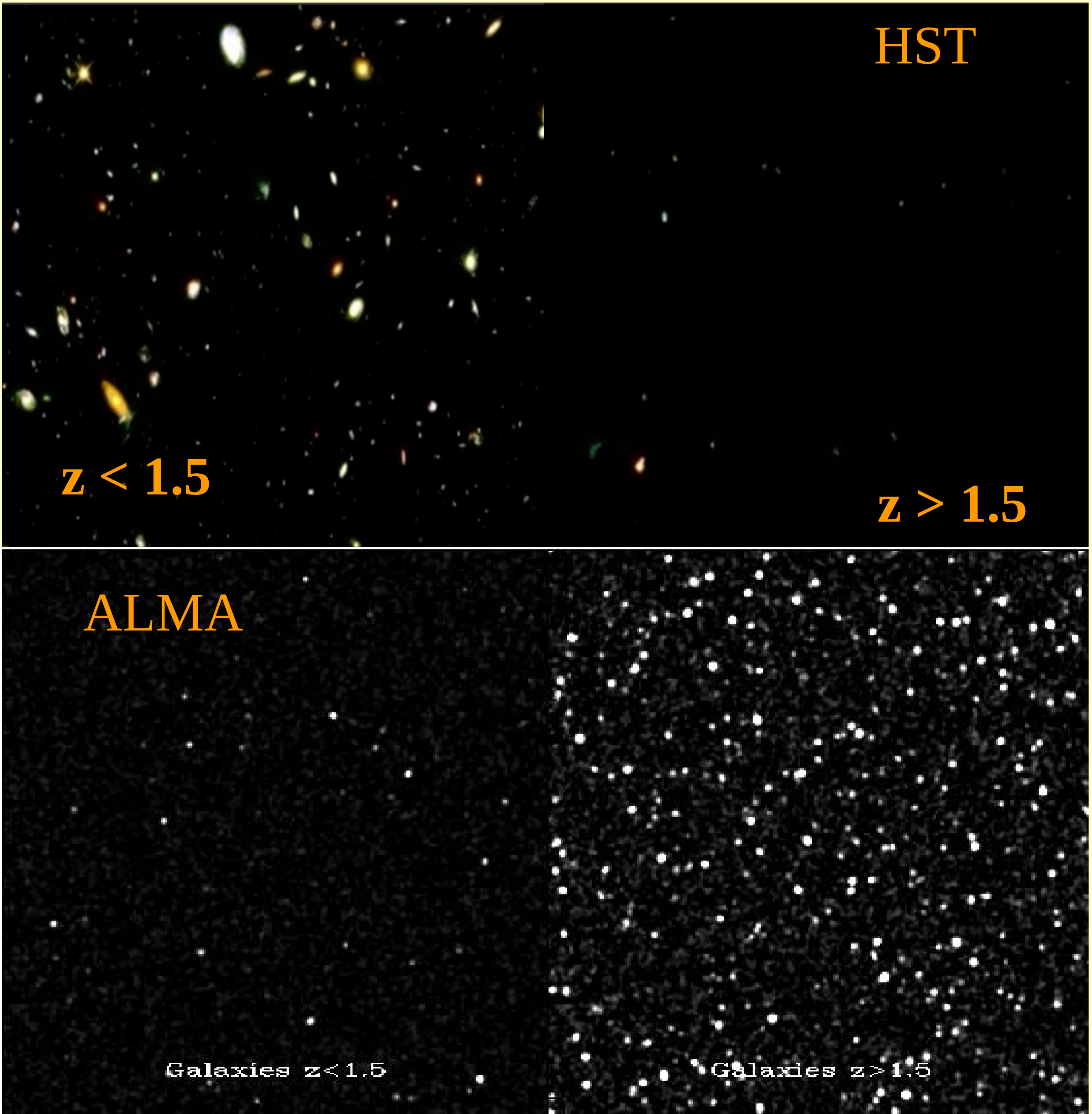
ELTs for First Light

- Highest redshift galaxies through Ly alpha
    - ***IR MOS, $D^2\Omega$, GLAO***
- Reionization history
  - Ly alpha galaxy mapping
    - ***IR MOS, $D^2\Omega$, GLAO***
  - GRBs and quasars
    - ***Single object IR spectrograph, D^4, LTAO***
  - First metals in the IGM
    - ***Single object IR spectrograph, D^4, LTAO***
  - **IGM spectscopy: unique to ELTs**
- First stars
  - HeII, signature of Pop.III
    - ***IR MOS, $D^2\Omega$, GLAO***
  - Extremely metal poor stars in the Galaxy
    - ***Single optical optical Echelle, D^2***
- **OH suppression technology will greatly enhance survey speed and observing efficiency**

ALMA/ELT Synergy

- ALMA, ELT are complementary probes of the first light and reionization
  - ALMA as z-machine for faint high-z galaxies
  - ALMA directly traces ISM, star formation and gas dynamics of the earliest galaxies

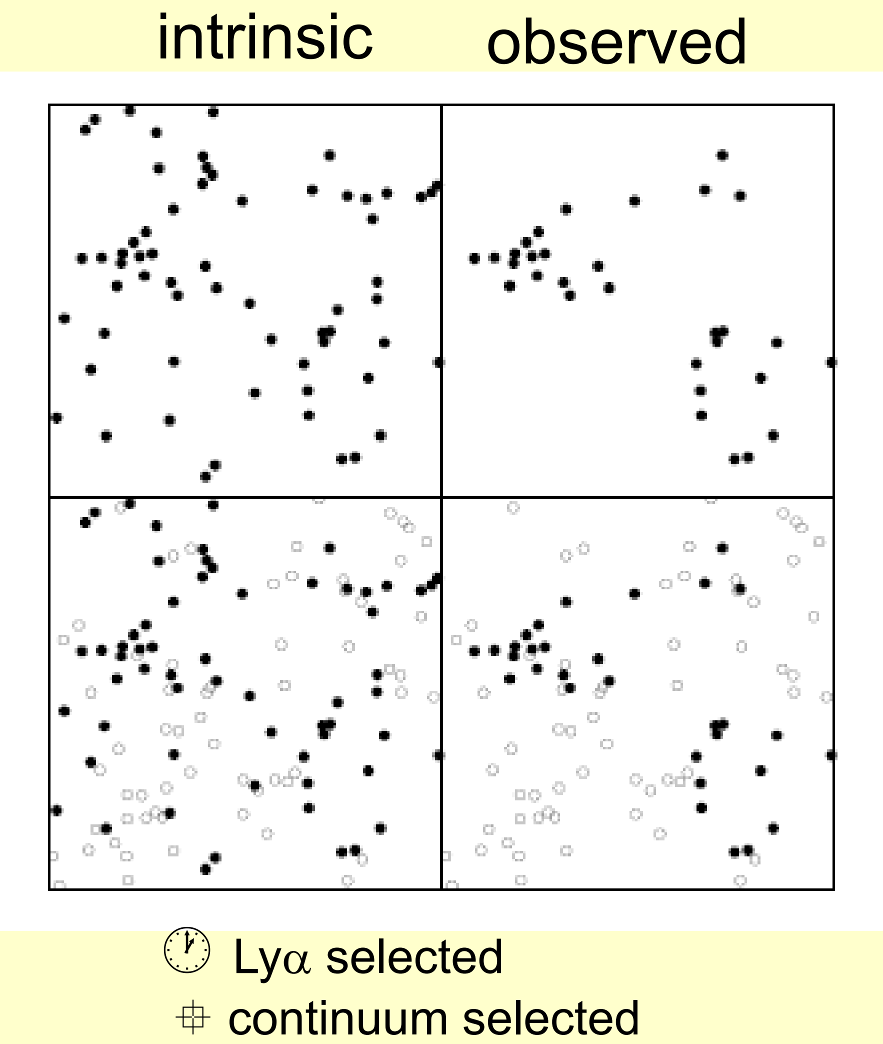
ALMA Deep field: ‘normal’ galaxies at high z



- Detect current submm gal in seconds!
- ALMA deep survey: 3days, **0.1 mJy (5σ),** 4’
- HST: few 1000 Gal, most at z<1.5
- ALMA: few 100 Gal, most at z>1.5
- Parallel spectroscopic surveys, 100 and 200 GHz: CO/other lines in majority of sources
- Redshifts, dust, gas masses
- High res. images of gas dynamics, star formation

Lyα Emitter Surveys in ELT Era

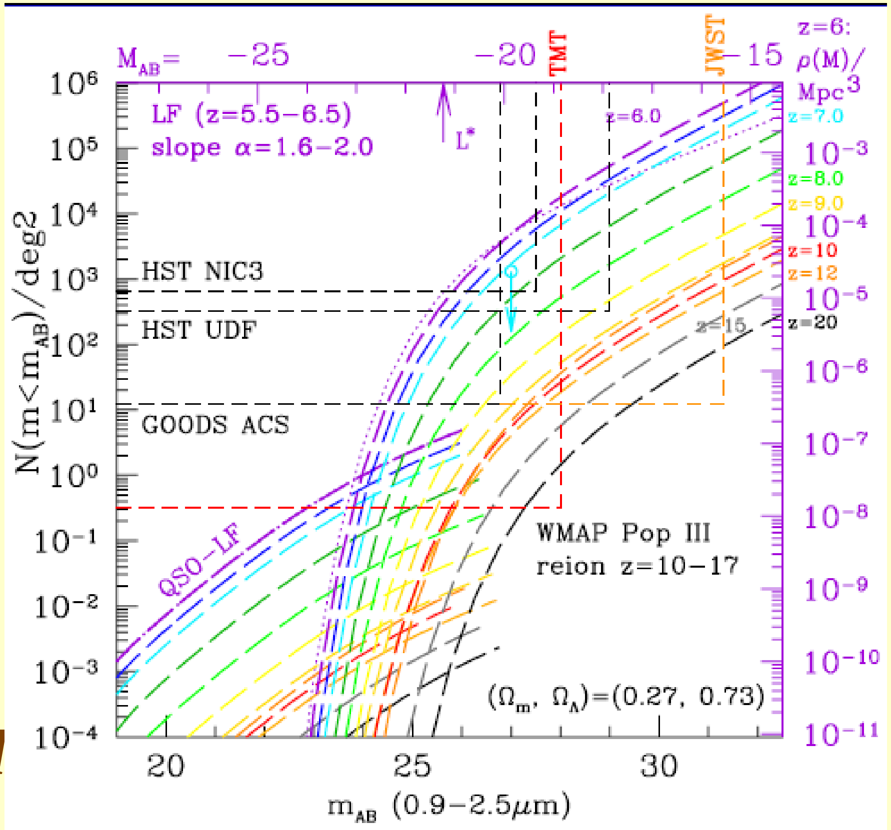
- Interpretation of Lyαgalaxies as probes of reionization alone is highly model dependent:
  - Evolution of continuum LF
  - Uncertainties in Ly α radiative transfer
  - Intrinsic clustering of galaxies etc.
- Requires surveys of continuum and SF selected samples



Rhoads 2007

Synergetic Survey of Galaxies in Reionization Era

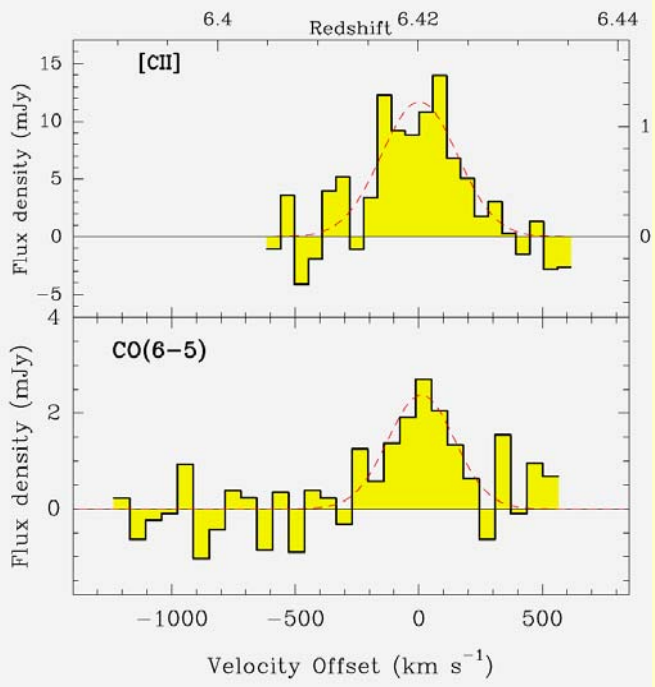
- **JWST will detect sources that reionization the Universe at z>10**
  - Ability to find high-z sources limited by whether the Universe managed to make them
- Ground-based and JWST/TFI will detect Lyα and HeII emitters to **probe reionization history and topology**
- ***ALMA will provide redshift and dust/star-formation/dynamics***
- ***Early coordination of deep field redshift surveys***

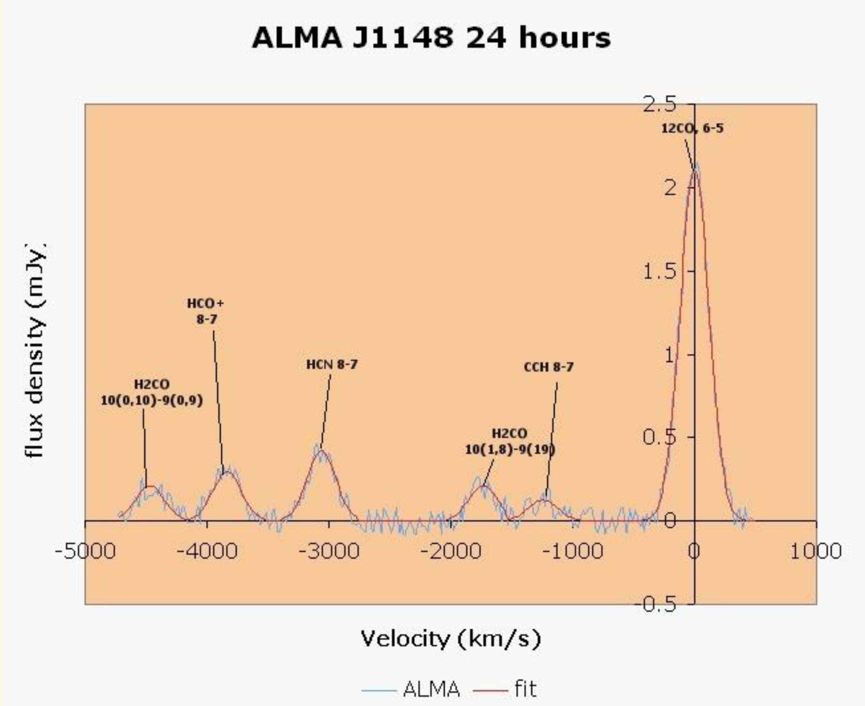


Windhorst et al.

Probing High-z Galaxy/BH Formation

- SDSS J1148+5251
  - $z=6.42$, $M_{BH}=3\times10^{9}M_{sun}$
  - Fine structure lines: [CII] 158um:dominant ISM gas cooling line, from with PDRs associated with star forming clouds
- ALMA:
  - Multiple ISM lines, broad-band spectroscopy
  - Gas dynamics at sub-kpc
- ELTs:
  - Galaxy morphology and stellar properties
  - BH growth and accretion





Do the Current Instrument Concepts Fully Address Science Case Needs?

- Optical Echelle
  - Cosmic dynamics; fundamental constant; metal poor star
  - **Ospec**, **HROS**, **CODEX**
- Optical MOS
  - BAO
  - **GMACS**, **WMOS**
- NIR MOS, GLAO
  - High-z Lyman alpha
  - **NIRMOS**, **IRMS, EAGLE**
- NIR narrow field spectrograph, LTAO
  - Reionization, first metal, SNe1,
  - **GMTNIRS**, **NIRES**, **HARMONI**
- NIR IFU, LTAO
  - lensing, BH
  - **GMTIFS**, **IRIS**, **EAGLE**
- Things to keep in mind...
  - **fast response?**
  - **Multiobject Echelle?**

Closing thoughts

- Future with the ELTs is bright for observational cosmologists
  - Ground-breaking experiments (eg Hubble expansion test) and new frontiers (eg first light)
  - Well-planned and complimentary instrument concepts
  - Strong synergy with ALMA; early coordination of legacy surveys?
- Two key areas of technology developments?
  - OH suppression in near-IR
  - Frequency comb for high resolution wavelength calibration
- Are we ready for the unknown-unknowns?
  - New classes of rare objects?
  - Transient events from LSST?
  - Fast, high efficiency response (mainly spectroscopy?)

Instrument Concepts

Concept	Function	λ range (microns)	Resolution ($\lambda/\Delta\lambda$)	FoV	
GMACS	Optical Multi-Object Spectrometer	0.35-1.0	1400-2500 (250-4000?)	MOS: 8’x18’	✓
NIRMOS	Near-IR Multi-Object Spectrometer	1.0-2.5	Up to ~4000	Imaging: 7’x7’ MOS: 5’x7’	✓
QSpec	Optical High Resolution Spectrometer	0.3-1.05	30K 1” slit	3” + fiber mode	✓
SHARPS	Optical High Resolution (Doppler) Spectrometer	0.4-0.7	150K	7 x 1” fibers	?
GMTNIRS	Near-IR High-Resolution Spectrometer	1.2- 5.0	25K-100K	Single object	✓ ✗
MIISE	Mid-IR Imaging Spectrometer	3.0-25.0	1500	30”	✓
HRCam	Near-IR AO Imager	0.9-5.0	5-5000	30”	✓
GMTIFS	NIR AO-fed IFU	0.9-2.5	3000-5000	3”	

Sensitivity and speed gains

- GMT gains most when exploiting both aperture & resolution advantages, i.e. for unresolved or barely-resolved sources
  - SMBH, 1st light, IGM (if using QSOs or GRBs as background sources)
  - Maybe for 1st gals (if star-forming regions small and dispersed)
  - Maybe for IGM (if using 1st gals as background sources)

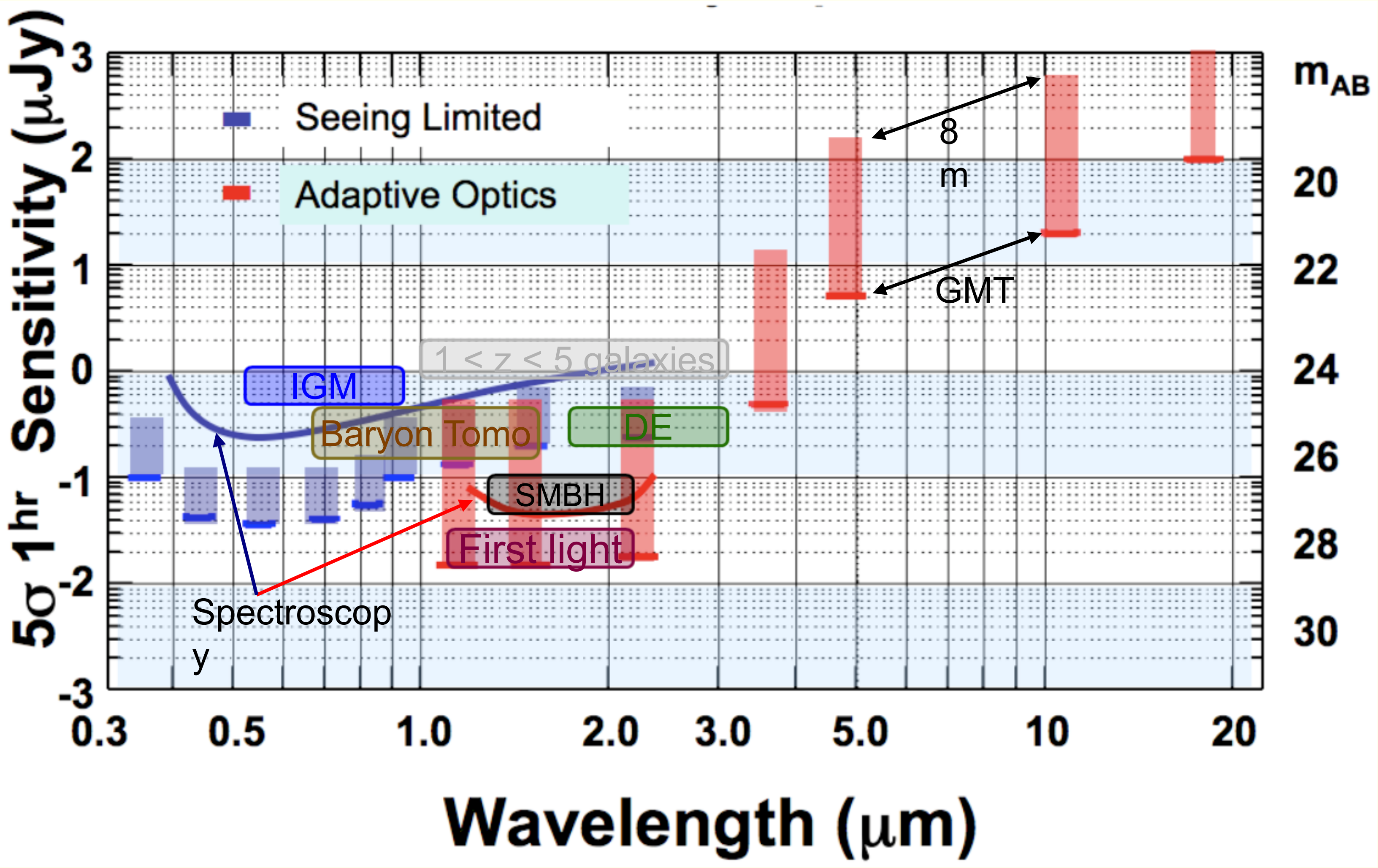
Instrument	Sensitivity	Speed	Notes
Optical Echelle	D	D^2	Sky-limited
Optical MOS	D	D^2	Seeing-limited
Near-IR MOS	D^1	$\sim D^3$	GLAO PSF
Near-IR AO-fed IFU*	D^{1-2}	D^{3-4}	Diff. limited
Near-IR Echelle	D^2	D^4	Source-limited
Mid-IR Imager	D^2	D^4	Sky-limited
PRV Echelle	D	D^2	Source-limited
Near-IR AO Imager	D^2	D^4	Sky-limited

  - But key science is not necessarily aligned with main instrumental gains

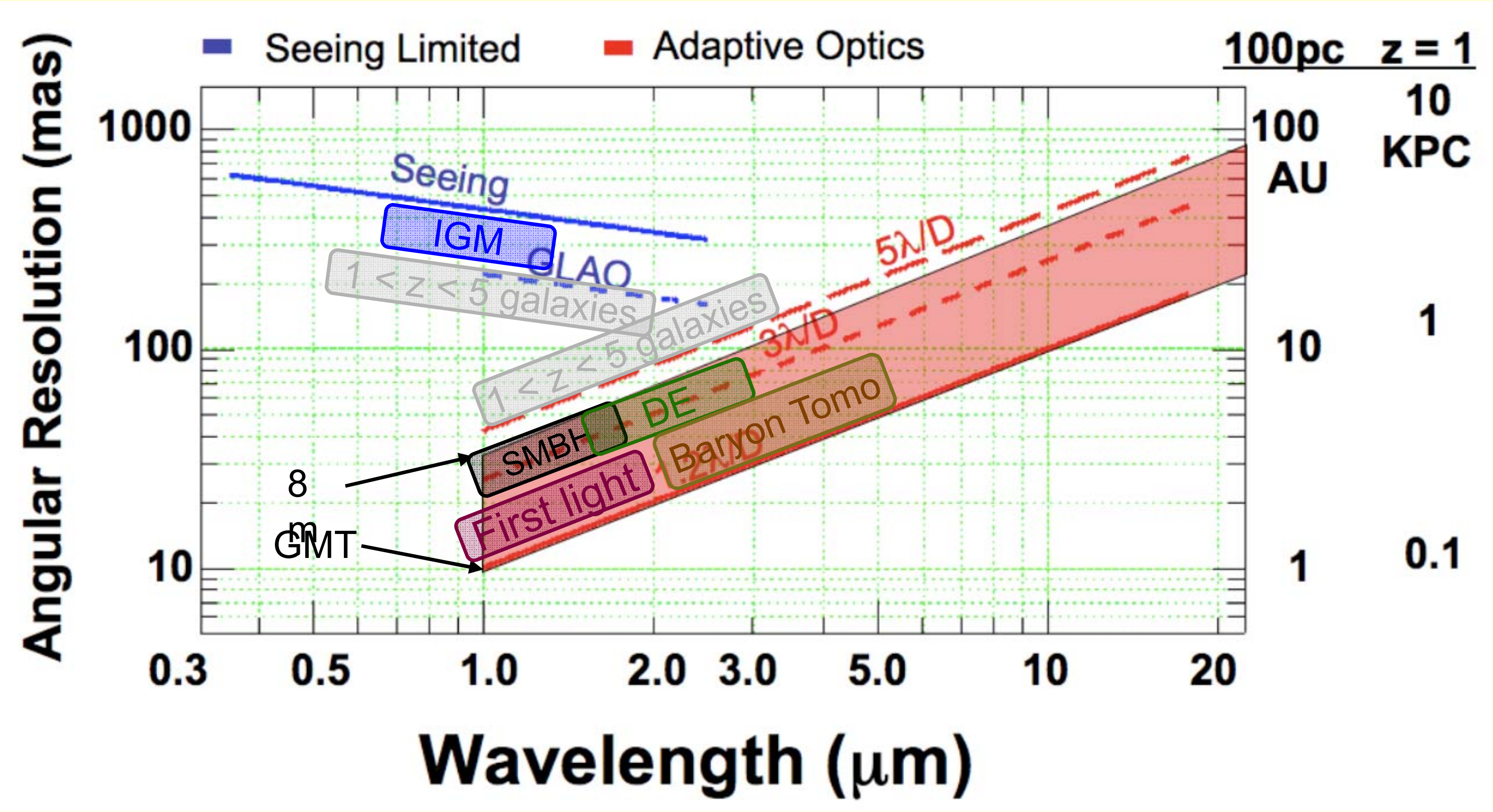
Applicability of GMT instruments

Instrument	λ range (microns)	Resolution	FOV	Applications
Optical Multi-Object Spectrometer	0.35-1.0	250-4000	18' x 18' MOS/imager	hi-z gals, IGM, 1st light, SMBH
Near-IR Multi-Object Spectrometer	1.0-2.5	Up to ~4000	7' x 7' MOS/IFU/imager	hi-z gals, IGM, 1st light, SMBH
Optical High Resolution Spectrometer	0.3-1.05	45K 1" slit	3" + fibre mode	IGM, BaryTom,
Near-IR Echelle	1.0 - 5.0	50-120K	Single Object	IGM, BaryTom
Mid-IR Imaging Spectrometer	3.0-25.0	1500	30"	
Near-IR AO Imager	0.9-5.0	5-5000	30" imager	1st light, SMBH, hi-z gals
NIR AO-fed IFU	0.9-2.5	3000-5000	1.5" IFU	IGM, BaryTom

Sensitivity discovery space



Angular resolution discovery space

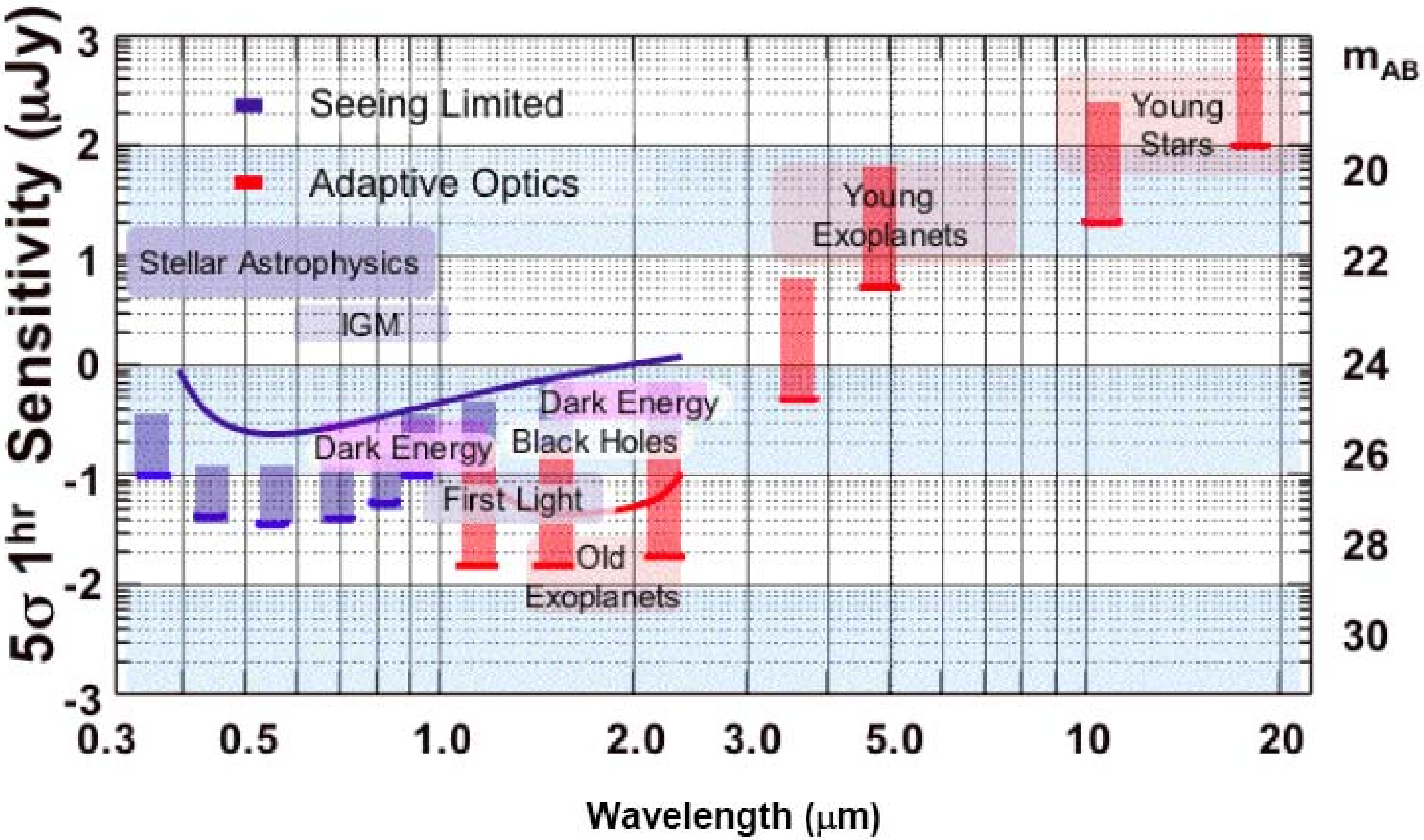


FoV, MOS & AO mode benefits

- The various science goals have different demands on FoV, the available modes of multi-object spectroscopy and AO
  - FoV is highly beneficial for cosmology/distant universe science
  - MOS + GLAO is broadly applicable (esp. good for baryon tomography)
  - LTAO/MOAO benefits IFU/multi-IFU applications (SMBH/hi-z galaxies)

Science	FoV?	MOS?	IFU?	MIF?
Cosmic expansion from primary distance indicators	✓✓	✓	✓	✗
The highest redshift galaxies (z>10)	✓✓	✓	✓	✓✓
Galaxies & AGN at the end of re-ionisation (z=5-10)	✓✓	✓	✓	✓✓
Astrophysics of high-redshift galaxies	✓✓	✓	✓	✓✓
Astrophysics of massive black holes	✗	✗	✓✓	✗
The assembly of galaxy haloes	✓✓	✓	✓	✓✓
Baryon tomography of the cosmic web	✓✓	✓✓	✗	✓

Adaptive optics mode	NS	GLAO	LTAO	MOAO



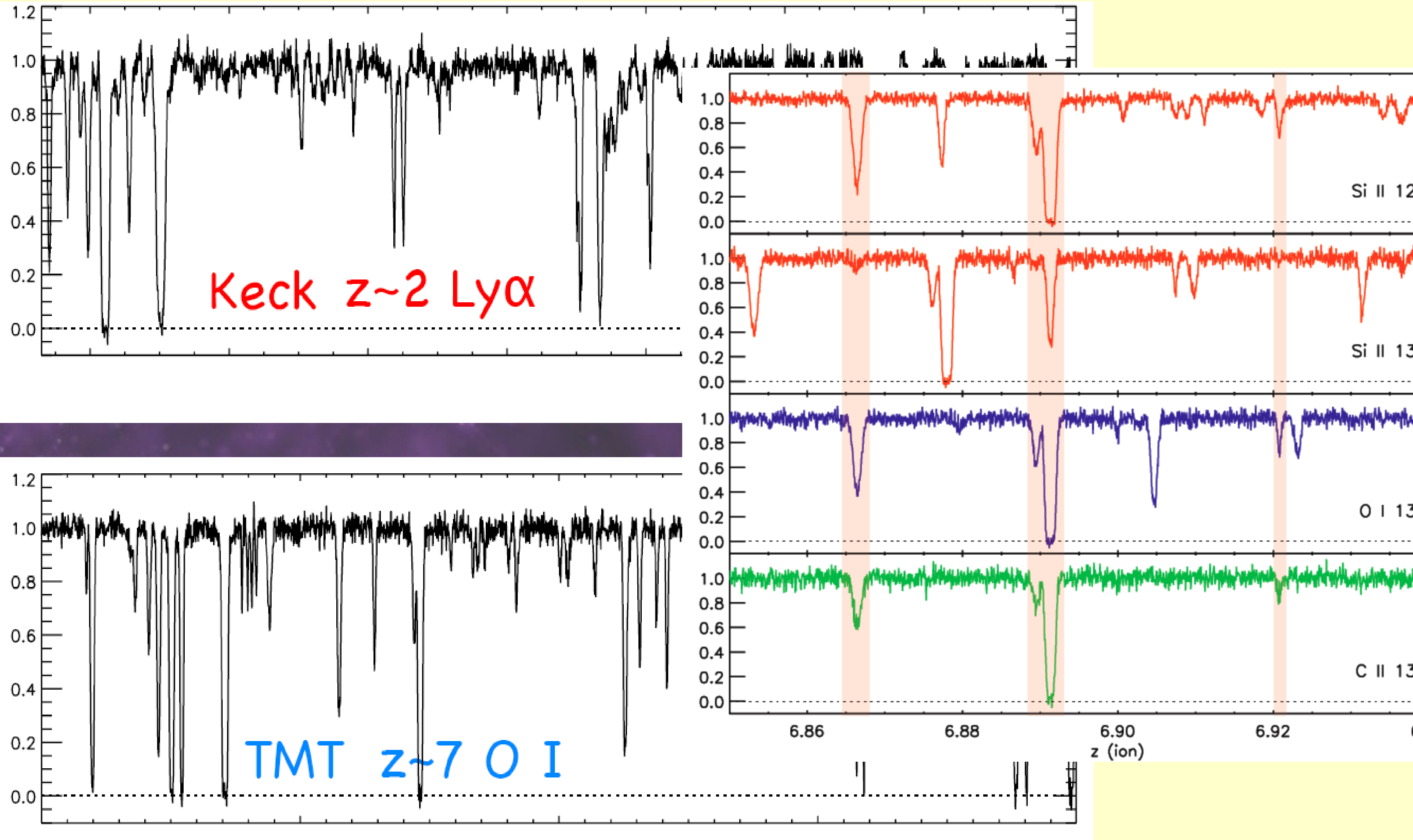
5σ 1hr Sensitivity (μJy)
3
2
1
0
-1
-2
-3
mAB
20
22
24
26
28
30
Seeing Limited
Adaptive Optics
Stellar Astrophysics
IGM
Dark Energy
Dark Energy
Black Holes
First Light
Old Exoplanets
Young Exoplanets
Young Stars
0.3
0.5
1.0
2.0
3.0
5.0
10
20
Wavelength (μm)

Instrument Studies

INSTRUMENT STUDY	MAIN OBSERVING MODES	PROCUREMENT MODUS / STATUS
EAGLE	WF, Multi IFU NIR Spectrograph. +AO	SSP / Agreement with Consortium of Institutes from France and UK
CODEX	High Resolution, High Stability Visual Spectrograph	ESO coordinates study with Institutes from Italy, Spain, Switzerland and UK
EPICS + XAO	Planet Imager and Spectrograph	ESO coordinates study with Institutes from France, Italy, Switzerland, UK
MICADO	NIR Camera sampling to the DF	Open Call / Agreement with Consortium of Institutes from Germany, Italy, The Netherlands
HARMONI	Single IFU, Wide Spectral Band Spectrograph	Open Call / Agreement with Consortium of Institutes from UK, France, Spain
MCAO Module	Provides DL images over a field up to 2’, with 2 additional DM	SSP / Agreement with Consortium of Institutes from Italy and France
MIR Instrum.	Mid IR camera /spectrograph	Open Call for fixed cost study; deadline March 08
New Concepts	Left to the bidders to propose	Open Call for up to 2 fixed cost studies; deadline May 14
LTAO Module	Provides DL images over a field <30”	Open Call for fixed cost study; deadline April 30 (tbd)

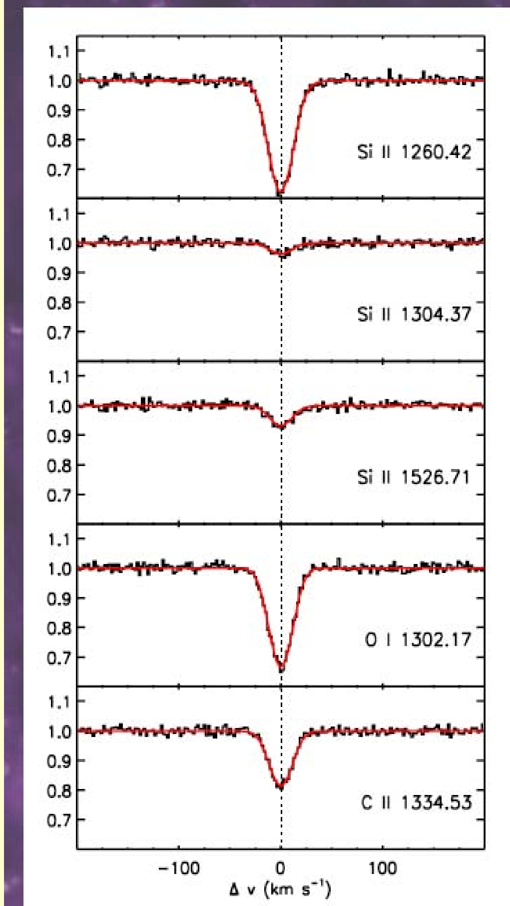
Instrument Studies

INST.	WAVELENGTH RANGE	FOV	RESOLUTION	AO MODE	LOCATION	
EAGLE	0.8 - 2.5 μm	Patrol field >= 5'	5000 (15000)	MOAO	GIF	> 20 arms
CODEX	0.37 - 0.69 μm (0.35 - 0.72 μm)		>120,000 (32,000)	GLAO	Coude	Stability: 2 cm/s over 30 years
EPICS	0.6 - 1.8 μm	2" (4")	>50	XAO (2additional DM)	Nasmyth	Contrast: NGS V<9, 10^{-9}
MICADO	0.8 - 2.4 μm	>30"		GLAO, LTAO (MCAO)	Nasmyth	Sampling of DL
HARMONI	0.8 - 2.4 μm (0.5 - 2.4 μm)	TBD	4000 (20,000)	LTAO (MCAO)	Nasmyth	
MIR INST	3 - 13 μm (16 - 20 μm)	>30"	TBD (100, 100,000)	TBD LTAO?	Nasmyth	controlling M4 with an internal WS, additional cryogenic DM

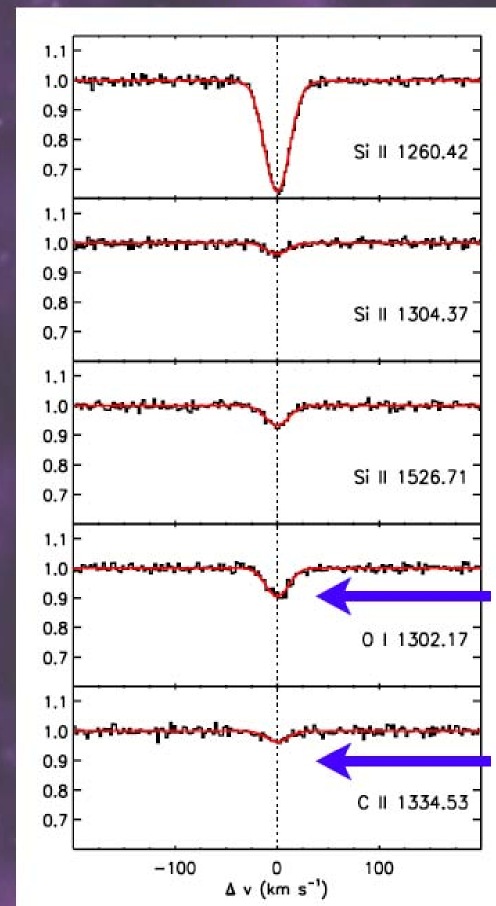


Keck z~2 Lyα
TMT z~7 O I
Si II 12
Si II 13
O I 13
C II 13
6.86
6.88
6.90
6.92
z (ion)

Type II SNe



Pop III



Evidence of VMSs from relative abundances